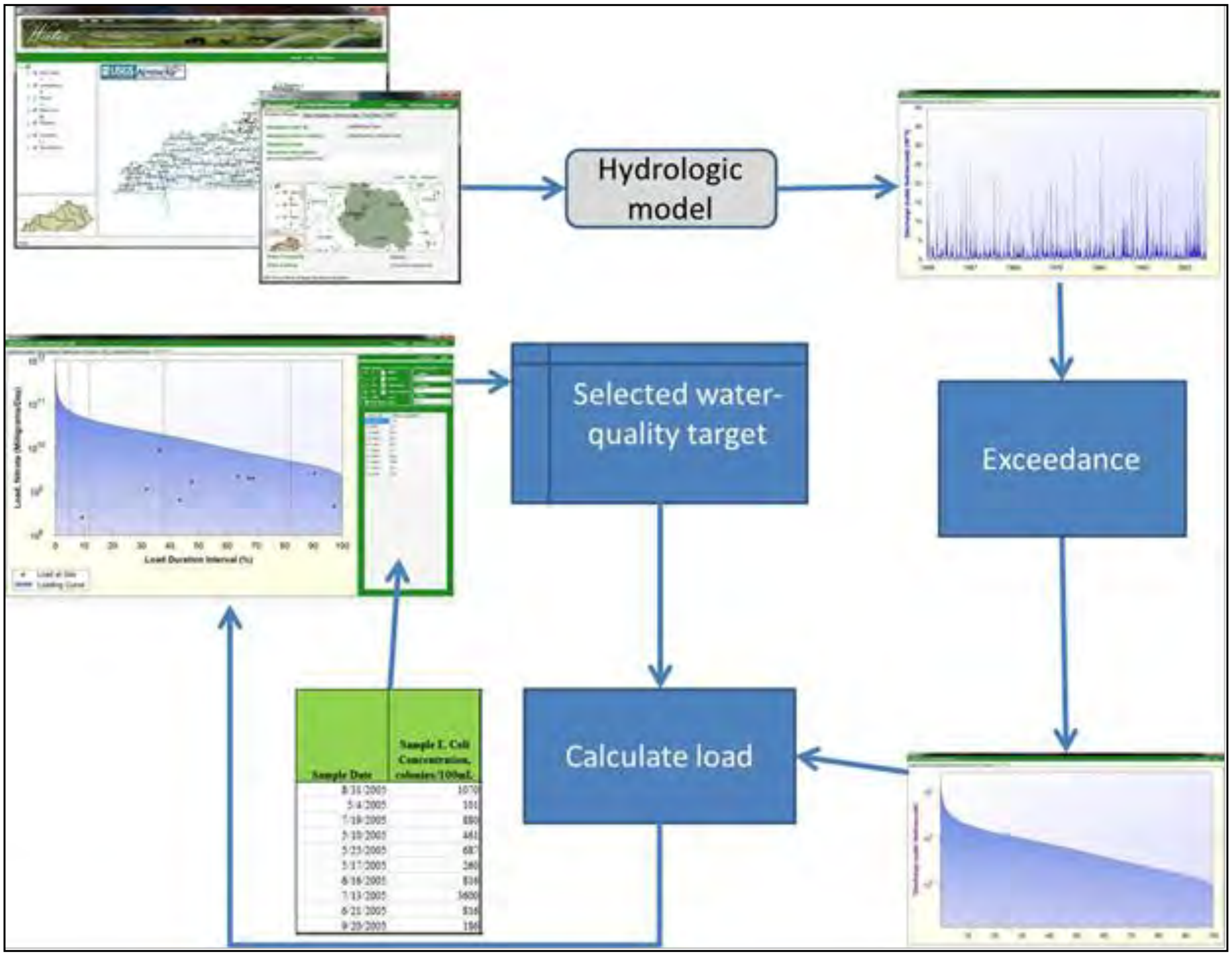
Estimation of Flow-Duration Curves for Streams in Kentucky



Project Final Report

Grant number: C9994861-07

Workplan Number: 07-05

Workplan Title: Estimation of Flow-Duration Curves for Streams in Kentucky

MOA number: 0700006594

Project period: February 2008 – August 2012

Author: Michael Unthank

Funding Statement:

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Funding for this project was provided in part by a grant from the U.S. Environmental Protection Agency (USEPA) through the Kentucky Division of Water, Nonpoint Source Section, to the USGS as authorized by the Clean Water Act Amendments of 1987, §319(h) Nonpoint Source Implementation Grant #C9994861-07KY. Mention of trade names or commercial products, if any, does not constitute endorsement. This document was printed on recycled paper."

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.61	kilometer (km)
	Area	
square mile (mi^2)	2.59	kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3 / s)	0.02832	cubic meter per second (m^3/s)
inch per day (in/d)	25.4	millimeter per day (mm/d)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
millimeter per day (mm/d)	0.039	inch per day (in/d)

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

Concentrations of chemical constituents in water are expressed in milligrams per liter (mg/L).

pH of water is expressed in standard units.

Concentrations of *Escherichia coli* (*E. coli*) and fecal coliform bacteria in water are expressed in colonies per 100 milliliters
(col/100 ml) or colony forming units per 100 milliliters.

Abbreviations used in the text

ADAPS	Automated Data-Processing System
DEM	digital elevation model
E_f	Nash-Sutcliffe Efficiency
GUI	graphical user interface
KDOW	Kentucky Division of Water
NEXRAD	Next Generation Radar
NWIS	National Water Information System
NWS	National Weather Service
SDP	sinkhole-drainage process
TMDL	total maximum daily load
TOPMODEL	TOPographically Based Hydrological MODEL
TWI	topographic wetness index
USGS	U.S. Geological Survey
WATER	Water Availability Tool for Environmental Resources

Estimation of Flow-Duration Curves for Streams in Kentucky

By Michael D. Unthank, Jeremy K. Newson, Tanja N. Williamson, and Hugh L. Nelson

Executive Summary

Flow- and load-duration curves were constructed from the model outputs of the U.S. Geological Survey's Water Availability Tool for Environmental Resources (WATER) application for streams in Kentucky. The WATER application was designed to access multiple geospatial datasets to generate more than 60 years of statistically based streamflow data for Kentucky. The WATER application enables a user to graphically select a site on a stream and generate an estimated hydrograph and flow-duration curve for the watershed upstream of that point. The flow-duration curves are constructed by calculating the exceedance probability of the modeled daily streamflows. User-defined water-quality criteria and (or) sampling results can be loaded into the WATER application to construct load-duration curves that are based on the modeled streamflow results.

Estimates of flow and streamflow statistics were derived from TOPographically Based Hydrological MODEL (TOPMODEL) simulations in the WATER application. A modified TOPMODEL code, SDP-TOPMODEL (Sinkhole Drainage Process-TOPMODEL) was used to simulate daily mean discharges over the period of record for 5 karst and 5 non-karst watersheds in Kentucky in order to verify the calibrated model. A statistical evaluation of the model's verification simulations show that calibration criteria, established by previous WATER application reports, were met thus

insuring the model's ability to provide acceptably accurate estimates of discharge at gaged and ungaged sites throughout Kentucky.

Flow-duration curves are constructed in the WATER application by calculating the exceedence probability of the modeled daily flow values. The flow-duration intervals are expressed as a percentage, with zero corresponding to the highest stream discharge in the streamflow record. Load-duration curves are constructed by applying the loading equation (Load = Flow*Water-quality criterion) at each flow interval.

Introduction and Background

The Commonwealth of Kentucky is required by the U.S. Environmental Protection Agency, under the authority of Section 303(d) of the Clean Water Act of 1972, to develop total maximum daily loads (TMDLs) for its waters that do not or are not expected to meet applicable water-quality standards with technology-based controls only. A TMDL is an estimate of the maximum pollutant load (material transported during a specified time period) that a receiving water body can accept without exceeding water-quality standards (U.S. Environmental Protection Agency, 1991).

TMDL development relies on accurate estimates of discharge and various streamflow statistics in the given stream. Streamflow statistics that support water-management decisions and TMDL development are easily calculated for locations where long-term, continuous-record gages have been in operation. However, at ungaged locations, statistics for TMDL development and water-management decisions are less accurate when estimated from other gaged locations that are hydrologically similar but are located on a different stream reach. This latter procedure often is complicated by differences between watershed characteristics of gaged and ungaged locations such as geology, drainage area, land use, and many other variables that not only differ from region to region, but can drastically change from stream to stream. Without a thorough knowledge of watershed characteristics and an adequate number of long-term, continuous-record streamflow-gaging stations, it is difficult to accurately estimate streamflow at ungaged sites. For this reason, the U.S. Geological Survey's Water Availability Tool for Environmental Resources (WATER) application was developed in cooperation with the Kentucky Division of Water (KDOW) to provide a consistent and statistically based method of estimating streamflow in ungaged watersheds.

A flow-duration curve is one method that can be used to assess whether or not the TMDL criterion of a stream is being exceeded. Use of the flow-duration curve with appropriate water-quality data yields a contaminant load, which is based on the magnitude of the streamflow and also projects the expected annual duration of that load. Flow-duration curves for continuous-record streamflow-gaging stations can be generated using the U.S. Geological Survey (USGS) automated data-processing system (ADAPS), a component of the National Water Information System (NWIS). A method for estimating the flow-duration curves of ungaged sites is needed. Although the WATER application was initially designed for water-budget assessment of individual watersheds, outputs from its TOPographically Based Hydrological MODEL (TOPMODEL) simulations can easily be used for the construction of flow- and load-duration curves used to prepare TMDL estimates.

Purpose and Scope

This report describes the construction of estimated flow- and load-duration curves for areas in Kentucky with limited or no long-term monitoring data. The estimated flow- and load-duration curves can provide a mechanism to evaluate streamflow on ungaged streams for many uses including assessing water-availability, determining sustained flow requirements, and developing TMDLs.

This study was done in cooperation with the KDOW, in part to provide water-resource managers, planners, and regulators with reliable and accurate streamflow statistics at ungaged sites throughout Kentucky. The specific study objectives were to

1. test and, if necessary, refine the ability of the TOPMODEL simulations in the WATER application to generate an estimated flow-duration curve for representative user-selected streamflow sites in Kentucky; and
2. combine available water-quality data with the estimated flow-duration curve to calculate estimated load-duration curves of the selected streamflow sites.

The TOPMODEL application was tested and calibrated using streamflow records from 24 long-term, continuous-record, streamflow-gaging stations in Kentucky by comparing simulated flows with observed flows (Williamson and others, 2009, and Taylor and others, 2012); additional verification of the model was comprised of flow comparisons for the period of record for selected calibration watersheds. Hypothetical water-quality data supplied by the KDOW were used to construct an example of a load-duration curve for an ungaged streamflow site.

Previous Studies

TOPMODEL is a physically based watershed model that simulates hydrologic fluxes of water (infiltration-excess overland flow, saturation overland flow, infiltration, exfiltration, subsurface flow, and evapotranspiration) through a watershed (Beven and others, 1994). This hydrologic forecasting model can be used to predict watershed response using only measured and estimated parameters without optimization. In Beven and Kirby (1979), the authors provide a model code capable of predicting the streamflow in ungaged watersheds, incorporating information derived directly from the watershed itself without resorting to regional statistical generalizations of model parameters.

Within the WATER application, Williamson and others (2009) incorporated a version of the TOPMODEL code into a Java-based graphical user interface (GUI). The WATER application and embedded TOPMODEL code accessed an extensive database of watershed characteristics and other pertinent background data to provide comprehensive estimates and presentations of the watershed processes, including water budgets, streamflows, and slope processes in watersheds of varying size for non-karst topographic regions in Kentucky. The WATER application was built upon a physically based hydrologic model, which simulates the variable-source-area concept of streamflow and is an extension of the TOPMODEL code described in Wolock (1993). Through proper application, the user is provided with a consistent and defensible method of estimating streamflow and water availability in ungaged watersheds throughout Kentucky.

This study extends the previous studies by Williamson and others (2009) and Taylor and others (2012) by incorporating water-quality data with the WATER-generated flow-duration curves to calculate load-duration curves for gaged and ungaged streamflow sites in Kentucky.

Materials and Methods

Flow-duration curves have been used for many years by hydrologists, engineers, and water-use planners. The flow-duration curve is a cumulative frequency curve that indicates the percentage of time that a particular streamflow has been equaled or exceeded. Streamflow data in the curve are not in chronological order. The flow-duration curve applies only to the period of record for which the streamflow data were collected.

Flow-duration curves can be prepared for daily, weekly, monthly, or other frequencies of discharge measurements. The streamflow duration data are arranged according to their magnitude in a range of classes, and the percentage of the time that each class exceeds the total is computed; a curve then can be drawn through the data. The techniques used by the USGS for drawing flow-duration curves are described by Searcy (1959).

To develop flow-duration curves for ungaged stream sites that do not have measured discharge values, streamflows can be estimated through a modeling approach. The TOPMODEL computer program simulates the movement of water through a watershed from the time it enters the watershed as precipitation to the time it exits the watershed as streamflow. Using a time series of precipitation and temperature data, TOPMODEL predicts streamflow, estimates overland and subsurface flow, and estimates the depth to the water table. Model components simulate the variable-source-area concept of streamflow generation (Wolock, 1993), snow accumulation and melt, evapotranspiration, streamflow generation from impervious areas, and channel routing of flow from delivery to the stream through to the watershed outlet. For a complete discussion on the development and operation of TOPMODEL, including theoretical background, model equations, and methods to determine parameter values, refer to Wolock (1993).

WATER was developed to provide a consistent and statistically based method of estimating streamflow and water availability in ungaged watersheds in Kentucky. The tool provides hydrographs, flow-duration curves, and a separation of flow components that can be used to assist in making water-management decisions. The WATER application relies mainly on topographic, pedogenic, and anthropogenic water-use data and requires no additional input from the user.

The WATER application uses the TOPMODEL code described in Wolock (1993) to simulate the variable-source-area concept of streamflow. Critical source data include a historical record of daily temperature and precipitation, digital elevation models (DEMs) of watershed topography, the Natural Resources Conservation Service Soil Survey Geographic Database (U.S. Department of Agriculture, 2007), and historical records of water discharges and withdrawals. Most of the required input data for a model run are contained in the watershed-characteristics database of the WATER application; some input parameters require additional preprocessing by statistical sampling of spatial data layers. The TOPMODEL portion of the WATER application also requires a histogram of the topographic wetness index (TWI). The TWI is used to describe how water accumulates in the watershed based on a DEM (Quinn and others, 1997). Current (2011) output types from the WATER application include hydrographs, flow-duration curves, annual and monthly water budgets, climatic histories, and load-duration curves. For a complete listing and description of the model-input parameters, data-processing routines, and model documentation, refer to Williamson and others (2009).

Model Calibration and Verification

The calibration of a model is the procedure used to reduce the difference between simulated results and observed data by reasonable adjustment of input parameters of the model until an acceptable range of differences is achieved. In Williamson and others (2009), twelve non-karst watersheds (fig. 1) were used to statistically evaluate and calibrate the model using daily mean streamflow values for the period of December 31, 2000 to August 8, 2006. A range of values for each of the input parameters of rooting depth, hydraulic conductivity, and scaling factor were tested along with variations in model methodology and precipitation records from two different datasets: USGS/National Weather Service (NWS) cooperative gaging-station network and Next Generation Radar (NEXRAD) (NEXRAD data are available at *http://www.roc.noaa.gov/WSR88D/*). The NEXRAD data provided a superior match of simulated and observed daily mean streamflows and, consequently, were utilized for all calibration efforts. The best fit for model calibration was determined using four statistics that commonly are used in hydrologic-modeling studies: bias, root mean square error, correlation, and Nash-Sutcliffe Efficiency (E_f) (Wolock and McCabe, 1999; Martin and others, 2000). Williamson and others (2009) demonstrated that the WATER-TOPMODEL program developed for use in Kentucky was capable of providing acceptable estimates of surface flows for a 2,047-day period of record in non-karst area basins based on Nash-Sutcliffe efficiencies ranging from 0.26 to 0.72 (Taylor and others, 2012). A list of the 12 non-karst calibration watersheds, results of the model-calibration runs, and the final values of the parameters for the non-karst calibration watersheds are presented in this report.

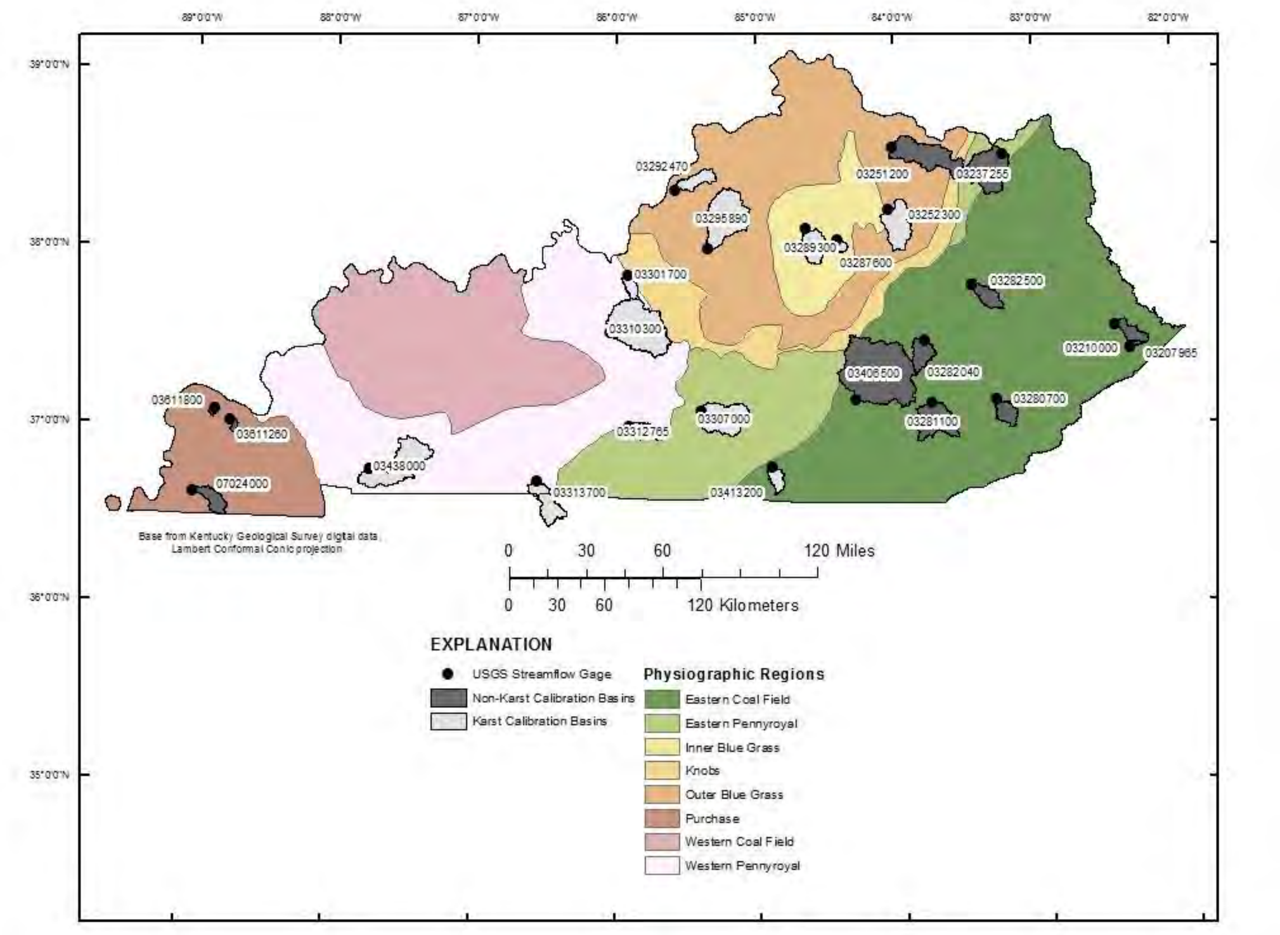

Figure 1. Map showing locations of major physiographic regions, selected watersheds and streamflow-gaging stations used for Water Availability Tool for Environmental Resources (WATER) model calibration, and watersheds and streamflow-gaging stations used for model verification in Kentucky.

As previously reported, the TOPMODEL code in the WATER application was modified so that sinkholes and sinking-stream catchments in karst areas could be identified and physically represented as hydrologic components of the surface-drainage network. Taylor and others (2012) described this sinkhole-drainage process (SDP), documented the modifications to the TOPMODEL code (SDP-TOPMODEL), and evaluated the model's performance for 12 karst test watersheds (fig. 1). Similar to the calibration process presented by Williamson and others (2009), visual comparisons of simulated hydrographs with statistical measures (bias, root mean square error, correlation, and Nash-Sutcliffe efficiency) applied to the simulated discharge data indicated that the SDP approach provided acceptably accurate estimates of discharge for most flow conditions and typically provided more accurate simulation of stream discharge in karstic watersheds compared to the standard TOPMODEL approach for the calibration period of December 31, 2000 to August 8, 2006 (Taylor and others, 2012).

Additional simulations using the SDP-TOPMODEL code were run on a subset of the calibration watersheds to verify the results of the calibrated model. Flow simulations were run for 5 non-karst and 5 karst calibration watersheds for their respective period of records using daily mean discharges. Summary statistics (bias, root mean square error, correlation, and Nash-Sutcliffe efficiency) were calculated for each verification simulation with the results compared to the summary statistics from the calibration runs. Table 1 presents the results for the model verification.

Station Number	Station Name	Karst (K) or Non-karst (NK)	Watershed area (km2)	Period of Record	Number of observations	Min Flow (mm/d)		Max Flow (mm/d)		Bias		RMSE		Correlation		Ef	
						Obs	Sim	Obs	Sim	Cal	Ver	Cal	Ver	Cal	Ver	Cal	Ver
0321000	Johns Creek near Meta, Ky	NK	146	04/01/1948 - 03/31/1975	9861	0	0.08	50	52	0.28	0.33	3.32	1.94	0.55	0.79	0.29	0.59
03280700	Cutshin Creek at Wooten, Ky	NK	158	04/01/1958 - 03/31/1989	11323	0	0.15	76	64	0.15	0.08	2.85	2.26	0.69	0.75	0.48	0.56
03282500	Red River near Hazel Green, Ky	NK	171	04/01/1954 - 03/31/1971	6209	0	0.14	43	34	0.19	0.2	1.51	1.36	0.79	0.71	0.64	0.5
03611260	Massac Creek near Paducah, Ky	NK	27	04/01/1972 - 03/31/1993	7670	0.01	0.07	161	91	0.11	0.69	1.99	4.56	0.8	0.73	0.65	0.52
03611800	Bayou Creek near Heath, Ky	NK	17	04/01/1994 - 03/31/2006	4383	0.003	0.01	102	84	0.1	0.47	1.81	3.16	0.78	0.66	0.6	0.4
03307000	Russell Creek near Columbia, Ky	K	448	04/01/1948 - 03/31/1980	11688	0.002	0.05	136	80	-0.01	-0.03	1.53	1.85	0.84	0.9	0.71	0.8
03312765	Beaver Creek at Highway 31E near Glasgow, Ky	K	128	04/01/1992 - 03/31/2002	3652	0.03	0.12	56	44	0.33	-0.09	1.49	2.42	0.8	0.8	0.68	0.57
03313700	West Fork Drakes Creek near Franklin, Ky	K	236	04/01/1969 - 03/31/1979	3652	0.02	0.18	133	70	0.23	0.05	2.4	2.92	0.77	0.85	0.59	0.71
03413200	Beaver Creek near Monticello, Ky	K	112	04/01/1969 - 03/31/1995	6939	0.02	0.06	91	56	0.36	0.08	2.45	2.45	0.81	0.76	0.69	0.57
03438000	Little River near Cadiz, Ky	K	632	04/01/1948 - 03/31/1962	5113	0.03	0.1	44	44	0.19	0.2	1.51	1.36	0.85	0.89	0.68	0.78

km - kilometer
Min - minimum
Max - maximum
mm/d - millimeter per day
Obs - observed
Sim - simulated
RMSE - root mean square error
Ef - Nash-Sutcliffe efficiency
Cal - Calibration
Ver - Verification

Table 1. Ten U.S. Geological Survey (USGS) streamflow-gaging stations used in the USGS Water Availability Tool for Environmental Resources (WATER) simulations for model verification in Kentucky.

In general, the results of the verification simulations prove that the input parameters for the SDP-TOPMODEL code used for model calibration provide a satisfactory fit for each of the tested watersheds over the longer period of record for daily mean discharges. Using the calibration criteria established in Williamson and others (2009), the Nash-Sutcliffe efficiencies range from 0.40 to 0.80 for the verification simulations, somewhat better than the calibration range of 0.26 to 0.72. The successful verification of the model code establishes greater confidence in the model calibration and its ability to accurately simulate streamflow conditions for flow-duration curve development.

Results and Discussion

Construction of Estimated Flow-Duration Curves Using WATER

The flow-duration curve is a cumulative frequency curve that indicates the percentage of time that a particular streamflow has been equaled or exceeded. This section describes and demonstrates the underlying concepts and construction of an estimated flow-duration curve using the WATER application. The WATER application is designed to access multiple geospatial datasets to generate approximately 60 years of statistically based streamflow data for user-selected sites throughout Kentucky. In general, the WATER-application user graphically selects a site on a stream and the application processes the underlying data sets to generate streamflow and a flow-duration curve for the selected site (fig. 2). The construction of flow-duration curves is performed in three steps: first, identifying and delineating the contributing watershed area; second, loading the appropriate data; and third, running the model and plotting the resulting flow-duration curve.

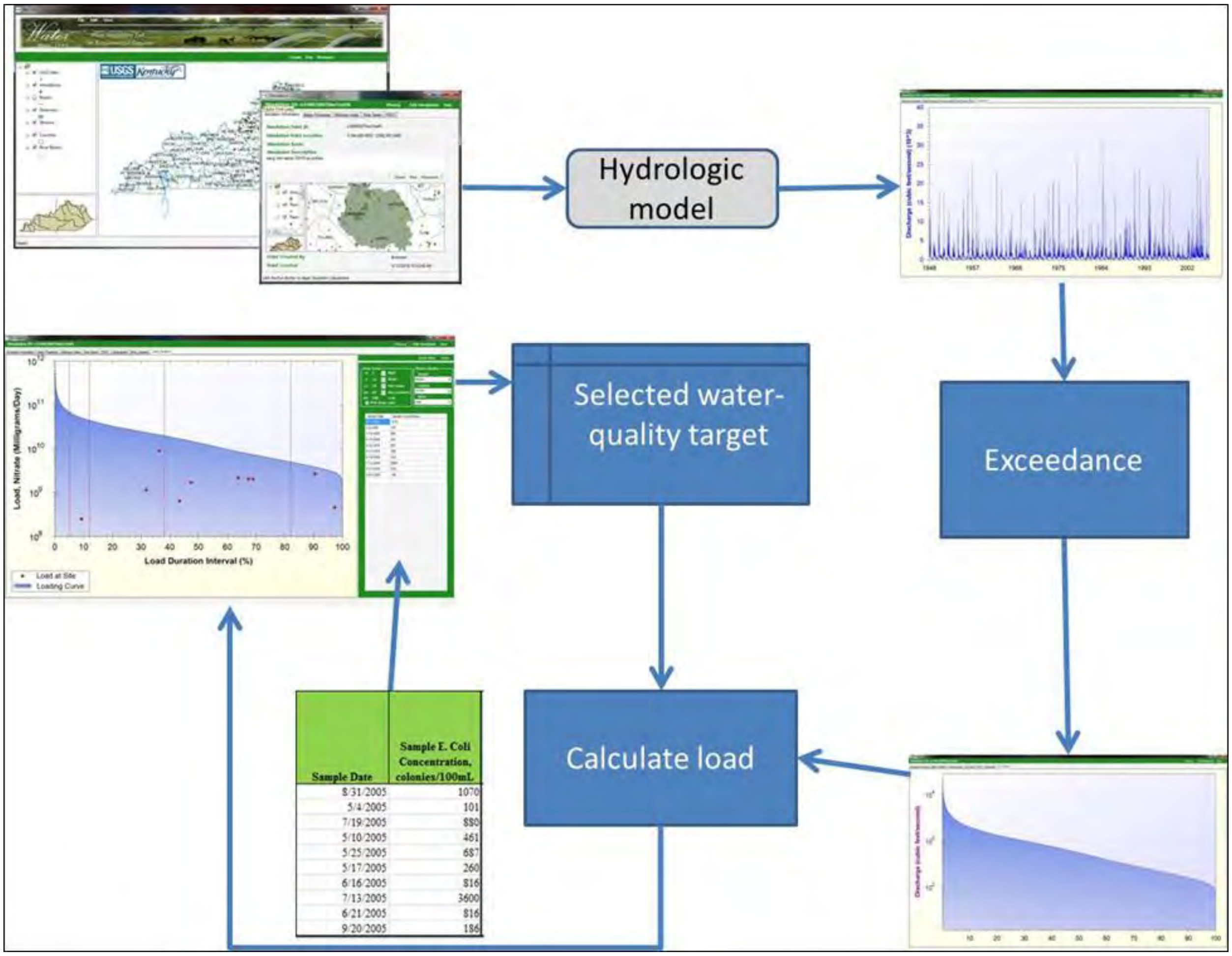

Figure 2. Flow- and load-duration flow chart for the Water Availability Tool for Environmental Resources (WATER) application.

Identifying and Delineating the Contributing Watershed

A contributing watershed for a selected site is identified and delineated by the user while interacting with the main window of the WATER application (fig. 3). The purpose of the main window is to provide the user with basic geographic functionality to locate and select the area of interest and create a simulation point that will become the outlet of the created watershed. The main window is subdivided into three sections:

1. the table of contents section, which allows the user to toggle geospatial layers on and off;

2. the overview section, which provides the user with a general location map; and
3. the map section, where the user can use the supplied interactive tools (located above the main interactive section) to zoom in or out, or pan to a desired stream section. Additional tools are provided to assist the user during the identification and delineation of the simulation point.

When the user has identified a simulation point where a flow-duration curve is to be developed, the user must set the simulation point (the "pour point" where surface water discharges from the modeled watershed) by zooming in close enough for the “Pour Point” button to become enabled. Once enabled, the user can click the pour point button (located above the main map section) and select a location on the stream to set the point. When the simulation point is set, the WATER application plots and presents the user with the selected point location and queries the user to identify the name of the simulation point and a description of the simulation (fig. 4). These descriptions are optional and default values (coordinates of the point) may be used. When accepted, the simulation point is set and a local simulation data folder is created in the background, storing the user’s name, the simulation point’s spatial location, and additional spatial data required during the delineation and data processing steps. Once the simulation point is set, the delineation process is enabled and can be initiated by selecting the enabled “Delineate” button, located above the map section (figs. 4 and 5). The delineation process may take a few minutes, depending on the watershed size, as the WATER application is accessing and creating spatial datasets that represent the local landscape and how the water will flow toward the simulation point. When complete, the watershed is stored to the local simulation data folder created during the previous step, and the watershed is visually displayed so the user can review it prior to loading the data for the study area.

Compiling the Watershed Data

The watershed data are compiled by selecting the “Load Data” button, located on the simulation window (fig. 5). The “Load Data” button initiates the process to identify the required data parameters to execute the model, and then those parameters are extracted or calculated from the stored spatial geodatasets. The WATER application compiles the data for the TOPMODEL program by using the delineated watershed as a template and seamlessly opening the required spatial geodatasets, such as the 2001 National Land Cover Database (Homer and others, 2004), for estimating the average impervious land and road cover, and the Soil Survey Geographic Database (U.S. Department of Agriculture, 2007), for estimating numerous hydrologic soil values and TOPMODEL- associated values within the watershed. For a complete list of datasets, refer to Williamson and others (2009). Additional modeling parameters, such as latitude, are spatially calculated directly from the watershed. When the WATER application has completed the data-loading process, model-specific data (fig. 6) will be shown in the window through a series of tab-based displays. These tabs include:

1. simulation information—this is the main tab showing the delineated watershed and user-defined site descriptors;
2. basin characteristics—this tab shows basin characteristics that are the mean value of spatial data extracted or calculated from datasets for the delineated watershed; these data can be edited by selecting the ‘Edit Simulation’ button;
3. topographic wetness index—this tab shows the distribution of the TWI; the TWI represents how water accumulates in the basin (Williamson and others, 2009); and
4. available climatic data—this tab shows temperature and precipitation data.

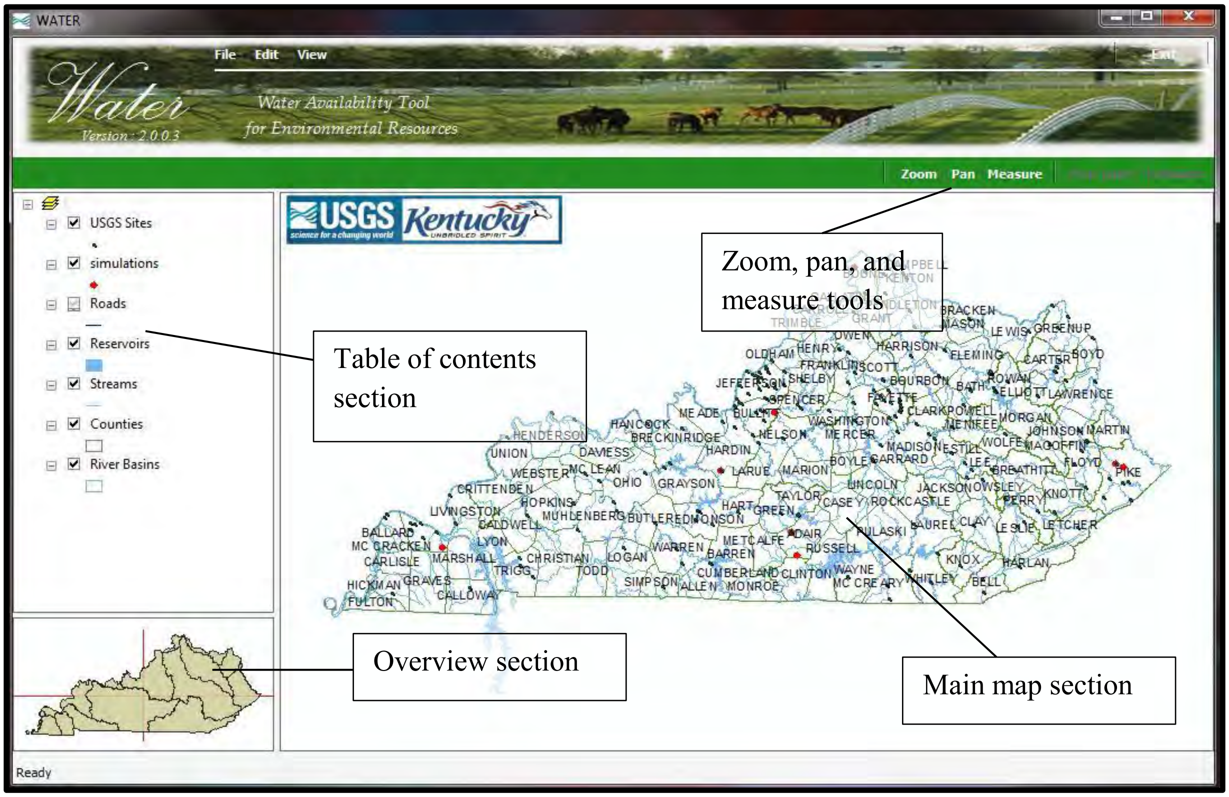

Figure 3. Main interactive window of the Water Availability Tool for Environmental Resources (WATER) application.

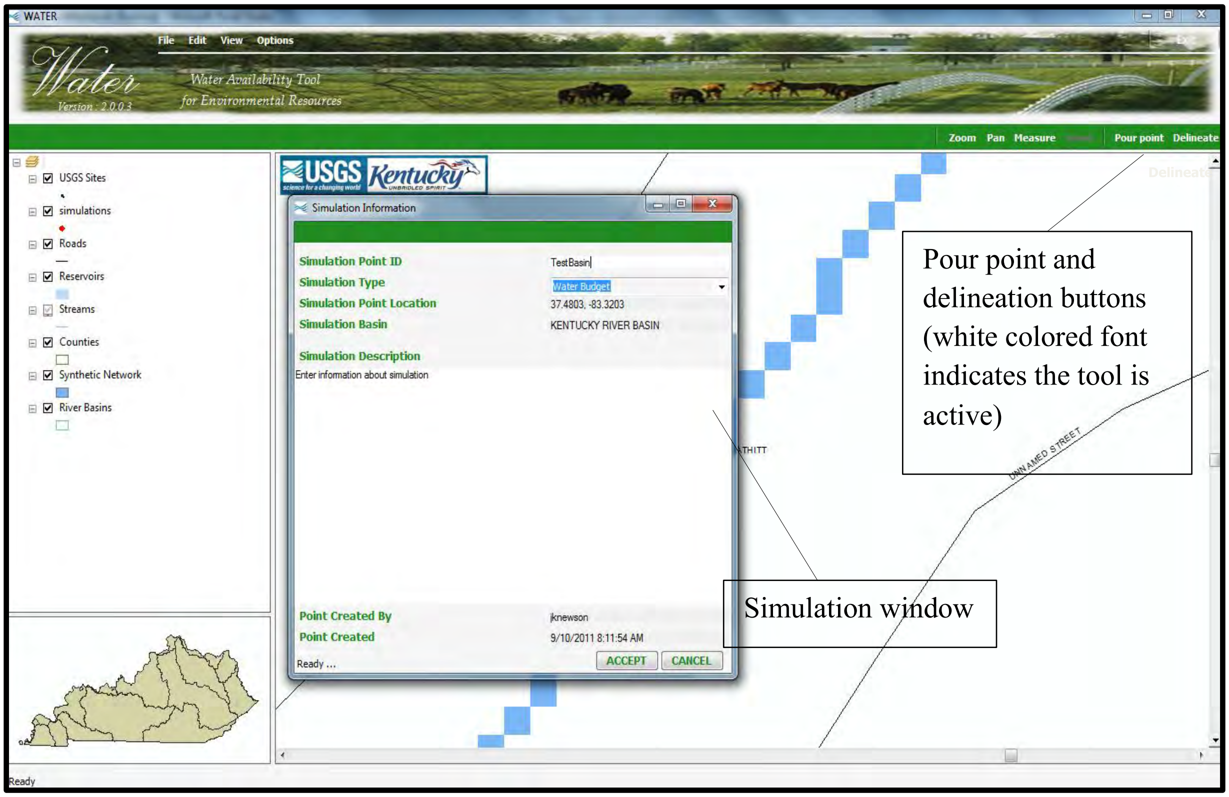

Figure 4. Selecting and identifying a simulation/watershed catchment point on the main interactive window of the Water Availability Tool for Environmental Resources (WATER) application.

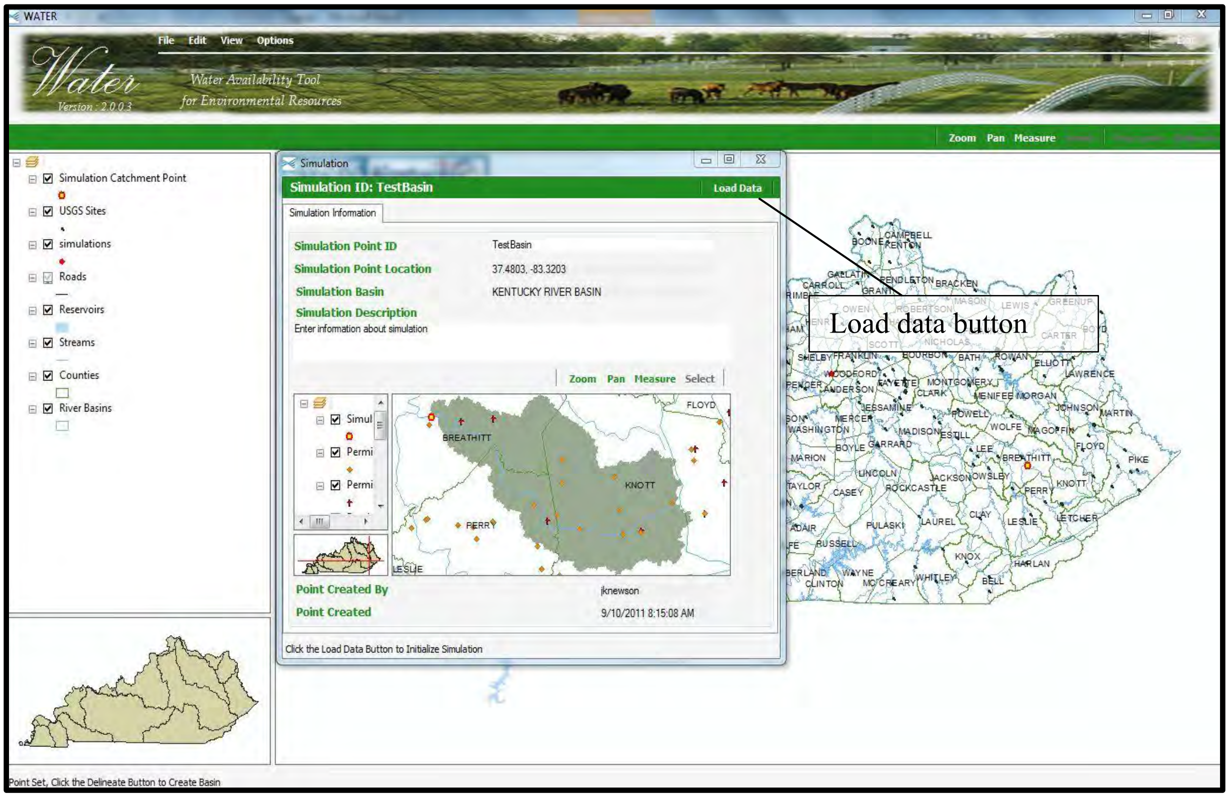

Figure 5. Delineated watershed of the Water Availability Tool for Environmental Resources (WATER) application.

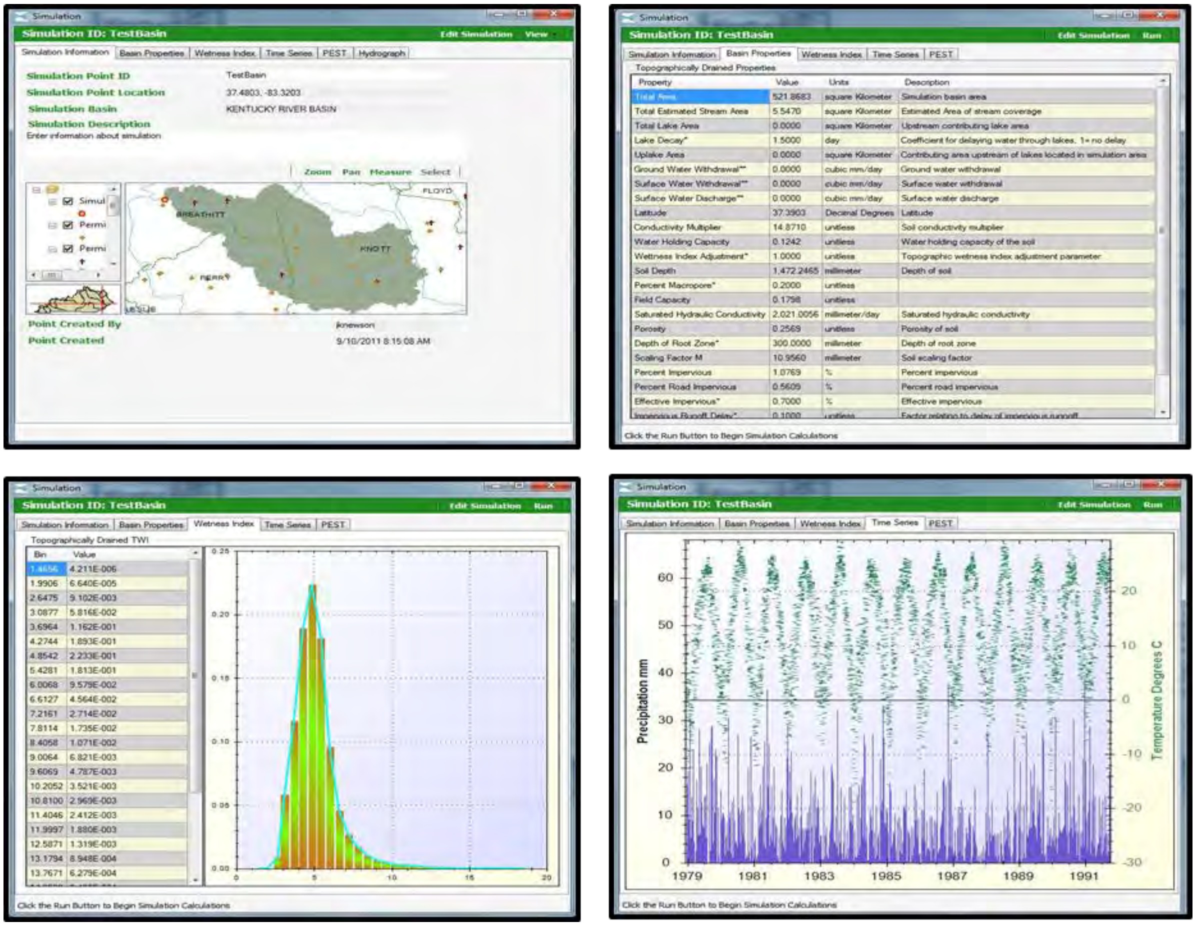

Figure 6. Example of data required for the hydrologic model of the Water Availability Tool for Environmental Resources (WATER) application: *A*, simulation information, *B*, basin characteristics, *C*, topographic wetness index, and *D*, available climatic data.

Running TOPMODEL and Plotting the Flow-Duration Curve

TOPMODEL is initiated by selecting the “Run” button, located at the top of the simulation window. Selecting this option allows the WATER application to import the data into TOPMODEL and, consequently, run the model for each precipitation and temperature value. When completed, the results of the model run are stored in the form of a text file in the previously created directory structure and displayed in graphical form on an additional tab (fig. 7). Flow- and load-duration curves are obtained in WATER by selecting the “Duration” submenu under the “Views” button.

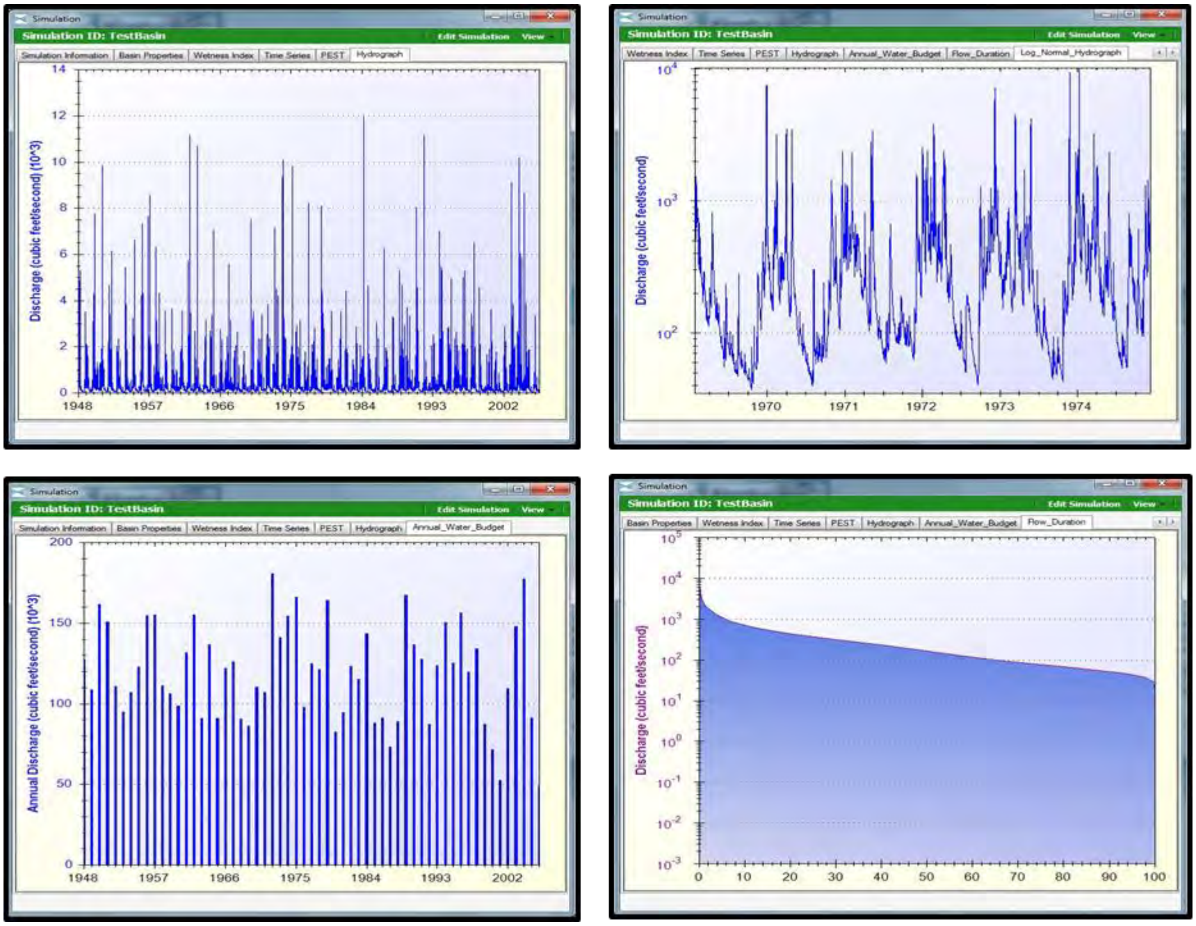

Figure 7. Example of output from the hydrologic model of the Water Availability Tool for Environmental Resources (WATER) application: A, hydrograph, *B*, log-normal hydrograph, *C*, annual water budget, and *D*, flow duration.

Flow-duration curves are constructed in the WATER application by calculating the exceedance probability of the modeled, daily flow values. The flow-duration intervals are expressed as a percentage, with zero corresponding to the highest stream discharge in the record.

Construction of Estimated Load-Duration Curves Using WATER

Flow duration curves serve as the foundation for development of load-duration curves. A load-duration curve is developed by multiplying streamflow with a numeric water-quality target or criterion and a conversion factor for the water-quality constituent of concern. Using the load-duration curve approach, the frequency and magnitude of water-quality standard exceedances, allowable loadings, and size of load reductions are easily presented (U.S. Environmental Protection Agency, 2007).

An underlying premise of the load duration curve is correlation of water-quality impairments to flow conditions. Load-duration curves characterize water-quality concentrations (or water-quality data) at different flow regimes. The WATER application provides a method to visually display the relationship between streamflow and loading capacity. The WATER application constructs the load-duration curve by applying the loading equation (equation 1) at each flow interval:

$$Load = Flow * T * C \qquad (1)$$

where

Load	is the load of the applicable water-quality constituent,
Flow	is the estimated daily streamflow provided by the model (in cubic feet per second),
T	is the selected water-quality criterion (see table 2), and
C	is a multiplication factor to ensure unit consistency.

Table 2. Criteria and associated default value and units provided by the U.S. Geological Survey Water Availability Tool for Environmental Resources (WATER) application.

[mg/L, milligrams per liter; *E. coli, Escherichia coli*; mL, milliliter; ft^3/s, cubic foot per second]

Criterion	Default value	Provided units
Chloride	600	mg/L (default unit)
Dissolved oxygen	5.0	mg/L (default unit)
pH (H+ Ions)	6.0	Standard (default unit)
Pathogens (*E. coli*)	240	Colonies/100 mL (default unit); billion colonies/100 mL; colony forming units /100 mL; billion colony forming units/100 mL
Pathogens (fecal coliform)	240	Colonies/100 mL (default unit); billion colonies/100 mL; colony forming units /100 mL; billion colony forming units/100 mL
Nitrate	10	mg/L as N (default unit)
Total phosphorus	.1	mg/L as P (default unit)
Total dissolved solids	250	mg/L (default unit)
Total suspended solids	250	mg/L (default unit)
Sulfate	250	mg/L (default unit)
Flow	1	ft^3/s (default unit)

The load-duration curve tool in the WATER application (fig. 8) is grouped into five flow zones (used as general indicators of hydrologic conditions): high, moist, midrange, dry, and low flows. Corresponding default flow-regime intervals are set at 0–5, 5–12, 12–38, 38–82, and 82–100 percent, respectively. The user may redefine these intervals. Additional interactive functionality within the WATER application provides the user with methods to select the desired water-quality target, define the applicable flow regime, and enter user-supplied water-quality data. The user may enter water-quality data with qualifiers, and select a sample date (flow will be taken from model-derived estimates for that specific day) or enter a measured, instantaneous flow (in cubic feet per second). Water-quality data are loaded into the WATER application by a simple copy-and-paste method that utilizes the clipboard of the user's operating system. The user-supplied data must be formatted in two columns that contain either sample date and water-quality concentration or measured streamflow and water-quality concentration, and the data must be transferred from an outside application (i.e. Microsoft Excel or a text file) into the WATER application by selecting the "Paste Data" button. Data are displayed in gridded view and are plotted on the load-duration curve for a graphical display. Water-quality data are plotted on the load-duration curve by determining the exceedance interval of the measured or estimated flow associated with that particular sample. For example, given a list of hypothetical water quality *E. Coli* concentrations (table 3) with corresponding water quality target, criteria, and units set to "Pathogens (*E.coli*), 240.0, Col/100 ml." respectively would result with a load-duration curve as shown in figure 8.

Table 3. Hypothetical water quality *E. coli* concentrations used as input for the load-duration curve of the U.S. Geological Survey Water Availability Tool for Environmental Resources (WATER) application.

[col/100 mL, colonies per 100 milliliters]

Sample date	Sample *E. coli* concentration (col/100 mL)
7/26/2002	199,020
7/25/2003	18,786
3/17/2004	163,680
7/28/2004	85,746
8/16/2004	127,782
9/18/2004	48,360
4/14/2006	151,776
7/25/2006	669,600
8/1/2006	151,776
9/24/2006	34,596

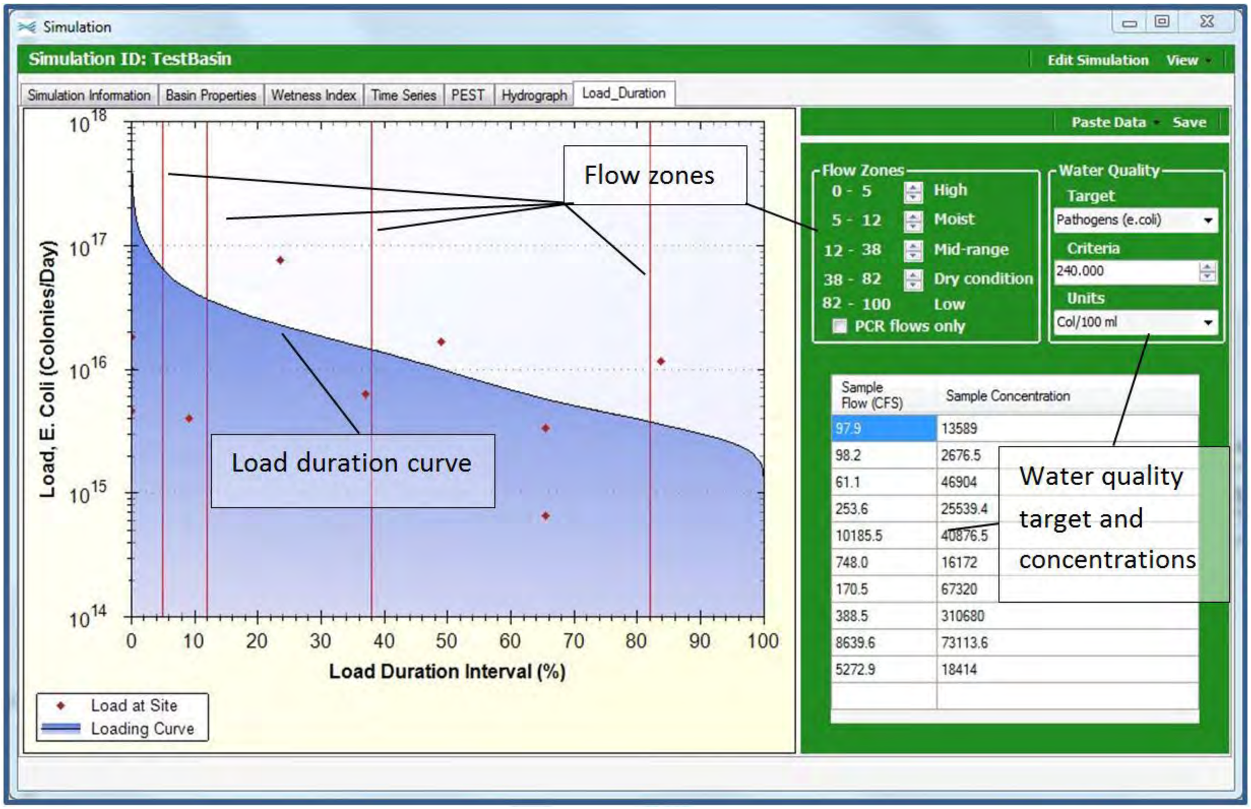

Figure 8. Example of flow-duration curve tool for the U.S. Geological Survey Water Availability Tool for Environmental Resources (WATER) application.

Conclusions

The Water Availability Tool for Environmental Resources (WATER) application was developed, in part, to provide a consistent and statistically based method of estimating streamflow and water availability in ungaged basins in Kentucky. The application provides hydrographs, flow- and load-duration curves, and a separation of flow components that can be used to make water-resource management decisions including TMDLs for streams. The WATER application uses the TOPographically Based Hydrological MODEL (TOPMODEL) code to simulate the movement of water through a watershed from the time it enters the watershed as precipitation to the time it exits the watershed as streamflow. Model outputs from the TOPMODEL simulations can then be used to construct flow- and load-duration curves for ungaged streams.

A modified TOPMODEL code, SDP-TOPMODEL, was used within the WATER application to simulate daily mean discharges over the period of record for a select number of karst and non-karst watersheds in Kentucky in order to verify the calibrated model. A statistical evaluation of the model's verification simulations show that calibration criteria established by previous model reports were met thus insuring the model's ability to provide acceptably accurate estimates of discharge at gaged and ungagged sites throughout Kentucky.

Flow-duration curves are constructed in the WATER application by calculating the exceedance probability of the modeled daily flow values. The flow-duration intervals are expressed as a percentage, with zero corresponding to the highest stream discharge in the streamflow record. Load-duration curves are constructed by applying the loading equation (Load = Flow * Water-quality criterion) at each flow interval.

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Appendix 1: Financial and Administrative Closeout

Budget Report

Project Timeline

Budget Report

Budget Categories	2008	2009	2010	Total
Personnel	$57,852	$32,343	$56,260	$146,455
Office supplies	$0	$123	$350	$473
Travel	$0	$0	$0	$0
Freight	$0	$0	$0	$0
Vehicle	$0	$0	$101	$101
Operating Costs	$48,502	$30,523	$36,382	$115,407
Training	$0	$0	$0	$0
Subtotal	$106,354	$62,989	$93,092	$262,436
Funding sources				
319 Funding (KDOW)	$53,177	$31,177	$56,646	$141,000
USGS Non-Federal matching funds	$53,177	$30,523	$10,300	$94,000
USGS Federal special-initiative funding			$26,146	
Subtotal	$106,354	$61,700	$66,946	$235,000

Project Timeline

Milestone	Expected Begin Date	Expected End Date	Actual Begin Date	Actual End Date
1. Sign agreement with DOW.	Feb 08	Feb 08	Feb 08	Feb 08
2. Compile, evaluate, and review existing streamflow data.	Feb 08	May 08	Feb 08	Apr 08
3. Convene meetings with KDOW to discuss available data and period of record implications.	Mar 08	Mar 08	Apr 08	Apr 08
4. Prepare quarterly progress review reports.	Mar 08	Jun 09	Jul 08	Ongoing
5. Prepare quarterly non-fed match reports.	Mar 08	Jun 09	KDOW	KDOW
6. Begin statistical analyses.	Mar 08	Mar 09	Mar 08	May 10
7. Meet with KDOW Water Quality Branch to discuss the use of pollutant load data and water criteria.	Apr 08	Apr 08	Apr 08	Apr 08
8. Begin GUI programming.	May 08	Jun 09	May 08	May 10
9. Submit annual report.	Dec 08	Dec 08	Dec 08	Dec 08
10. Prepare presentation for annual NPS and KWRRI conference.	Feb 09	Mar 09	Nov 08	Nov 08
11. Convene meeting with KDOW to discuss GUI program, education, and training.	Jul 09	Jul 09	Dec 09	Jan 10
12. Archive information and transfer to KDOW	Mar 10	Mar 10	Sep 11	Sep 11
13. Provide education/outreach to discuss and interpret the study results and provide hands-on training for using the GUI	Mar 10	Mar 10	Jun 10	Jun 10
14. Submit final product to KDOW for review and approval.	Apr 10	Apr 10	Sep 11	Aug 12
15. USGS SIR report.	May 10	May 10	Sep 11	Aug 12
16. Distribute Final Report	Jun 10	Jun 10	Oct 11	Aug 12

Appendix 2: WATER Training Sessions – June 11, 2010

Training session agenda

Morning training session attendees list

Afternoon training session attendees list

Training presentation slides

Training Announcement

Introduction to WATER

Water **A**vailability **T**ool for **E**nvironmental **R**esources

AGENDA

Date: June 11, 2010

Time: Morning session 9 am to 11 am

Afternoon session 1 pm to 3 pm

Place of Training: Kentucky State University GIS Lab, Cooperative Extension Building, Room 121

Students should choose to attend either the morning or afternoon session

- Morning session – 9 am to 11 am
  - Introductions
  - Overview of WATER application
  - Instructor-led demonstration
  - Hands-on delineations and applications
  - Review – questions and comments
- Lunch Break
- Afternoon session – 1 pm to 3 pm
  - Same training program as above

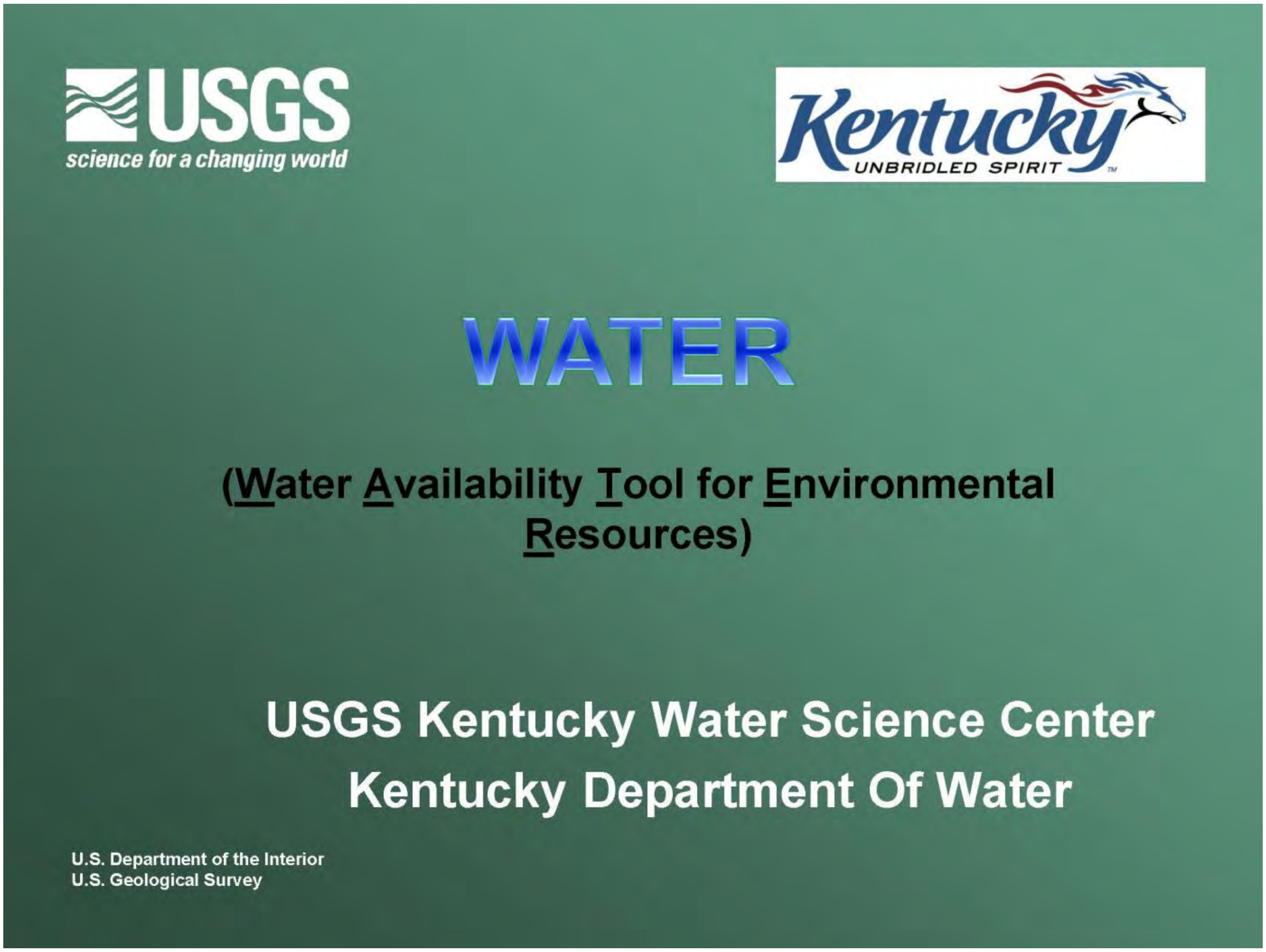
This work was funded in part by a grant from the U.S. Environmental Protection Agency under §319(h) of the Clean Water Act.

WATER Training – June 11, 2010 Morning Session

Name	Signature	Representing	Email address
~~Akers, Paulette~~			
Agouridis, Carmen	[illegible]	UK	cagourid@bae.uky.edu
Amawi, Shafiq	Shafiq S. Amawi	DOW	Shafiq.Amawi@ky.gov
Croasdaile, Michael	M. [illegible]	U of L	mcroasdaile@louisville.edu
Esarey, Andrew	Andrew Esarey	Strand	andrew.esarey@strand.com
~~Finzer, Elizabeth~~			
Fredenburg, Ann	Andrea Fredenburg	DOW	andrea.fredenburg@ky.gov
Haight-Maybriar, L.	Lajuanda Haight Maybriar	DOW	lajuanda.haight-maybriar@ky.gov
Hicks, Lisa			
Jackson, David	David [illegible]	DOW	davida.jackson@ky.gov
McDonald, Cindy	Cindy McDonald	DOW	cindy.mcdonald@ky.gov
Seitz, Courtney	Courtney Seitz	DOW	Courtney.Seitz@KY.GOV
Shireman, Brooke	[illegible]	DOW	brooke.shireman@ky.gov
Siewert, Amy	Amy Siewert	DOW	amy.siewert@ky.gov
Sowder, Larry			
Stapleton, Scarlett			
~~Vesely, Bill~~			
~~Jeong~~ Park, Jeong	[illegible]	U of L	jwpark01@louisville.edu
Webb, John	John Webb	DOW	john.webb@ky.gov

WATER Training – June 11, 2010 Afternoon Session

Name	Signature	Representing	Email address
~~Bland, BJ~~			
Caldwell, Bill	Bill Caldwell	KDOW	bcaldwell@ky.gov
Evans, Steve	[illegible]	Third Rock	sevans@thirdrockconsultant
Faulkner, Jerome	Jerome Faulkner	NRCS	jerome.faulkner@ky.usda.
~~Fister, Gerry~~			
Goode, Greg	[illegible]	Ky DOW	greg.goode@ky.go
Gray, Brooke	[illegible]	KY DOW	brooke.gray@ky.gov
Ingram, Allen	[illegible]	KDOW	allen.ingram@ky
Jones, Margi	Margi Jones	KDOW	margi.jones@ky.gov
Keith, Sonya	Sonya Keith	NRCS	sonya.keith@ky.usda
Kipp. Jim	JIM KIPP	KWRRI	KIPP@UKY.EDU
Kuhn, Jack	[illegible]	NRCS	Jack.kuhn@KY.USDA.gov
Lewis, John	[illegible]	KDOW	john.lewis@ky.gov
Liebenauer, Eric	[illegible]	" "	ERIC.LIEBENAUER@KY.GOV
McMurray, Paige	[illegible]	KDOW	paige.mcmurry@ky.g
Roe, James	[illegible]	Ky DOW	james.roe@ky.gov
Rothman, Paul			
Smoak, Julie	[illegible]	KY DOW	julie.smoak@ky.gov
Tucker, Sarah	Sarah Tucker	KY DOW	tucker@ky.g
Yeary, Chris	[illegible]	DOW	christopher.yeary@k
~~Zimmer, Chip~~			
RANDALL, DREW	[illegible]	URS	drew_randall@urscorp.c


USGS
science for a changing world
Kentucky
UNBRIDLED SPIRIT
WATER
(Water Availability Tool for Environmental Resources)
USGS Kentucky Water Science Center
Kentucky Department Of Water
U.S. Department of the Interior
U.S. Geological Survey

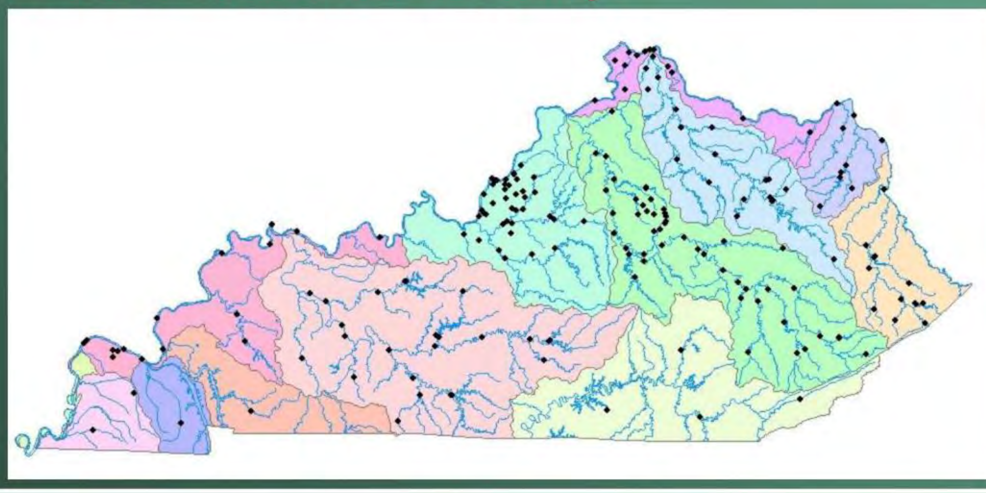
Overview

- Purpose
- Value
- Configuration
- Demonstration
- Potential Applications
- Conclusions

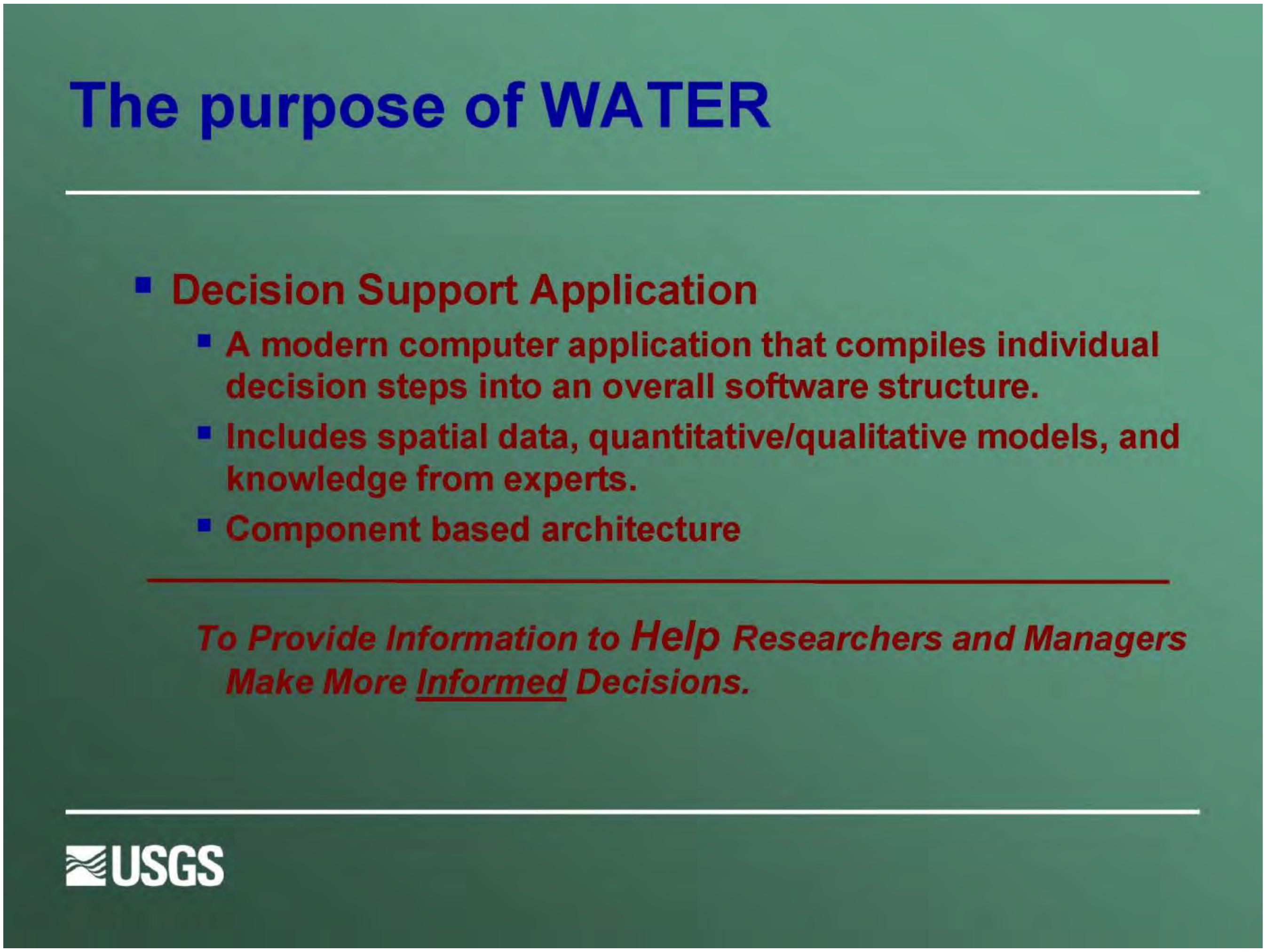
USGS

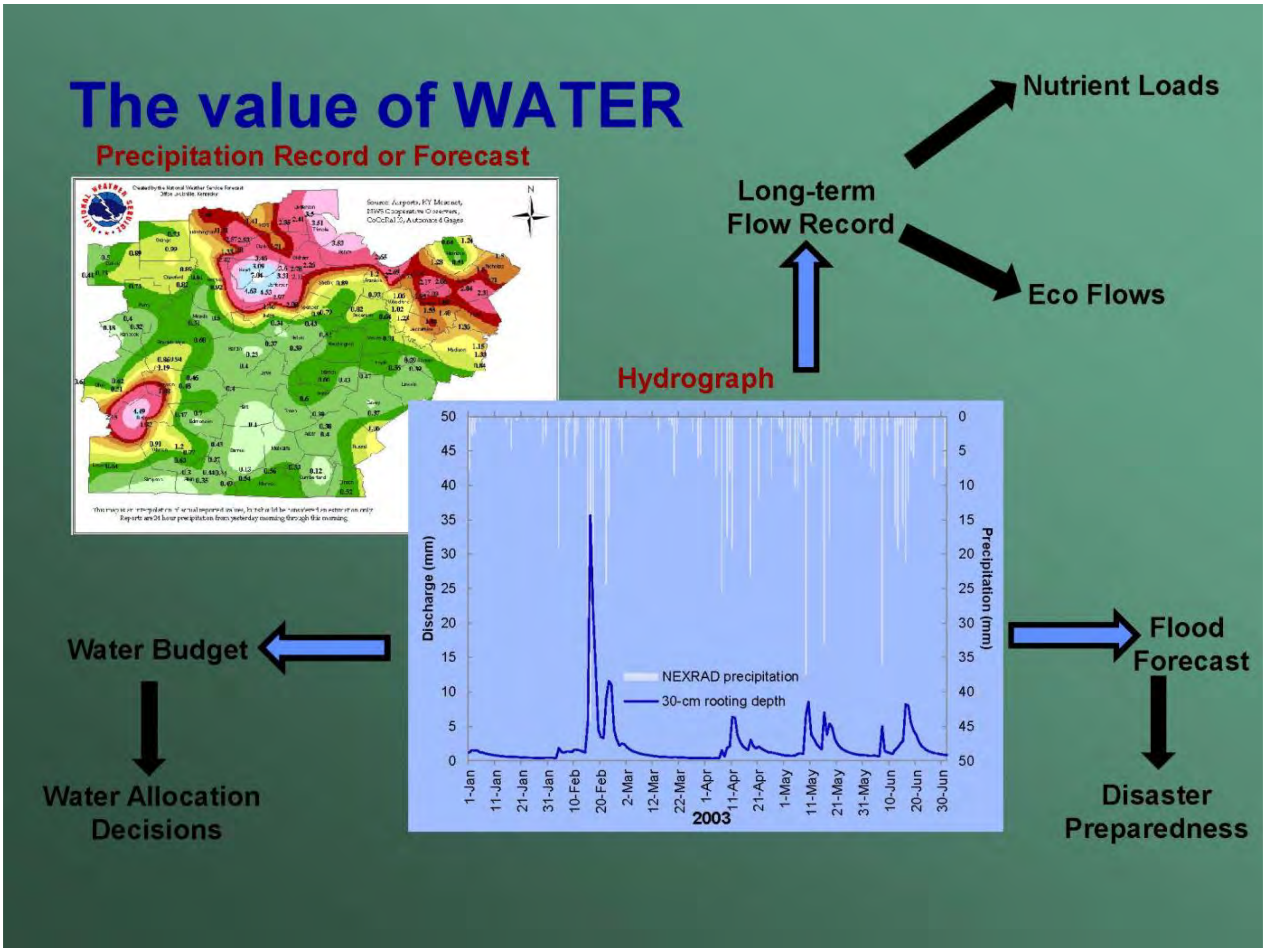
The purpose of WATER

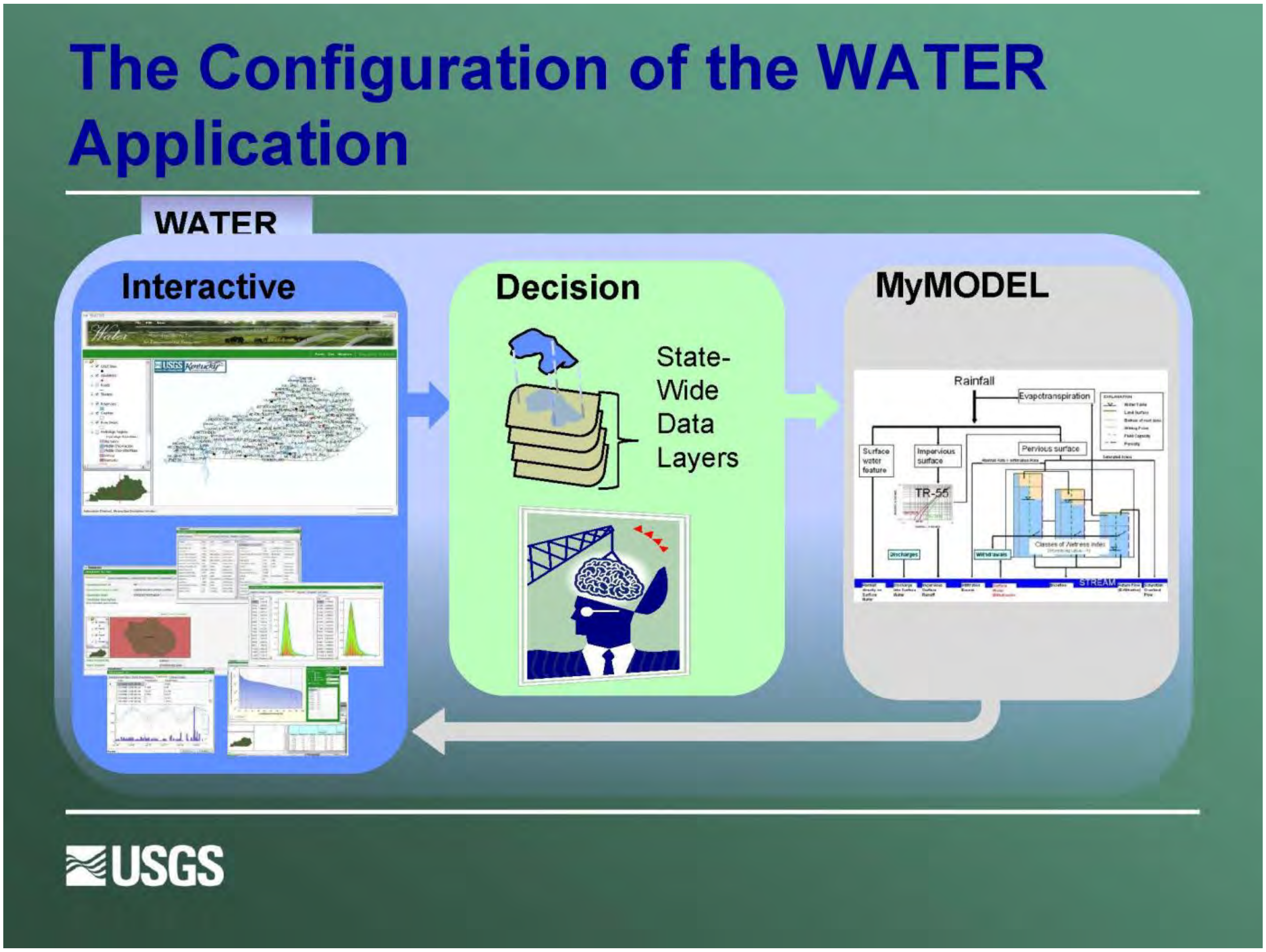
- **Quantifiable and consistent method for estimating streamflow in ungaged basins within the Commonwealth of Kentucky.**



USGS

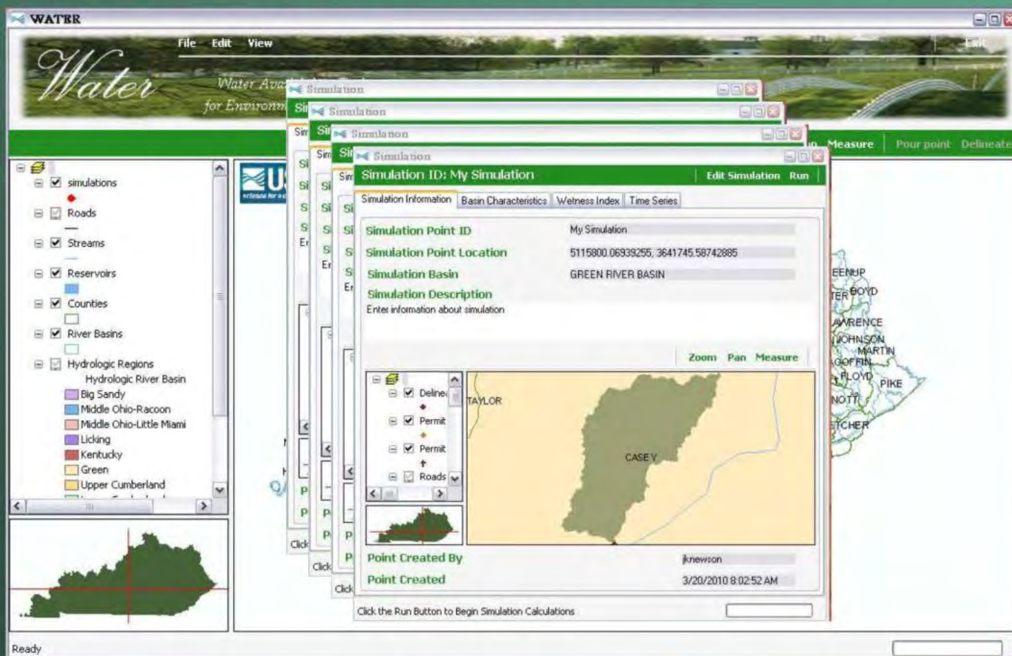

The purpose of WATER
Decision Support Application
A modern computer application that compiles individual decision steps into an overall software structure.
Includes spatial data, quantitative/qualitative models, and knowledge from experts.
Component based architecture
To Provide Information to Help Researchers and Managers Make More Informed Decisions.
USGS


The value of WATER
Precipitation Record or Forecast
Long-term
Flow Record
Nutrient Loads
Eco Flows
Hydrograph
Discharge (mm)
Precipitation (mm)
NEXRAD precipitation
30-cm rooting depth
2003
Water Budget
Water Allocation
Decisions
Flood
Forecast
Disaster
Preparedness

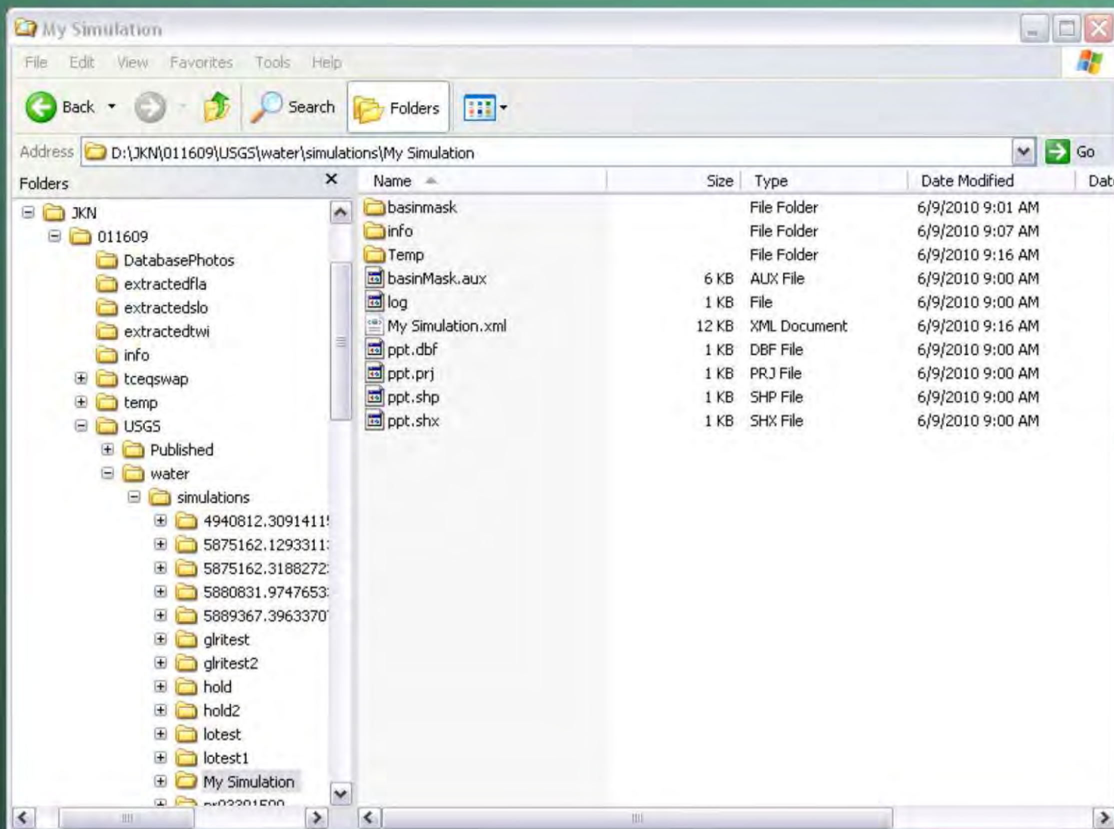

The Configuration of the WATER Application
WATER
Interactive
Decision
MyMODEL
State-Wide Data Layers
Rainfall
Evapotranspiration
Surface water feature
Impervious surface
Pervious surface
TR-55
Discharges
Withdrawals
STREAM
USGS

User Interface

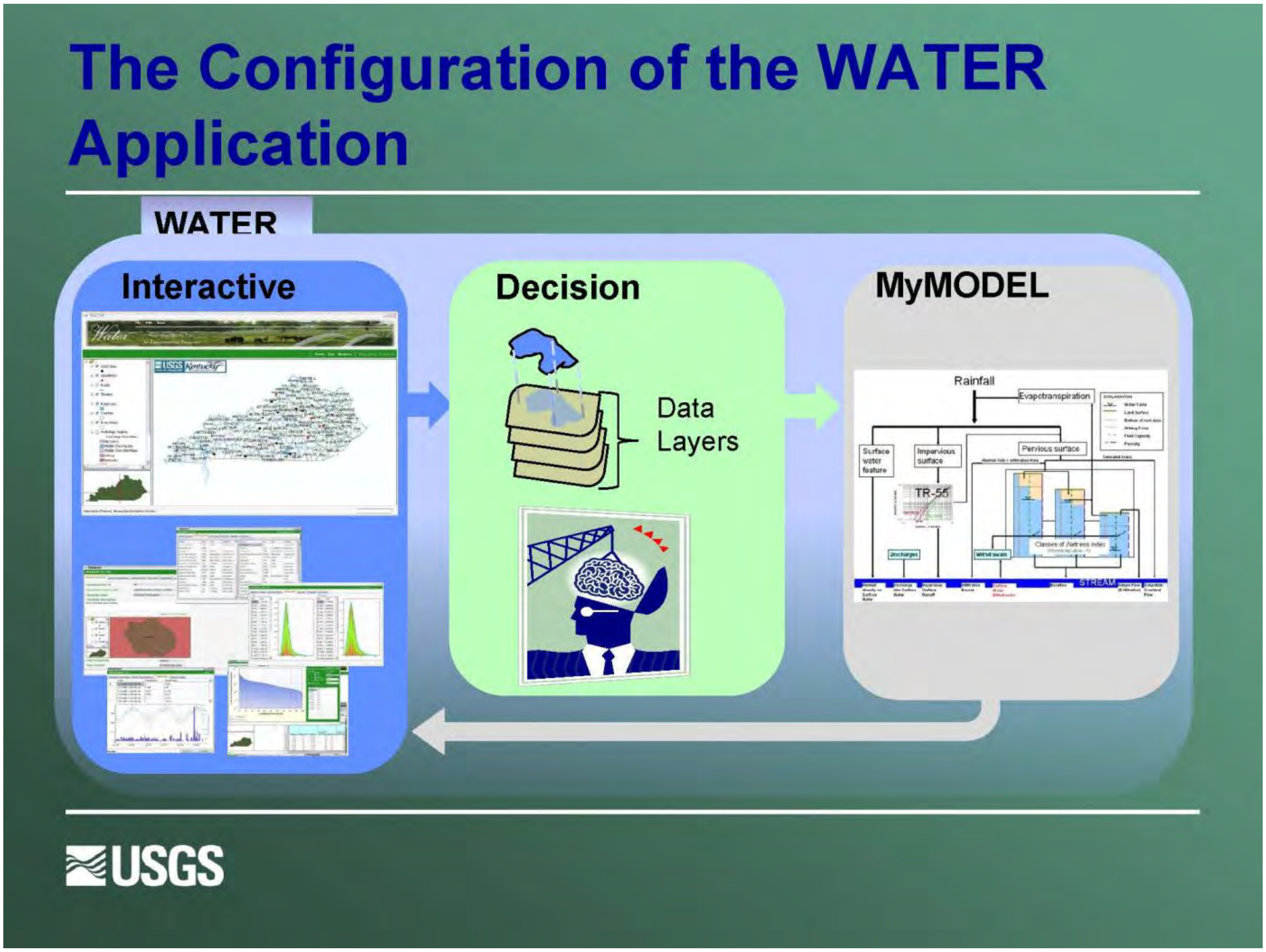
- Hide Complexities and Technical Details
- Provide Feedback
- Allow User to Select Simulation Area

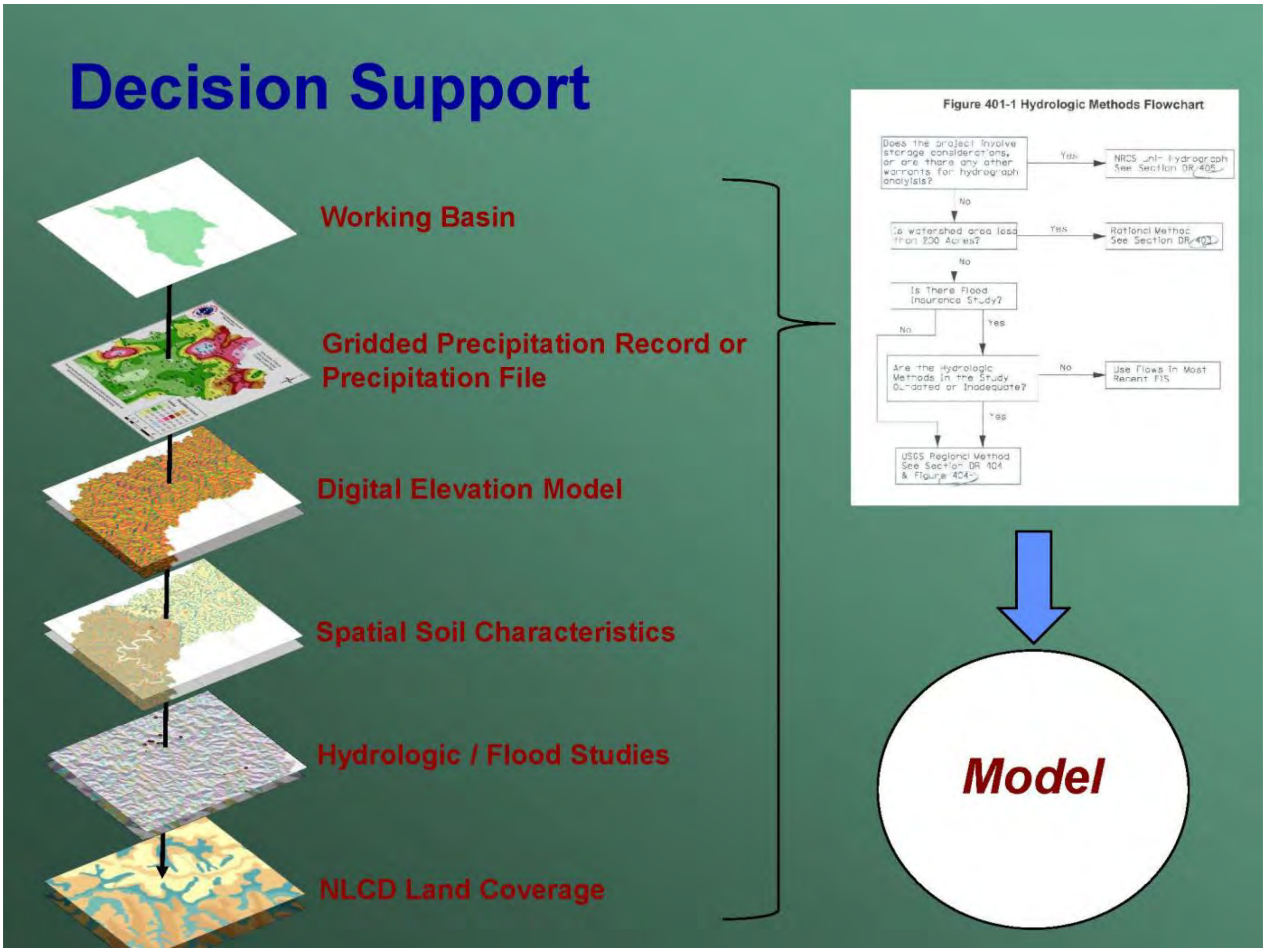


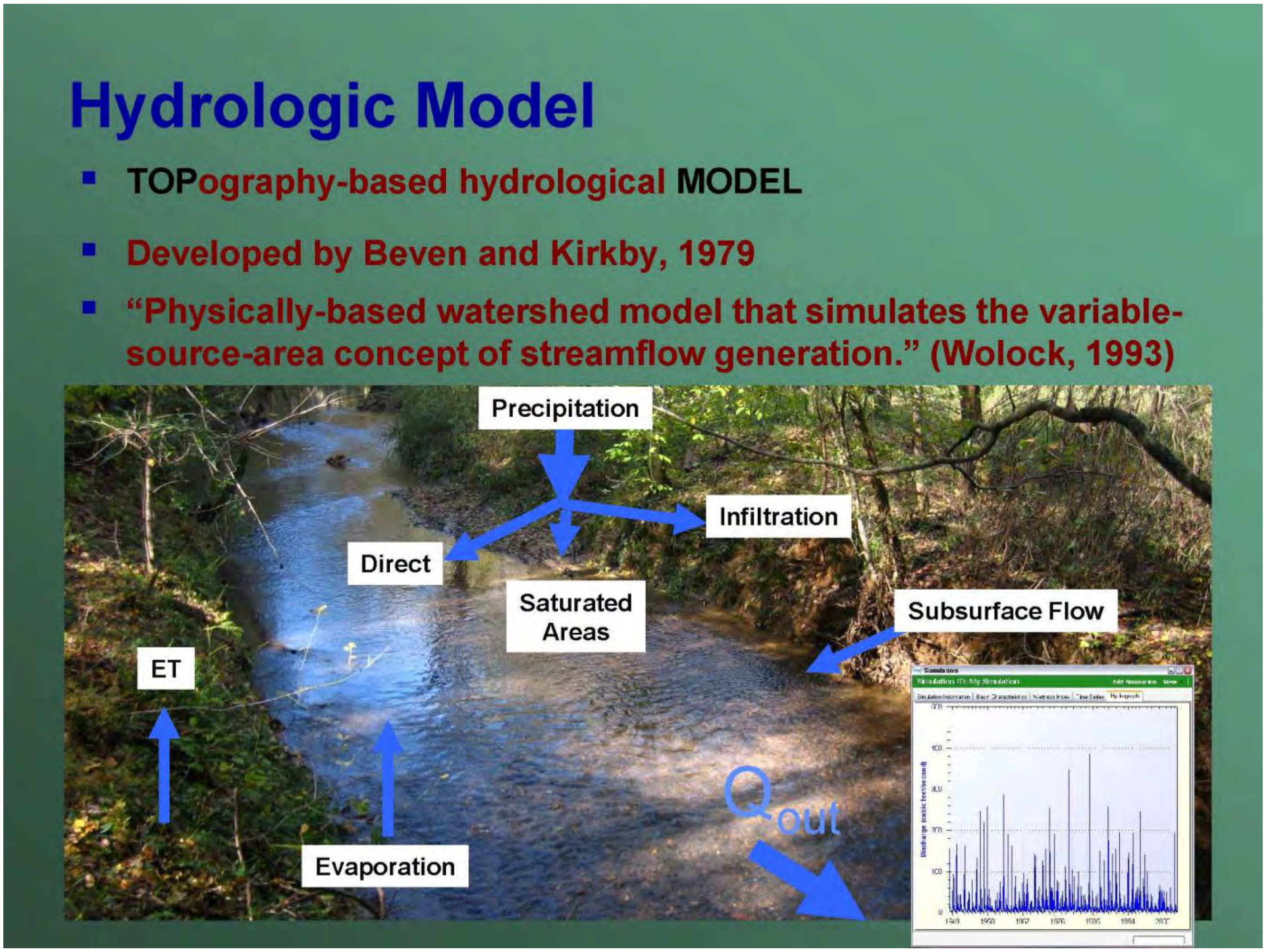
Database


My Simulation
File Edit View Favorites Tools Help
Back
Search
Folders
Address D:\JKN\011609\USGS\water\simulations\My Simulation
Go
Folders
JKN
011609
DatabasePhotos
extractedfla
extractedslo
extractedtwi
info
tceqswap
temp
USGS
Published
water
simulations
glritest
glritest2
hold
hold2
lotest
lotest1
My Simulation
Name
Size
Type
Date Modified
basinmask File Folder 6/9/2010 9:01 AM
info File Folder 6/9/2010 9:07 AM
Temp File Folder 6/9/2010 9:16 AM
basinMask.aux 6 KB AUX File 6/9/2010 9:00 AM
log 1 KB File 6/9/2010 9:00 AM
My Simulation.xml 12 KB XML Document 6/9/2010 9:16 AM
ppt.dbf 1 KB DBF File 6/9/2010 9:00 AM
ppt.prj 1 KB PRJ File 6/9/2010 9:00 AM
ppt.shp 1 KB SHP File 6/9/2010 9:00 AM
ppt.shx 1 KB SHX File 6/9/2010 9:00 AM


DEMO
•Install WATER Application
•Set Simulation point
•Delineate Basin


The Configuration of the WATER Application
WATER
Interactive
Decision
MyMODEL
Data
Layers
Rainfall
Evapotranspiration
Surface
water
feature
Impervious
surface
Pervious surface
TR-55
Discharges
Withdrawals
STREAM
USGS


Decision Support
Working Basin
Gridded Precipitation Record or Precipitation File
Digital Elevation Model
Spatial Soil Characteristics
Hydrologic / Flood Studies
NLCD Land Coverage
Figure 401-1 Hydrologic Methods Flowchart
Model


Hydrologic Model
TOPography-based hydrological MODEL
Developed by Beven and Kirkby, 1979
"Physically-based watershed model that simulates the variable-source-area concept of streamflow generation." (Wolock, 1993)
Precipitation
Infiltration
Direct
Saturated Areas
Subsurface Flow
ET
Evaporation
Qout

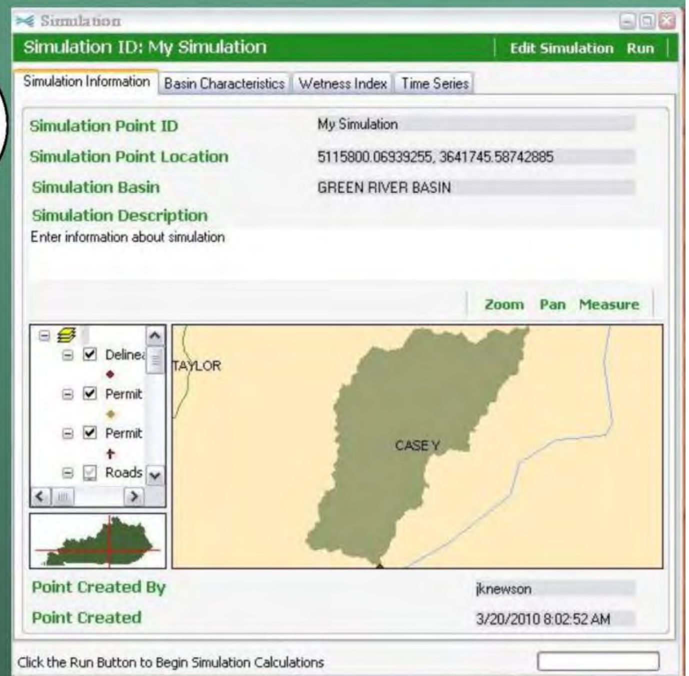
Data Sources

NOAA/NWS Temperature and Precipitation Cooperative-Station and NEXRAD Data

Climate Generator (model) and(or) gridded NEXRAD data

- DEM → Stream Network
- KY Dam Safety Commission
- Soil Survey Geographic Data
- TR-55 Impervious Erosion Curve
- National Land Cover Data 2001
- KY Pollutant Discharge Elimination System
- KY Division of Water

TopMODEL Inputs



Soil Characteristics

SSURGO Variables	Calculated "m"
▪ Hydraulic conductivity (moderately high or higher) ▪ Available Water Capacity ▪ Field Capacity ▪ Porosity ▪ Depth (based on conductivity) And..... ▪ Scaling Parameter "m" computed from processed SSURGO data ▪ *m* = readily drained soil porosity/rate of decrease with depth	**Conductivity Multiplier** $\frac{K_{sat} - High_{surface}}{K_{sat} - Low_{depth}}$ **Scaling Parameter** $f = \frac{\ln(conductivity\ multiplier)}{soil\ depth}$ $m = \frac{porosity - field\ capacity}{f}$

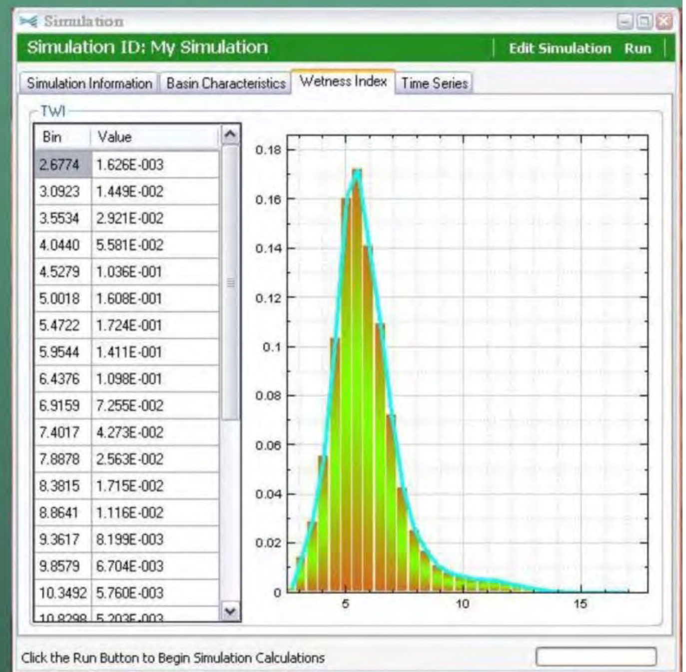
USGS

Data Sources

NOAA/NWS
Temperature and
Precipitation
Cooperative-Station
and NEXRAD Data

DEM → Stream Network
KY Dam Safety Commission
Soil Survey Geographic Data
TR-55 Impervious Erosion Curve
National Land Cover Data 2001
KY Pollutant Discharge
 Elimination System
KY Division of Water

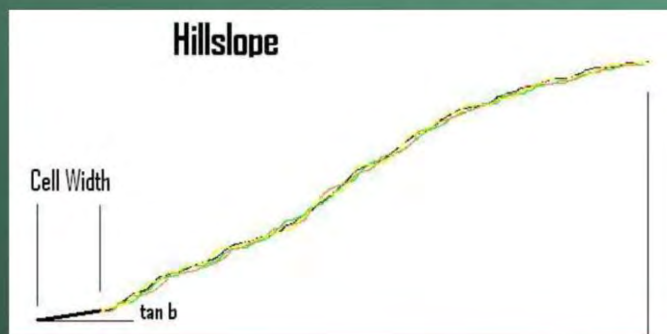
TopMODEL Inputs



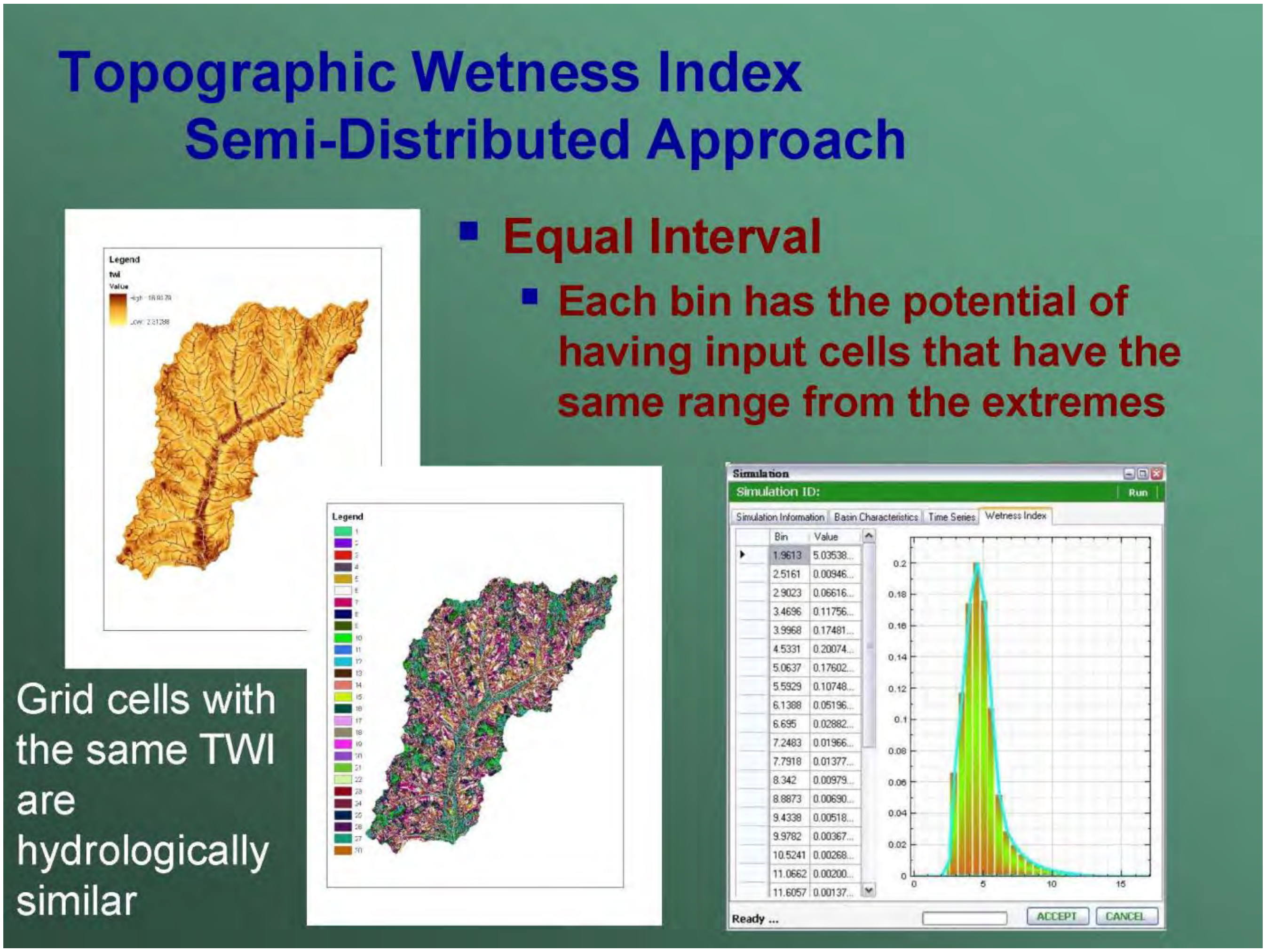
Topographic Wetness Index
Semi-Distributed Approach

How does water accumulate in the basin?

$$TWI = \ln\left(\frac{upslope\ contributing\ area}{\tan\ slope}\right)$$



High values of TWI → High potential for saturation
Low values of TWI → Low potential for saturation


Topographic Wetness Index
Semi-Distributed Approach
Equal Interval
Each bin has the potential of having input cells that have the same range from the extremes
Grid cells with the same TWI are hydrologically similar
Legend
Simulation
Simulation ID:
Run
Simulation Information
Basin Characteristics
Time Series
Wetness Index
Bin
Value
Ready ...
ACCEPT
CANCEL

Basic TopMODEL equation:

$$S_x = \bar{S} + m\left(\overline{TWI} - TWI_x\right)$$

S – saturation deficit
TWI – topographic wetness index
m –controls range of variability in saturation deficit

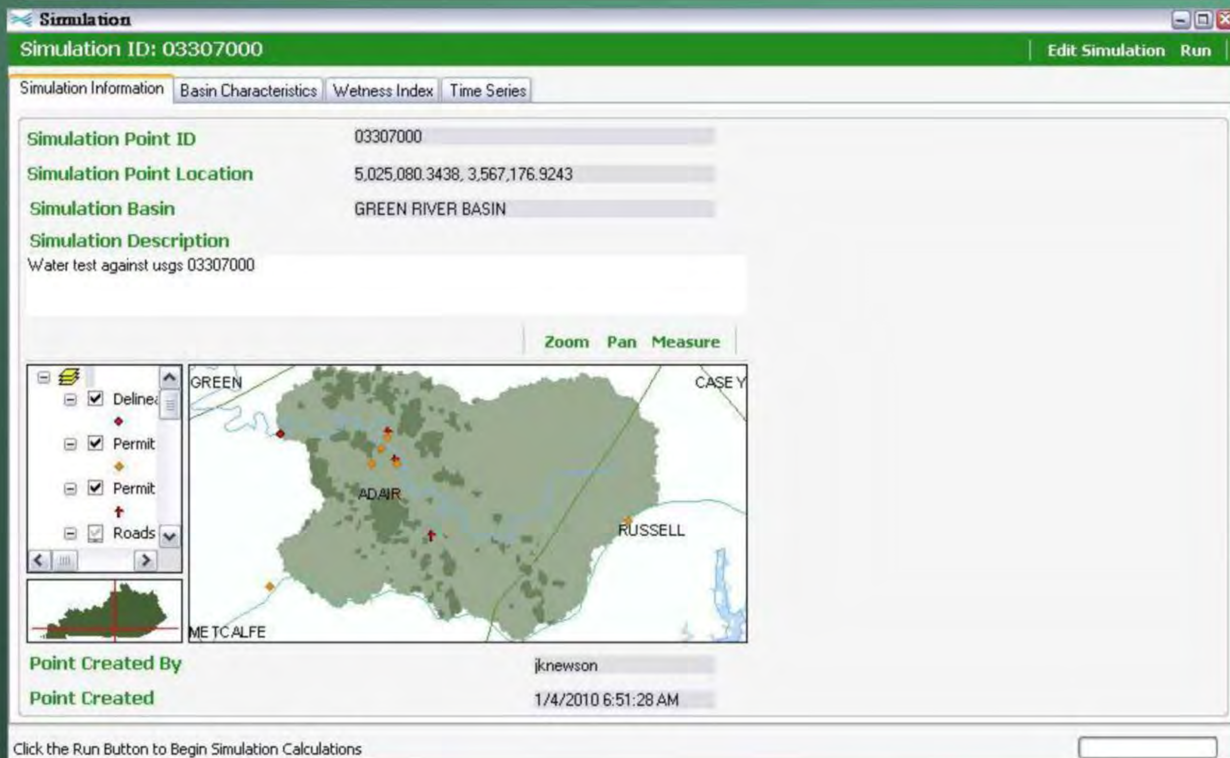
as *m* ↑, variability in *S* ↑ and water table gradient ↑

due to increased effect of topography -

this attenuates peak flow and steadies base flow

USGS

Identifying Internally Drained Regions



Identifying Internally Drained Regions

Simulation

Simulation ID: 03307000

Edit Simulation Run

Simulation Information | Basin Characteristics | Wetness Index | Time Series

Characteristics

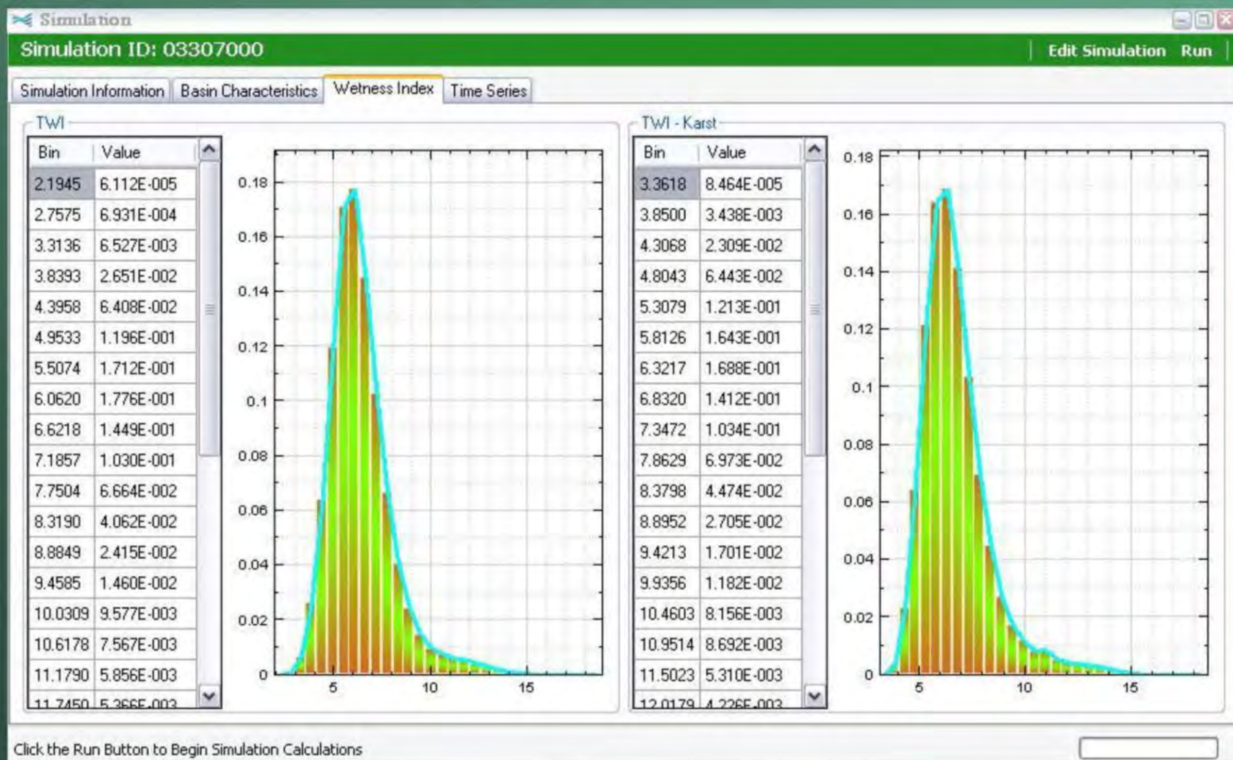
Property	Value	Units	Description
Simulation ID	03307000		Simulation ident...
Total Area	422.0808	square Kilometer	Simulation basi...
Total Lake Area	0.0000	square Kilometer	Upstream contri...
Saturated Hydraulic Conductivity	1,018.6806	millimeter/day	Saturated hydra...
Soil Depth	982.5435	millimeter	Depth of soil
Field Capacity	0.2458	unitless	
Water Holding Capacity	0.1513	unitless	Water holding c...
Porosity	0.3690	unitless	Porosity of soil
Percent Impervious	1.0254	%	Percent impervi...
Percent Road Impervious	0.4800	%	Percent road im...
Latitude	37.0769	Decimal Degrees	Latitude
Site ID	03307000		Site ID
Effective Impervious*	0.7000	%	Effective imper...
Conductivity Multiplier	6.2732	unitless	Soil conductivit...
Percent Macropore*	0.2000		
Scaling Factor M	11.0041	millimeter	Soil scaling factor
Ground Water Withdrawal**	0.0000	million gal/year	Ground water w...
Surface Water Withdrawal**	68.9994	million gal/year	Surface water ...

Karst Characteristics

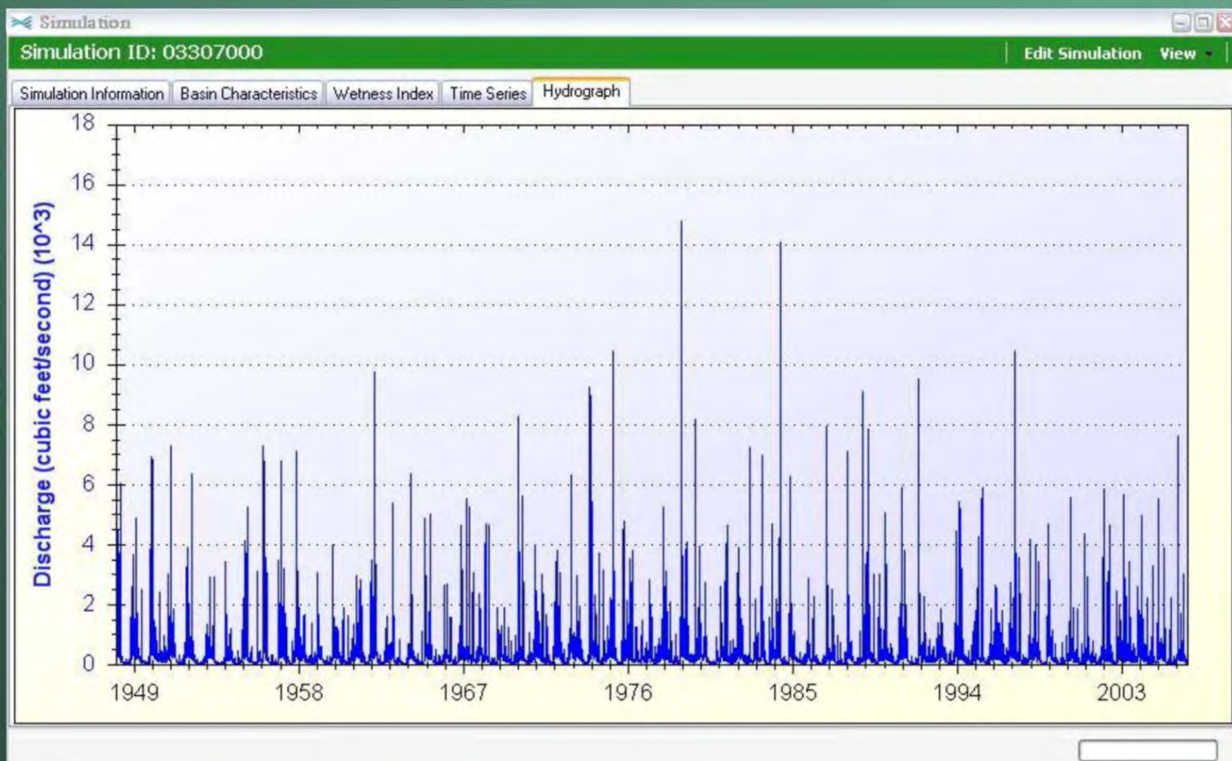
Property	Value	Units	Description
Simulation ID	03307000		Simulation ident...
Total Area	41.6370	square Kilometer	Simulation basi...
Total Lake Area	0.0000	square Kilometer	Upstream contri...
Saturated Hydraulic Conductivity	683.9106	millimeter/day	Saturated hydra...
Soil Depth	1,059.1249	millimeter	Depth of soil
Field Capacity	0.2767	unitless	
Water Holding Capacity	0.1626	unitless	Water holding c...
Porosity	0.3849	unitless	Porosity of soil
Percent Impervious	0.8484	%	Percent impervi...
Percent Road Impervious	0.4251	%	Percent road im...
Latitude	37.0896	Decimal Degrees	Latitude
Site ID	03307000		Site ID
Effective Impervious*	0.7000	%	Effective imper...
Conductivity Multiplier	9.3131	unitless	Soil conductivit...
Percent Macropore*	0.2000		
Scaling Factor M	7.6392	millimeter	Soil scaling factor
Ground Water Withdrawal**	0.0000	million gal/year	Ground water w...
Surface Water Withdrawal**	0.0000	million gal/year	Surface water ...

Click the Run Button to Begin Simulation Calculations

Identifying Internally Drained Regions

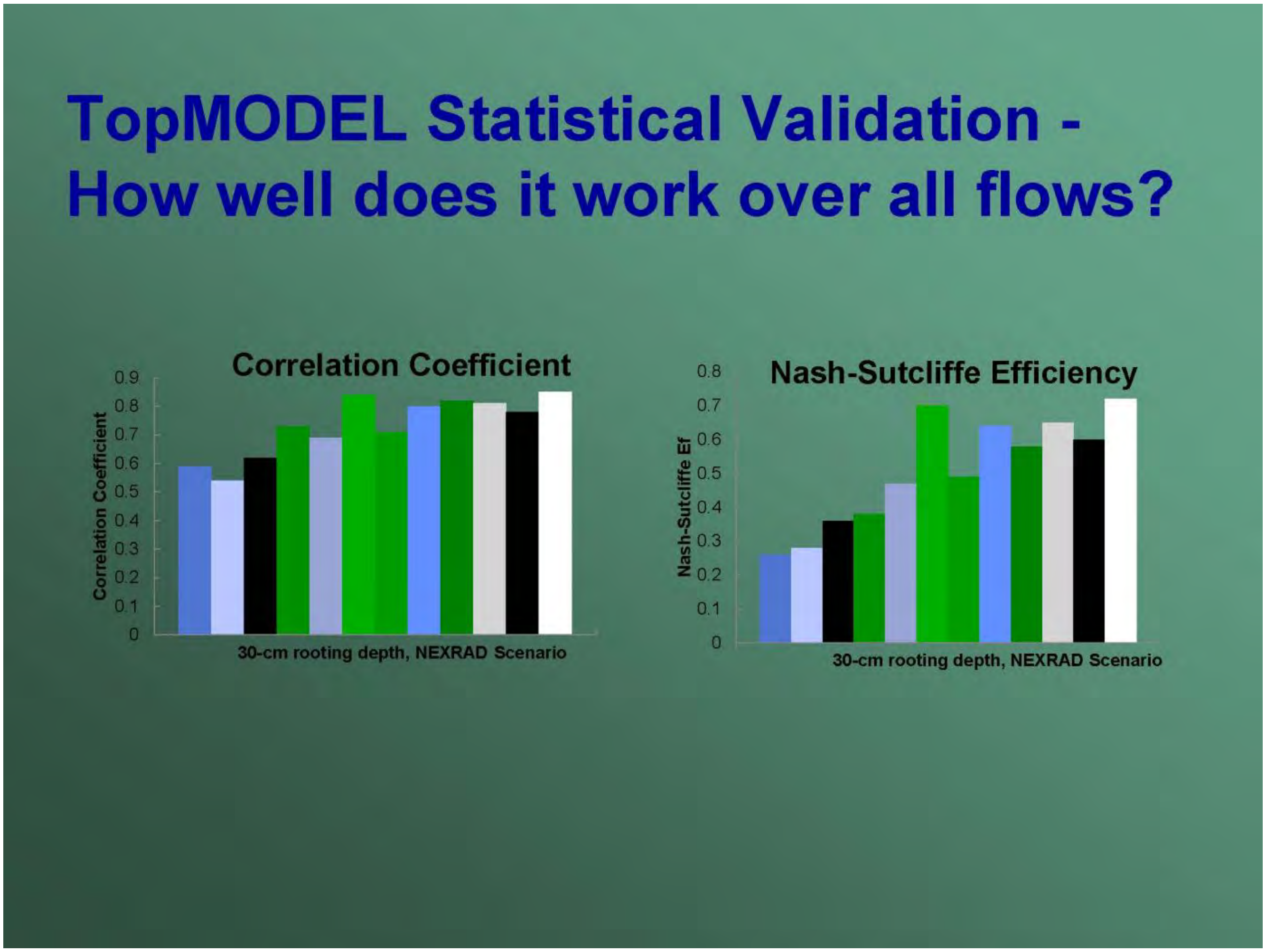


Identifying Internally Drained Regions



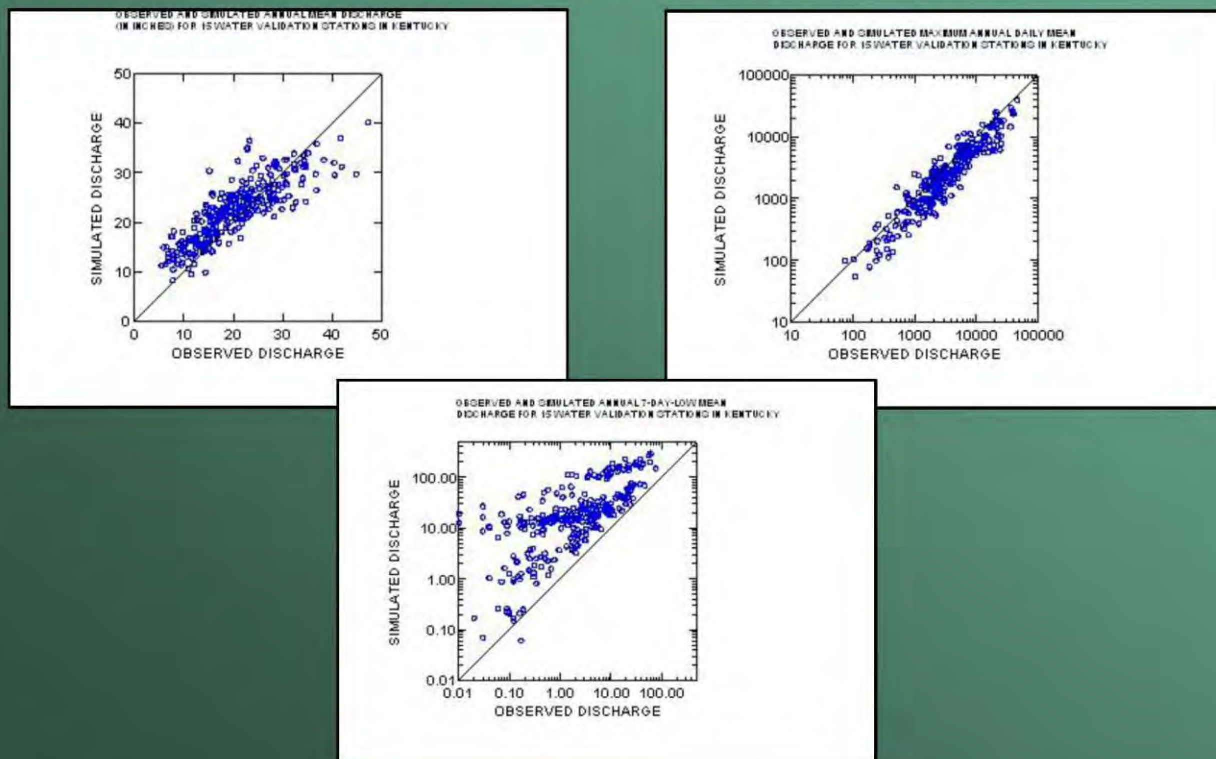
DEMO

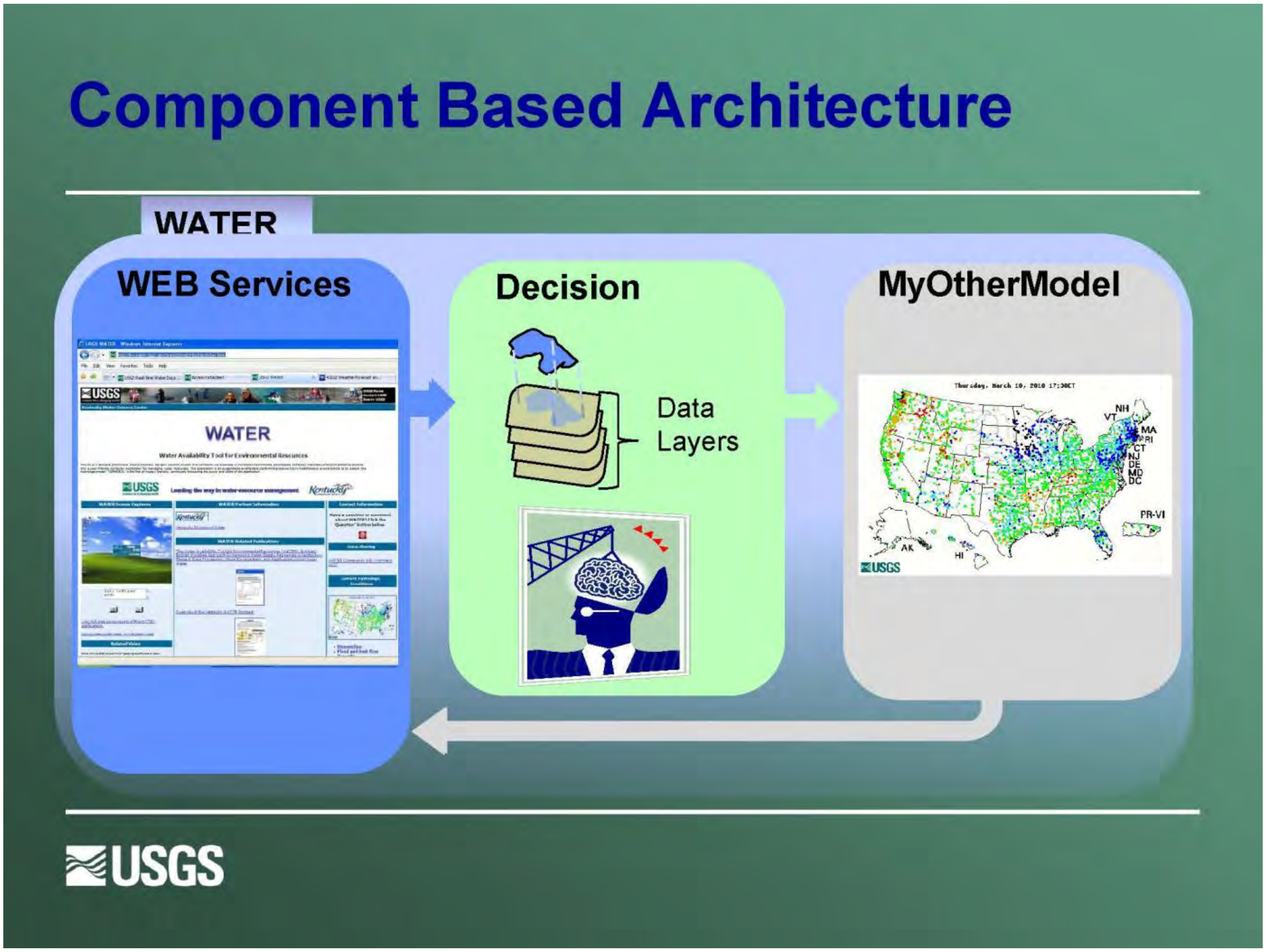
- Load Data from layers
- Run Model


TopMODEL Statistical Validation -
How well does it work over all flows?
Correlation Coefficient
Correlation Coefficient
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
30-cm rooting depth, NEXRAD Scenario
Nash-Sutcliffe Efficiency
Nash-Sutcliffe Ef
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
30-cm rooting depth, NEXRAD Scenario

TopMODEL Statistical Validation

How well does it work by flow regime?





Component Based Architecture
WATER
WEB Services
WATER
Water Availability Tool for Environmental Resources
Decision
Data
Layers
MyOtherModel
NH
VT
MA
RI
CT
NJ
DE
MD
DC
PR-VI
AK
HI
USGS

Potential Applications

- Estimating water availability for permitting land use planning
- Flow statistics
- Drought mitigation
- Flood forecasting
- Water quality
- Source water assessments
- Defining ecoflows for aquatic habitats
- etc …

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Conclusion

- WATER is component based → provides a flexible platform to add functionality.
- WATER incorporates knowledge from <u>experts</u>, spatial data and quantitative/qualitative models.
- WATER is an application that compiles decision steps in order to provide information to help researchers and manager make more informed decisions.

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WATER Application Website:
http://ky.water.usgs.gov/projects/waterbudget/index.html