JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
VOL. 35, NO. 5 AMERICAN WATER RESOURCES ASSOCIATION OCTOBER 1999

CONTINENTAL SCALE SIMULATION OF THE HYDROLOGIC BALANCE[1]

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ABSTRACT: This paper describes the application of a continuous daily water balance model called SWAT (Soil and Water Assessment Tool) for the conterminous U.S. The local water balance is represented by four control volumes; (1) snow, (2) soil profile, (3) shallow aquifer, and (4) deep aquifer. The components of the water balance are simulated using "storage" models and readily available input parameters. All the required databases (soils, landuse, and topography) were assembled for the conterminous U.S. at 1:250,000 scale. A GIS interface was utilized to automate the assembly of the model input files from map layers and relational databases. The hydrologic balance for each soil association polygon (78,863 nationwide) was simulated without calibration for 20 years using dominant soil and land use properties. The model was validated by comparing simulated average annual runoff with long term average annual runoff from USGS stream gage records. Results indicate over 45 percent of the modeled U.S. are within 50 mm of measured, and 18 percent are within 10 mm without calibration. The model tended to underpredict runoff in mountain areas due to lack of climate stations at high elevations. Given the limitations of the study, (i.e., spatial resolution of the data bases and model simplicity), the results show that the large scale hydrologic balance can be realistically simulated using a continuous water balance model.
(KEY TERMS: surface water hydrology; modeling/statistics; evapotranspiration; plant growth; geographic information systems.)

INTRODUCTION

The renewable water resources for the conterminous United States are derived from an average annual precipitation of 760 mm. Seventy percent of this rainfall is consumed through evaporation and transpiration. The remaining 30 percent of precipitation constitutes an average annual runoff of about 230 mm (WRC, 1978). Management and utilization of these resources depends upon the spatial distribution of rainfall, location of reservoirs, evapotranspiration (ET) potential, soil and groundwater storage, and water quality. All of these factors vary from basin to basin. Continental scale maps representing some of the above components have been prepared such as annual runoff (Langbein, 1980) and precipitation-evaporation (Winter, 1990). While important in illustrating regional trends, these studies do little toward assessing the potential interaction of the components of the water balance. Basin scale assessments have been made to determine the adequacy of water supply regions (WRC, 1968, 1978; Hirsch *et al.,* 1990) and make projections based on estimates of population and land use, but again are not designed to account for interactions between the components of the system. Projections are made by predicting average values into the future without regard to potential thresholds or feedback loops within the system.

Water balance models attempt to predict the partitioning of water among the various pathways inherent to the hydrologic cycle (Dooge, 1992). Early models developed in the 1940s are essentially bookkeeping procedures which estimate the balance between inflow (precipitation and snowmelt) and outflow (ET, streamflow, and groundwater) (Alley, 1984). While generalized global water balance maps have been prepared, they often lack the necessary scale to be useful in even the simplest modeling efforts (UNESCO, 1978). More advanced water balance models have been used to assess the effects of land

[1]Paper No. 98053 of the *Journal of the American Water Resources Association.* **Discussions are open until June 1, 2000.**
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management, seasonal irrigation demands, prediction of streamflow and lake levels, recharge to the groundwater system, groundwater storage, and as a means of assessing the impact of vegetation on water yield (runoff, soil flow, and groundwater flow) and sediment yield (Chiew and McMahon, 1990; Winter, 1981; Essery, 1992; Thomas *et al.*, 1983; Bultot *et al.*, 1990; Arnold *et al.*, 1993). Robbins Church *et al.* (1995) developed a simple water balance equation using measured precipitation and runoff to compute ET and runoff precipitation ratios for the northeast United States. More recently, general circulation models (GCMs) have linked atmospheric models to land-surface water balance models and emphasized the importance of the land based hydrologic cycle to global energy fluxes (Wood *et al.*, 1992), and conversely, the effects of atmospheric contaminants (CO_2), on land surface runoff (Miller and Russell, 1992). Recent research on the land based component of the water balance using simplified inputs of potential evapotranspiration and soil water holding capacity (0.5 degree resolution) have shown the importance of soil storage control in the regional water balance (Milly, 1994). Liang *et al.* (1994) used a simple two layer soil storage model with a vegetation component to model surface water and energy fluxes for GCMs.

The SWAT model (Arnold *et al.*, 1998) provides the modeling capabilities of the HUMUS (Hydrologic Unit Model of the United States) project (Srinivasan *et al.*, 1993). The major components of the HUMUS project are: (1) SWAT to simulate surface and subsurface water quality and quantity; (2) a Geographic Information System (GIS) to collect, manage, analyze, and display the spatial and temporal inputs and outputs (Srinivasan and Arnold, 1994); and (3) relational data bases required to manage the non-spatial data (Figure 1). HUMUS simulates the hydrologic budget, sediment and nutrient movement for approximately 2,100 8-digit hydrologic unit areas as delineated by the USGS. Findings of the project are being used in the Resource Conservation Act (RCA) Assessment conducted by the Natural Resources Conservation Service. Planning scenarios include agricultural and municipal water use, tillage and cropping system trends, and fertilizer/manure management.

The purpose of this study is to present findings of the HUMUS continental scale modeling effort of all the major river basins of the conterminous United States as they relate to regional runoff and water supply. This modeling effort has been validated against average annual runoff using all existing gaging stations of the USGS. The modeled results allow assessment of spatial variations in runoff of the conterminous United States. If runoff can be simulated with reasonable accuracy, the model can then be validated for sediment and nutrient yields for further NRCS national agricultural policy scenarios. Results should also allow for more accurate assessments of the effects of land use changes and water management initiatives as well as provide a tool for parameterization of GCMs.

THEORETICAL FRAMEWORK

Overview

The overriding objective of this study is to develop the most realistic physical representation of the water balance possible while utilizing data that is readily available for large regions of the U.S. This requires that model input parameters are physically based and that calibration is not attempted. Most model input parameters are physically defined such as topography (slopes and flow lengths), soil properties (texture, bulk density, saturated conductivity, etc.) and plant characteristics (biomass to energy conversions, maximum height and rooting depth, etc.). Some of the relationships used in the model, such as the curve number, are based on physical properties such as soil type and land use and do not require calibration (i.e., measured stream flow and ET are not required). However, there is often considerable uncertainty in model inputs due to spatial variability and measurement errors. In most watershed studies, inputs are allowed to vary within a realistic uncertainty range for calibration and validation then is performed on another period of data. In this study, the model was only validated using average annual runoff.

The other main objective of this study is to develop the ability to simulate the impact of climate and land use changes on the water balance. Climate change scenarios include projected annual and seasonal changes in precipitation, temperature, and CO_2. Land use scenarios include vegetative changes (i.e., forest to agricultural land) and cropping system changes. This requires the ability to simulate tillage systems and nutrient/pesticide application scenarios.

Spatial and Temporal Variability

A common approach in simulating the water balance of large areas is to subdivide the area into homogeneous modeling subareas. Although there are numerous discretization schemes that are possible, we chose to use soil associations as the basis for modeling subareas. The dominant (by area) soil series, and the corresponding physical properties, for each soil association polygon were used. While, there is

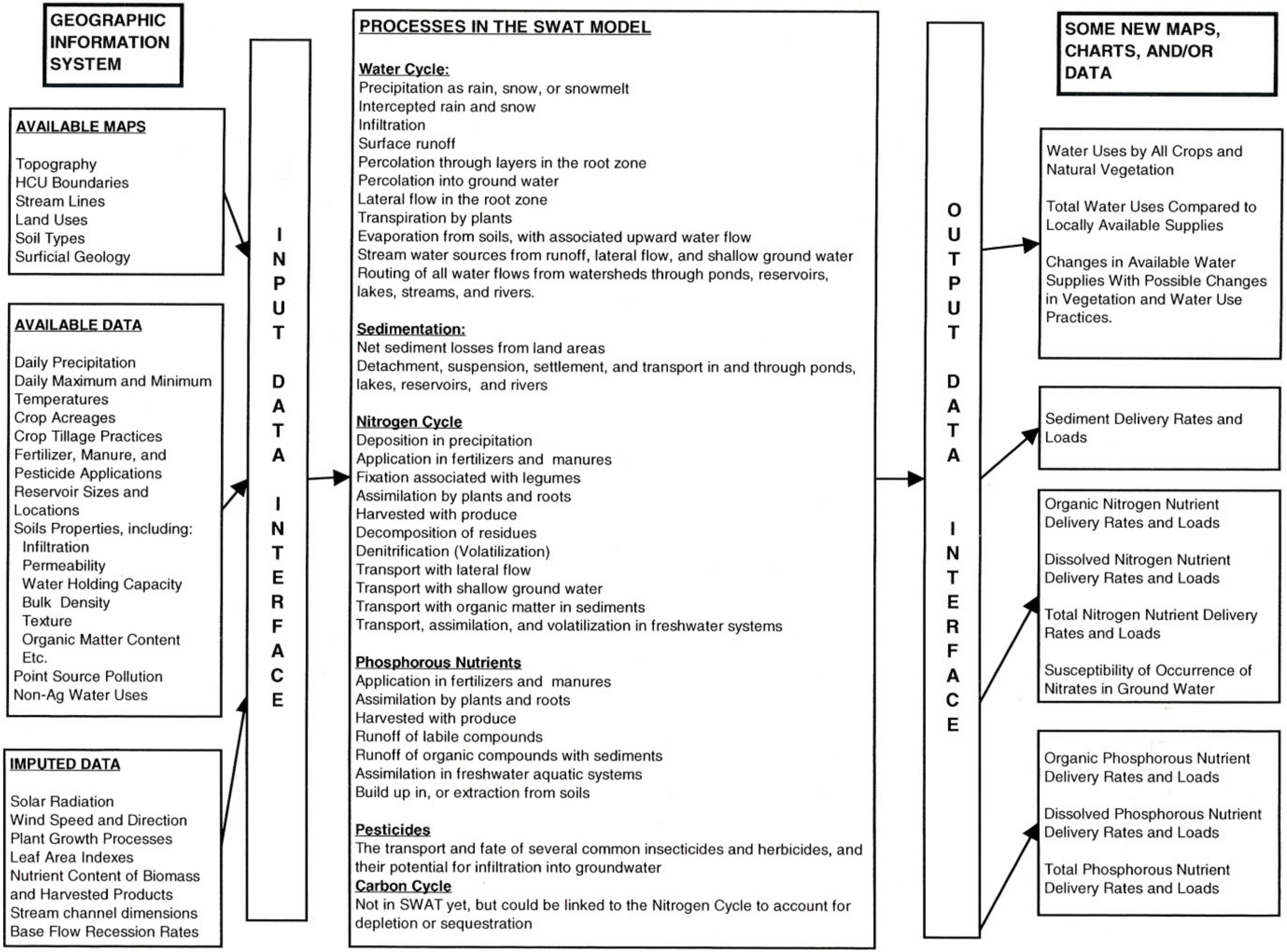


Figure 1. The HUMUS Project System.

considerable variability in soil hydraulic properties even at relatively small scales (Warrick and Nelson, 1980), some lumping of soil properties must be made since available regional-scale data bases do not include sufficient spatial detail.

Vertical variability within the polygon is modeled by dividing the water balance into three control volumes; the soil profile, shallow aquifer, and deep aquifer. The soil profile can be subdivided further to account for soil horizons that may have a significant impact on percolation, surface runoff, and root growth. The shallow aquifer is directly below the soil profile and is assumed to (1) actively circulate groundwater and respond rapidly to changes in discharge and recharge, (2) have relatively short travel times, and (3) supply a large percentage of baseflow to the stream (Moody, 1990). Seepage from the shallow aquifer recharges the deep aquifer. The deep aquifer does not contribute to streamflow in the model.

To represent temporal variability, the model continuously updates the water balance on a finite time step (one day). Thus, the model can run continuously for many years and describe annual and seasonal variability. A long-term regional database of weather data at sub-daily time steps is not currently available at similar spatial resolution as daily weather data. Also, a monthly time step cannot account for the variation in individual surface runoff events within the month. Daily weather data is readily available and daily stochastic weather generators (for a point) have been parameterized and such an approach has been in use for many years (Richardson, 1981).

Description of Algorithms

Water storage is divided into four distinct components as shown in Figure 2: (1) snow profile (above the ground surface), (2) soil profile (0-2 m), (3) shallow aquifer (2-50 m), and (4) deep aquifer (> 50 m). Equations and detailed descriptions are found in Arnold *et al.* (1998).

Snow Cover. The control volume for snow cover is bounded above by the snow-atmosphere interface and below by the snow-soil interface. The mass balance of water in the snow control volume consists of snow fall, snow melt and sublimation.

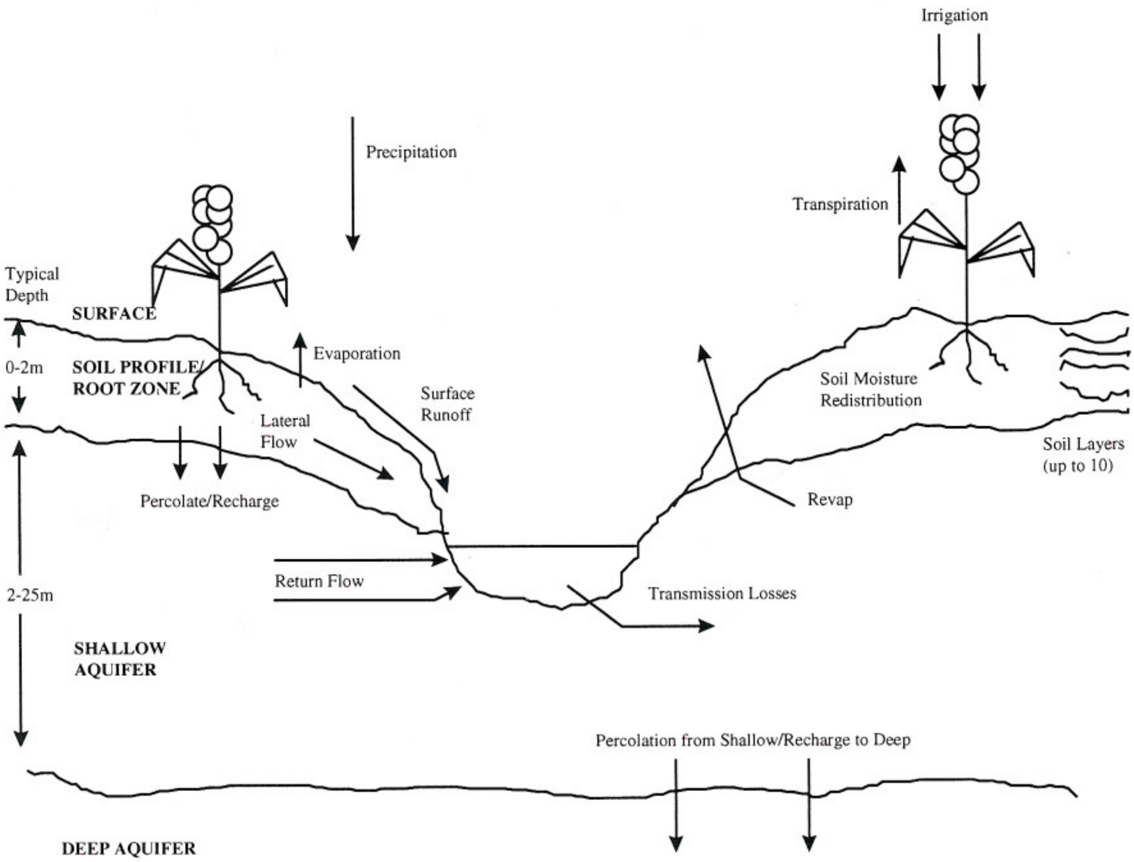


Figure 2. Schematic of Subbasin Hydrologic Balance.

Soil Profile. The upper boundary of the soil profile is the soil-atmosphere (or soil-snow if snow is present) interface. The lower boundary corresponds to the average rooting depth of the vegetation. This normally coincides with the depth that the soils have been characterized in soil surveys and is less than two meters. Since a modeling subarea is considered homogeneous, the horizontal extent of the soil control volume is irrelevant (soil heterogeneity and topographic effects are neglected). However, it should be noted that horizontal water flux between subareas is not considered. Processes simulated include: surface runoff, lateral soil flow, percolation, evapotranspiration, soil temperature, plant growth, and management (irrigation, fertilization and residue management).

Shallow Aquifer. Ground water flow systems can be classified into three types of depth and proximity to surface drainage features: (1) shallow, (2) intermediate, and (3) regional flow systems (Toth, 1963). The shallow flow systems: (1) actively circulate ground water and respond rapidly to changes in discharge and recharge, (2) have relatively short travel times, and (3) supply a large percentage of base flow to the stream (Cannon, 1989). The shallow ground water flow component in SWAT is intended for general use where extensive field work to obtain inputs (pump tests, etc.) is not feasible and thus the model must use readily available inputs. For more detailed, site-specific studies, Sophocleous *et al.* (1999) have linked SWAT to MODFLOW, a two-dimensional ground water flow model.

The shallow aquifer control volume is bounded above by the soil-shallow aquifer interface and below by the interface with the deep aquifer. Typical depth of the shallow aquifer is 2-25 m and processes simulated include return flow, plant water uptake, percolate to the deep aquifer, and water withdrawals. A complete description of the ground water flow component is found in Arnold *et al.* (1993).

Deep Aquifer. It is assumed that there is no interaction between the deep aquifer and the stream. Also, no underflow is allowed to occur from one modeling subarea to another. Processes simulated in the deep aquifer are percolate from the shallow aquifer and water withdrawals.

PREVIOUS MODEL VALIDATION

Ideally, we would like to validate all simulated components of the hydrologic balance (surface runoff, groundwater flow, ET, recharge, etc.) with measured estimates for the entire U.S. Unfortunately, measured estimates of the individual components of the hydrologic balance are not generally available. However, the SWAT model has been compared against measured components of the hydrologic balance at several locations throughout the U.S. Table 1 shows the location, reference, basin area, and validated components for each location. These locations represent a wide range of soils, land use, climate, and topography. The most comprehensive testing was performed for three basins in Illinois (Arnold and Allen, 1996). Schicht and Walton (1961) used precipitation, streamflow, and groundwater level data to ascertain groundwater recharge, runoff, and ET for all three basins. This data was then compared against SWAT simulated results with reasonable agreement.

A component of the model that has had limited testing is ET. Monthly simulated ET was compared against measured ET from lysimeters growing corn and bluegrass. The impact of irrigation on annual ET and corn yields at Bushland, Texas, was simulated by the model illustrating corn yield response to increasing volumes of irrigation water (Arnold and Williams, 1985). Arnold and Stockle (1991) demonstrated the models ability to simulate dryland wheat yields under extreme differences in climate and soil conditions. While the runoff validation in this study only compares average annual values, it is important to note that the model has been validated against monthly time series and is capable of simulating seasonal variability. Numerous studies (Table 1) confirm that this modeling approach is capable of simulating realistic monthly time series of runoff, and several other components of the hydrologic balance across the U.S.

APPLICATION

The model presented in the section entitled "Theoretical Framework" was tested for its ability to reproduce components of the annual water balance. The test region is the entire coterminous United States. The first part of this section describes how the input variables were estimated. All the required databases (soils, land use and DEM) were assembled at 1:250,000 scale. A GIS interface (Srinivasan and Arnold, 1994) was utilized to automate the assembly of the model input files from map layers and relational databases. The hydrologic balance for each soil association polygon (78,863 nationwide) was simulated for 20 years using dominant soil and land use properties. Channel and impoundment routing were not simulated and thus inputs were not developed.

TABLE 1. Model Validation Studies.

Location	Reference	Drainage Area (km^2)	Water Yield/ Streamflow	Soil Water	Surface Runoff	Base Flow	Soil ET	GW ET	GW Recharge	Plant Biomass
1. Middle Bosque River, Texas	Arnold *et al.* (1993)	471	X		X	X			X	
2. Coshocton, Ohio	Arnold and Williams (1985)	lysimeter					X			
3. Bushland, Texas	Arnold and Williams (1985)	field plot					X			X
4. Riesel, Texas	Savabi *et al.* (1989)	1.3	X	X			X			
Sonora, Texas	Savabi *et al.* (1989)	4.1	X	X						
5. Seco Creek, Texas	Srinivasan and Arnold (1994)	114	X							
6. Neches River Basin, Texas	King *et al.* (1999)	25,032	X							
7. Colorado River Basin, Texas	King *et al.* (1999)	40,407	X							
8. Lower Colorado, Texas	Rosenthal *et al.*	8,927	X							
9. White Rock Lake, Texas	Arnold and Williams (1987)	257	X							
10. North Carolina	Jacobson *et al.* (1995)	4.6	X		X					
11. Goose Creek, Illinois	Arnold and Allen (1996)	246	X	X	X	X	X	X	X	
12. Hadley Creek, Illinois	Arnold and Allen (1996)	122	X	X	X	X	X	X	X	
13. Panther Creek, Illinois	Arnold and Allen (1996)	188	X	X	X	X	X	X	X	
14. Goodwin Creek Watershed, Mississippi	Binger *et al.* (1996)	21.3	X							
15. Watersheds in: Oklahoma, Ohio, Georgia, Idaho, Mississippi, Vermont, Arizona	Arnold and Williams (1987)	9.0-538	X							
16. Bushland, Texas Logan, Utah Temple, Texas	Arnold and Stockle (1991)	field plot								X

The remainder of the section compares the modeled annual runoff with measured estimates and presents results of other selected validation studies.

Estimation of Inputs

Digital Elevation Model (DEM) Attributes – Overland slope and slope length for each subbasin was estimated using the 3-arc second DEM. Overland slope was estimated using the neighborhood technique (Srinivasan and Engel, 1991) for each cell and calculating an average slope for the entire subbasin.

Land Use Attributes – The USGS-LUDA (land use/land cover) data (USGS, 1990) were used to develop plant inputs to the model. The dominant land use was used for each subbasin and a plant parameter database was used to characterize each crop. The broad classification used in the LUDA was urban, agriculture/pasture, range, forest, wetland, and water as categories. A heat unit scheduling algorithm was used to find probable planting dates of a land use based on location (latitude and longitude) of a subbasin, monthly mean temperature, and land use type. Due to lack of information about specific crops from the LUDA database, this study used corn as the agricultural crop across the U.S., which was thought to be appropriate since corn is the major crop grown in many parts of the U.S. and since it will have a similar impact on the water balance as other summer crops.

Soils Attributes – The STATSGO-soil association map (USDA,1992) was used for selection of soil attributes for each subbasin. Each polygon contains multiple soil series, and the areal percentage of each is given (without regard to spatial location). The dominant soil series (largest area) was selected by the GIS interface. Once the soil series was selected, the interface extracted the properties for the model from a relational database. Soil physical properties include texture, bulk density, saturated conductivity, available water capacity, and organic carbon. The curve number (CN) was assigned to each subbasin, based on land use and the hydrologic soil group of the dominant soil series.

Irrigation Attributes – This study used the STATSGO database to identify locations using irrigation due to lack of spatial irrigation databases showing irrigated agricultural areas. STATSGO reports irrigated crop yield for any crop in this table, and if the land use (from the USGS-LUDA) was agriculture, the entire subbasin was assigned as irrigated agriculture. Figure 3 shows the location of irrigated agriculture identified through above process. Using this irrigation layer the input interface created input parameters for automated irrigation application for each subbasin. The model automatically irrigates a subbasin and replenished soil moisture to field capacity when the crop stress reaches a user defined level.

Weather Attributes – The model utilized monthly weather generator parameters from approximately 1130 weather stations to simulate daily precipitation, maximum and minimum temperatures, solar radiation, wind speed, and relative humidity. The GIS interface selected the nearest weather station for each subbasin. (Figure 4). The interface also extracted and stored the monthly weather parameters in a model input file for each subbasin.

Comparisons With Observed Runoff for Entire U.S.

The model was run for 20 years to obtain average annual values of runoff to compare against observed runoff. Observed runoff was determined by Gebert *et al.* (1987) from measured streamflow from 5951 gaging stations that were unaffected by reservoirs, diversions or return flow. This analysis covered the entire U. S. for the period 1951-1980. Modeled runoff is defined as the sum of surface, lateral flow from the soil profile, and groundwater flow from the shallow aquifer which corresponds to observed runoff determined by Gebert *et al.* (1987). The model assumes that groundwater flow returns within the subbasin and that there is no net groundwater inflow or outflow. No calibration was performed and model inputs were taken without modification from the existing databases. Streamflow and potential ET were not used in developing model inputs. The modeled and observed annual runoff estimates are shown in Figures 5a and 5b. The large-scale features of the observed runoff are apparent in the simulated runoff. High values of runoff are observed from the Northeast States through the Appalachian mountains down to the northern coast of the Gulf of Mexico. Runoff decreases from east to west between the Mississippi River and the Rocky Mountains. The high runoff of the Pacific Northwest rainforest is also simulated by the model.

The difference between observed and simulated runoff is shown in Figure 6. Negative values identify areas where the model overpredicts while positive numbers signify model underprediction. The model has a general tendency to underpredict runoff in mountain areas. This is evident in Figure 6 in the Appalachian Mountains and the western U.S. This is attributed to the lack of weather data in higher elevations. Typically, weather stations in the western U.S. are located in the valleys which generally have lower

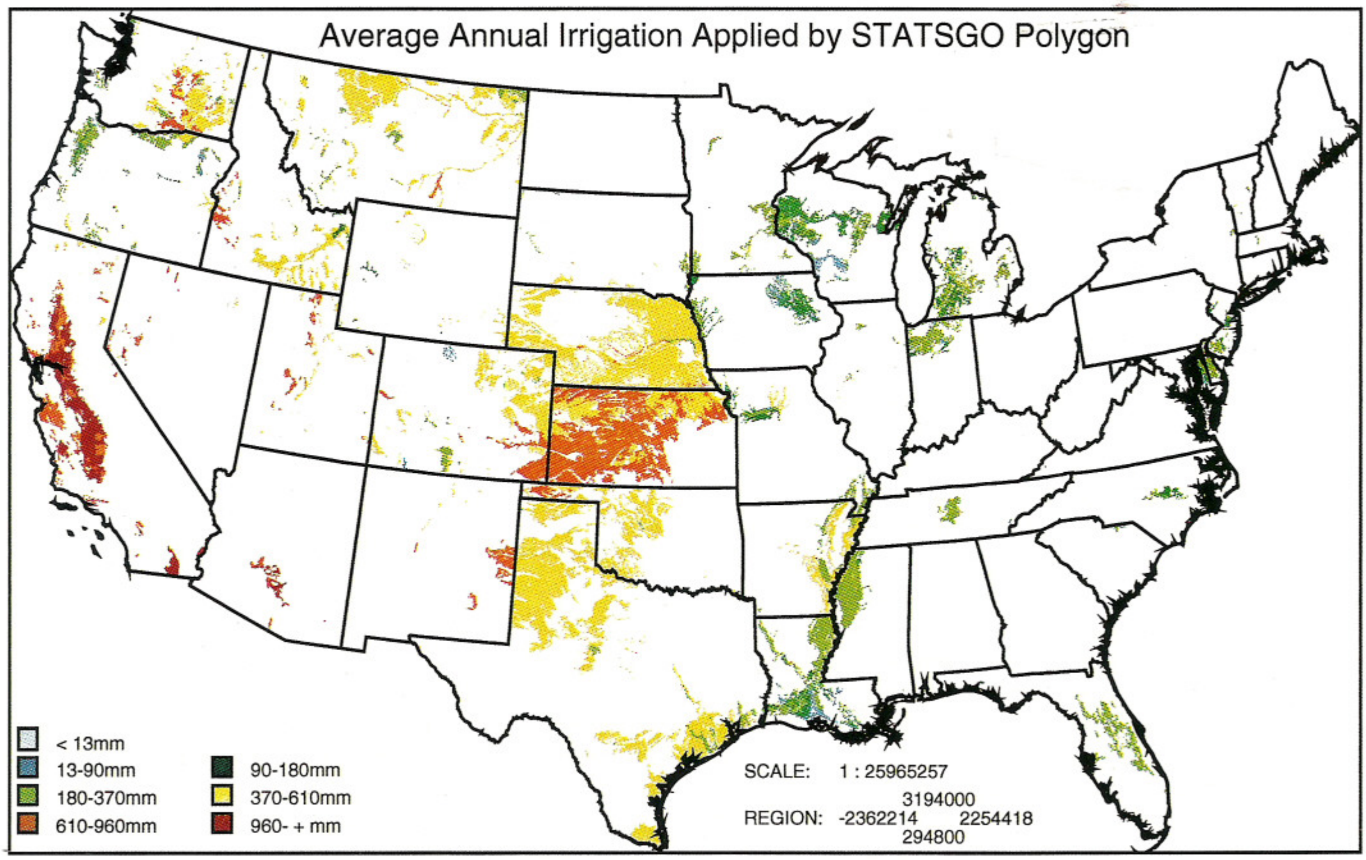


Figure 3. Location and Amount of Annual Irrigation Water Applied.

precipitation. There was not attempt in this study to correct precipitation and temperature for elevation. The model tends to overpredict runoff in areas that are irrigated (see Figure 3). This may be due to the previous assumption used in the model where irrigation was applied to the entire subbasin when the database reports that cropland within that subbasin may be irrigated. This is a limitation of the irrigation data base as well as using only the dominant soil and land use for each subbasin. It should be noted that the spatial resolution of the simulated runoff (Figure 5b) is considerably finer than the observed runoff (Figure 5a). Some discrepancies in the two maps actually may be due to lack of resolution in the observed runoff, fewer stations and more smoothing of the data set.

Summation of runoff error shows that over 45 percent of the runoff difference between modeled and observed falls within 50 mm and 18 percent fall within 10 mm. This compares well considering input uncertainty and the fact that no calibration was performed. It also compares favorably with others studies (Milly, 1994). The simple water balance model of Liang *et al.* (1994) produced major errors in peak runoff. However, the purpose of the evaluation was to provide evidence that the model is producing a reasonable soil water balance to GCMs. For that purpose, the runoff simulations of Liang *et al.* (1994) were judged adequate.

Regression analysis was performed by state (Figure 7) and by soil association polygon (Figure 8). Average runoff by state compares well with a regression slope of 0.95 and an R^2 of 0.78. The R^2 determined by comparing measured and simulated runoff for each of the 78,863 soil association polygons was lower at 0.66. The model displayed a general tendency to underpredict subareas with high runoff. This is again attributed to both the use of only the dominant soil in each polygon and the lack of a more precise irrigation database.

Figure 9 shows simulated potential and actual ET. Although validation was not performed, expected large-scale features were evident and potential ET compares favorably to the method of Thornwaite (Legates and Willmott, 1990).

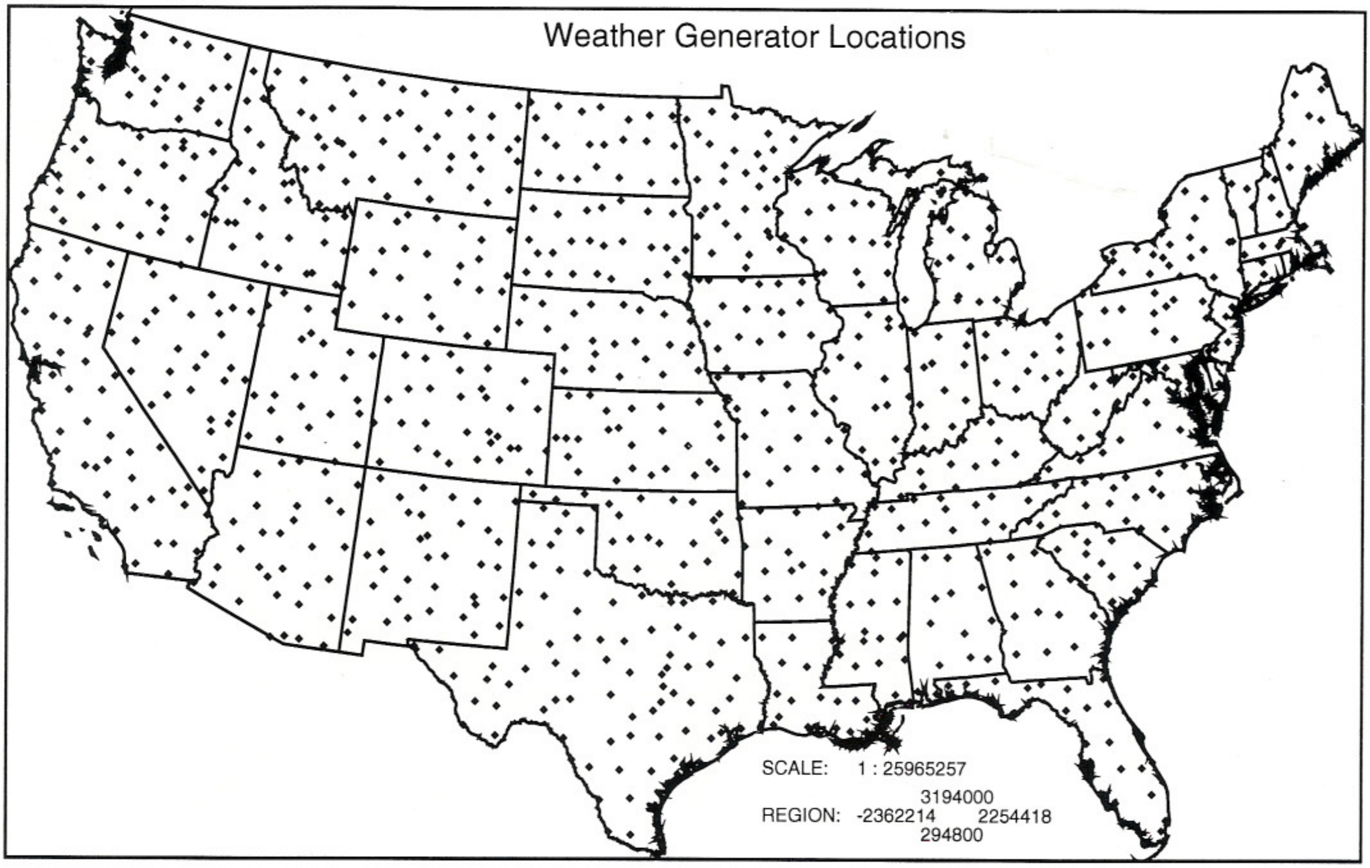


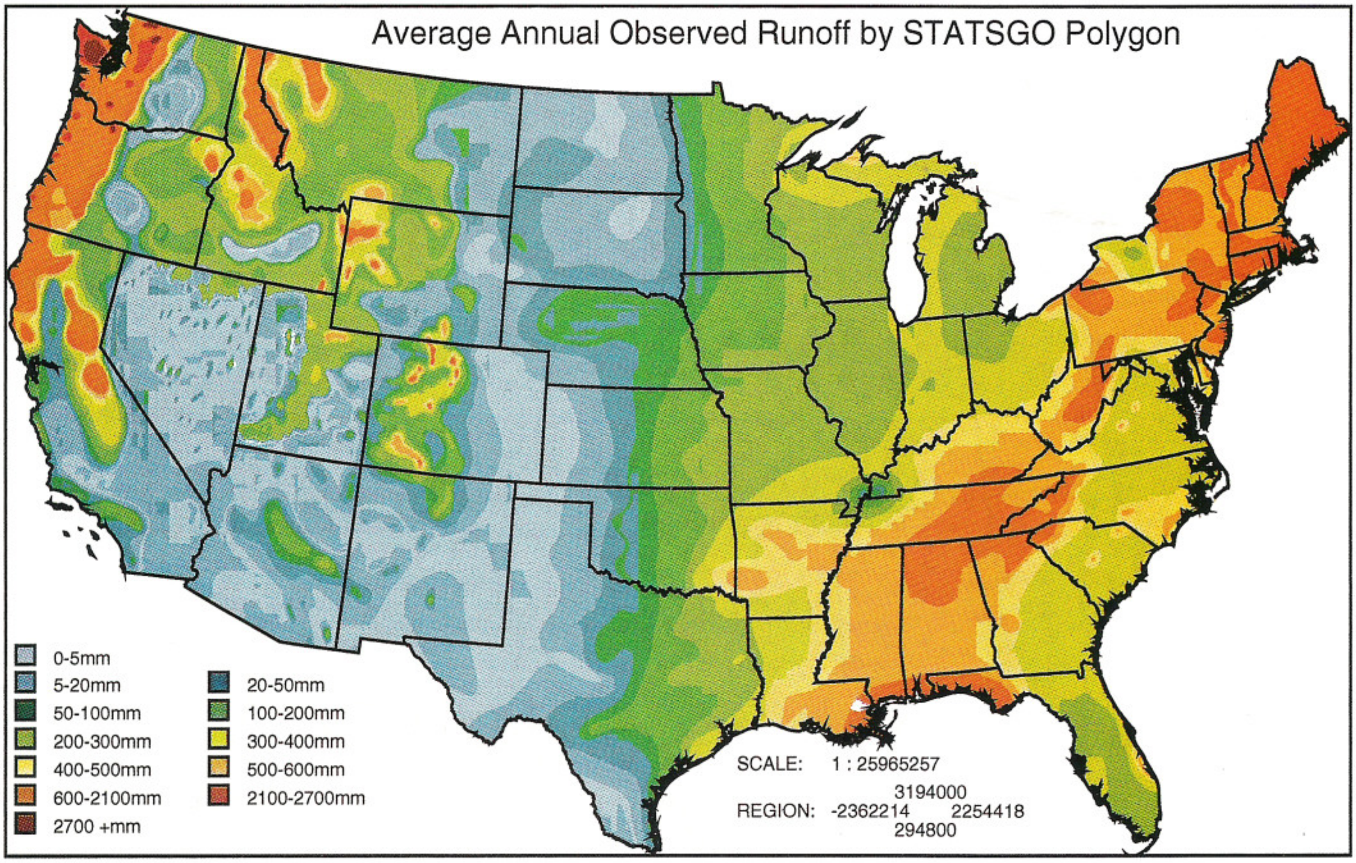
Figure 4. Location of Weather Generator Parameter Sites.

Limitations and Implications for Future Studies

Databases. There are several limitations of the databases used in this study. Soil properties for each series are reported as a range and the midpoint was selected for model input. Within each soil association polygon only areal percentages of soil series are given without regard to spatial position within the polygon. Selecting the dominate soil to represent the entire polygon can cause runoff errors of 30 percent or more (Arnold, 1992). Using the dominant land use for each subbasin can similarly impact model output as the runoff is a function of soil and land use combinations.

Another database limitation involves the location of the weather stations. Elevation and orographic effects are not considered since the vast majority of the weather stations in the coterminous U.S. are located near airports or in valleys next to cities and not distributed in the higher elevations. This can significantly affect the hydrologic balance and is the probable reason for the discrepancies between measured and predicted runoff in the western mountain areas.

Model Algorithms. Selection of a rainfall runoff model is a compromise between model complexity and available input data. While more complex models may better represent the physical processes, the assumption that they lead to more reliable results has been questioned (Loague and Freeze, 1985). They have shown that the simpler, less data intensive models provided as good or better prediction than the physically based models. An empirical model is a representation of data and has no real theoretical basis. A physically based model is one that has a theoretical basis and whose parameters and variables are measurable in the field (Beven, 1983). In reality, many empirical relationships are used for parameter estimation by the "physically based" models (Wilcox *et. al.,* 1990). The SCS runoff equation is basically an empirical model which came into common use in the 1950s is the product of more than 20 years of studies of rainfall runoff relationships from small rural watersheds. The model was developed to provide a consistent basis for estimating the amounts of runoff under varying landuse and soil types (Rallison and Miller, 1981). No other rainfall-runoff model has been used as successfully or as often on ungaged rangeland



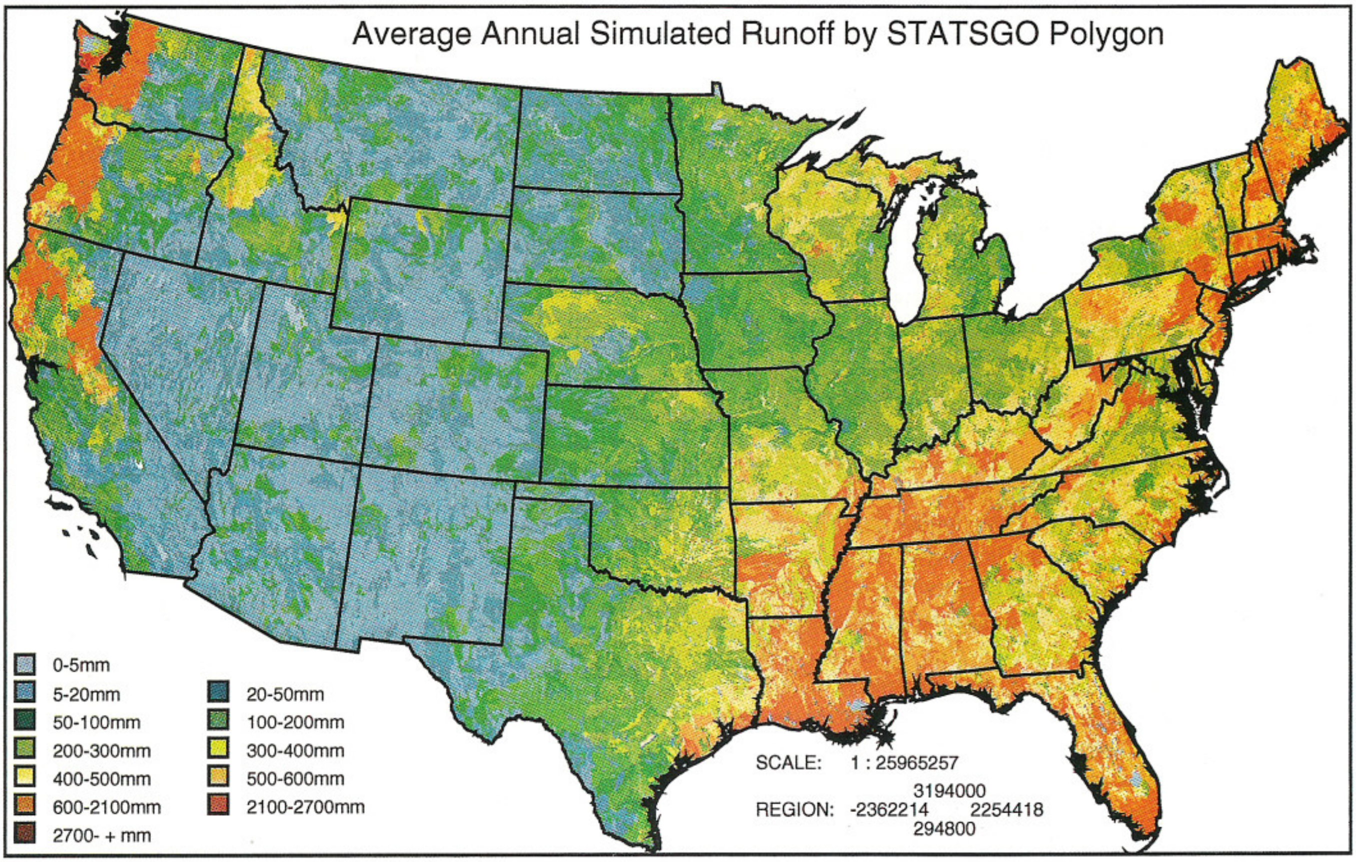


Figure 5. (a) Observed Average Annual Runoff for U. S. from USGS Streamflow Records (top); and (b) Simulated Average Annual Runoff for the U.S. (bottom).

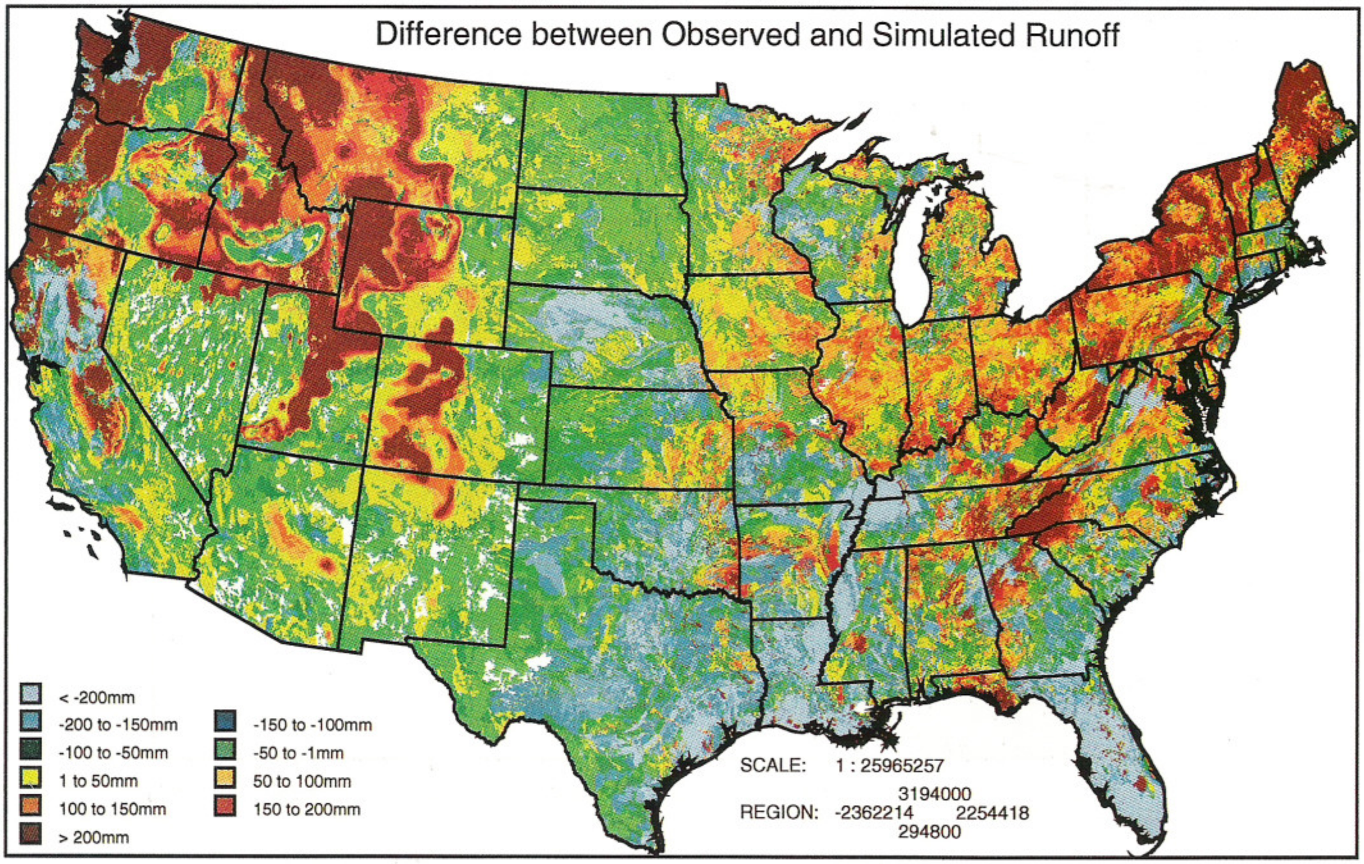


Figure 6. Difference Between Observed and Simulated Average Annual Runoff.

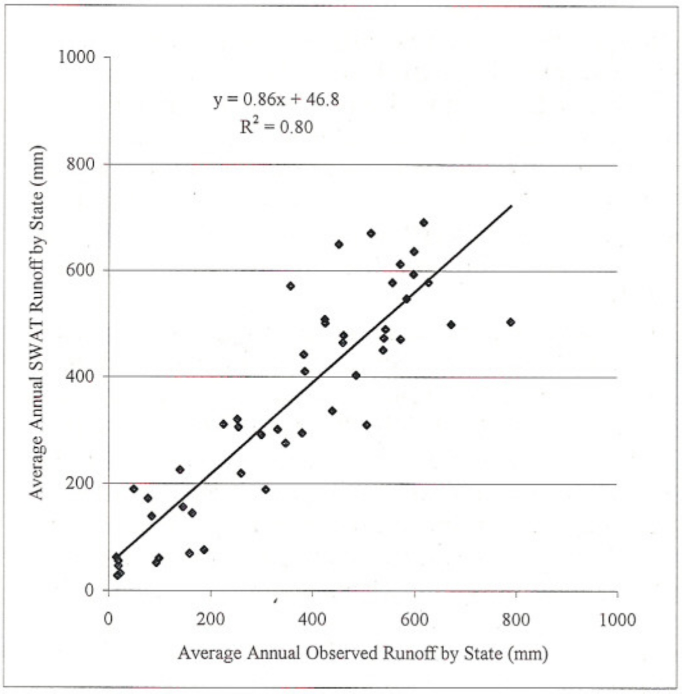


Figure 7. Regression of Observed and Simulated Runoff by State.

catchments as the CNM (Graf, 1988). A major limitation of the curve number method is that rainfall intensity and duration are not considered, only total rainfall volume. Time based physical models such as Green Ampt are thought to better mimic the impacts of land use on runoff because infiltration parameter can be directly related to catchment characteristics (Wilcox *et. al.,* 1990). However, such models require disaggregated daily precipitation, which are only available in select areas of the country. Even though the Green Ampt equation has a physical basis, much may be lost or diluted by the regression equations needed to parameterize the model (Wilcox *et. al.,* 1990). In a study of 585 storm events on 36 watersheds in six physiographic provinces of the Central and Eastern U.S., Bales and Betson (1981) concluded that the curve number appears to be a good numeric index of land use and is potentially a useful basin characteristic for use in hydrologic model regionalization. Studies by Wilcox *et. al.* (1990) on six small catchments in Idaho, Arizona, Texas, Oklahoma, and Nebraska showed that the CNM gave similar results to those obtained by the Green Ampt model. So while the CNM is conceptually simple, it is regarded as an

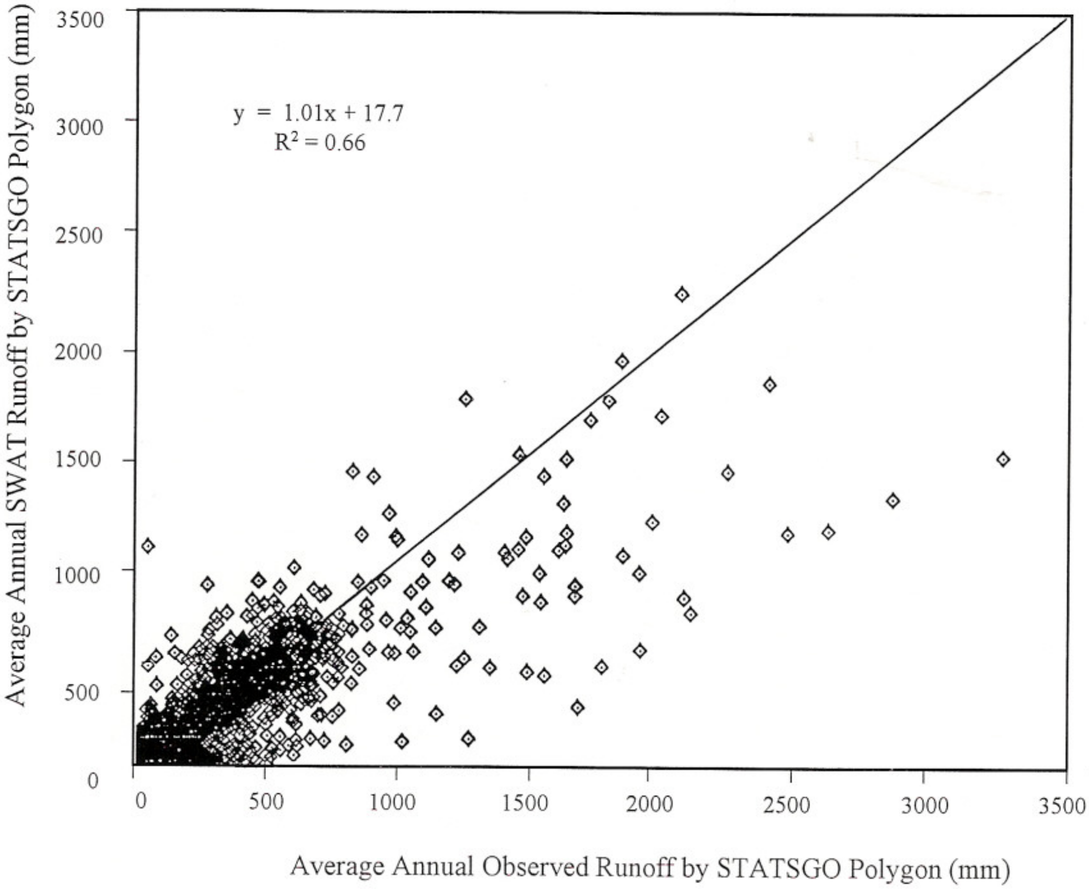


Figure 8. Regression of Observed and Simulated Runoff by Soil Association Polygons.

adequate procedure to use in regional estimates of runoff.

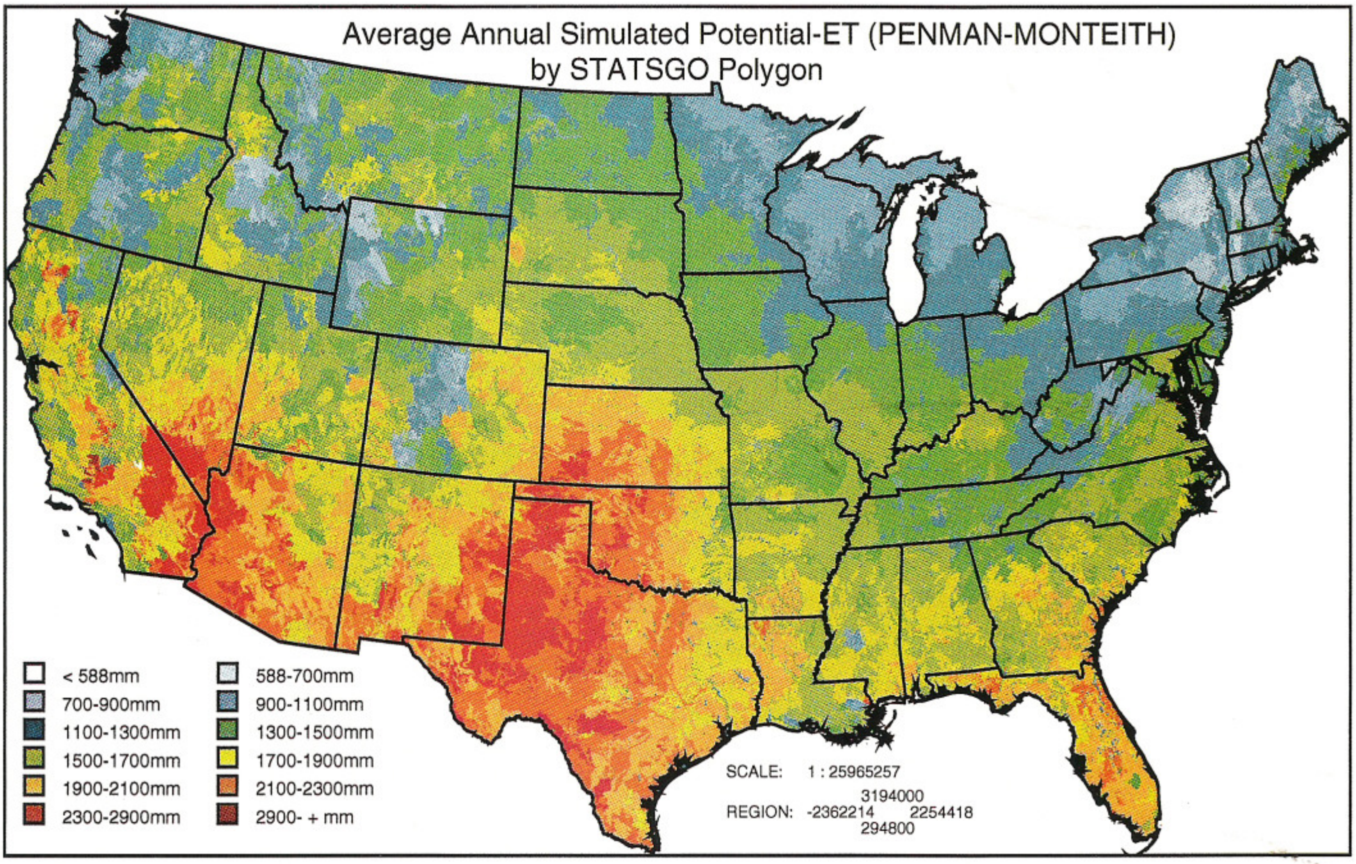
Other model components (snow melt, soil water routing, and shallow aquifer storage) are also rather simplistic and may not be representative of the actual flow system. However, inputs are readily available for large regions and the algorithms have provided reasonable results without calibration. It also has been assumed that there is no deep flow from one subbasin to another. While this assumption is incorrect, it is not believed to cause major error in the overall model output due to the small percentage of the overall water budget involved in recharging the deep aquifer system.

Summary

This paper describes the application and validation of a model of continuous daily water balance. The local water balance was represented by four control volumes; (1) snow, (2) soil profile, (3) shallow aquifer, and to a lesser extent (4) deep aquifer and the components of the water balance were simulated using "storage" models and readily available input parameters. The model operates on a daily time step and is able to predict seasonal variations, which are important for water resources planning. The control volumes have been found to be critical in timing of flows, surface runoff occurs in hour to days, soil lateral flow in days to weeks, shallow aquifer in months to years, and deep aquifer flow (not simulated) in years to decades.

It is also important to simulate management/land use and climate scenarios since the model is being used by NRCS in national agricultural policy planning and by EPA in TMDL (Total Maximum Daily Load) analysis. Algorithms are included to simulate plant growth including the impact of various land use and cropping systems on the hydrologic balance. The impact of climate is also considered including precipitation, temperature which directly effects plant growth (indirectly ET), snow fall and melt, and soil temperature. Carbon dioxide concentration directly impacts ET and plant biomass growth.

The model was validated by comparing simulated average annual runoff (20 year model simulation) with long-term average annual runoff from USGS



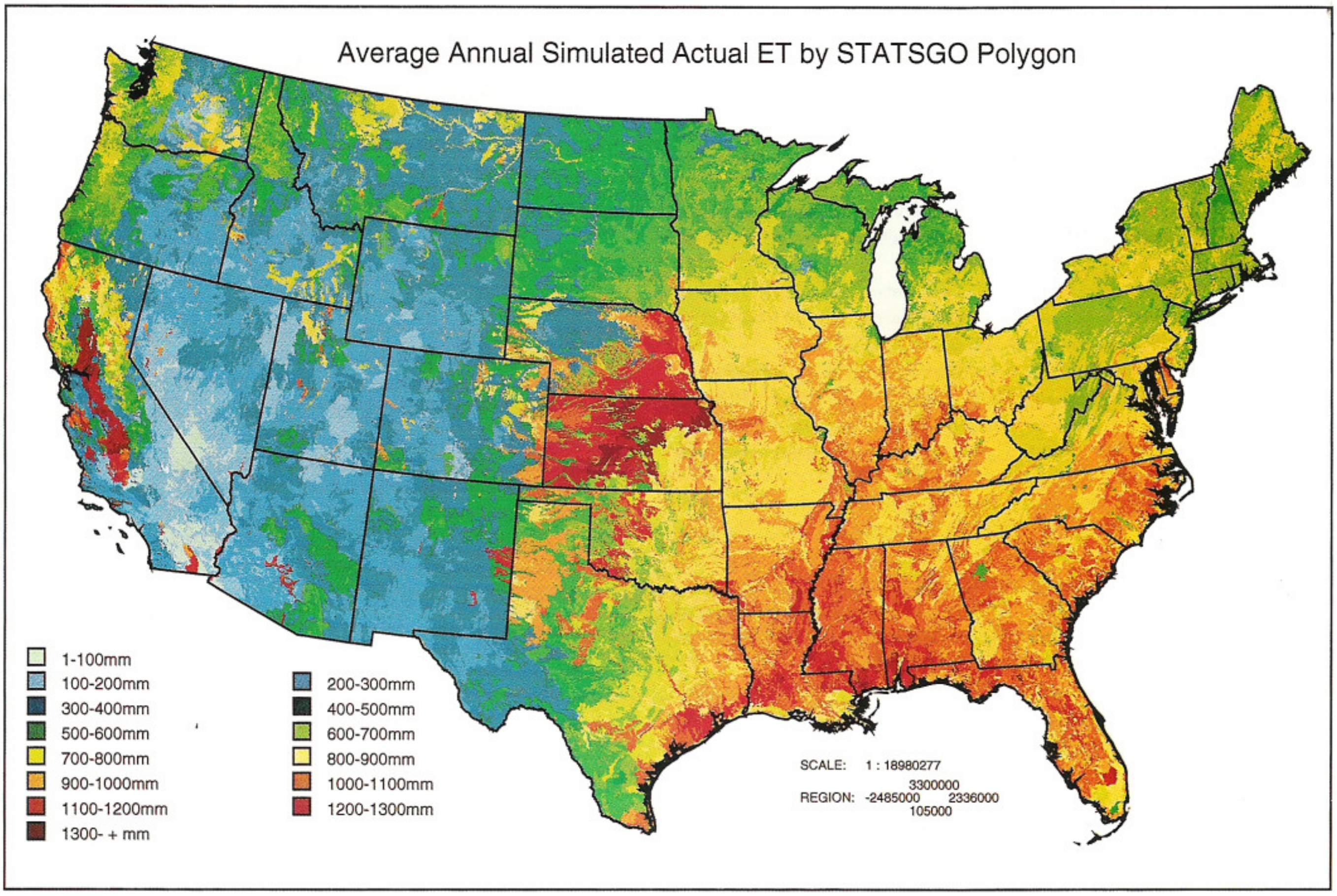


Figure 9. (a) Average Annual Simulated Potential ET for U.S. (top); and (b) Average Annual Simulated Actual ET for U.S. (bottom).

stream gage records. Comparisons show that over 45 percent of the conterminous U.S. within 50 mm of measured, and 18 percent within 10 mm. This was accomplished without calibration. Given the errors associated with model inputs (spatial variability, measurement errors, etc.), these results appear realistic. In this study, at the continental scale, only average annual runoff was validated. Examples of previous model validation at numerous sites across the U.S. were used to show that the model was capable of simulating other components of the hydrologic balance (surface runoff, groundwater flow, and ET) and of producing monthly and daily time series of runoff.

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