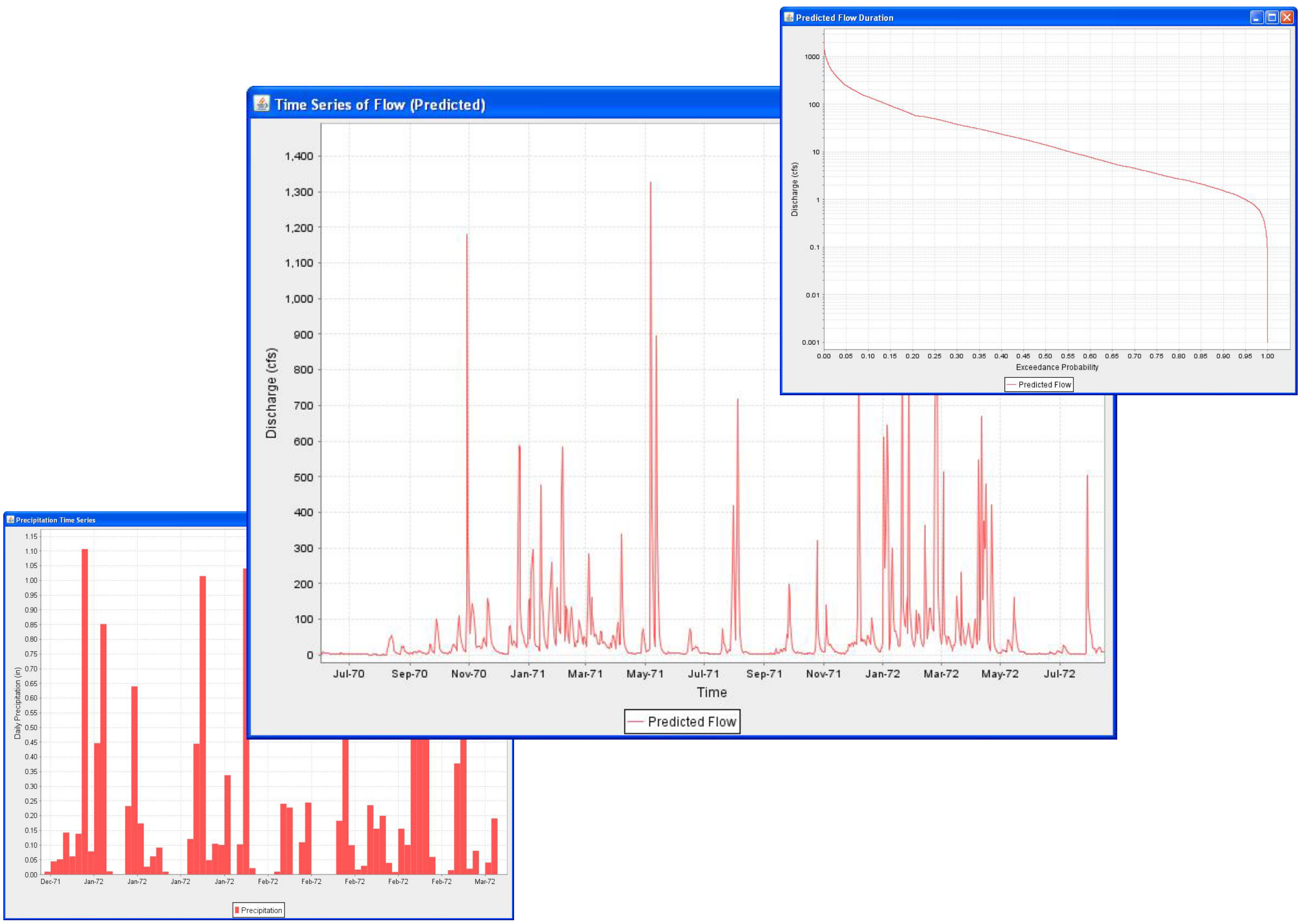
Prepared in cooperation with the Kentucky Division of Water

The Water Availability Tool for Environmental Resources (WATER): A Water-Budget Modeling Approach for Managing Water-Supply Resources in Non-Karst Areas of Kentucky (Phase I)—Data Processing and Model Structure Documentation



Scientific Investigations Report 2009–5248

U.S. Department of the Interior
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Cover: Screen-capture images of model output from the Water Availability Tool for Environmental Resources (WATER), Phase I, application.

The Water Availability Tool for Environmental Resources (WATER): A Water-Budget Modeling Approach for Managing Water-Supply Resources in Kentucky—Phase I: Data Processing, Model Development, and Application to Non-Karst Areas

By Tanja N. Williamson, Kenneth R. Odom, Jeremy K. Newson, Aimee C. Downs, Hugh L. Nelson Jr., Peter J. Cinotto, and Mark A. Ayers

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U.S. Department of the Interior
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Conversion Factors and Abbreviations

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
acre	0.4047	hectare (ha)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Hydraulic conductivity	
inch per hour (in/hr)	7.057	micrometer per sec (µm/sec)
micrometer per second (µm/s)	0.1417	inch per hour (in/hr)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)

Abbreviations used in the text

ASCII	American Standard Code for Information Exchange
COOP	National Weather Service Cooperative Network
DEM	Digital elevation model
E_f	Nash-Sutcliffe efficiency
GUI	Graphic user interface
HB	Histogram builder
KDOW	Kentucky Division of Water
KPDES	Kentucky Point Discharge Elimination System
K_{sat}	Saturated hydraulic conductivity
NEXRAD	Next Generation Radar
NLCD	National Land Cover Database

NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
RMSE	Root mean square error or standard deviation
SSURGO	Soil Survey Geographic Database
STATSGO	State Survey Geographic Database
TWI	Topographic wetness index (also known as the compound topographic index or wetness index)
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WATER	Water Availability Tool for Environmental Resources

The Water Availability Tool for Environmental Resources (WATER): A Water-Budget Modeling Approach for Managing Water-Supply Resources in Non-Karst Areas of Kentucky (Phase I)—Data Processing and Model Structure Documentation

By Tanja N. Williamson, Kenneth R. Odom, Jeremy K. Newson, Aimee C. Downs, Hugh L. Nelson, Peter J. Cinotto, Mark A. Ayers

Abstract

The Water Availability Tool for Environmental Resources (WATER) was developed in cooperation with the Kentucky Division of Water to provide a consistent and defensible method of estimating streamflow and water availability in ungaged basins. WATER is process oriented; it is based on the TOPMODEL code and incorporates historical water-use data together with physiographic data that quantitatively describe topography and soil-water storage. The result is a user-friendly decision tool that can estimate water availability in non-karst areas of Kentucky without additional data or processing. The model runs on a daily time step, and critical source data include a historical record of daily temperature and precipitation, digital elevation models (DEMs), the Soil Survey Geographic Database (SSURGO), and historical records of water discharges and withdrawals. The model was calibrated and statistically evaluated for 12 basins by comparing the estimated discharge to that observed at U.S. Geological Survey streamflow-gaging stations. When statistically evaluated over a 2,119-day time period, the discharge estimates showed a bias of -0.29 to 0.42, a root mean square error of 1.66 to 5.06, a correlation of 0.54 to 0.85, and a Nash-Sutcliffe Efficiency of 0.26 to 0.72. The parameter and input modifications that most significantly improved the accuracy and precision of streamflow-discharge estimates were the addition of Next Generation radar (NEXRAD) precipitation data, a rooting depth of 30 centimeters, and a TOPMODEL scaling parameter (***m***) derived directly from SSURGO data that was multiplied by an adjustment factor of 0.10. No site-specific optimization was used.

Introduction

A detailed water-budget analysis is a critical starting point for developing realistic targets for within-basin and basin-to-basin water-supply development. In compliance with the Kentucky Department of Environmental Protection Management Plan, the U.S. Geological Survey (USGS), in cooperation with the Kentucky Division of Water (KDOW), directed the development of a computerized water-budgeting tool, eventually planned for statewide implementation, to aid water-allocation decisions.

Some of the criteria for development were that the approach

- be successful in various land covers and physiographic terranes,
- require minimal training and data interaction by users, and
- be built around a database that could be easily updated.

The outcome is the Water Availability Tool for Environmental Resources (WATER), a process-oriented, data-driven model that provides a better understanding of streamflow and water balance than was previously available for ungaged basins in Kentucky.

For planning purposes, the model development was divided into two implementation phases: the first phase (Phase I) included basic model development and calibration for flows in non-karst basins only, and the second phase (Phase II) incorporated additional model development to account for flows in karstic basins, enhanced parameter regionalization techniques, and more diverse graphical user interface (GUI) functionality. The outcome of Phase I was a Water-Availability Toolbox, later renamed the Water Availability Tool for Environmental Resources (WATER), that was based on a TOPMODEL approach (Beven and Kirkby, 1979; Wolock, 1993) but that has been implemented by incorporating recently released data for state topography, soils, and water use. WATER was designed to work for Hydrologic Unit Code 12 (HUC-12) basins (85 km^2 on average in Kentucky); however, it has been tested in basins ranging in area from 16 to 1,565 km^2.

WATER provides a better means than was previously available for assessing and predicting streamflow and water balance in ungaged watersheds in Kentucky. Consequently, the Commonwealth will now have a higher level of confidence in estimates of water availability and will be better able to identify areas where shortages are likely. Although WATER has been designed mainly for assessment of water budgets for individual basins, model outputs can be useful in stormwater and water-quality analyses, including hydrographs, flow-duration curves, and overland-flow distributions.

WATER packages several data-analysis functions into one GUI. In the Phase I version of WATER, the Fortran TOPMODEL code has been encapsulated into a Java GUI that accesses an extensive database of basin characteristics, as well as other background data. The result is a versatile water-quantification program that meets the water-availability assessment needs of KDOW. WATER has also been designed so that it can be expanded for other regulation-related computations including, but not limited to, sediment and nutrient loads, as well as flows that are necessary for ecological viability.

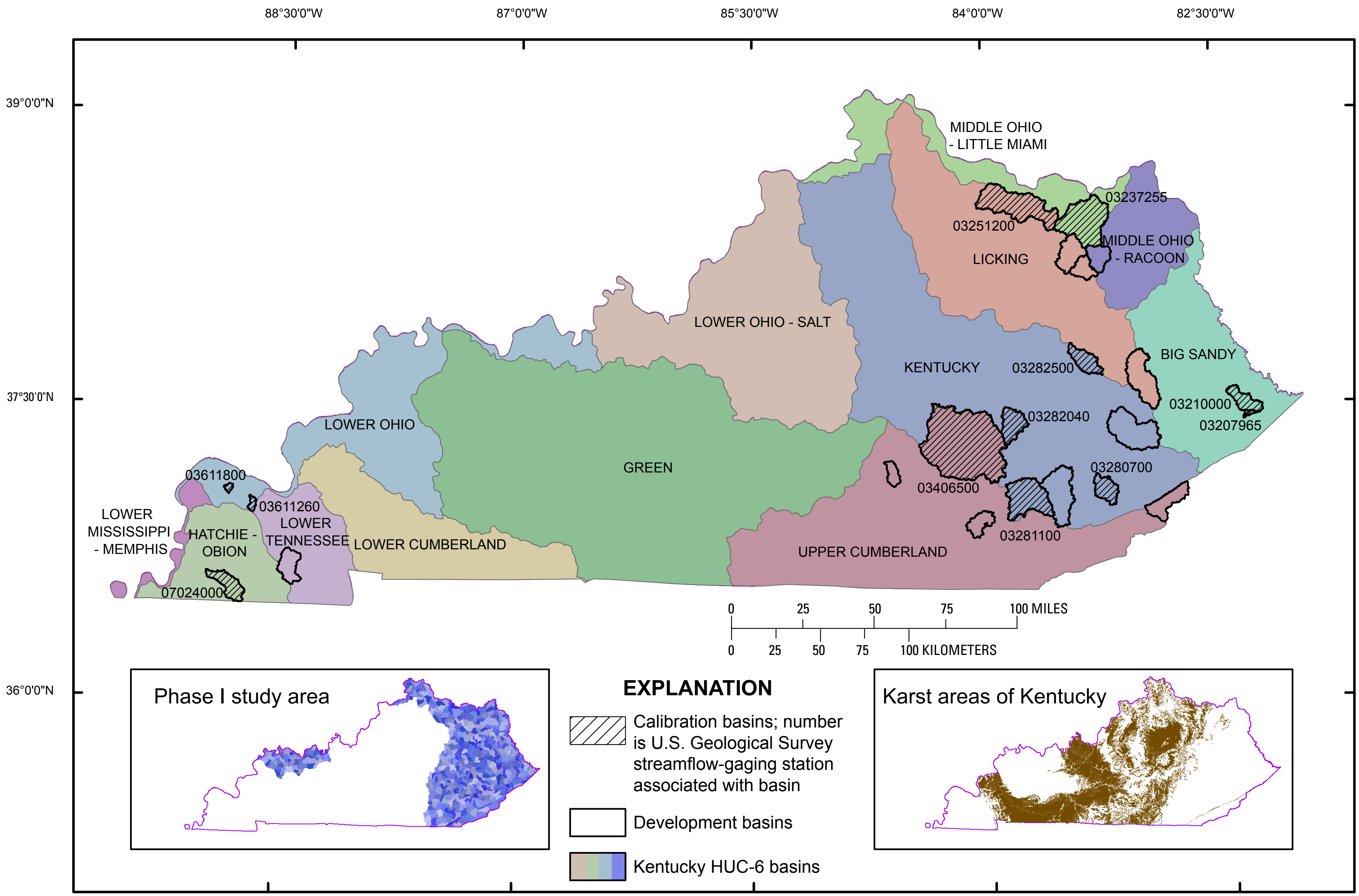
Purpose and Scope

This report details the process-oriented approach of WATER in terms of data available for the Commonwealth of Kentucky. WATER was developed in two phases; the first phase is the subject of this report and focused on the design of WATER and implementation of the tool for two non-karst areas of Kentucky, including the Southwestern and Central Appalachians and Western Allegheny Plateau Ecoregions (Woods and others, 2002). For Phase I, basin characteristics were aggregated for 500 HUC-12 basins in the non-karst areas of Kentucky (fig. 1). The second phase will involve preparation of WATER for the remaining 782 HUC-12 basins of Kentucky and will include development of a model to address flow in karst-area basins and improve GUI functionality.

Basic model development, including data and program structure, preprocessing decisions and statistical sampling of spatial-data layers, and selection of development and calibration basins are illustrated and explained. Finally, the Phase I WATER calibration process for non-karst basins in Kentucky is explained. This report is intended as a technical manual for the Phase I version of WATER, to explain the data decisions, processing steps, and limitations that model users will need to know for successful application of WATER.

Previous Studies

WATER is built upon a physically based hydrologic model that simulates the variable-source-area concept of streamflow and is an extension of the TOPMODEL code described in Wolock (1993). The TOPMODEL code was originally developed by Beven and Kirkby (1979); however, many researchers have extensively modified the TOPMODEL code, and numerous versions now exist in several program languages (for example, Robson and others, 1992; Romanowicz, 1997). TOPMODEL has been used to study a variety of hydrologic research topics, including topographic effects on water quality (Wolock, 1988; Wolock and others, 1989, 1990), topographic effects on streamflow (Beven and Wood, 1983; Beven and others, 1984; Kirkby, 1986), spatial-scale effects on hydrologic processes (Sivapalan and others, 1987, 1990; Beven and others, 1988; Wood and others, 1988, 1990; Famiglietti and Wood, 1991; Famiglietti, 1992), and the geomorphic evolution of basins (Ijjász-Vásquez and others, 1992). TOPMODEL has also been used for estimating regional-scale variability in hydrologic properties in the United States (for example, Wolock, 2003), flood frequency (Beven, 1986a and b), effects of climate change on hydrologic processes (Wolock and Hornberger, 1991), carbon budgets (Band and others, 1991), base-flow residence times (Vitvar and others, 2002), and ecological-flow factors (Kennen and others, 2008). Finally, TOPMODEL has been used to reveal interactions among variables in model-parameter calibration (Hornberger and others, 1985; Wolock, 1988; Wolock and McCabe, 1995), including an understanding of how input data must change with a change in digital-data resolution (Brassington and Richards, 1998).



Base from U.S. Geological Survey digital data, 1983, 1:100,000
Lambert Conformal Conic projection
Standard parallels 37°N and 39°N, central meridian 85°45'W

Karst Occurence in Kentucky
by Kentucky Geolgical Survey, 2005

Figure 1. Water Availability Tool for Environmental Resources (WATER) Phase-I development and calibration basins and study area, with hydrologic unit code six (HUC-6) basins shown for reference.

WATER is dependent on input that incorporates climatic, topographic, and pedogenic data. Wolock and McCabe (1999) showed that an accurate precipitation record was the most significant requirement for a successful hydrologic-response model; soil-moisture storage, derived from pedogenic data, was identified as an additional critical variable. WATER provides a historical climate record that extends from 1948 through 2006; however, the period 2000–06 includes NEXRAD precipitation data. Over and others (2007) showed that NEXRAD data were consistently within ±10 percent of tipping-bucket rain gage estimates, with the NEXRAD data showing relatively fewer large precipitation values and more small precipitation values. This difference in recorded precipitation is largely owing to the area sampled by each: 0.03 m^2 by the rain gage and 16 km^2 by the radar. Disposition of precipitation into soil storage, overland flow, and base flow has historically been estimated by using soil parameters from a combination of State Soil Geographic Database laboratory data (STATSGO; *http://soils.usda.gov/survey/geography/statsgo/*) and manual estimation (for example, Brassington and Richards, 1998; Wolock, 2003; Kennen and others, 2008); these soil parameters include available water-holding capacity, field capacity, porosity, soil thickness, saturated hydraulic conductivity, the conductivity multiplier, and the scaling parameter. However, Williamson and Odom (2007) showed that the Soil Survey Geographic Database (SSURGO; *http://soils.usda.gov/survey/geography/ssurgo/*) included data at a resolution that was more appropriate for analysis of small basins and that yielded better results without the subjectivity of manual estimation.

Currently (2009), WATER, or some variant of the current tool, is being used in applied research for estimating water availability in Kentucky and Alabama, as well as generating load-duration curves for use in developing total maximum daily loads (TMDLs). Additionally, WATER is being used to evaluate the effects of hydrologic factors on ecological conditions within a fluvial system (Gary R. Buell, U.S. Geological Survey, oral commun., 2009), conduct flood assessments in small watersheds in Indiana (Scott E. Morlock, U.S. Geological Survey, written commun., 2009), and assess the hydrologic controls on the transport of mercury species in New York and South Carolina (Douglas A. Burns and Toby D. Feaster, U.S. Geological Survey, written commun., 2009).

Study Area, Data Sources, and Model Development and Calibration

The development and calibration of WATER included only basins from non-karst areas of Kentucky in order to focus on hydrologic processes that operate as a function of topography and soil characteristics. The Phase I version of WATER includes an historical climate record together with a database of physical parameters for basins in the non-karst areas of Kentucky. However, the spatial-data layers are available for the entire Commonwealth.

Selection of Non-Karst Study-Area and Calibration Basins

Twenty-two gaged basins in the non-karst areas of the Commonwealth, ranging in size from 16 to 1,565 km^2 (fig. 1), were used to develop the model, and 12 of these basins were used for calibration of the model. These 22 basins were chosen based on

- physiographic region,
- availability of a USGS streamflow-gaging station for the 2000–05 period,
- comprehensive information on withdrawals and discharges for the basin,
- a known absence of flow regulation, and
- a non-urban environment.

These 22 basins were used to design the data structure of WATER, select appropriate data sources and preprocessing methods for spatial-data layers, and identify potential sources of error. Only 12 of these basins were used as *calibration basins* (fig. 1), described below in “Statistical Evaluation and Calibration of WATER,” because the discharge record coincided with NEXRAD precipitation data that were available for Kentucky for the January 2000–August 2006 time period; these more accurate precipitation data were not available until much of WATER had already been developed.

Data Sources

To develop an approach that could be applied across the Commonwealth, including contrasting physiographic terranes, rigorous data processing was applied to several model input-data sources (table 1). Each data layer, discussed below in detail, was processed and statistically sampled for each basin using ArcGIS.

Model Development and Calibration Methods

Statistical evaluation of the TOPMODEL code and its individual components has been documented in numerous studies (for example, Wolock, 1993) and, therefore, rigorous statistical analysis of the variable source area concept and the basic TOPMODEL code is not repeated here. Statistical evaluation of WATER, as reported in the following sections, is limited to the comparison of the estimated discharge to that observed at the respective USGS streamflow-gaging station.

WATER was originally developed by visual evaluation of hydrographs and flow-duration curves of observed and modeled data for the 22 gaged watersheds. Although this process resulted in a functional model, the model could not be

Table 1. Data sources.

[WATER, Water Availability Tool for Environmental Resources]

Data source	Contribution to WATER
National Weather Service COOP TD3200 stations	Temperature and precipitation data for 1948–2006
National Weather Service River Forecast Centers Operational Forecast System NEXRAD (Next Generation radar) mean areal precipitation	Precipitation data for 2000–06
9.14-meter Digital Elevation Model of Kentucky (U.S. Geological Survey, 2008)	Basin areas, area of the stream channel, topographic wetness index
SSURGO (Soil Survey Geographic Database; U.S. Department of Agriculture, 2007)	Hydrologic soil variables and TOPMODEL specific variables
2001 NLCD (National Land-Cover Database; U.S. Geological Survey, 1992)	Impervious areas
Kentucky Division of Water (written commun., 2007)	Water withdrawals, lake areas
Kentucky Pollutant Discharge Elimination System (written commun., 2007)	Water discharges

statistically evaluated because of questions about the accuracy of the precipitation data. After the NEXRAD precipitation data became available, the 12 *calibration basins* for which discharge data were available for the same time period were used to statistically evaluate and calibrate the model by employing four statistics that are commonly used in hydrologic-modeling studies (for example Wolock and McCabe, 1999; Martin and others, 2000):

- Bias $$\frac{\sum(x_i - y_i)}{n} \quad (1)$$
- Root Mean Square Error $$\sqrt{\frac{\sum(y_i - x_i)^2}{n}} \quad (2)$$
- Correlation $$\frac{\sum(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum(x_i - \overline{x})^2 \sum(y_i - \overline{y})^2}} \quad (3)$$
- Nash-Sutcliffe Efficiency $$1 - \frac{\sum(y_i - x_i)^2}{\sum(x_i - \overline{x})^2} \quad (4)$$

where

x_i is observed mean discharge at the USGS streamflow-gaging station for an individual day,

y_i is modeled discharge for an individual day,

$\overline{x}$ is mean observed discharge for the period of record,

$\overline{y}$ is mean modeled discharge for the period of record, and

n is the number of observations.

Values of bias and root mean square error (RMSE, also known as standard deviation) that are closer to zero indicate better agreement between observed and model-estimated flow values. Correlation and Nash-Sutcliffe Efficiency (E_f) values that are closer to 1 indicate better model results; an $E_f = 0$ indicates that the model-flow estimates are no more accurate than using a mean-flow value, and an $E_f < 0$ indicates that the mean-flow value is more accurate than the model results (Nash and Sutcliffe, 1970; McCuen and others, 2006).

Structure and Output of WATER

WATER incorporates TOPMODEL Fortran code that has been successfully used to assess other hydrologic systems in the United States (for example, Kennen and others, 2008). However, the Java-based GUI (fig. 2) and data structure were developed for Phase I of the Kentucky model to create a user-friendly environment. The Phase I version of WATER uses a specific directory structure (fig. 3) that organizes preprocessed data (described below) for the encapsulated Fortran TOPMODEL code (figs. 4 and 5); these data include historical climate data, basin characteristics, and USGS streamflow data (for development and calibration). Consequently, no further data or preprocessing are required from the user to make the model run; because of this simplification,WATER has been run on a computer with as little as 512 MB of RAM and a 1-GHz processor.

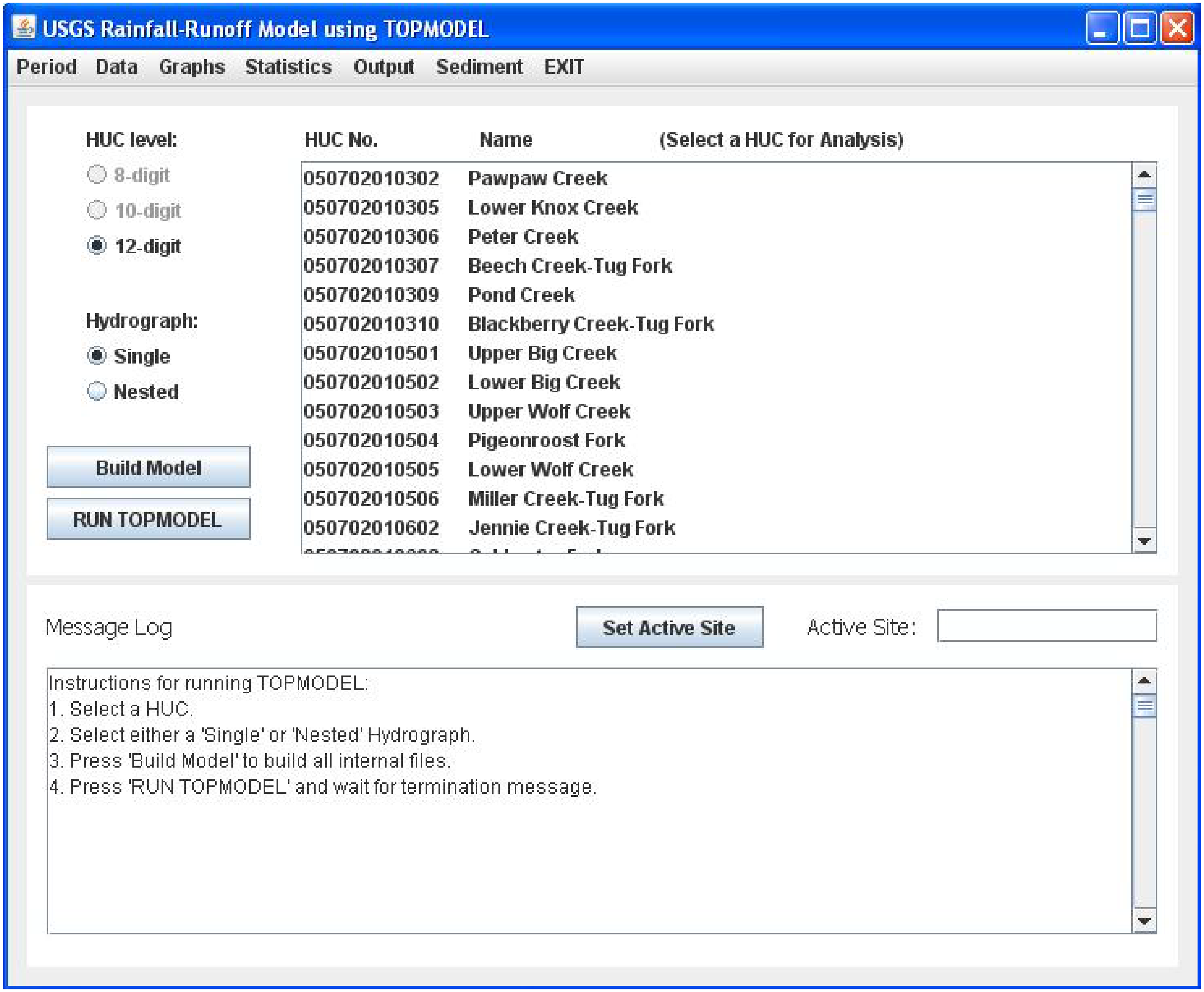


Figure 2. Graphic user interface for Water Availability Tool for Environmental Resources (WATER).

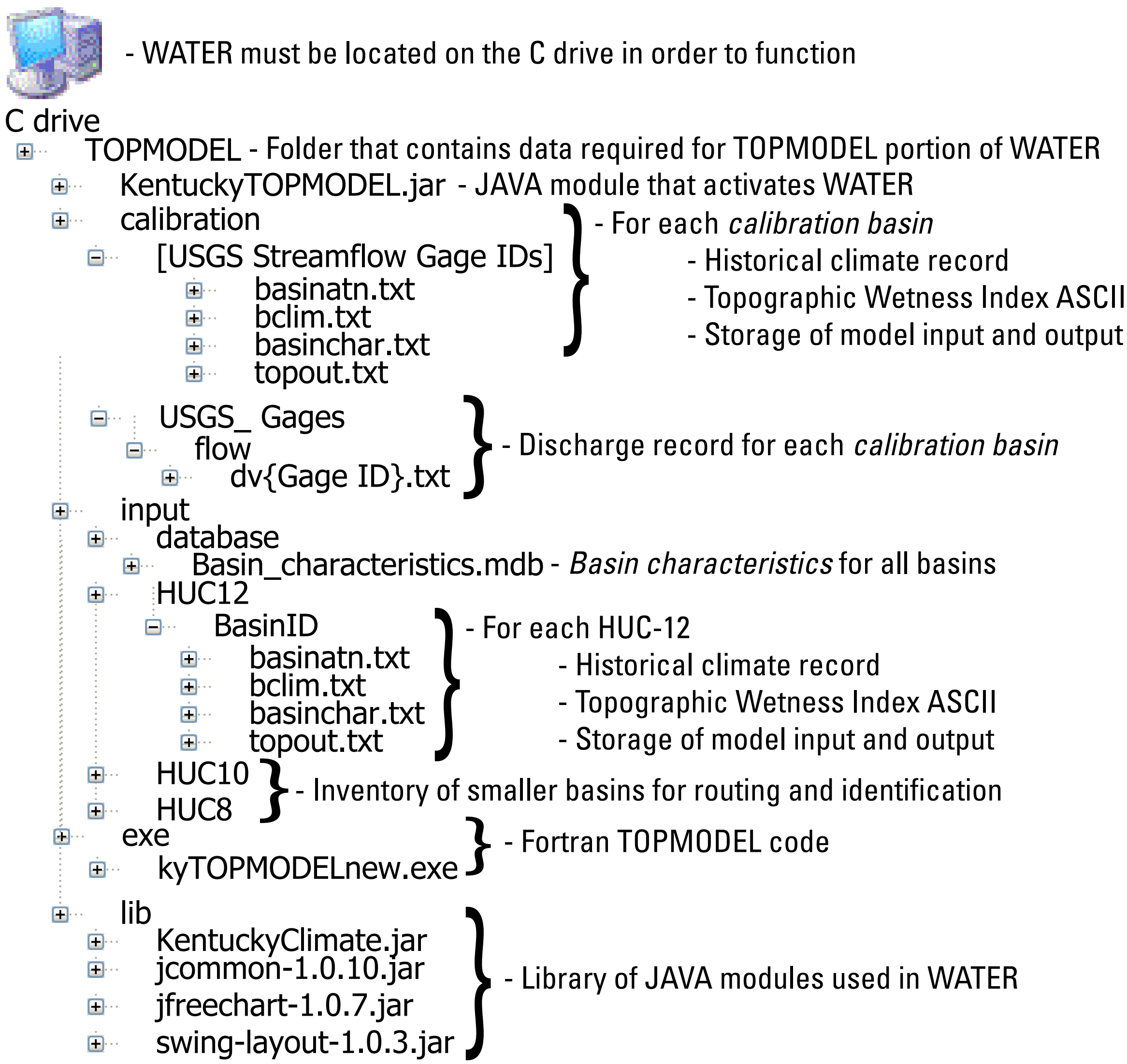


Figure 3. Directory structure of Water Availability Tool for Environmental Resources (WATER).

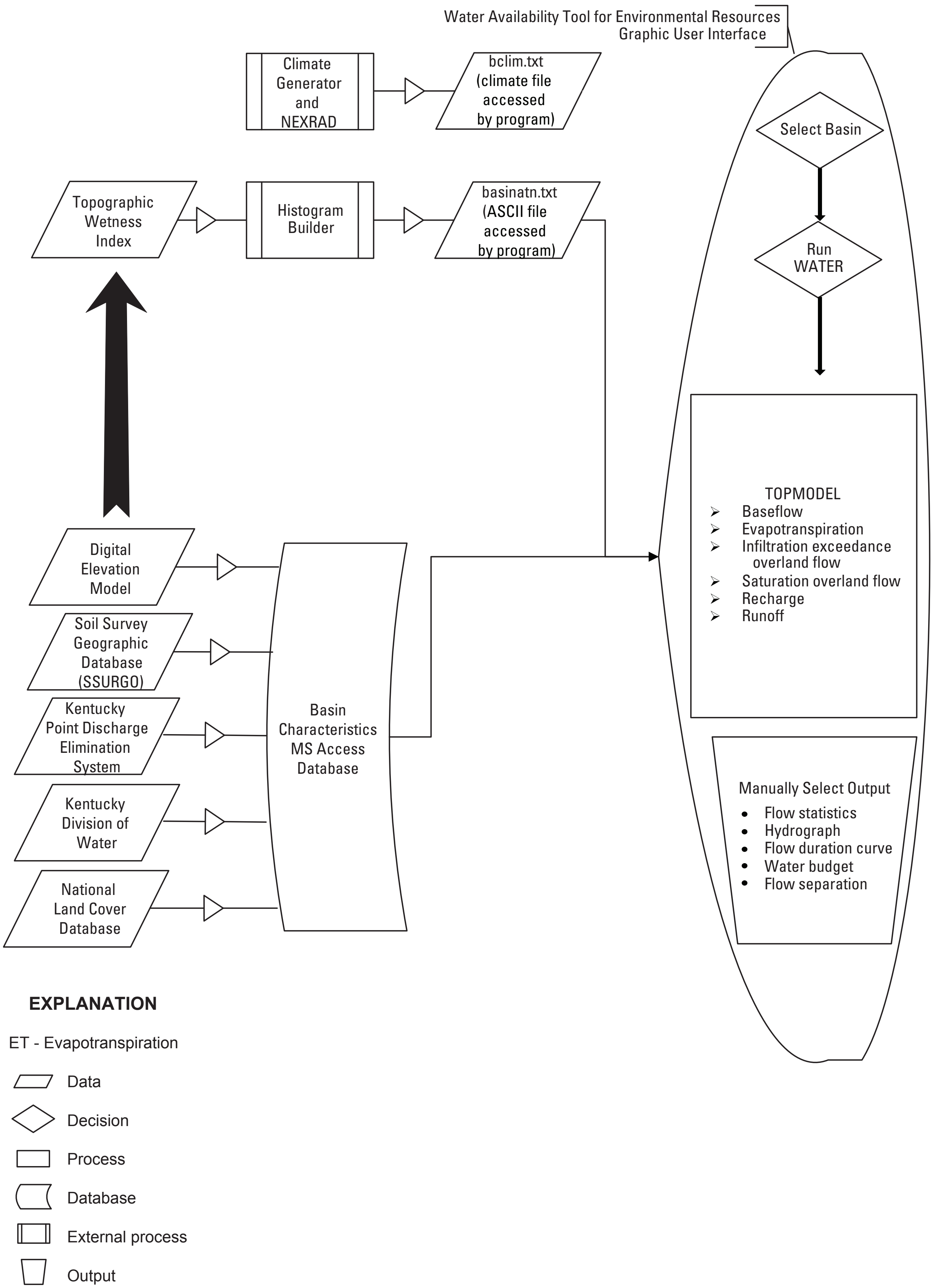


Figure 4. Data framework of Water Availability Tool for Environmental Resources (WATER).

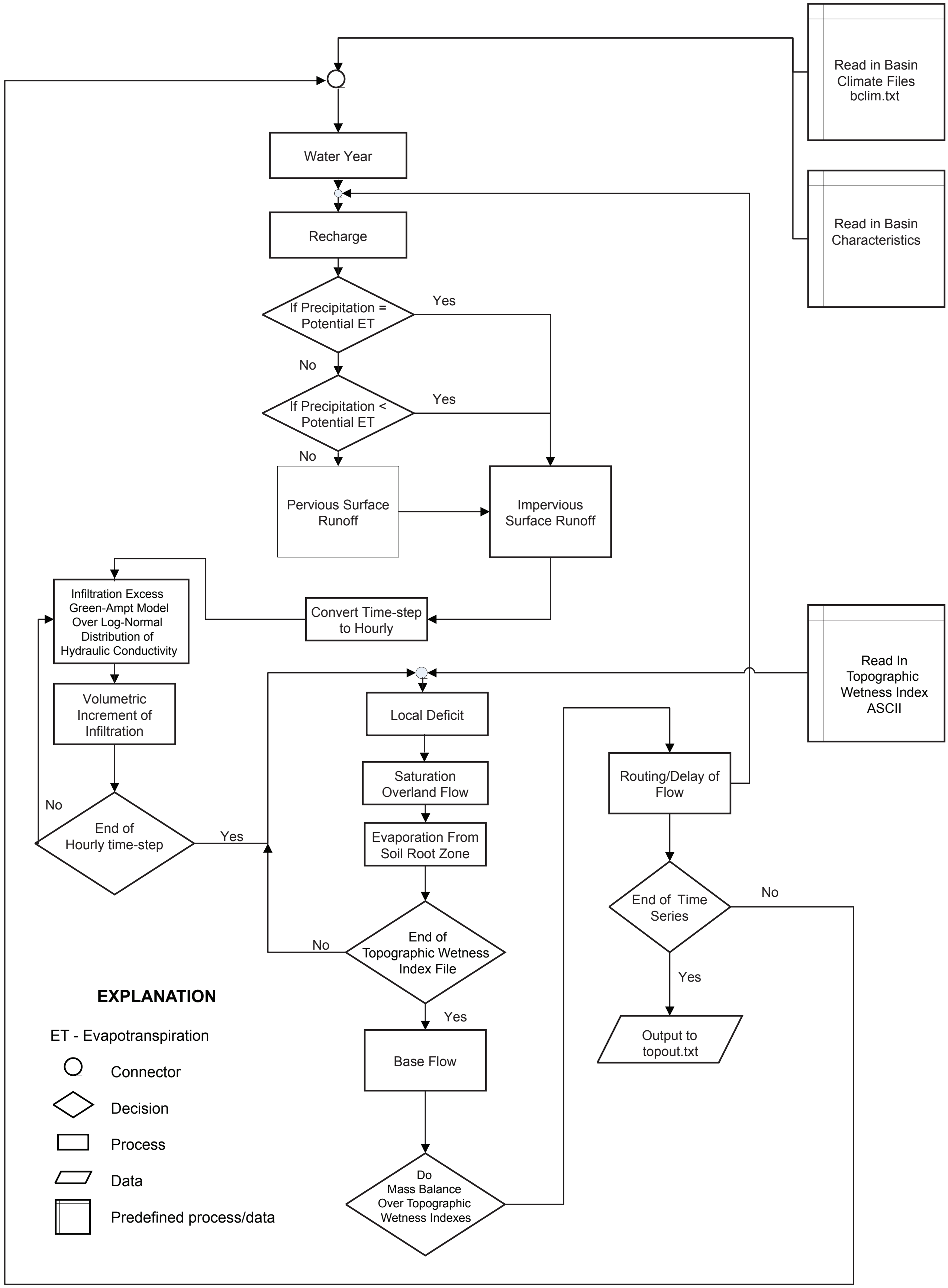


Figure 5. Fortran TOPMODEL code structure used by Water Availability Tool for Environmental Resources (WATER).

To run the model, the user activates WATER, and using the GUI (fig. 2) selects the basin of interest, chooses either a single basin or a nested-basin run, and selects *Run TOPMODEL*. A nested-basin run includes output for all upstream contributing HUC-12s. When a HUC-12 basin is selected and run in nested mode, the program writes the selected HUC-12 and all upstream HUC-12s to an external file called *UpstreamHucList.{initially selected HUC-12}*. A TOPMODEL execution loop is then set up according to the number of HUC-12s in this external file. Each TOPMODEL loop processes one HUC-12 from the external file, and the resulting estimates of streamflow are saved to an internal data object. After the TOPMODEL loop has completed and the estimates of streamflow have been stored, a method named *SimpleRoute* is called. *SimpleRoute* sums the hydrographs from all HUC-12s; delays or attenuations in flows are not accounted for. Because this model is based on daily flows, errors owing to traveltimes of less than 24 hours are thought to be minimal. Traveltimes greater than 24 hours may introduce more error. For this reason, this version of WATER sums flow only for HUC-12 basins that are nested within a single, larger, HUC-8 basin and will not sum flow for a HUC-12 sequence that crosses a HUC-8 boundary. If the drainage area is split among multiple HUC-8s, the flow estimates will include flow derived only from HUC-12s in the most downstream HUC-8; no flow from upstream HUC-8s will be included.

Currently (2009), standard output from the model provides graphic and tabular data, including

- hydrographs,
- flow-duration curves,
- annual and monthly water budgets, and
- climatic histories.

In addition, there is the option of simulating changes in climate or water use by altering the input file in the GUI *Data* menu; any changes that are made to this input file are saved in the *basinchar.txt* file in the *input* folder for the basin. The *basinchar.txt* file can be renamed for future reference; otherwise, it will be overwritten the next time WATER is run for the specified basin. Daily data for each parameter calculated by the TOPMODEL portion of the program are saved in the *topout.txt* file that is saved in the *input* folder for the basin. This file can also be renamed for future reference, or it can be imported into a spreadsheet program for further calculations; otherwise, this file will be overwritten the next time the program is run for this basin. Additional functionality is shown in the existing GUI; however, these functions (including period, statistics, and sediment) are not active in the Phase I application but will be developed in Phase II.

Data Processing and Organization

This initial development of WATER focused on identifying, obtaining, and processing the required background data that make the model scientifically and programatically function. The *Basin Characteristics* database includes most of the input data for WATER; table 2 summarizes each parameter and its source. All data layers were mapped and rasterized in the Kentucky single-plane projection using ArcMap 8.2; the uniform grid cell of each raster layer was 9.14 m (30 ft). Several of the attributes come from source data, listed in table 1, that then required some form of GIS preprocessing. In addition to the *Basin Characteristics* database, the TOPMODEL portion of WATER also requires a histogram of the topographic wetness index (TWI), as well as a climatic record for each basin. These processes are summarized below.

Stream-Channel Initiation and Width

Because WATER was developed to analyze basins from physiographically diverse terranes, hydrologic parameters such as stream-channel width and the drainage area required to initiate channelized streamflow had to be uniformly defined. To estimate stream-cell area, the stream network was defined by applying the following rules to DEMs derived from 1:24,000 topographic maps:

1. Streams were defined as 1-cell wide for the entire network.
2. Streams were initiated after accumulating a total of 0.25 km^2 (3,000 9.14-m cells) upstream area by using the Arc Hydro Flow Accumulation tool (with a single-flow direction algorithm).

These two flow-accumulation criteria area were established to include first-order, perennial, channelized drainages while excluding small, ephemeral, hillslope systems. Streams were defined as 1-cell wide to remove the highest values of the TWI from the distribution of TWI values in a given basin while still maintaining a representative riparian zone to serve as a variable source area for streamflow. Although this stream-network definition is representative of most HUC-12 streams (the basin size for which WATER was developed), utilization of WATER in larger or smaller basins may require adjustment of this parameter to accurately estimate stream response.

Table 2. Basin characteristics: attributes, data sources, and processing summary. —Continued

[km^2, square kilometers; m, meter; cm, centimeter; mm, millimeter; µm, micrometer; in, inch; hr, hour; s, second; %, percent; Mgal, million gallons; yr, year; d, day; conmult, conductivity multiplier; ET, evapotranspiration; K_{sat}, Saturated hydraulic conductivity; ***m***, scaling parameter; DEM, Digital Elevation Model; KDOW, Kentucky Division of Water; KPDES, Kentucky Pollutant Discharge Elimination System; NLCD, National Land Cover Database; SSURGO, Soil Survey Geographic Database; USDA, U.S. Department of Agriculture; USGS, U.S. Geological Survey. **Note:** Parameter titles and units are artifacts of FORTRAN program.]

Basin property	Title in *Basin Characteristics* database	Title in program	Units in program	Example or default value	Data source	Processing specifications
Total area	totalArea	totalarea	km^2	200.2061	USGS 9.14-m DEM	For calibration, basins were delineated on the basis of gage location using the flow accumulation tool in ArcHydro; otherwise, HUC-12 basin areas were used.
Lake area	lakeArea	alake	km^2	0.04	Kentucky Division of Water, Dam Safety	Only included lakes larger than 10 acres.
Stream cell area	# of stream cells	streamCells	Unitless	26431	USGS 9.14-m DEM	Single cell-width channel derived from Spatial Analyst Flow Direction and Flow Accumulation commands in ArcMap. Streams initiated at sum of 3,000 cells. The number of cells are then converted within WATER as: $$stream\ area = \frac{stream\ cells}{total\ cells} \times total\ area \quad (5)$$
Total cells	totalCells	totalCells	Unitless	3763302	USGS 9.14-m DEM	Total cell count for basin.
Saturated hydraulic conductivity	permeability	K_{sat}	in/hr	1.818932	SSURGO	Values for soil properties were averaged in Microsoft Access for the thickness where $K_{sat} > 1$ µm/s as reported in the SSURGO database. Representative values as reported for each soil map unit were rasterized and sampled by drainage basin.
Soil thickness	soilDepth	ztot and soildepin	in	51.18267	SSURGO	Thickness for which $K_{sat} > 1$ µm/s. Converted to in. from cm. Representative values as reported for each soil map unit were rasterized and sampled by drainage basin.
Field capacity	fieldCapacity	thfc and fieldcap	Decimal	0.205983	SSURGO	Values for soil properties were averaged for the thickness where $K_{sat} > 1$ µm/s in Microsoft Access. Representative values as reported for each soil map unit were rasterized and sampled by drainage basin.
Water holding capacity	watholCapacity	whcin	Decimal	0.128884	SSURGO	Values for soil properties were averaged for the thickness where $K_{sat} > 1$ µm/s in Microsoft Access. Representative values as reported for each soil map unit were rasterized and sampled by drainage basin. Converted from cm/cm to %.

Table 2. Basin characteristics: attributes, data sources, and processing summary. —Continued

[km^2, square kilometers; m, meter; cm, centimeter; mm, millimeter; µm, micrometer; in, inch; hr, hour; s, second; %, percent; Mgal, million gallons; yr, year; d, day; conmult, conductivity multiplier; ET, evapotranspiration; K_{sat}, Saturated hydraulic conductivity; ***m***, scaling parameter; DEM, Digital Elevation Model; KDOW, Kentucky Division of Water; KPDES, Kentucky Pollutant Discharge Elimination System; NLCD, National Land Cover Database; SSURGO, Soil Survey Geographic Database; USDA, U.S. Department of Agriculture; USGS, U.S. Geological Survey. **Note:** Parameter titles and units are artifacts of FORTRAN program.]

Basin property	Title in *Basin Characteristics* database	Title in program	Units in program	Example or default value	Data source	Processing specifications
Porosity	porosity	poros	Decimal	0.322057	SSURGO	Values for soil properties were averaged for the thickness where K_{sat} > 1 µm/s in Microsoft Access. Representative values as reported for each soil map unit were rasterized and sampled by drainage basin.
Percent impervious	perImpervious	perimp	%	1.13	NLCD 2001	Imperviousness layer.
Percent road impervious	perRoadImpervious	perroad	%	0.58	NLCD 2001 National Map 2001	Imperviousness layer clipped to National Map transportation layer.
Latitude	latitude	xlat	Decimal degrees	37.42	NWIS	Latitude at visual center of each HUC-12 or *calibration basin*.
Site ID	siteID	staid	NA	03282040	NWIS	HUC-12 (Michael Griffin, USGS Kentucky Water Science Center, oral commun., 2009) or USGS Station Identification number for *calibration basins*.
Effective impervious	effImpervious	Effimp	%	0.7	User defined	Held constant. Used to decrease the percent impervious that is not roads.
Conductivity multiplier	conductMultiplier	conmult	Unitless	3.38956	SSURGO	$conmult = \frac{K_{sat} - high_{surface}}{K_{sat} - low_{\text{"bottom"}}}$ (6) equation explained in text Values for soil properties were averaged for the thickness where K_{sat} > 1 µm/sec in Microsoft Access. Representative values as reported for each soil map unit were rasterized and sampled by drainage basin.
Percent macropore flow	perMacroporeFlow	pmac	%	0.2	User defined	Constant
m	scalingParameter	szm	mm	124.46	SSURGO	$f = \frac{\ln conmult}{soil\ thickness}$ (7) equation explained in text $\boldsymbol{m} = \frac{porosity - field\ capacity}{f}$ (8) equation explained in text Values for soil properties were averaged for the thickness where K_{sat} > 1 µm/s in Microsoft Access. Representative values as reported for each soil map unit were rasterized and sampled by drainage basin. This parameter was calibrated uniformly for all basins (see discussion).
Groundwater withdrawal	groundwaterWithdrawal	Gw	Mgal/yr	69.93	KDOW	Monthly averages of water-withdrawal permits Converted to Mgal/yr as 1/0.00274 Mgal/d.

Table 2. Basin characteristics: attributes, data sources, and processing summary. —Continued

[km², square kilometers; m, meter; cm, centimeter; mm, millimeter; µm, micrometer; in, inch; hr, hour; s, second; %, percent; Mgal, million gallons; yr, year; d, day; conmult, conductivity multiplier; ET, evapotranspiration; K_{sat}, Saturated hydraulic conductivity; ***m***, scaling parameter; DEM, Digital Elevation Model; KDOW, Kentucky Division of Water; KPDES, Kentucky Pollutant Discharge Elimination System; NLCD, National Land Cover Database; SSURGO, Soil Survey Geographic Database; USDA, U.S. Department of Agriculture; USGS, U.S. Geological Survey. **Note:** Parameter titles and units are artifacts of FORTRAN program.]

Basin property	Title in *Basin Characteristics* database	Title in program	Units in program	Example or default value	Data source	Processing specifications
Surface-water withdrawal	surfacewaterWithdrawal	Sw	Mgal/yr	218.21	KDOW	Monthly averages of water-withdrawal permits Converted to Mgal/yr as 1/0.00274 Mgal/d.
Surface-water discharge	surfacewaterDischarge	sdisch	Mgal/yr	178.83	KPDES	Monthly averages of water-discharge permits. Converted to Mgal/yr as 1/0.00274 Mgal/d.
Change impervious surface	flagImpSurfaceHistory	iischg	Unitless	0	User defined	Changing to 1 employs algorithm that alters impervious surface TR-55 curve number. Held constant at 0.
Topographic wetness index adjustment	wiAdjustment	Atn_adj	Unitless	1	User defined	A multiplier that alters the topographic wetness index histogram distribution. Held constant at 1 (no adjustment).
Celerity wave velocity	celerityWave	Subv	km/d	20	User defined	Not currently being used; commented out in code.
Depth of root zone	rootZoneDepth	Zroot	m	0.3	Hendrick and Pregitzer, 1996	Representative depth of plant roots in Kentucky based on literature search. Held constant.
Impervious runoff constant	imperviousRunoffDelay	imp_const	Unitless	0.1	User defined	Held constant; must be > 0. Delays concentration of flow from non-road impervious area.
TR55 curve number	imperviousCurveNumber	imp_cn	Unitless	98	User defined	Held constant. Runoff from impervious areas is calculated after the USDA (1986) method for small urban watersheds. Because a conservative estimate of impervious area is being used, this “urban” curve number is used for all basins.
Uplake area	uplakeArea	uplake	km²	2.221391	10-m DEM	Area upstream of lake outlets—this area includes lake area. This value was determined using the flow accumulation tool in ArcHydro.
Lake delay	lakeDelay	Rip_decay	Day	1.5	User defined	Coefficient for delaying water through lakes; runoff from the uplake area is temporarily stored before entering the stream: 1 = no delay and 2 = flow from uplake area is delivered in equal increments over 2 days. This number must be ≥ 1; there is no upper limit.
Evapotranspiration adjustment	etExponent	Et_exp	Unitless	0	User defined	$$ET_{labile} = ET_{calculated} \times \left(\frac{soil\ \ storage}{maximum\ \ soil\ \ storage} \right)^{Exponent} \quad (9)$$ Held constant at 0; calculated value is based on soil storage.
Return flow	returnFlowFlag	iretflow	Unitless	1	User defined	Held constant; a value of 1 allows return flow to the channel.

Table 2. Basin characteristics: attributes, data sources, and processing summary. —Continued

[km^2, square kilometers; m, meter; cm, centimeter; mm, millimeter; µm, micrometer; in, inch; hr, hour; s, second; %, percent; Mgal, million gallons; yr, year; d, day; conmult, conductivity multiplier; ET, evapotranspiration; K_{sat}, Saturated hydraulic conductivity; ***m***, scaling parameter; DEM, Digital Elevation Model; KDOW, Kentucky Division of Water; KPDES, Kentucky Pollutant Discharge Elimination System; NLCD, National Land Cover Database; SSURGO, Soil Survey Geographic Database; USDA, U.S. Department of Agriculture; USGS, U.S. Geological Survey. **Note:** Parameter titles and units are artifacts of FORTRAN program.]

Basin property	Title in *Basin Characteristics* database	Title in program	Units in program	Example or default value	Data source	Processing specifications
Hourly precipitation data	hourlyPrecipFileLocation	hrlyppt	Varies	'None'	Varies	Currently unused, but provides flexibility for future applications that may need more precise precipitation data (either using an index station or hourly rainfall data for the basin).
Description				None	User defined	Necessary text for internal model code
Impervious scenario flag	Imp_Flag	IFlag	Unitless	0	User defined	Placeholder for future upgrade to program to model impacts of changes in impervious surface area. 0 signifies that no scenario has been created. 1 signifies that scenario has been created and will be stored in the specific HUC folder for processing by TOPMODEL at runtime.
Withdrawal scenario flag	Withd_Flag	WFlag	Unitless	0	User defined	Placeholder for future upgrade to program to model water withdrawals. 0 signifies that no scenario has been created. 1 signifies that scenario has been created and will be stored in the specific HUC folder for processing by TOPMODEL at runtime.
Discharge scenario flag	Disch_Flag	DFlag	Unitless	0	User defined	Placeholder for future upgrade to program to model water discharges. 0 signifies that no scenario has been created. 1 signifies that scenario has been created and will be stored in the specific HUC folder for processing by TOPMODEL at runtime.
Climate scenario flag	Climate_Flag	CFlag	Unitless	0	User defined	Placeholder for future upgrade to program to model changes in temperature or precipitation. 0 signifies that no scenario has been created. 1 signifies that scenario has been created and will be stored in the specific HUC folder for processing by TOPMODEL at runtime.

Soil-Data Aggregation

Soil data for WATER were downloaded during February and March 2008 from the Soil Survey Geographic Database (SSURGO; U.S. Department of Agriculture, 2007). Spatial data were compiled in a single geodatabase by using ArcMap 8.2. SSURGO representative values of soil parameters were aggregated by using a series of queries in Microsoft Access; soil parameters of interest included

- porosity (saturated water content),
- field capacity (1/3 bar water content),
- available water-holding capacity,
- saturated hydraulic conductivity (K_{sat}; listed as permeability in the *Basin Characteristics* database), and
- soil thickness.

For compilation of this database, soil thickness was defined as the portion of the soil for which the representative $K_{sat} > 1$ µm/s. This is equivalent to choosing all soil layers for which K_{sat} is “moderately high or higher” as defined by the Natural Resources Conservation Service (U.S. Department of Agriculture, 1993). The decision to use layers with $K_{sat} > 1$ µm/s was based on two criteria: (1) elimination of soil layers defined as restrictive in the SSURGO database and (2) field observations that a portion of the subsoil remained moist regardless of the moisture condition of the overlying soil, thus indicating that these subsoil layers are not involved in the daily water processes simulated by the TOPMODEL portion of WATER (fig. 6). Consequently, the first query run on the SSURGO data eliminated all soil layers that did not meet this criterion. The remaining soil layers were used to determine the *soil thickness*: this is the sum of each of the layers for which $K_{sat} > 1$ µm/s. In Kentucky, 472 of 5,766 (8 percent) of the soil-mapping units included a horizon with $K_{sat} > 1$ µm/s that was bounded above by a layer with $K_{sat} \leq 1$ µm/s; this amounted to 7 percent of the total area. In these cases, the bounded layers were included in the *soil thickness*; this decision will be reevaluated in later versions of the model.

Using only soil layers for which $K_{sat} > 1$ µm/s, a soil-mapping-unit value was calculated for each of the five soil parameters. A thickness-weighted mean of each soil parameter was calculated for each soil component by using the thickness of individual soil layers. A component-weighted mean of each soil parameter was then calculated by using the relative percentages of individual soil components that were reported for each soil-mapping unit.

In addition to the soil parameters listed above, two calculated soil parameters—the conductivity multiplier (*conmult*) and the scaling parameter (***m***)—were calculated from SSURGO data (U.S. Department of Agriculture, 2007). Although this procedure ignores the effect of macropores on K_{sat}, it is consistent with the findings of Brassington and Richards (1998), who reported that when using DEM rasters on the order of 20 m, a laboratory determined K_{sat} and correspondingly small scaling-parameter value produced the most accurate results. In most previous TOPMODEL-based research, these two soil parameters have been altered to optimize the discharge estimate (for example, Wolock, 1993; Kennen and others, 2008). For WATER, these parameters were calculated from SSURGO data and functions that describe how soil water relates to overland flow and base flow (Beven, 1984). This process included a series of queries and calculations that was run for each soil-mapping unit:

1. In most cases, high and low K_{sat} values were reported in SSURGO, in addition to the representative value. The highest K_{sat} value for the soil-mapping unit was identified from the K_{sat}-high data for the surface layer. The lowest K_{sat} value for the soil-mapping unit was identified from the K_{sat}-low data for the *bottom* layer (as defined by the *soil thickness*).

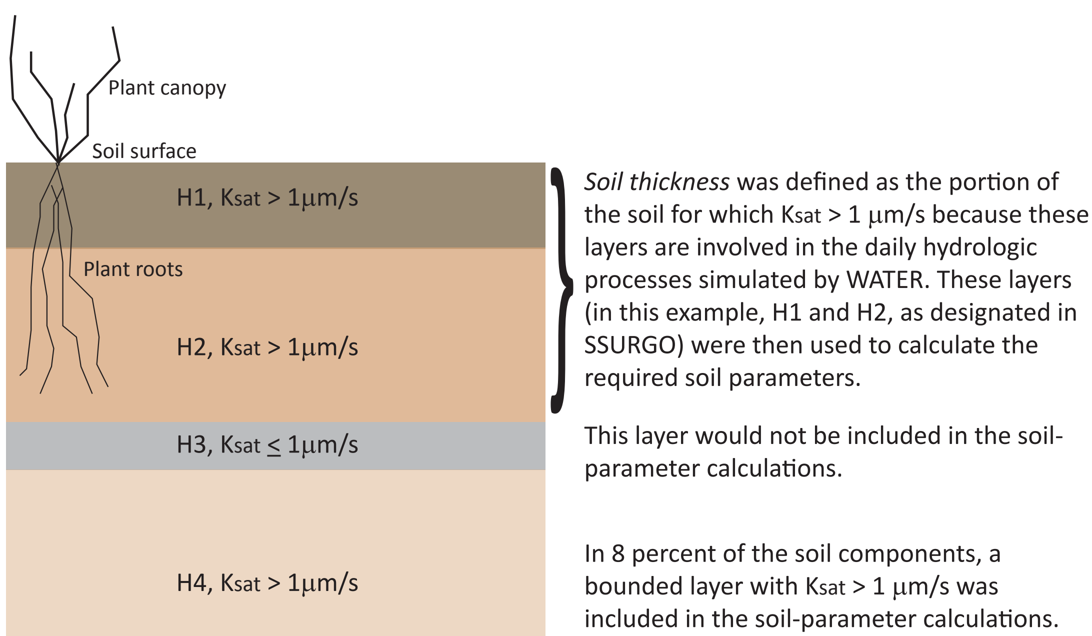


Figure 6. Schematic of soil layers and relation to Water Availability Tool for Environmental Resources (WATER).

2. The conductivity multiplier for each soil-mapping unit was calculated as follows:

$$conmult = \frac{K_{sat} - high_{surface}}{K_{sat} - low_{"bottom"}} \quad (6)$$

where

K_{sat}-$high_{surface}$ is the high K_{sat} value for the surface layer and

K_{sat}-low_{bottom} is the low K_{sat} value for the bottommost soil layer for which the representative K_{sat} > 1 µm/s.

3. The scaling parameter (***m***) was then calculated for each soil-mapping unit:

where
$$f = \frac{\ln conmult}{soil\ thickness} \quad (7)$$

and
$$\boldsymbol{m} = \frac{porosity - field\ capacity}{f} \quad (8)$$

The component-weighted mean that was calculated for each SSURGO soil-mapping unit was then joined to the SSURGO spatial data by using the unique identifiers of the soil-mapping-unit polygons. These polygons, attributed with an individual soil parameter, were then converted to a 9.14-m raster; this resulted in a total of seven rasters (porosity, field capacity, available water-holding capacity, K_{sat}, soil thickness, *conmult*, ***m***). For each of these soil parameters, the mean soil-parameter value for the basin (*calibration basins* or HUC-12) was calculated by using ArcMap. During development of WATER, the calculated ***m*** value was divided by 25 to improve the output based on visual inspection of estimated hydrographs; this is the development scaling parameter ($\boldsymbol{m}_d$). Once NEXRAD data became available, this parameter was calibrated uniformly using the 12 *calibration basins*.

Withdrawal and Discharge Data

Withdrawal and discharge data were provided by the KDOW. Withdrawal data from KDOW permits were averaged for a period from 2002 to 2006 (Rita Hockensmith, Kentucky Division of Water, Water Availability and Use Branch, written commun., 2007). Discharge data from the Kentucky Pollutant Discharge Elimination System (KPDES) were averaged for a period from 1989 to 2004 (Vickie Prather, Kentucky Division of Water, Kentucky Pollutant Discharge Elimination System Branch, written commun., 2005). All discharge categories were included except for the KPDES stormwater runoff waste code; this runoff is accounted for elsewhere in the TOPMODEL portion of WATER. Median monthly discharge was averaged over the specified time period and summed (for HUC-12 or *calibration basins*) to attain a representative annual value. Data were compiled and averaged using SAS and Microsoft Excel. For each basin, the sum of surface-water withdrawals and discharges, as well as groundwater withdrawals and discharges, is reported in the *Basin Characteristics* database.

Topographic Wetness Index Data

The topographic wetness index (TWI) is defined as

$$TWI = \ln\left({A}/{\tan\beta} \right) \quad (9)$$

where

A is upslope contributing area per unit contour width (meters) and

β is local slope (degrees).

The TWI, sometimes referred to as the wetness index or compound topographic index, is used to describe how water accumulates in the drainage basin based on a DEM (Quinn and others, 1997). This relation is the basis of TOPMODEL, and it illustrates the model assumption that flow of subsurface water reflects surface topography. However, the functionality of TOPMODEL, and consequently, WATER, is derived from how the model includes the TWI information. Instead of basing computations on each cell in a basin individually, the cells are distributed in a histogram, and each bin of cells from the histogram (histogram interval) is dealt with as a group based on the mean value of that bin. All of the cells from each bin are treated the same way for all future calculations on the principle that cells with a similar TWI will have a similar hydrologic response (Beven and Kirkby, 1979).

For WATER, the TWI raster was processed from the original DEM; the stream network defined previously (with a 9.14-m width and 0.25-km^2 flow accumulation) was used to remove stream-cell TWI values because these high values do not reflect hillslope processes (Quinn and others, 1997). The resulting raster was then exported as an ASCII file and processed with the WATER Histogram Builder.

Overview of the WATER Histogram Builder

Because it is necessary to process numerous TWI rasters in an objective, consistent, and efficient manner, the Histogram Builder (HB) was developed for use in the preprocessing of data for WATER. The HB requires a TWI raster that has been converted to an ASCII format. The ASCII file includes one TWI value for each cell of the DEM, and the cell width can be variable depending on the cell size of the DEM from which the TWI values were derived. The user must specify the number of histogram bins desired in the final output file; 30-bin histograms were used for development of WATER.

The HB operates in batch mode to allow the user to process a large number of TWI ASCII files from a single execution of the program. After starting the program, the user must select a batch-list file that contains a listing of all the TWI ASCII files to be processed. The user must then select a directory where the TWI ASCII files reside. The filenames in the batch list must correspond exactly to the TWI ASCII filenames and include the filename extensions; incorrect or incomplete filenames will result in termination of the HB. An output directory must also be selected to store the output files. Upon successful completion of these preconditions, the user presses the START button to begin processing.

The processing starts by reading the entire ASCII file to get the total, minimum, and maximum TWI values. These minimum and maximum values, along with the user-specified number of bins, are used to determine the low and high value of each individual bin for a set of equal-width bins. The count for each bin is also divided by the total number of TWI values to determine the fraction of the watershed that each bin represents. A second read through the entire original file puts each individual TWI value into the bin whose low and high values bracket that specific TWI value. For each bin, TWI values are summed, and the sums are divided by the counts to get the mean TWI value for each bin. Finally, the output data are written to an ASCII text file called *basinatn.txt* file for use in WATER. The first line of the output file contains the number of bins requested by the user. The reported value on this line may be smaller than the user-specified value if one or more of the bins is empty after the processing of the ASCII file. Each of the remaining lines in the text file represents one histogram bin. The first value on the line is the mean TWI value for the histogram bin, and the second value is the fraction of the watershed represented by that bin. The output file is then ready for use in WATER; no further processing is necessary.

Climate Data

Originally, both temperature and precipitation input data for WATER were derived by using the Kentucky Watershed Modeling Information Portal climate-data generator (*http://technology.ky.gov/gis/kwmip/*). This climate-data generator computes daily climate data (daily precipitation in inches and maximum/minimum temperature in degrees Fahrenheit) for each day of a requested time period. The climate-data generator employs an inverse distance-weighting approach coupled with an elevation adjustment (after Hay and others, 2002) using X-Y-Z (latitude-longitude-elevation) data from 243 climate stations (National Weather Service COOP TD3200 stations) in and near Kentucky; this creates an irregular spatial precision of approximately 400 km^2. The model was optimized by using *shuffled complex evolution* given user-assigned weighting to the inverse distance versus the elevation approach. All interpolated data were estimated and stored on a 1-km grid—one raster for each variable for each day of the 1948–2006 time period. These daily mean rasters were then sampled for each basin (HUC-12 or *calibration basin*) and these data were aggregated in the *bclim.txt* text file.

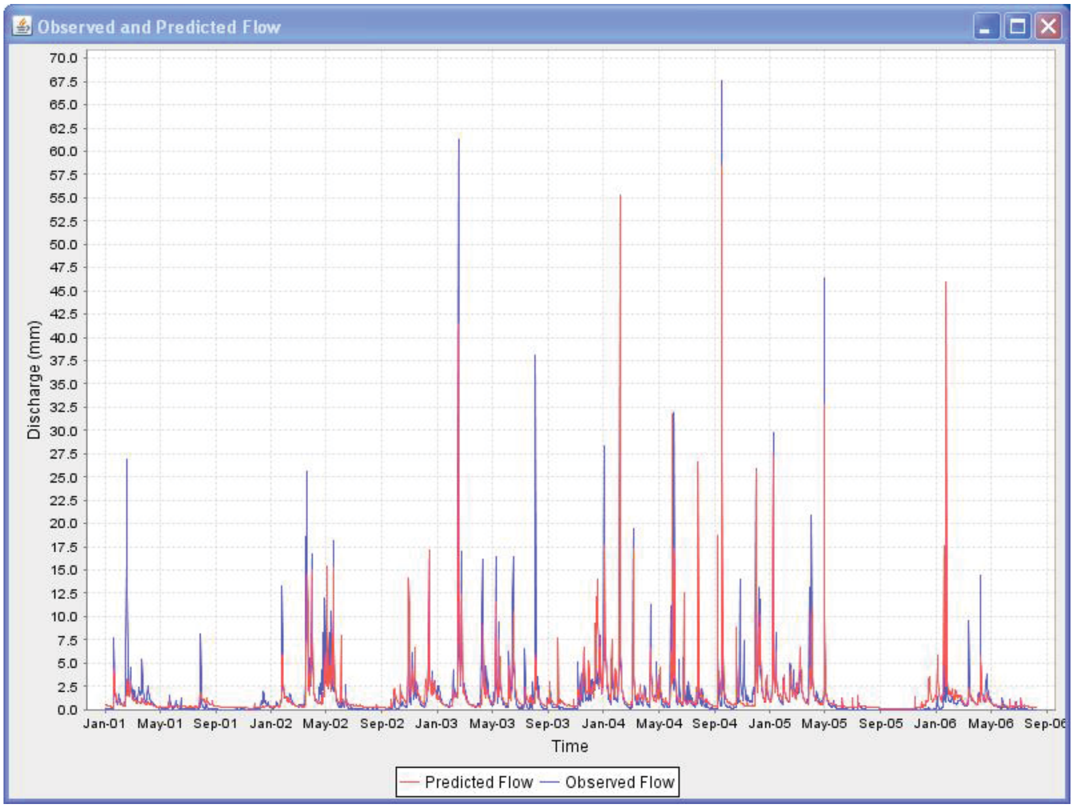
After the initial development of WATER, it was evident that the precipitation data developed by means of the climate generator were at too coarse of a resolution to properly calibrate the model. The observed discharge record from USGS streamflow-gaging stations, located within *calibration basins*, indicated storm events that did not correspond with the modeled flow events in either timing or magnitude, although the general size of peaks and duration of events was similar. The Next Generation radar (NEXRAD) Stage III data for 2000–08 were acquired from the NOAA National Weather Service, Ohio River Forecast Center (Ray Davis, written commun., 2008). These data were provided as daily totals summed from hourly rasters that had a spatial resolution of 4 km for the entire study area. These daily totals were averaged by basin (*calibration basin* or HUC-12) and aggregated into a single precipitation record for each basin. These NEXRAD precipitation values were then merged with the previously calculated temperature values to produce a more accurate climatic record for the 2000–06 time period. Consequently, this 2000–06 time period was used for the statistical evaluation and calibration of WATER.

Statistical Evaluation and Calibration of WATER

During initial development of WATER, evaluation of the general accuracy of the model output was based on visual inspection of hydrographs and flow-duration curves (fig. 7) for the 2000–05 time period. However, once the NEXRAD data were acquired and processed, statistical evaluation and calibration of WATER were possible. Statistical evaluation and calibration were done for the 12 non-karst *calibration basins* (fig. 1 and table 3) that were part of the initial model development and for which there were USGS streamflow-gaging records that continued through August 8, 2006.

Tested Scenarios

For each basin, modeled discharge was compared to observed discharge for a series of scenarios (table 4). First, the two precipitation sources were compared to quantify the significance of the new NEXRAD data. Second, rooting depth was manipulated because this value affects the evapotranspiration calculations in the model; during model development, changes in this parameter visibly affected both the peak and the duration of storm events. WATER was initially developed with a 20-cm rooting depth, but it was hypothesized that the NEXRAD precipitation data might document localized storm events that previously were missed. Consequently, rooting depths of 20 cm, 30 cm, and 40 cm were tested. Further scenarios included the manipulation of K_{sat}, a parameter used by previous researchers to improve TOPMODEL estimations (for example, Wolock, 1993); this soil parameter was tested with factors of 0.5, 1.5, and 2 times the value calculated by using the SSURGO database (U.S. Department of Agriculture, 2007) and compared to output when the calculated value from SSURGO was used directly (that is, a factor of 1). For each of these scenarios, all other soil parameters were calculated directly from the SSURGO; the scaling parameter development value ($\boldsymbol{m}_d$) was the SSURGO value divided by 25.



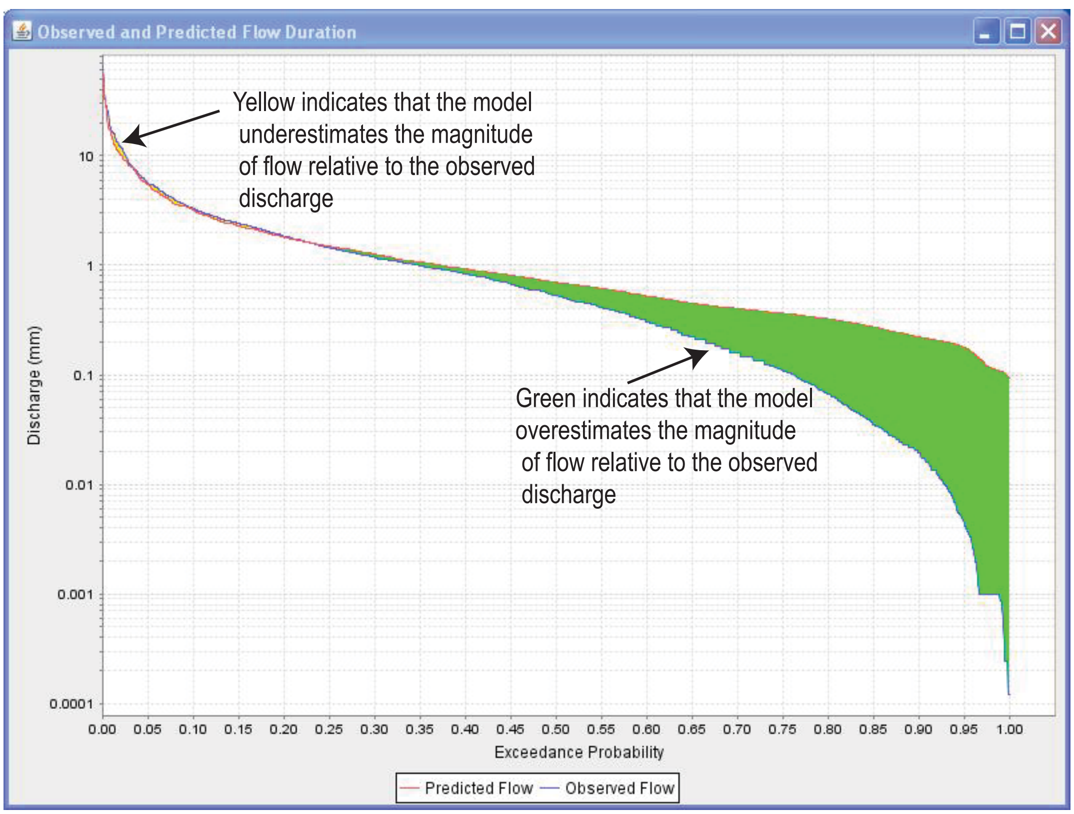


Figure 7. Example hydrograph and flow-duration curve produced by Water Availability Tool for Environmental Resources (WATER) for calibration basin 03282040.

Table 3. Calibration basins used for statistical evaluation and calibration of WATER.

[WATER, Water Availability Tool for Environmental Resources; USGS, U.S. Geological Survey; km^2, square kilometers; HUC, hydrologic unit code]

USGS site identification	Site name	Basin area (km^2)	HUC-12	Comments
03207965	Grapevine Creek near Phyllis, Ky.	16.80	050702020204	None
03210000	Johns Creek near Meta, Ky.	146.01	050702030301	None
03237255	Kinniconick Creek below Trace Creek at Tannery, Ky.	554.02	050902010103	None
03251200	North Fork Licking River near Mt. Olivet, Ky.	583.25	051001011001	None
03280700	Cutshin Creek at Wooton, Ky.	158.31	051002020102	None
03281100	Goose Creek at Manchester, Ky.	422.69	051002030104	None
03282040	Sturgeon Creek at Crestmont, Ky.	200.54	051002040101	None
03282500	Red River near Hazel Green, Ky.	170.69	051002040201	None
03406500	Rockcastle River at Billows, Ky.	1,564.48	051301020302	None
03611260	Massac Creek near Paducah, Ky.	26.97	051402060301	None
03611800	Bayou Creek near Heath, Ky.	16.96	051402060701	None
07024000	Bayou de Chien near Clinton, Ky.	178.00	080102010104	Tile drained

Table 4. Matrix of scenarios tested for WATER efficiency and calibration.

[WATER, Water Availability Tool for Environmental Resources; COOP, National Weather Service COOP TD3200 stations; NEXRAD, Next Generation radar; K_{sat}, saturated hydraulic conductivity; $\boldsymbol{m}$, scaling parameter]

Root depth (centimeters)	Model parameter					
	COOP	NEXRAD	0.5 K_{sat}	1.5 K_{sat}	2 K_{sat}	$\boldsymbol{m}$
20	•	•	•	•	•	
30		•				•
40		•				•

Model Results

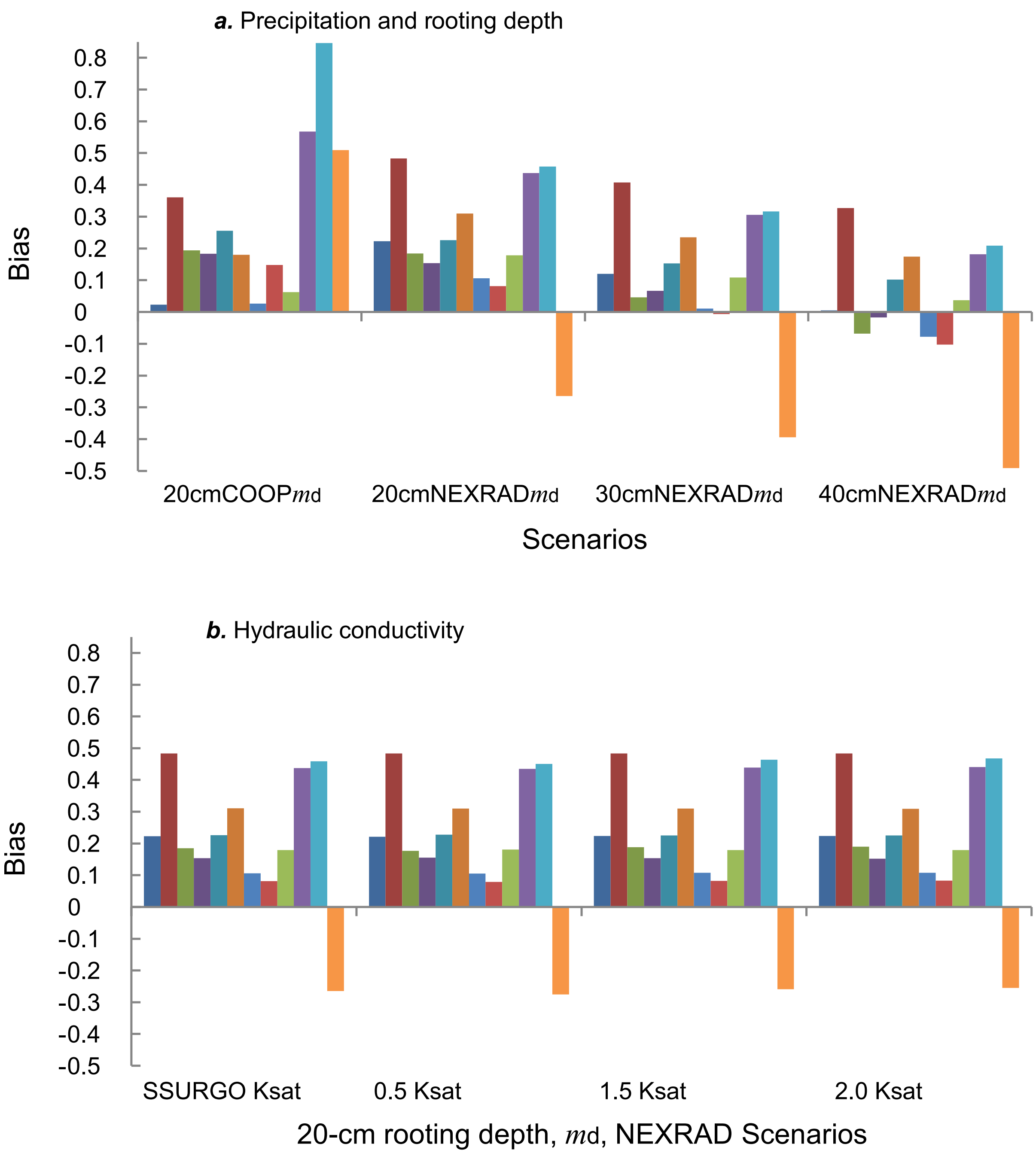
Each of the tested scenarios was evaluated on the basis of a combination of four statistics: bias, RMSE, correlation, and E_f. Scenarios were tested in each of the 12 *calibration basins* for the January 1, 2000, to August 8, 2006, time period; one year of data are used to equilibrate the model, so discharge estimates were statistically evaluated for the period from December 31, 2000, to August 8, 2006 (a total of 2,119 days). Because the statistics varied between basins, final model selection was based on the consistency of each statistic for a given scenario; for example, a scenario that produced all $E_f > 0.25$ was preferable to a scenario that produced an $E_f = 0.8$ in one basin but an $E_f < 0$ in another basin.

Precipitation Data Source

The precipitation sources (NWS COOP and NEXRAD) were compared by using the 20-cm rooting depth; only the precipitation data were changed (figs. 8a–11a). The bias of the model output from the NWS COOP network was inconsistent and ranged from 0.02 to 0.85. The NEXRAD model output showed a smaller bias (-0.26-0.48); the only basin with a negative bias is tile drained (USGS ID 07024000) and also showed a negative bias in all other NEXRAD scenarios. The other statistics showed no consistent differences between the two models; however, visual inspection of the hydrographs from the NEXRAD scenarios confirmed a better relation between precipitation events and peak discharges (fig. 12). Consequently, the NEXRAD data (for 2000–06) were used for all subsequent models.

Rooting Depth

WATER was originally developed with a 20-cm rooting depth on the basis of visual inspection of the hydrograph and the goal of balancing low flows with seasonal evapotranspiration patterns. However, with the incorporation of NEXRAD data, the relation between precipitation and discharge events became more precise, thus the soil storage and evapotranspiration relation changed. Rooting depths of 20 cm, 30 cm, and 40 cm were compared by using model scenarios that included NEXRAD precipitation data (figs. 8a–11a and 13). There was little difference in RMSE or correlation between the scenarios; however, the E_f was consistently better for discharge estimates in combination with the 30-cm or 40-cm rooting depth compared to the 20-cm rooting depth. The mean model bias decreased as the rooting depth increased; however, the bias range was smallest for the 20-cm rooting depth and largest for the 40-cm rooting depth. The 40-cm rooting depth also resulted in several basins where the discharge estimates were negatively biased, not just the tile-drained basin (USGS ID 07024000). Consequently, the 30-cm rooting depth was used during the calibration of the $\boldsymbol{m}$ parameter, and the 40-cm rooting depth was not tested again until the final $\boldsymbol{m}$ value had been determined.



EXPLANATION

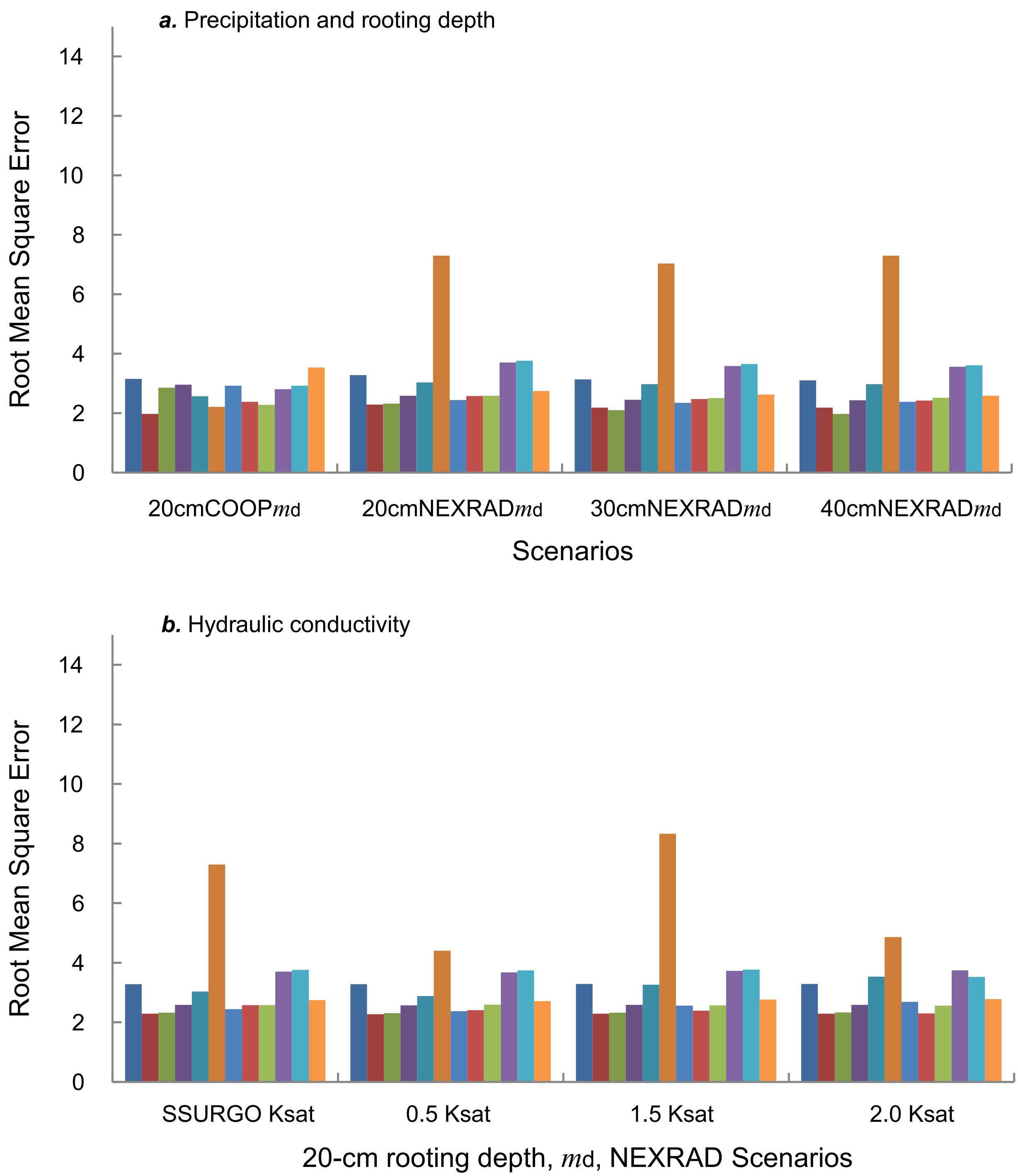
U.S. Geological Survey site identification

03207965	03282040
03210000	03282500
03237255	03406500
03251200	03611260
03280700	03611800
03281100	07024000

Scenario parameters

20cm	20-centimeter rooting depth	2.0	2.0 x SSURGO calculated value
30cm	30-centimeter rooting depth	1.5	1.5 x SSURGO calculated value
40cm	40-centimeter rooting depth	0.5	0.5 x SSURGO calculated value
COOP	National Weather Service Cooperative Network	SSURGO	State Soil Survey Geographic database
		Ksat	Saturated hydraulic conductivity
NEXRAD	Next Generation Radar	*md*	Model-development scaling parameter

Figure 8. Bias of Water Availability Tool for Environmental Resources (WATER) calibration scenarios.



EXPLANATION

U.S. Geological Survey site identification

03207965	03282040
03210000	03282500
03237255	03406500
03251200	03611260
03280700	03611800
03281100	07024000

Scenario parameters

20cm	20-centimeter rooting depth	2.0	2.0 x SSURGO calculated value
30cm	30-centimeter rooting depth	1.5	1.5 x SSURGO calculated value
40cm	40-centimeter rooting depth	0.5	0.5 x SSURGO calculated value
COOP	National Weather Service Cooperative Network	SSURGO	State Soil Survey Geographic database
		Ksat	Saturated hydraulic conductivity
NEXRAD	Next Generation Radar	*m*d	Model-development scaling parameter

Figure 9. Root mean square error of Water Availability Tool for Environmental Resources (WATER) calibration scenarios.

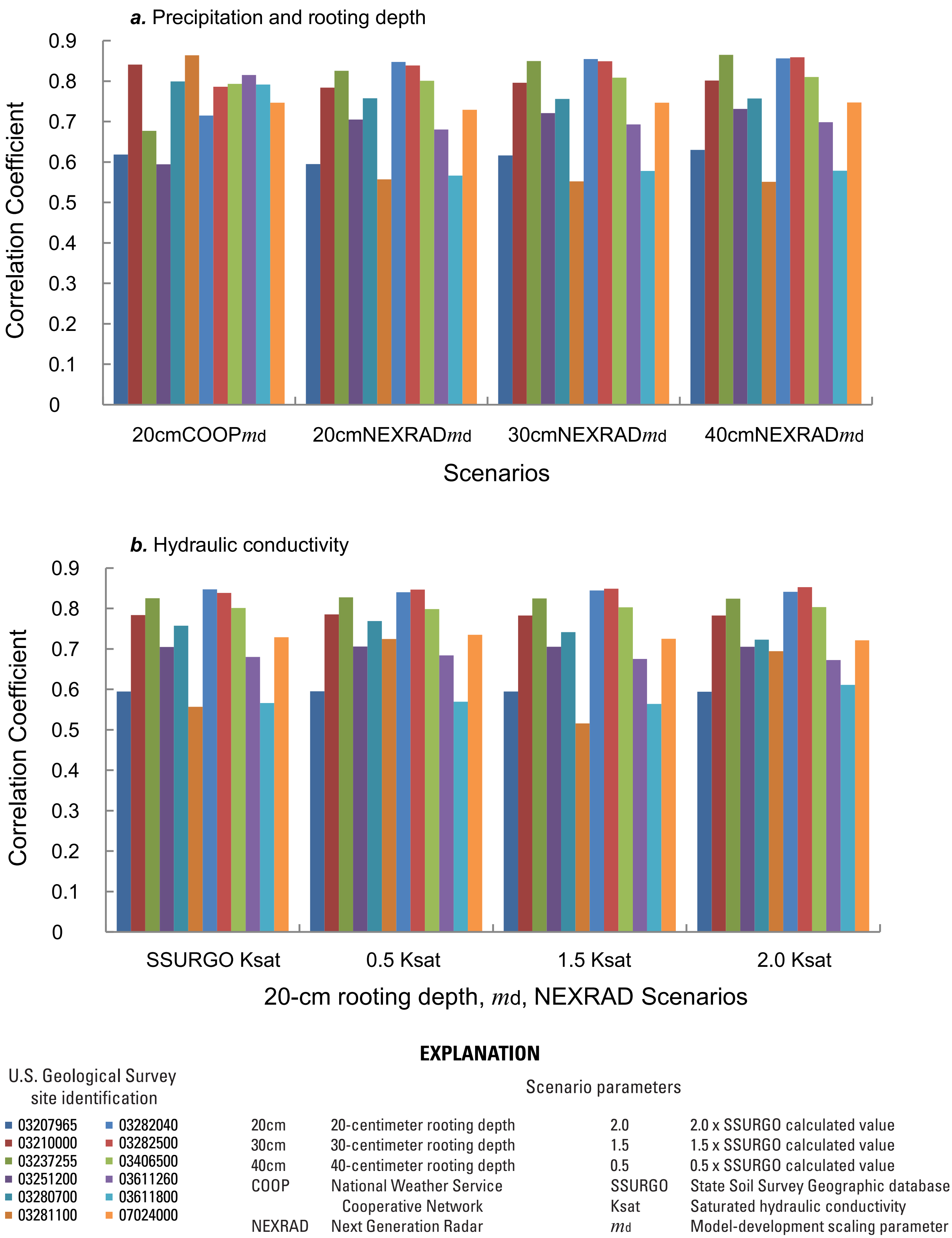


Figure 10. Correlation coefficients of Water Availability Tool for Environmental Resources (WATER) calibration scenarios.

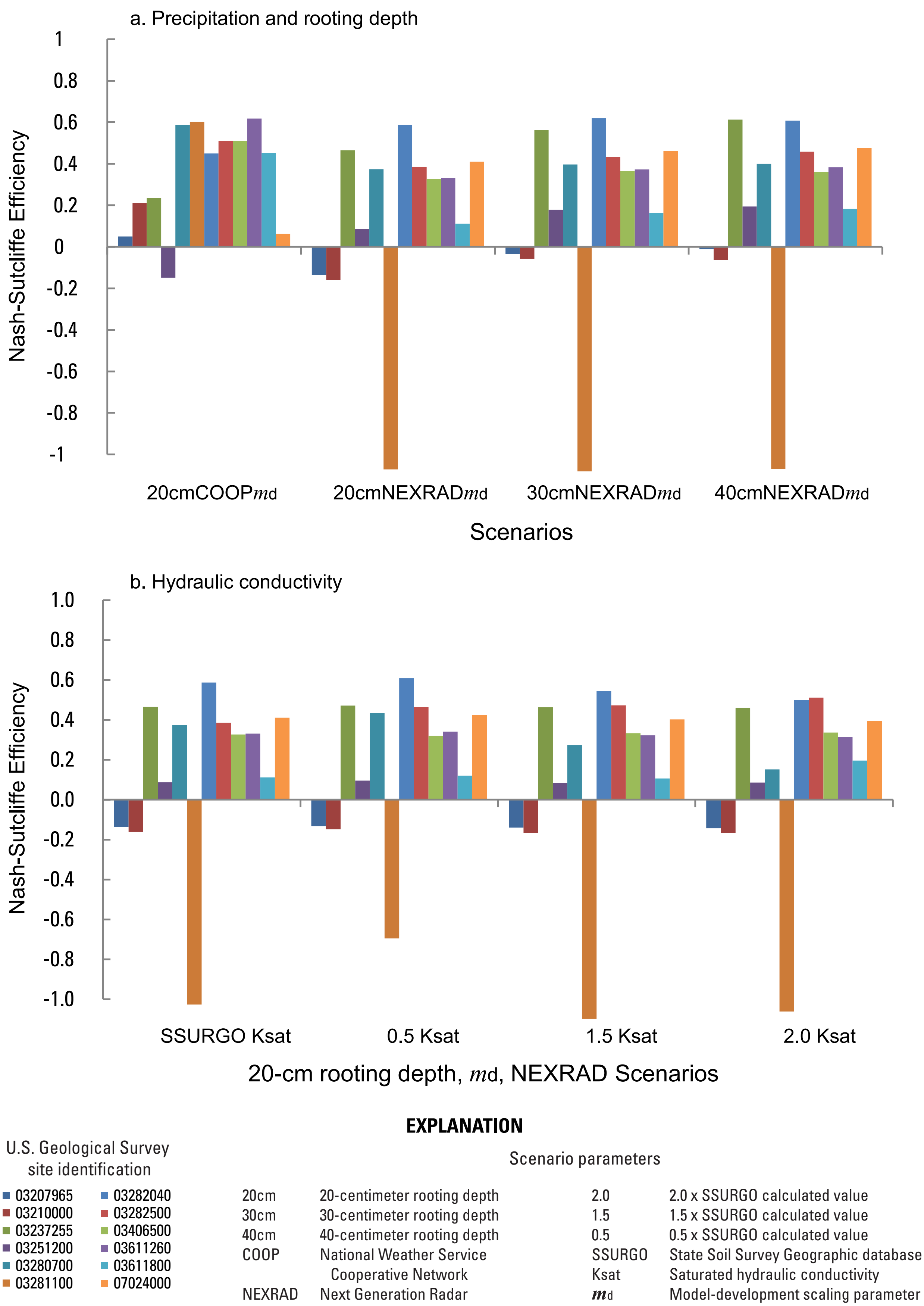


Figure 11. Nash-Sutcliffe efficiency of Water Availability Tool for Environmental Resources (WATER) calibration scenarios.

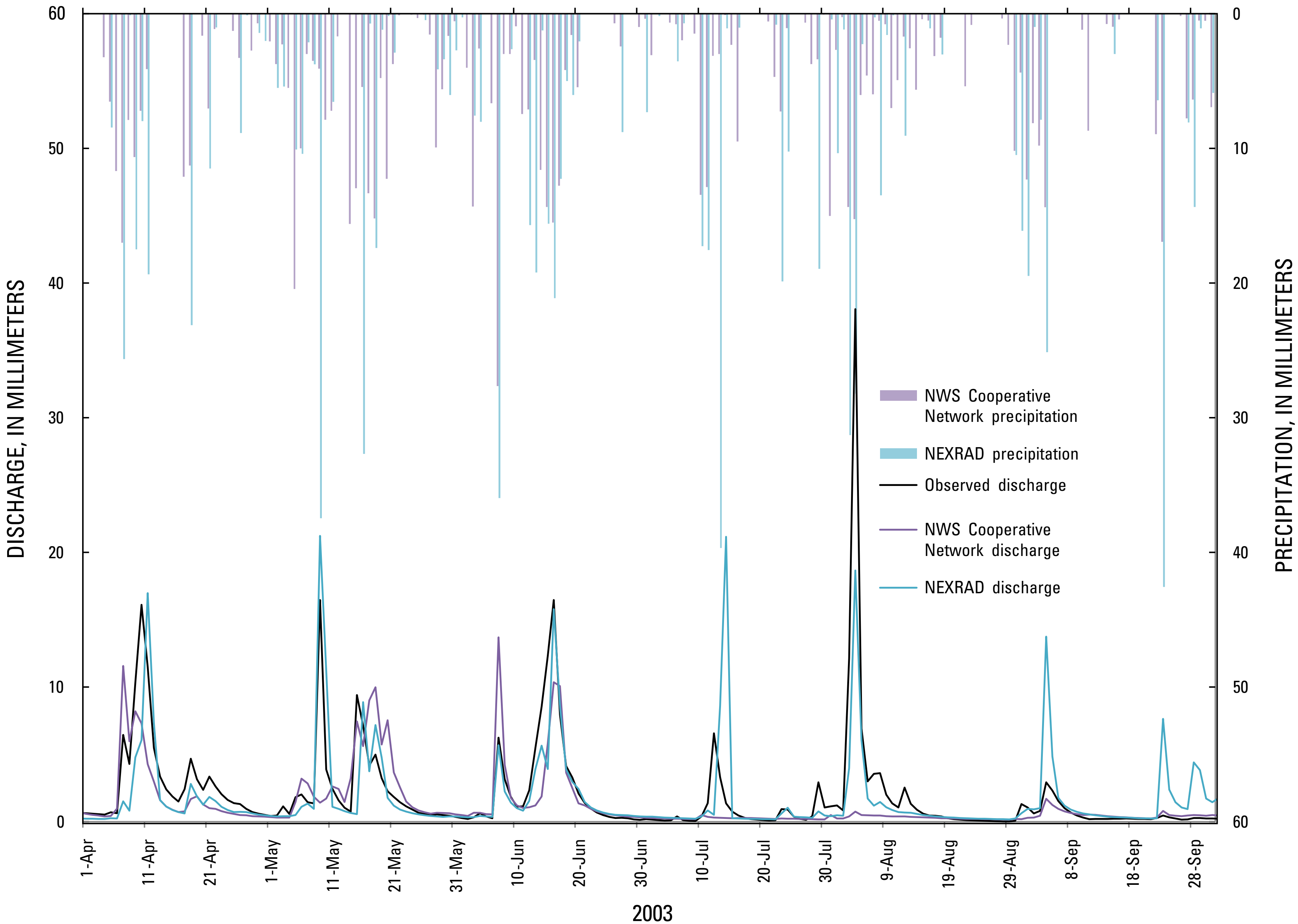


Figure 12. Comparison of precipitation sources and discharge for calibration basin 03282040.

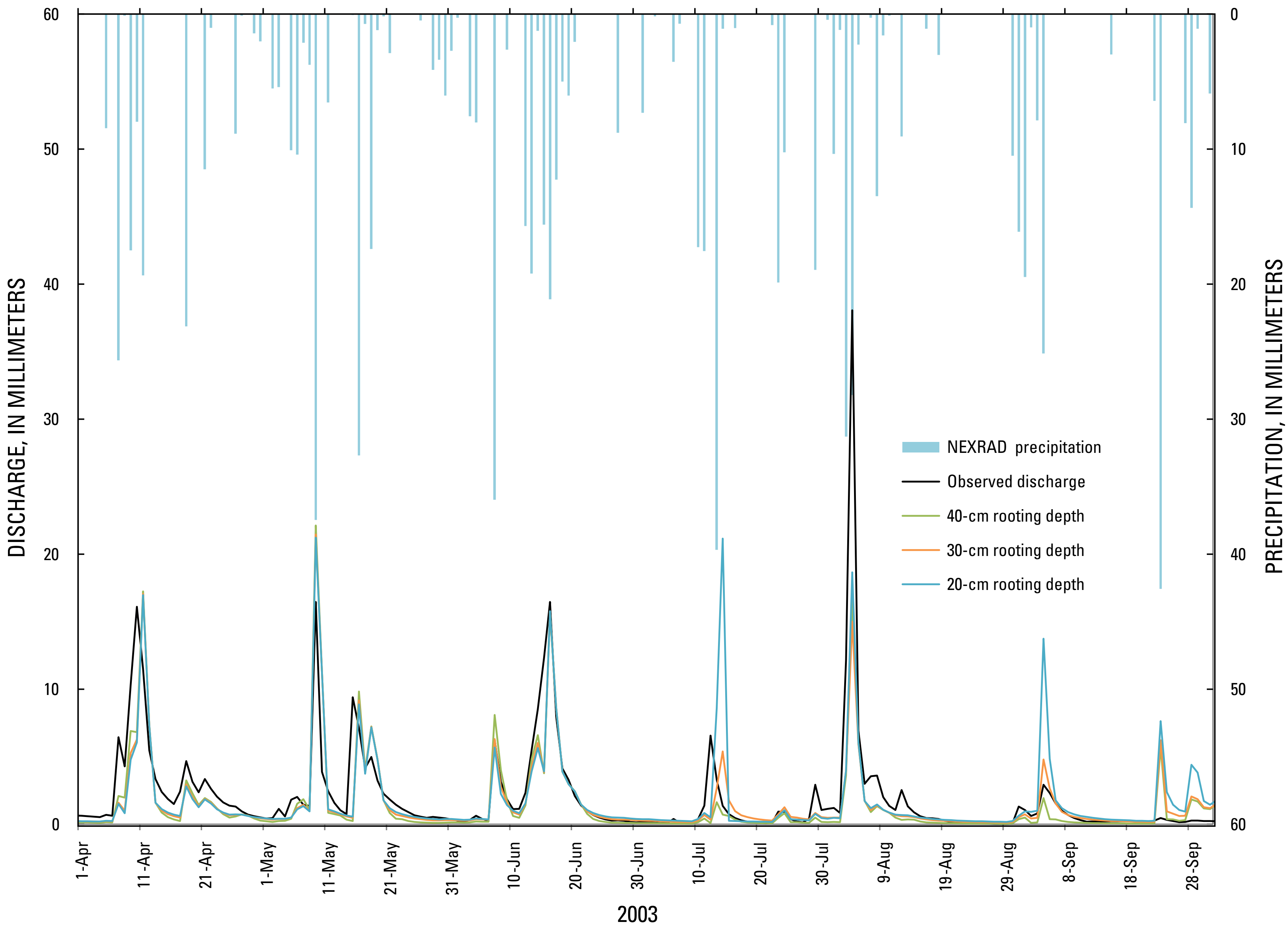


Figure 13. Comparison of rooting depths and discharge for calibration basin 03282040.

Hydraulic Conductivity

The hydraulic conductivity (K_{sat}) was evaluated in models that used NEXRAD precipitation data, a 20-cm rooting depth, and $\boldsymbol{m}_d$ (figs. 8b–11b). For each individual watershed, there was little difference in any of the statistics between the 0.5 K_{sat}, 1.5 K_{sat}, or 2 K_{sat} scenarios as compared with the original scenario that used the K_{sat} calculated directly from SSURGO. Consequently, these transformations were eliminated from the model input.

Scaling Parameter

During development of WATER, visual inspection of estimated hydrographs indicated the need to adjust ***m***; therefore, a development scaling parameter ($\boldsymbol{m}_d$) was used that equaled 1/25 (0.39) the calculated value from SSURGO. Once NEXRAD data became available, this parameter was calibrated uniformly using the 12 *calibration basins*. The scaling factor (***m***) was evaluated in models that used NEXRAD precipitation data, a 30-cm rooting depth, and a K_{sat} calculated directly from SSURGO. A model simulation using the development value $\boldsymbol{m}_d$ was compared to discharge estimates using different factors of the SSURGO-calculated ***m***, including 1, 0.5, 0.25, 0.10, and 0.05 (fig. 14). All four statistics illustrated that the 1, 0.5, and 0.25 ***m*** scenarios were poor, and the modeled hydrographs show that these event peaks were too low and the recession after a peak too slow (fig. 15); consequently, these transformations were eliminated as a model input. Model output from the 0.10 ***m*** scenario resulted in all positive E_f values, in contrast to model output from the original $\boldsymbol{m}_d$ scenario. Although the 0.05 ***m*** scenario hydrograph was as good or better for some of the calibration basins (fig. 15), the statistical analysis showed that this transformation created inconsistent results among the basins, including a negative E_f value for calibration basin 03281100. Consequently, the 0.10 ***m*** transformation ($\boldsymbol{m}_{0.10}$) was determined to be the best model parameter.

Based on the similarity of each of the four statistics (figs. 8a–11a), the 30-cm and 40-cm rooting depth scenarios were repeated with the $\boldsymbol{m}_{0.10}$ value in combination with NEXRAD precipitation. There was little statistical difference between these two scenarios (fig. 16); however, the hydrographs showed that streamflow-event peaks were more accurate with the 30-cm-rooting-depth scenario (fig. 17).

WATER was designed for use at a HUC-12 basin size. In Kentucky, these basins range from 8.5 to 91.6 km^2; the mean area of the 1,283 HUC-12 basins is 84.9 km^2. The calibration basins ranged in size from 16.8 to 1,564.5 km^2; however, the statistical analysis shows that the results are the most accurate for those basins in the 26.9- to 422.7-km^2 range (fig. 18).

In summary, WATER successfully estimated long-term flow for twelve HUC-12 basins in non-karst areas of Kentucky, with a mean bias of 0.10±0.18, a mean RMSE of 2.47±0.98, a mean correlation of 0.73±0.10, and a mean E_f of 0.51±0.16. This statistical evaluation of the model indicates that WATER successfully estimates long-term flow in the non-karst areas of Kentucky.

Model Applications and Limitations

Many methods for simulating streamflow (both hydrologic and hydraulic) are readily available; selection and application of the correct model is generally based on the intended use of the model, limitations of available data, and, often, the experience of the user (see *http://water.usgs.gov/software/* or *http://smig.usgs.gov/SMIC/model_pages/* for model summaries). Where greater precision is required for a specific purpose and experienced personnel are available to set up the model, hydraulic-routing models and (or) some combination of hydraulic and hydrologic models may be preferable; for example, BRANCH (Schaffranek and others, 1981). Where streamflow and water quality are the primary focus, other models incorporate hydrology and hydraulics (for example, HSPF; Bicknell and others, 1997). WATER is a regional-scale hydrologic model that will optimally function in smaller, unregulated, upland watersheds where precise channel-geometry data are not available or are unfeasible to collect. Users of WATER should be aware of the limitations regarding a regional hydrologic model including the temporal nature of surface-water model data (for example, withdrawal and discharge data). However, these limitations are offset by the benefits of preprocessing the large amounts of complex digital data (for example, topographic and soil parameters), as well as decisions about model parameters, that have been incorporated by WATER, resulting in a more user-friendly, enhanced hydrologic-modeling tool.

WATER, and the underlying TOPMODEL code, provide a comprehensive picture of basin processes, including water budget, streamflow, and slope processes in basins of varying size and with a database that can readily be aggregated for an extensive geographic area. Given the wide range of potential models and modeling applications, the WATER application was written in such a way that it may be upgraded or combined with models that use basin processes to estimate water quality and ecosystem needs. This ability to adapt the model code is required as new uses for the model become apparent and the availability of input data improves. For example, NOAA NEXRAD precipitation data have been incorporated into the current WATER application to improve precision and accuracy over previous versions of TOPMODEL. Recent advances in LIDAR (light detection and ranging) are among the more promising improvements that could potentially build increased precision and accuracy into future versions of WATER by greatly improving topographic resolution.

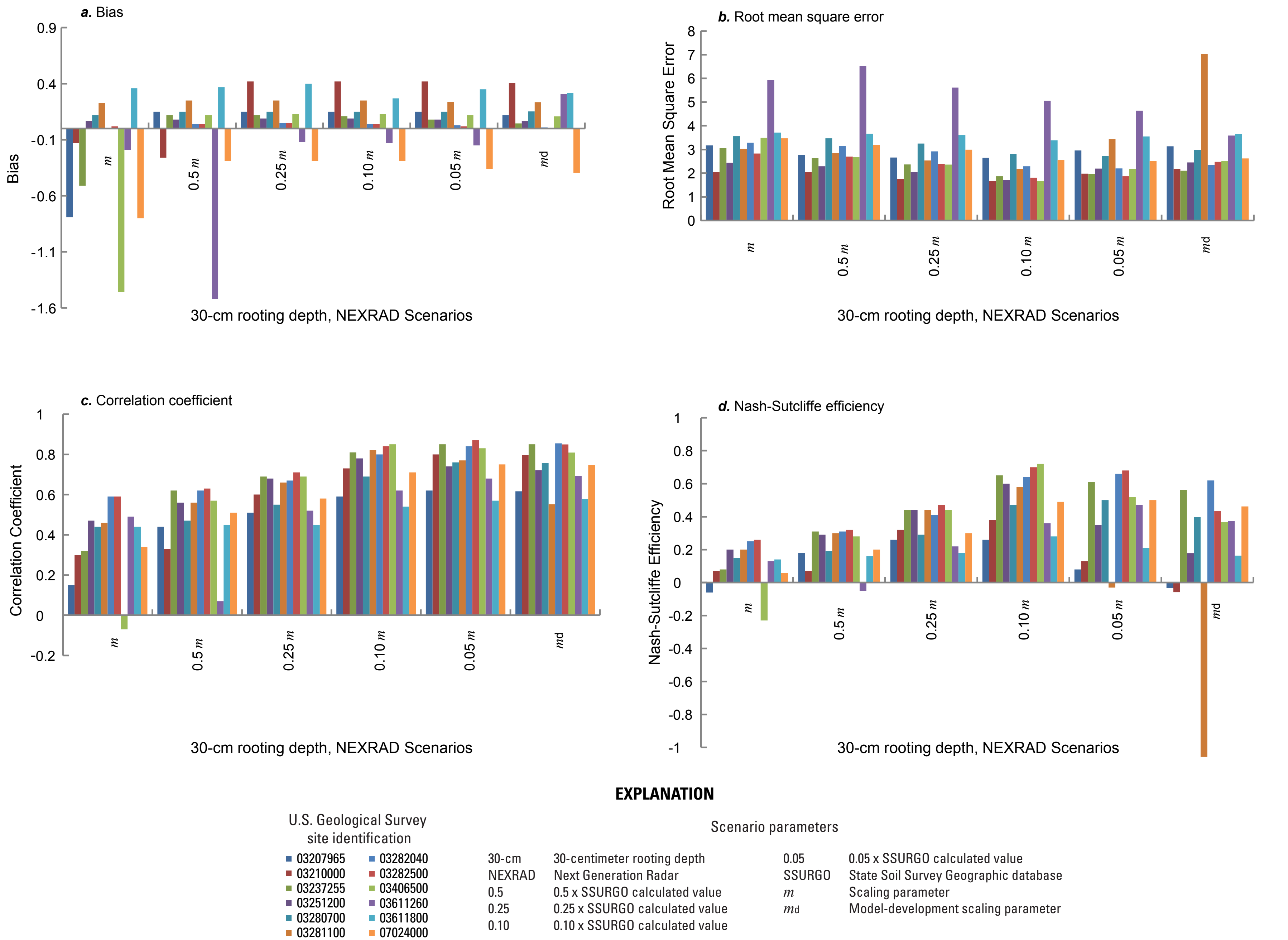


Figure 14. Statistical summary of scaling parameter (*m*) calibration scenarios.

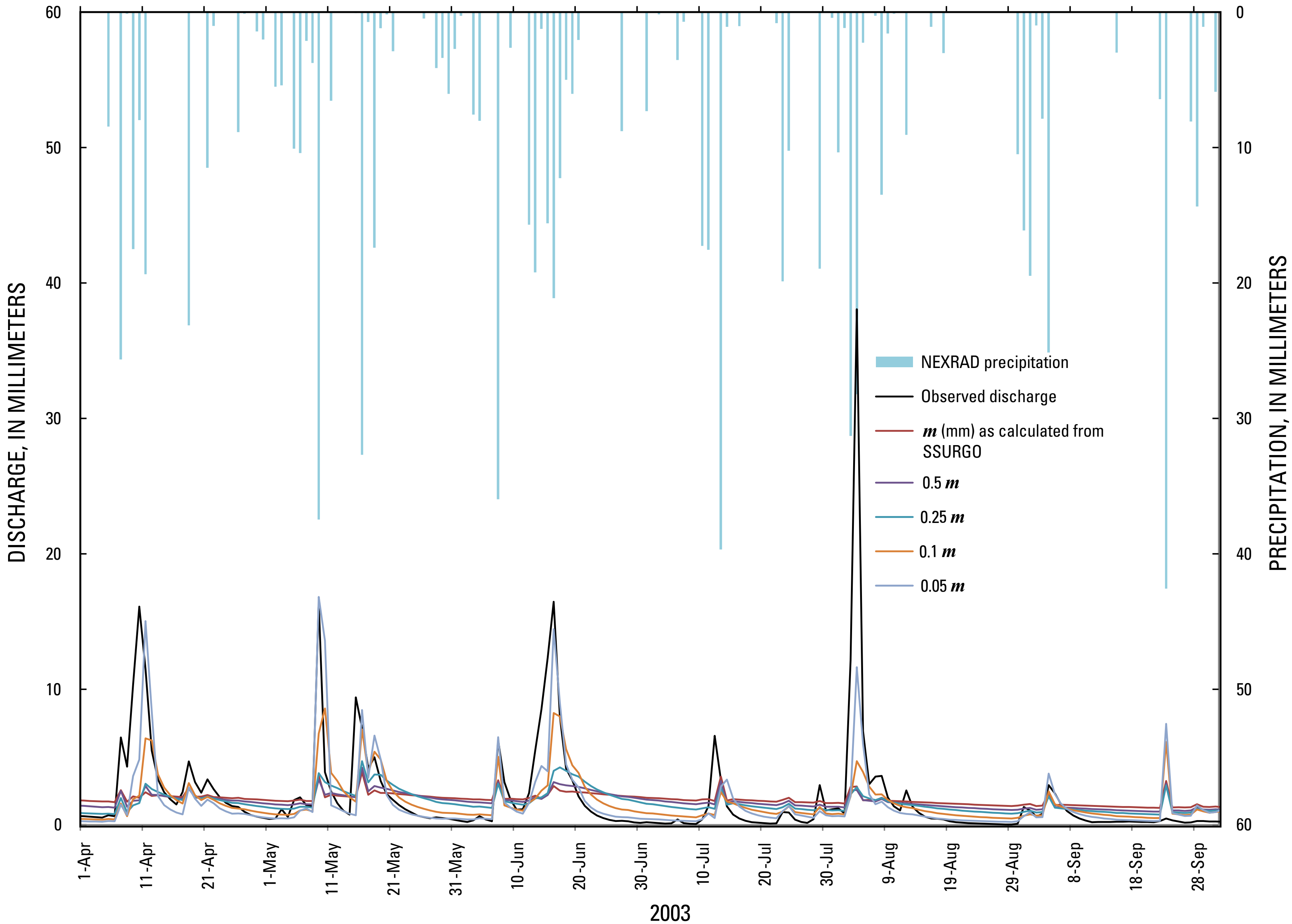


Figure 15. Comparison of scaling parameter (***m***) scenarios and discharge for calibration basin 03282040.

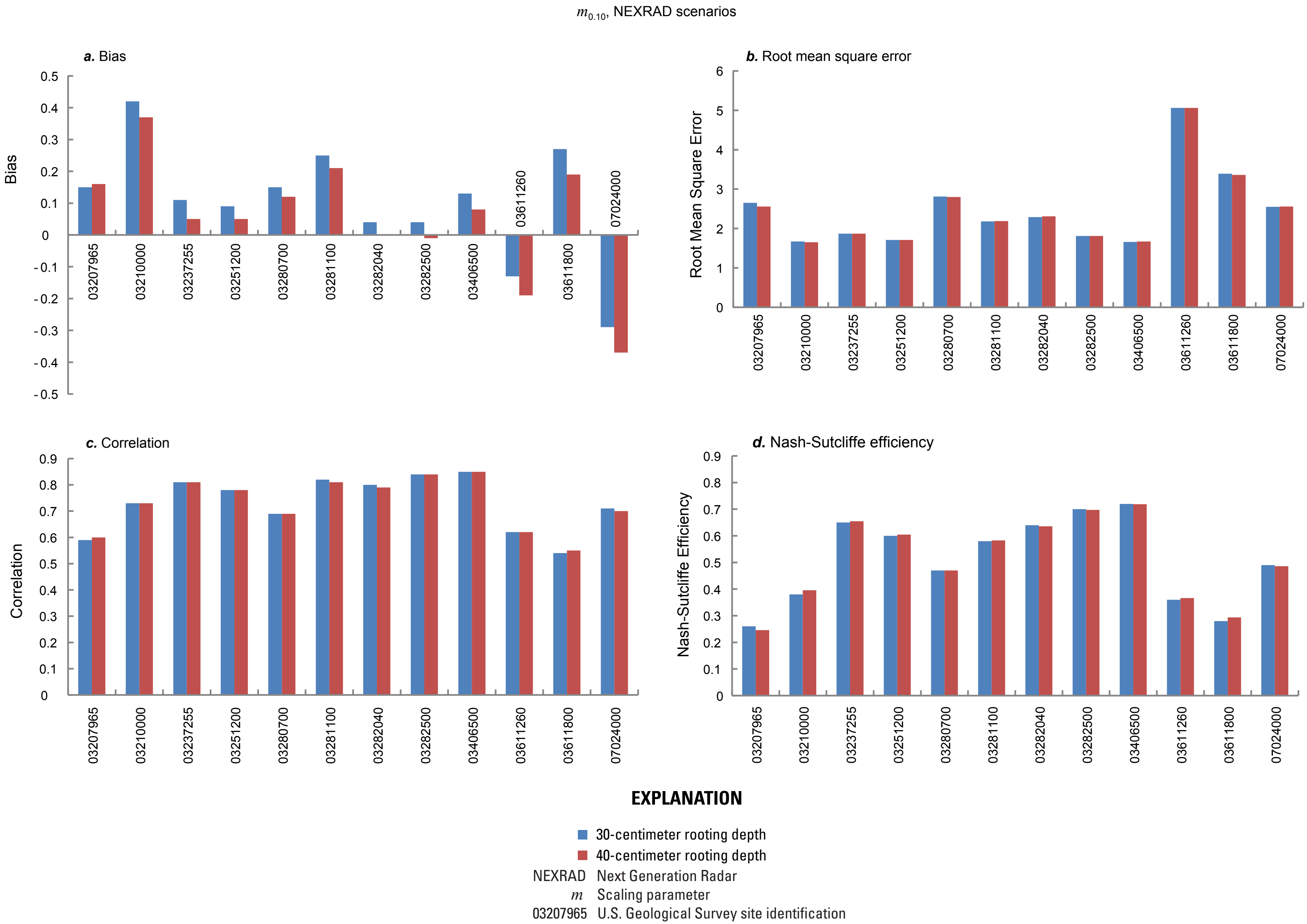


Figure 16. Statistical summary of Water Availability Tool for Environmental Resources (WATER) estimates for 30- and 40-centimeter rooting-depth scenarios.

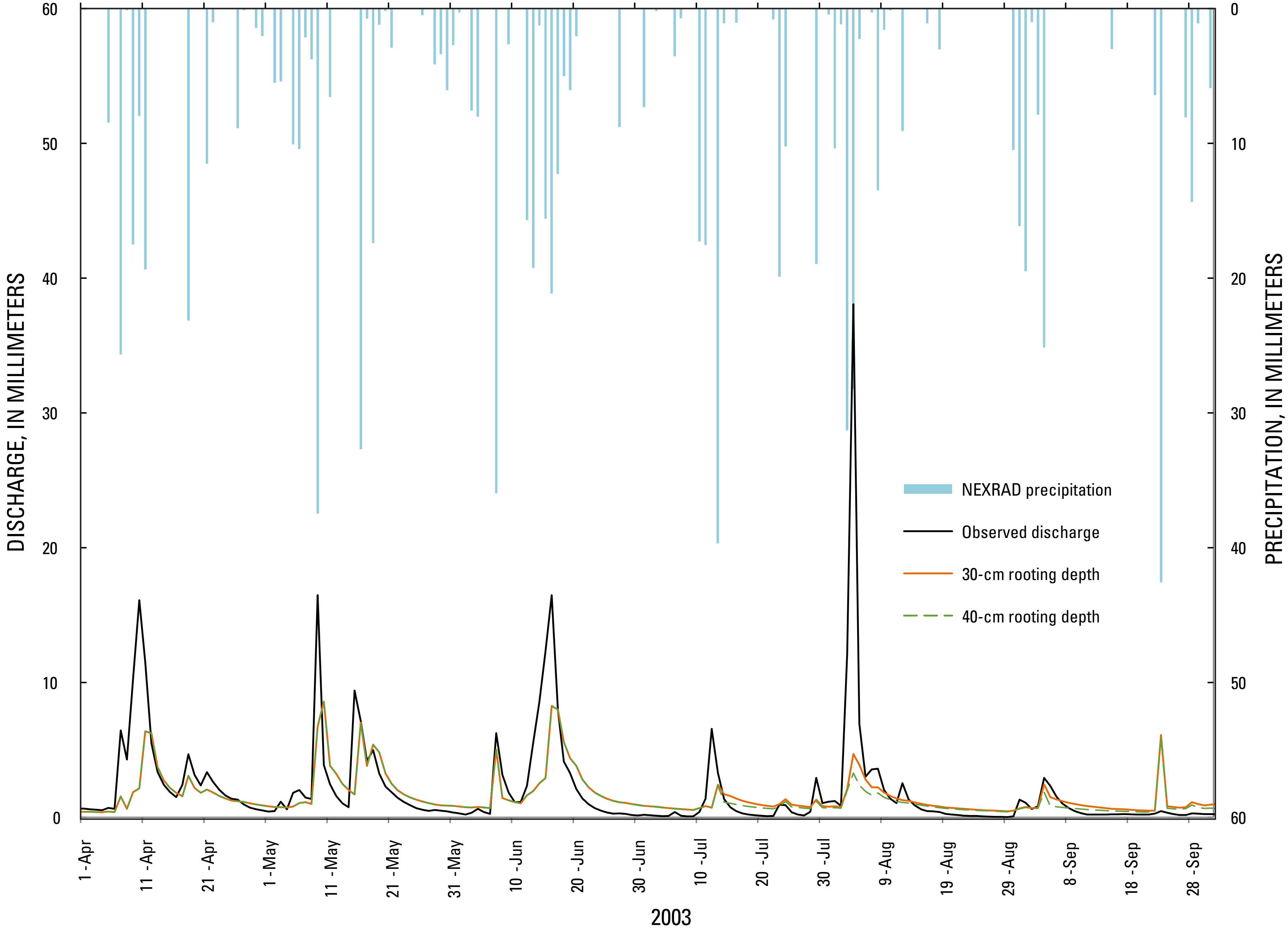
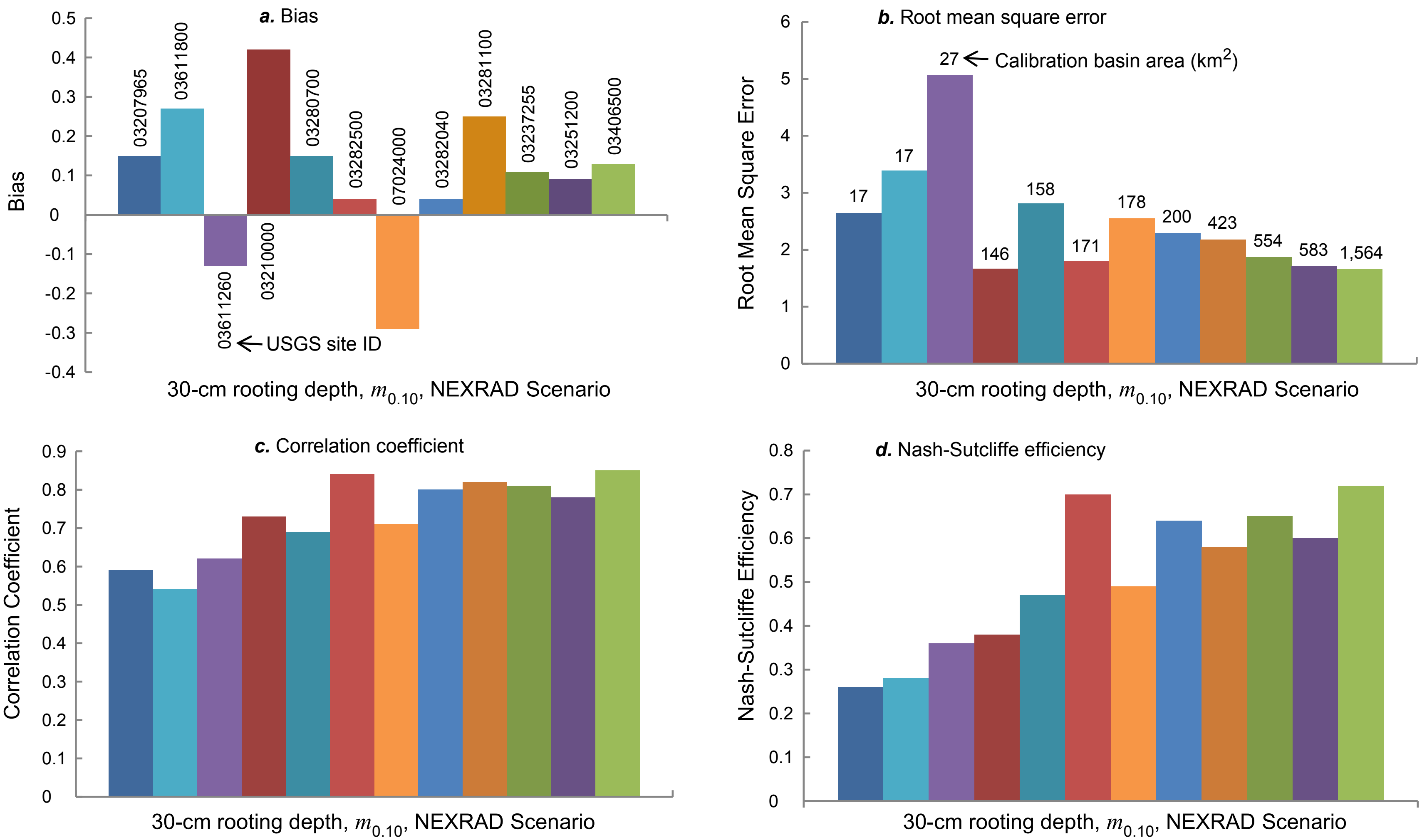


Figure 17. Comparison of 30- and 40-centimeter rooting-depth scenarios using 0.1 m for calibration basin 03282040.



EXPLANATION

U.S. Geological Survey site identification

03207965	03282040
03210000	03282500
03237255	03406500
03251200	03611260
03280700	03611800
03281100	07024000

Scenario parameters

30-cm	30-centimeter rooting depth
COOP	National Weather Service Cooperative Network
NEXRAD	Next Generation Radar
m	Scaling parameter

Figure 18. Statistical summary of Water Availability Tool for Environmental Resources (WATER) estimates for calibration basins in order of basin area.

Summary

The Water Availability Tool for Environmental Resources (WATER) was developed in phases to model ungaged streams in Kentucky; Phase I, discussed herein, modeled non-karst areas of Kentucky. WATER provides hydrographs, flow-duration curves, and a separation of flow components—together with a 58-year (1948–2006) climatic record—that can be used in to help make water-management decisions. The model is firmly based in topographic, pedogenic, and anthropogenic water-use data; it requires no additional input from the user. Consequently, it is easy to use, requires little training, and provides consistent and defensible analyses.

The model has been statistically tested and calibrated for 12 gaged basins over the 2000–06 time period. (Evaluation statistics were bias, root mean square error, correlation, and Nash-Sutcliffe efficiency.) This statistical evaluation showed that the use of Next Generation radar (NEXRAD) precipitation data, as opposed to precipitation data of coarser spatial resolution, is critical to accurately estimating discharge events. This statistical evaluation also showed that multiple physiographic terranes can be modeled accurately and that these discharge estimates are the most consistent when a 30-centimeter rooting depth is used together with a Soil Survey Geographic Database (SSURGO) derived scaling factor of 0.10 ***m***. Although the statistics indicate that localized optimization of the model could improve discharge estimates, for example in cases of tile-drained landscapes, WATER successfully performs with these model inputs across the entire study region—the non-karst areas of Kentucky.

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