Prepared in cooperation with the Kentucky Division of Water

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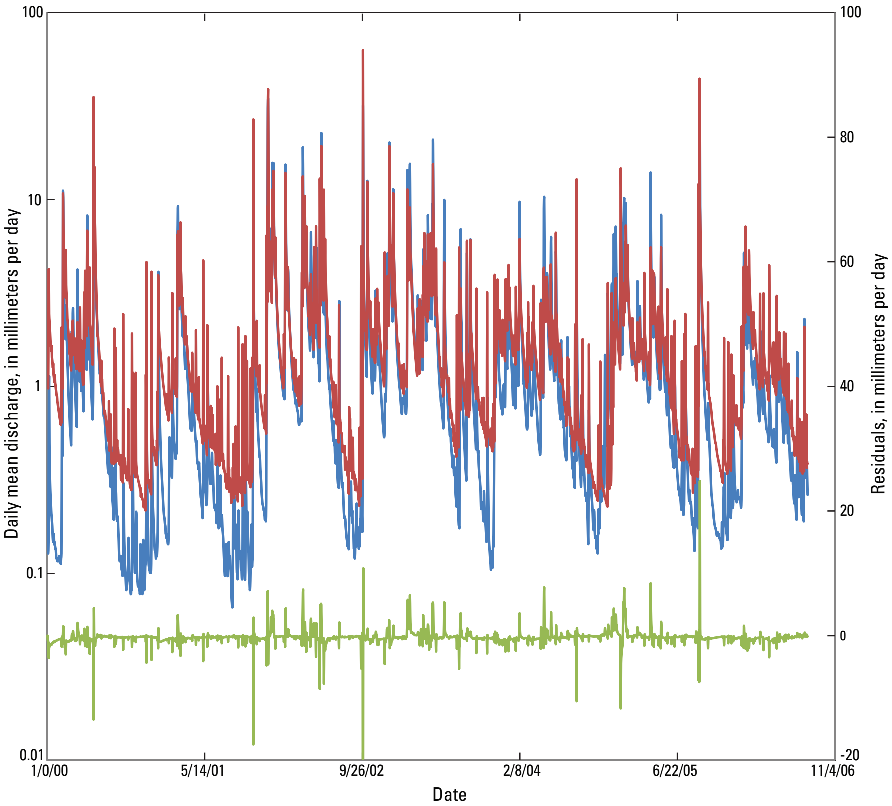

Scientific Investigations Report 2012–5071

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

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	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)

Abbreviations

DEM – digital elevation model

Ef – Nash-Sutcliffe efficiency

GIS – geographic information system

GUI – graphical user interface

HUC – hydrologic unit code

KDOW – Kentucky Division of Water

KPDES – Kentucky Pollutant Discharge Elimination System

NEXRAD – Next Generation Weather Radar

NHD – National Hydrography Dataset

NLCD – National Land Cover Data

Qbase – base-flow coefficient

RMSE – root mean square error

SD – sinkhole drainage

SDP – sinkhole-drainage process

SSURGO – Soil Survey Geographic Database

STATSGO – State Soil Geographic Database

SWAT – Soil and Water Assessment Tool

TD – topographically drained

TWI – Topographic Wetness Index

USGS – U.S. Geological Survey

WATER – Water Availability Tool for Environmental Resources

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Abstract

This report describes Phase II modifications made to the Water Availability Tool for Environmental Resources (WATER), which applies the process-based TOPMODEL approach to simulate or predict stream discharge in surface basins in the Commonwealth of Kentucky. The previous (Phase I) version of WATER did not provide a means of identifying sinkhole catchments or accounting for the effects of karst (internal) drainage in a TOPMODEL-simulated basin. In the Phase II version of WATER, sinkhole catchments are automatically identified and delineated as internally drained subbasins, and a modified TOPMODEL approach (called the sinkhole drainage process, or SDP-TOPMODEL) is applied that calculates mean daily discharges for the basin based on summed area-weighted contributions from sinkhole drainage (SD) areas and non-karstic topographically drained (TD) areas. Results obtained using the SDP-TOPMODEL approach were evaluated for 12 karst test basins located in each of the major karst terrains in Kentucky. Visual comparison of simulated hydrographs and flow-duration curves, along with statistical measures applied to the simulated discharge data (bias, correlation, root mean square error, and Nash-Sutcliffe efficiency coefficients), indicate that the SDP-TOPMODEL approach provides acceptably accurate estimates of discharge for most flow conditions and typically provides more accurate simulation of stream discharge in karstic basins compared to the standard TOPMODEL approach.

Additional programming modifications made to the Phase II version of WATER included implementation of a point-and-click graphical user interface (GUI), which fully automates the delineation of simulation-basin boundaries and improves the speed of input-data processing. The Phase II version of WATER enables the user to select a pour point anywhere on a stream reach of interest, and the program will automatically delineate all upstream areas that contribute drainage to that point. This capability enables automatic delineation of a simulation basin of any size (area) and having any level of stream-network complexity. WATER then automatically identifies the presence of sinkholes catchments within the simulation basin boundaries; extracts and compiles the necessary climatic, topographic, and basin characteristics datasets; and runs the SDP-TOPMODEL approach to estimate daily mean discharges (streamflow).

Introduction

The U.S. Geological Survey (USGS), in cooperation with the Kentucky Division of Water (KDOW), began a project in 2007 to develop a customized hydrologic-modeling and geospatial data-processing tool needed to assist State water-resource regulators with water-budget assessments and other water-resource management decisions. For planning purposes, the project was divided into two phases. Phase I of the project involved assembling the basic geospatial, climatic, and hydrologic-input datasets necessary for hydrologic-response modeling and developing the computer code needed to employ the TOPMODEL rainfall-runoff approach originally developed by Beven and Kirkby (1979). The outcome of the Phase I project was named the Water Availability Tool for Environmental Resources (WATER), and the programming structure, input-data requirements, output, and calibration and testing for stream basins in the non-karst areas of Kentucky were fully described in a previously published report by Williamson and others (2009).

Since its development, the results of trial-run simulations using WATER to simulate stream discharges in the non-karst areas of Kentucky have been evaluated by the USGS and its cooperators to explore the practical uses and limitations of the TOPMODEL approach and determine what additional programming modifications are required to improve the accuracy of simulations, enhance ease of use, and expand the usefulness of WATER as a water-resources management tool. Feedback received as a result of these evaluations led to implementation of Phase II of the project, which was undertaken during 2008–10.

Purpose and Scope

This report summarizes the modifications made to the WATER program during Phase II of its programming development to (1) improve the graphical user interface (GUI) to enable fully automated delineation of the simulation basin and improve the speed of input-data extraction and hydrologic modeling, and (2) to develop a modified TOPMODEL method that better simulates the unique drainage characteristics of karstic watersheds (basins) of Kentucky. Results of these programming modifications are evaluated by comparing simulated discharge against measured (observed) discharge for 12 karst test basins located throughout the state. Simulated and observed hydrographs and flow-duration curves are presented for each test basin, and statistical evaluations of the modeled basin discharge are presented and discussed.

Previous Work

As noted previously, the hydrologic-modeling capability of WATER is built upon the TOPMODEL rainfall-runoff approach originally developed by Beven and Kirkby (1979). The TOPMODEL approach applies the variable-source-area concept to describe how water accumulates in a simulation basin and derives estimates of stream discharge from the frequency-distribution histogram of Topographic Wetness Index (TWI) values computed by the following equation:

$$TWI = ln\ \{A/tan\beta\} \qquad (1)$$

where

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

β is local slope (degrees) as derived from a preprocessed digital elevation model (DEM)-based raster dataset (Quinn and others, 1997).

Other critical input parameters used in the TOPMODEL approach are obtained using climate data (precipitation and temperature), and mean soil properties obtained from the Soil Survey Geographic Database (SSURGO; *http://soils.usda.gov/survey/geography/ssurgo/*). Wolock and McCabe (1999) showed that an accurate precipitation record was the most significant variable required for a successful hydrologic-response model, while soil-moisture storage (derived from pedological data) was identified as the next most critical variable.

Williamson and others (2009) documented the creation of programming code and the input-data files used for applying the TOPMODEL application to simulate streamflow characteristics of basins in the non-karst areas of Kentucky. Their report provides details about the programming and input-data-file structure of the Phase I WATER-TOPMODEL code and describes procedures used in the calibration, testing, and statistical evaluation of TOPMODEL outputs obtained for 20 test basins ranging in area from 16 to 1,565 km^2 and located throughout the State. Historically, input data for the TOPMODEL application have been estimated by using soil parameters from a combination of the State Soil Geographic (STATSGO) Database (*http://soils.usda.gov/survey/geography/statsgo/*) and manual estimation techniques (Brasington and Richards, 1998; Wolock, 2003) with soil parameters including available water-holding capacity, field capacity, porosity, soil thickness, saturated hydraulic conductivity, a conductivity multiplier, and a basin-scaling parameter as the principal physical-input parameters. However, Williamson and Odom (2007) showed that the SSURGO Database provided input data at a resolution that was more appropriate for analysis of small upland basins and yielded better results without the subjectivity of manual estimation. Using SSURGO data and Next Generation Weather Radar (NEXRAD) precipitation data, Williamson and others (2009) demonstrated that the WATER-TOPMODEL program developed for use in Kentucky was capable of providing acceptable estimates of surface flows in non-karst area basins, based on Nash-Sutcliffe efficiencies (Ef) ranging from .26 to .72.

Beyond its application to Kentucky, the TOPMODEL application has been used successfully to study a wide 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; Wood and others, 1988, 1990; Famiglietti and Wood, 1991; Famiglietti, 1992), and the geomorphic evolution of basins (Ijjász-Vásquez and others, 1992). TOPMODEL also has been used for estimating 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).

An Internet search of the published scientific literature typically will generate a large list of published studies using the keywords “karst” and “rainfall-runoff” or “hydrologic response” modeling; however, the majority of these studies discuss statistical methods or use of groundwater models to simulate discharges from karst springs (for example: Dooge, 1973; Neuman and de Marsily, 1976; Dreiss, 1982, 1989; Zhang and others, 1995; Wicks and Hoke, 2000; Scanlon and others, 2003). By comparison, there are relatively few published studies that address simulation of sinkhole or surface-stream drainage in well-developed karst areas. Arikan (1988) applied a linked multi-reservoir approach to create a numerical model of regional streamflows in a karst area of Turkey. Campbell and others (2003) evaluated the results and limitations of using conventional geographic information system (GIS) flow-accumulation methods to estimate stream discharges from a sinkhole-drained valley in northeastern Alabama. Spruill and others (2000) applied the Soil and Water Assessment Tool (SWAT) numerical model to simulate daily streamflows in a small karstic watershed in central Kentucky over a 2-year period. Wolfe and others (2004) developed a hydrologic model using a rainfall-runoff approach to estimate the duration of ponding in a karst wetland in middle Tennessee. Salerno and Tartari (2009) investigated the application of wavelet analysis to model and evaluate base-flow discharges of rivers in karst areas. Field (2010) describes theoretical mathematical models that can be used to simulate drainage into and out of flooded sinkholes of various shapes and volumes. To the best knowledge of the authors, this report documents the first attempt to apply a TOPMODEL-based rainfall-runoff approach to the problem of simulating surface-stream discharge in karstic watersheds.

Phase II Modification of WATER

Most hydrologic-modeling techniques, including the conventional TOPMODEL approach, rely on use of artificially smoothed DEM-input data, which eliminates the presence of internally drained “non-contributing areas” prior to applying flow-accumulation methods to estimate surface runoff to a grid-based stream network, and are therefore unsuitable for use in sinkhole-dominated karst terrains (Taylor and Greene, 2008). By most estimates, approximately 55 to 65 percent of Kentucky is characterized by moderately to well-developed karst (Paylor and Currens, 2001) whose geographic boundaries correlate broadly to four major physiographic regions: the Inner Bluegrass, the Outer Bluegrass, the Eastern Pennyroyal, and the Western Pennyroyal (fig. 1). Within these regions, normal (topographically controlled) surface drainage is altered to various degrees by sinkholes, sinking streams, and subsurface networks of solution conduits (Ray, 2001). Where karst features such as sinkholes are extensive and well developed, surface streamflows may be partly or completely pirated by underground conduits, and surface-stream reaches may be scarce and disconnected from one another. Surface runoff commonly is diverted underground by way of sinkholes and sinking streams, rapidly transported through pipe-like or channel-like subsurface conduits, and discharged back to the land surface at one or more karst springs, which are tributaries or headwaters for base-level surface streams.

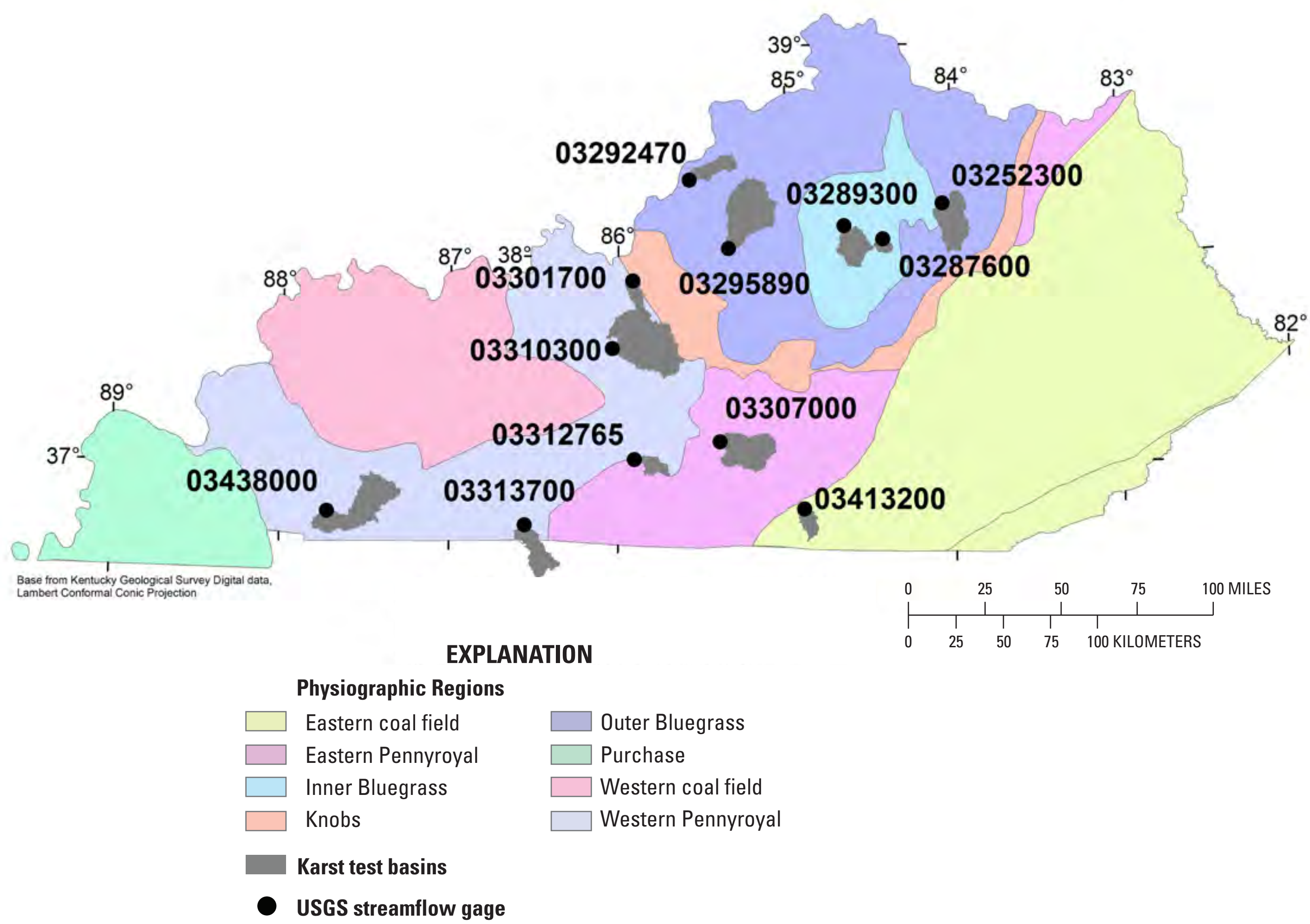

Figure 1. Physiographic regions of Kentucky and locations of karst test basins and U.S. Geological Survey streamflow gages used in the study

Sinkhole-Drainage Process

Conceptually, sinkholes can be treated as internally drained subbasins within the boundaries of the simulation basin that contribute water to the pour-point of the stream during storm events by way of subsurface stream reaches (conduits). To account for the anticipated differences in hydrologic responses between sinkhole drainage (SD) areas and normal topographically drained (TD) areas of a basin, a new raster input-data file was created to represent the locations and areas of sinkhole catchments previously mapped by Taylor and Nelson (2008), and then the TOPMODEL code used by WATER was modified so that the presence of sinkholes would generate a TWI distribution representative of the collective hydrologic response of all internally drained subbasins within the simulation-basin boundaries. This Phase II modification is called the sinkhole-drainage process, or SDP-TOPMODEL approach.

Figure 2 shows a schematic diagram which illustrates differences in the data-input and computational-processing steps between the standard (Phase I) WATER-TOPMODEL

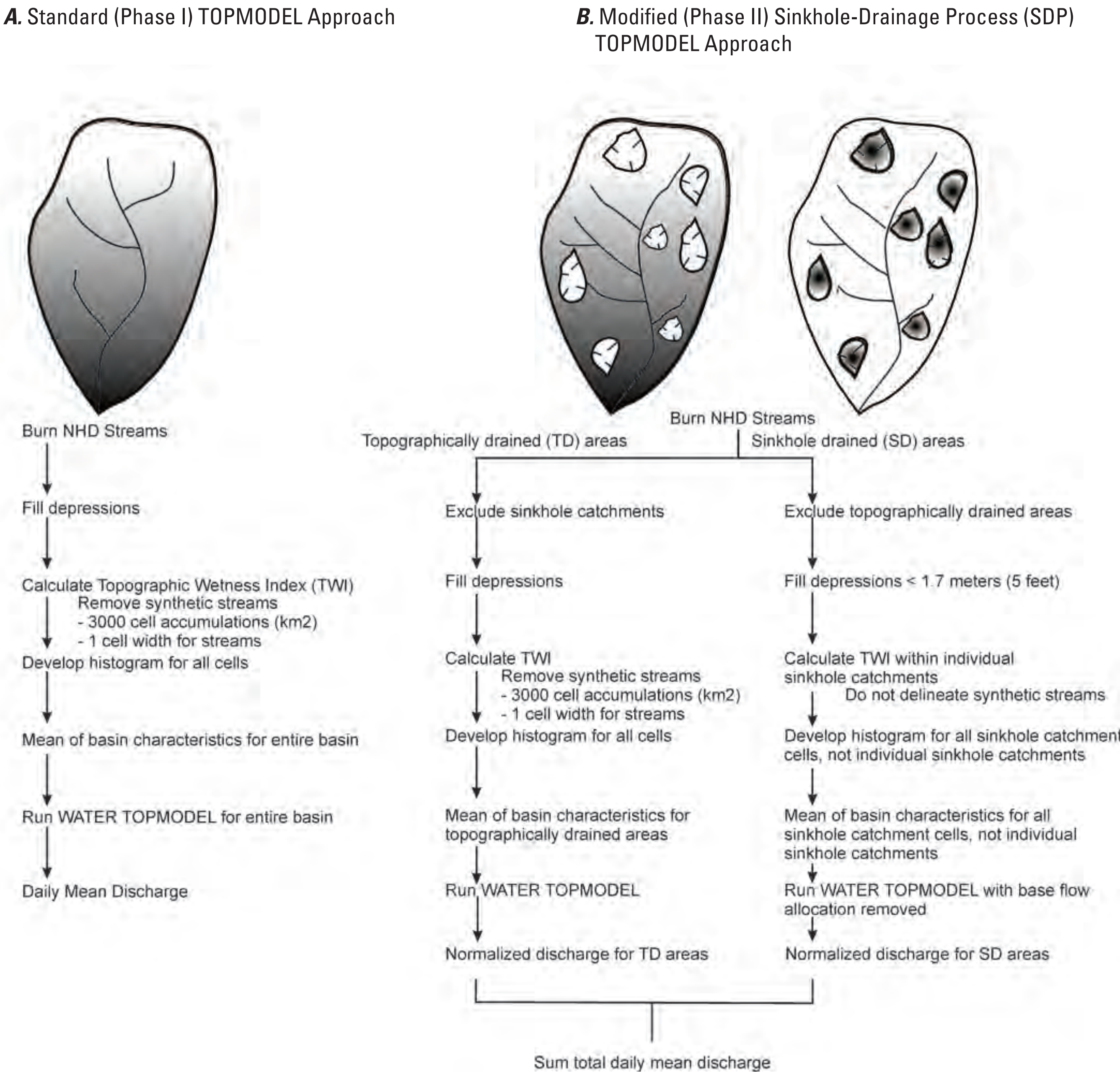

Figure 2. Major data-processing and computational steps in the *A*, standard (Phase I) TOPMODEL and *B*, modified (Phase II) sinkhole-drainage process (SDP) TOPMODEL approaches.

and the SDP-TOPMODEL approaches. Three major data-processing steps that are incorporated into the SDP-TOPMODEL approach that are not part of the standard (Phase 1) approach include: (1) mapped sinkhole and (or) sinking stream catchment areas (SD areas) are identified and delineated as internally drained subbasins of the larger simulation basin; (2) area-normalized discharge is computed separately for the normal topographically-drained areas and SD areas; and (3) the area-normalized discharges from the two are summed at the end of the modeling process to calculate a total discharge for the simulation basin.

As part of the third step, the water-budget accounting used in the standard TOPMODEL code was modified so that the drainage into SD areas bypasses the base-flow coefficient (Qbase) and is computationally added directly to the stream-discharge coefficient at each time step. As indicated on fig. 2, no such modification is applied to the computation of drainage from TD areas, so the calculated base-flow contribution to the stream is derived entirely from the Qbase values for TD areas of the simulation basin. The practical effect of this programmed water-budget modification is to increase the storm-peak response of simulated hydrographs, thereby better simulating the flashy hydrologic behavior typically observed for streams in conduit-dominated karst regions in Kentucky.

Point-and-Click Basin Delineation

The original (Phase I) design for WATER incorporated a menu-driven GUI to select and extract pre-processed geospatial data for drainage basins having boundaries fixed at the hydrologic unit code (HUC)-12 level and to generate climatic data and hydrologic data needed by the TOPMODEL application to estimate streamflows (discharge) at the predefined pour point of the basin. During Phase II, the GUI and the programming were restructured to provide enhanced flexibility in basin delineation, faster geospatial-input data processing, and greater ease of use.

The Phase II GUI provides the user with the ability to select a pour point anywhere on a stream line of interest and have the program automatically delineate all upstream areas (subbasins) that contribute drainage to that point (fig. 3). The main benefit of this programming modification is to allow the user the ability to delineate a simulation basin of any size (or area) or having any level of stream-network complexity. Once the pour point is selected, WATER automatically runs a routine to delineate the boundaries of the simulation basin and begins to extract and compile the necessary climatic, topographic, and basin-characteristics data (such as soil properties) needed to run the TOPMODEL application, including an "on the fly" calculation of the TWI histogram. All these data are displayed and may be reviewed and edited if necessary

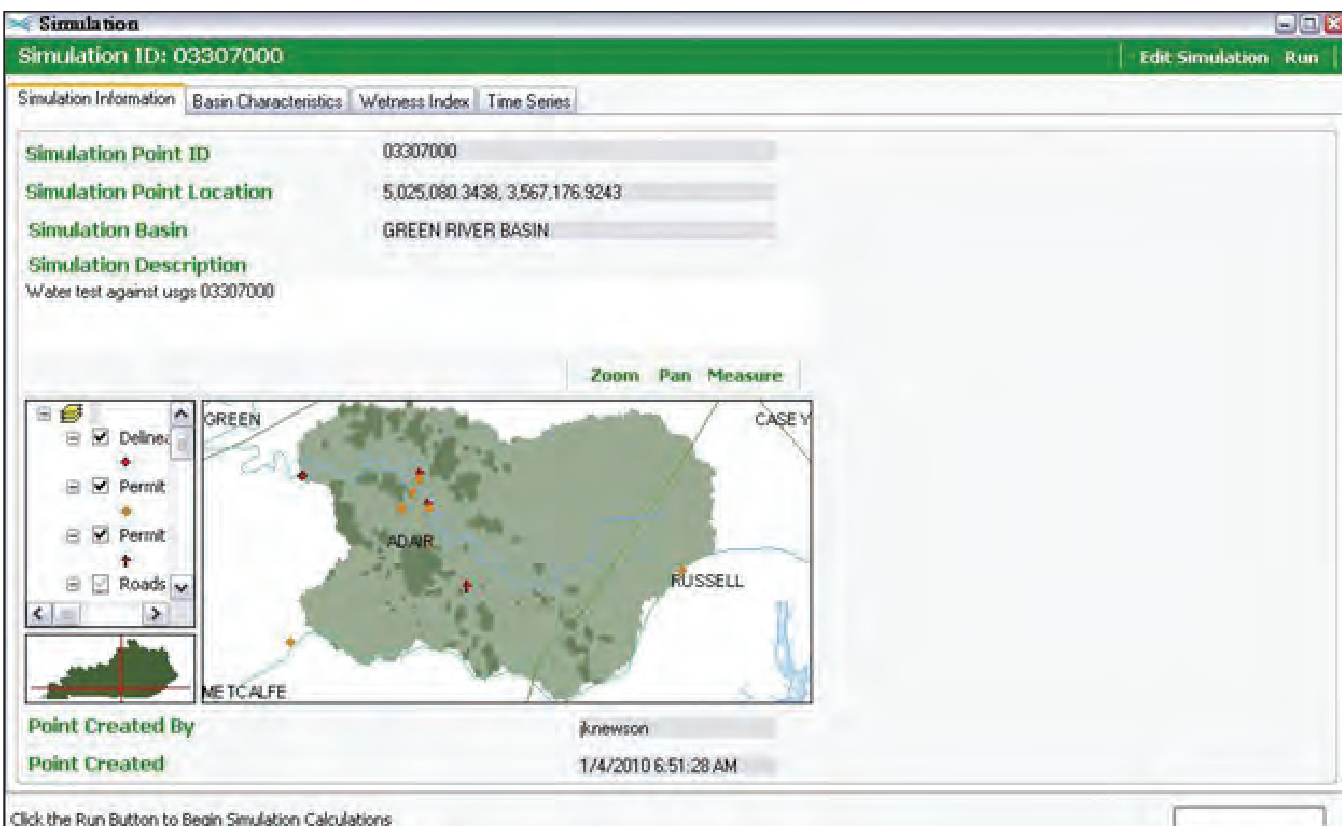

Figure 3. Screen image of WATER graphical user interface (GUI) showing boundaries of simulation basin and sinkhole catchment subbasins

by the user through the interactive GUI (fig. 4). No recognition of, or special adjustments for, karst terrain are required by the user. As part of the basin-delineation process, WATER automatically checks for, and the GUI displays, the presence of internally drained catchments, and employs the previously described SDP-TOPMODEL approach.

The input-data file structure used by the revised version of the WATER-TOPMODEL application is organized by the various folders and subfolders that facilitate data extraction for the automated basin-delineation processing and the subsequently used TOPMODEL application (fig. 5). The primary input datasets used by WATER are organized into six folders, which are summarized here:

1. admin folder: The administration folder contains the overall display datasets pertaining to the GUI, such as geographic boundaries, highways and roads, and USGS streamflow-data files. The folder also contains the simulations.shp file, which is a dataset generated by WATER to show the user where simulations have been created.

2. clim folder: The climate folder contains text files currently (2011) created by a separate climate-generator model that calculates the precipitation and temperature in the simula-

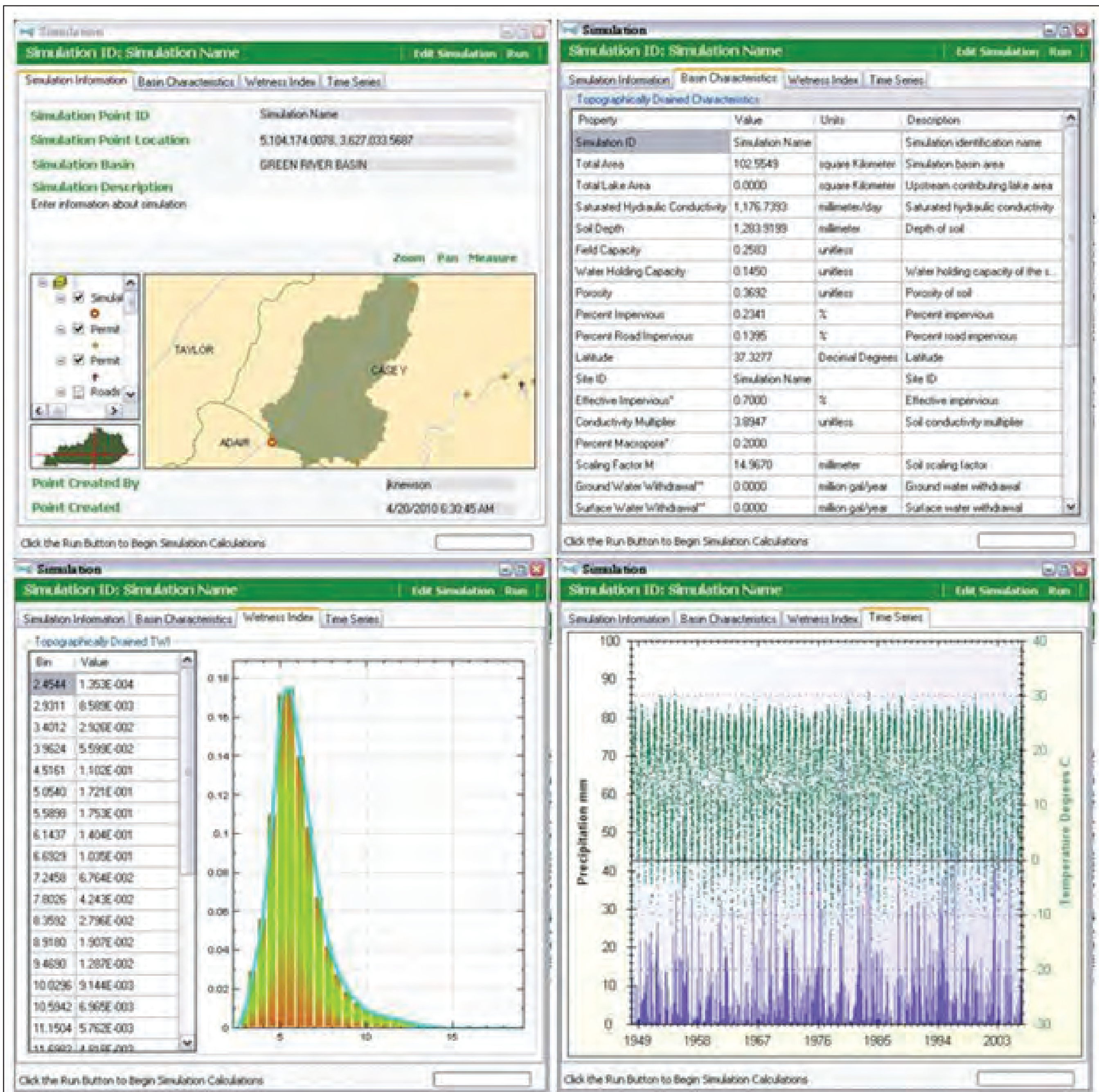

Figure 4. Screen-image examples of the information displays provided by the WATER graphical user interface (GUI).

tion basin from multiple climate stations and outputs a .txt file using the inverse distance-weighting approach coupled with an elevation adjustment at a HUC-12 level, as described in Williamson and others (2009). For simulations of hydrologic conditions beginning after January 1, 2000, NEXRAD is used for precipitation-data input (see Williamson and others, 2009, for more detail).

3. geog folder: Currently (2011), this folder contains only the mask used to identify any internally drained catchments and is the only dataset located in this folder. The TOPMODEL application uses this integer dataset to determine which areas contain sinkholes.

4. hydr folder: This folder contains specific GIS datasets used both for display purposes as well as for input-data extraction, including

   - *rsvr* – identification of ponds, lakes, and reservoirs greater than 10 acres.
   - *strm* – identification of stream and river reaches (greater than 3,000 cells in flow-accumulation raster file).
   - *nhd.mdb* – flow lines (feature class representing streams) contained in the National Hydrography Dataset (NHD), which are used during the automated basin delineation.
   - *dischargePermits* – a file listing the locations of surface-discharge permits reported by the Kentucky Pollutant Discharge Elimination System (KPDES) database. Under the present (Phase II) version, the locations are plotted on the GUI display; however, discharge and quantities are not used in basin discharge computations because of known or suspected errors and uncertainties in these data.
   - *lake_area* – a point dataset containing identified lakes and their associated bank full surface area.
   - *nhdrsvrgrid* – an integer-grid dataset used to calculate the upstream contributing area of each lake or manmade reservoir in the delineated basin of interest.
   - *withdrawalPermits* – a file listing the locations of surface-discharge permits reported by the KPDES database. Under the present (Phase II) version, the locations are plotted on the GUI display; however, discharge and quantities are not used in basin discharge computations because of known or suspected errors and uncertainties in these data. It contains a list of all water-withdrawal permits and their locations.

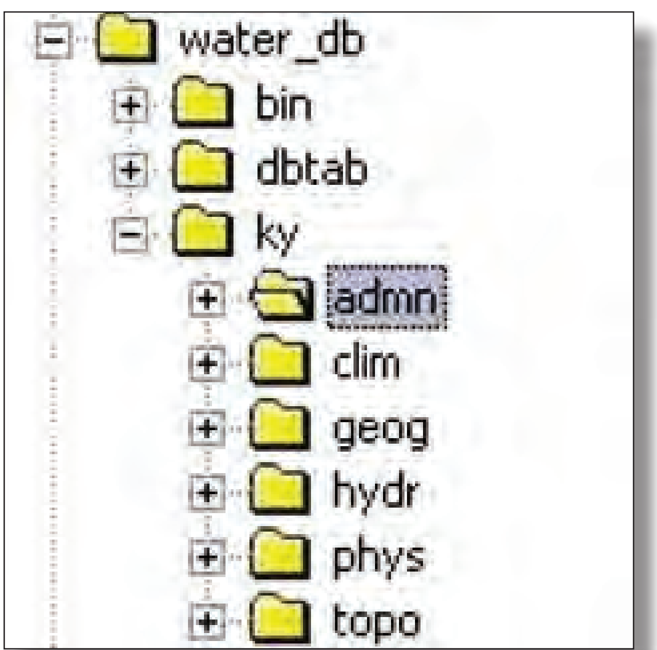

Figure 5. Screen image of the data tree structure for the six principal input-data folders used by WATER.

5. topo folder: contains several types of numerically generated topological data, organized at the HUC-6 level, including

   - *felv* – 10-m DEM data.
   - *flwa* – flow accumulation used by the WATER basin-delineation application.
   - *flwd* – flow directions used by the WATER basin-delineation application.
   - *snet* – synthetic stream network used by the WATER basin-delineation application to create the simulation area of interest.

6. *phys* folder: contains the TWI grids needed by TOPMODEL organized by HUC-6 code numbers, the SSURGO geodatabase that contains soil characteristics data, and other ancillary data including

   - *clipg* – State integer grid of 1, identifies Commonwealth of Kentucky State boundaries.
   - *hu6grid* – integer grid identifying the area of the HUC-6 basin.
   - *imp* – a dataset containing the percent ground impervious, obtained from National Land Cover Data (NLCD).
   - *imprd* - a dataset containing the percent road impervious, obtained by clipping the NLCD layer and clipping to the USGS National Map transportation layer.
   - *obsn* – database that contains basin names and locations.
   - *obsn12* – used to identify the climate directory of the simulated basin.
   - *wbd12* – identifies downstream basins.

Results of Karst Test-Basin Simulations

An evaluation of the SDP-TOPMODEL approach was conducted by simulating stream-discharge records obtained from continuous measurements collected during 2000–06 from USGS streamflow gages in 12 karst test basins (fig. 1) ranging from 57 to 671 km^2 in area, and having internally drained areas ranging from less than 2 to about 47 percent of the total basin area (table 1). The test basins were selected mainly on the basis of three criteria: (1) located wholly within one of four major karst physiographic regions in the State; (2) having, or having had, a USGS streamflow-gaging station measuring flow from a surface catchment (drainage) area completely underlain by karstic carbonate bedrocks; and (3) having a hydrograph period of record encompassing the 2000–06 period of NEXRAD precipitation data. Where possible, preference was given to gaged basins having a known absence of flow regulation and location in a non-urban environment.

Hydrograph plots for each test basin that illustrate observed versus simulated mean daily discharges, and residuals (differences between observed and simulated mean daily discharge values), are presented in appendix 1. Observed and SDP-TOPMODEL simulated hydrographs are plotted using log-scale because the range in stream discharge encompasses two or more orders of magnitude while residuals are plotted using linear-scale. The plots are difficult to characterize generally because the hydrologic responses vary from basin to basin and the hydrograph and residual trend lines exhibit considerable temporal variability. Four statistical measures applied in previous studies of TOPMODEL simulations conducted elsewhere by Wolock (1993) and Wolock and McCabe (1999), and in the Phase I investigation by Williamson and others (2009),

Table 1. Karst test basins and corresponding U.S. Geologcial Survey streamflow gages used for statistical evaluation of the karst-modified (Phase II) WATER-TOPMODEL sinkhole-drainage\process.

[USGS, U.S. Geological Survey; mi^2, square mile; <, less than]

Physiographic region (Karst terrain)[1]	USGS streamflow-gage number	USGS stream name	Drainage area (mi^2)	Percent internally drained	Available period of record (year-month-day)
Inner Bluegrass region	03289300	South Elkhorn Creek near Midway, Ky.	105	21.2	1987-12-30 2008-11-04
	03287600	North Elkhorn Creek at Bryan Station Road at Montrose, Ky.	21.5	2.2	1997-09-20 2008-11-05
Outer Bluegrass region	03252300	Hinkston Creek near Carlisle, Ky.	154	<2	1991-10-01 2008-11-05
	03295890	Brashears Creek at Taylorsville, Ky.	259	<2	1981-07-01 2008-11-05
	03292470	Harrods Creek at Highway 329, Ky.	70.3	2.2	1999-01-01 2008-11-05
Eastern Pennyroyal or Coal Field region	03413200	Beaver Creek near Monticello, Ky.	43.4	4.2	1968-10-01 2008-11-04
	03307000	Russell Creek near Columbia, Ky.	173	9	1939-10-01 2008-11-04
Western Pennyroyal region	03310300	Nolin River at White Mills, Ky.	240	35.4	1959-10-01 2008-11-04
	03313700	West Fork Drakes Creek near Franklin, Ky.	91	20.2	1968-06-01 2008-11-05
	03301700	Mill Creek near Fort Knox, Ky.	38.2	27.9	1998-04-16 2008-11-05
	03312765	Beaver Creek at Highway 31 E near Glasgow, Ky.	49.6	47.4	1999-09-01 2002-09-30
	03438000	Little River near Cadiz, Ky.	244	36.8	1940-02-06 2008-11-04

[1]Paylor and Currens (2001).

were applied during this study to better evaluate the results of the test-basin simulations discussed here. The statistics include

Bias: $$\frac{\sum (x_i - y_i)}{n} \quad (2)$$

Root mean square error (RMSE): $$\sqrt{\frac{\sum (y_i - x_i)^2}{n}} \quad (3)$$

Correlation: $$\frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \quad (4)$$

Nash-Sutcliffe efficiency (Ef): $$1 - \frac{\sum (x_i - \bar{x})}{\sum (y_i - x_i)} \quad (5)$$

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,

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

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

n is the number of observations.

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

Histograms that summarize the statistics computed from simulated hydrograph data obtained using the standard (Phase I) TOPMODEL and SDP-TOPMODEL approaches are shown in figures 6–9 for each of the 12 test basins. Compared to the other statistics, the bias (fig. 6) exhibited the greatest variability among the test basins and between the standard TOPMODEL and SPD-TOPMODEL simulations. Bias values ranging from −.3 to .3 were obtained for 8 of the 12 test basins using both the standard TOPMODEL and the

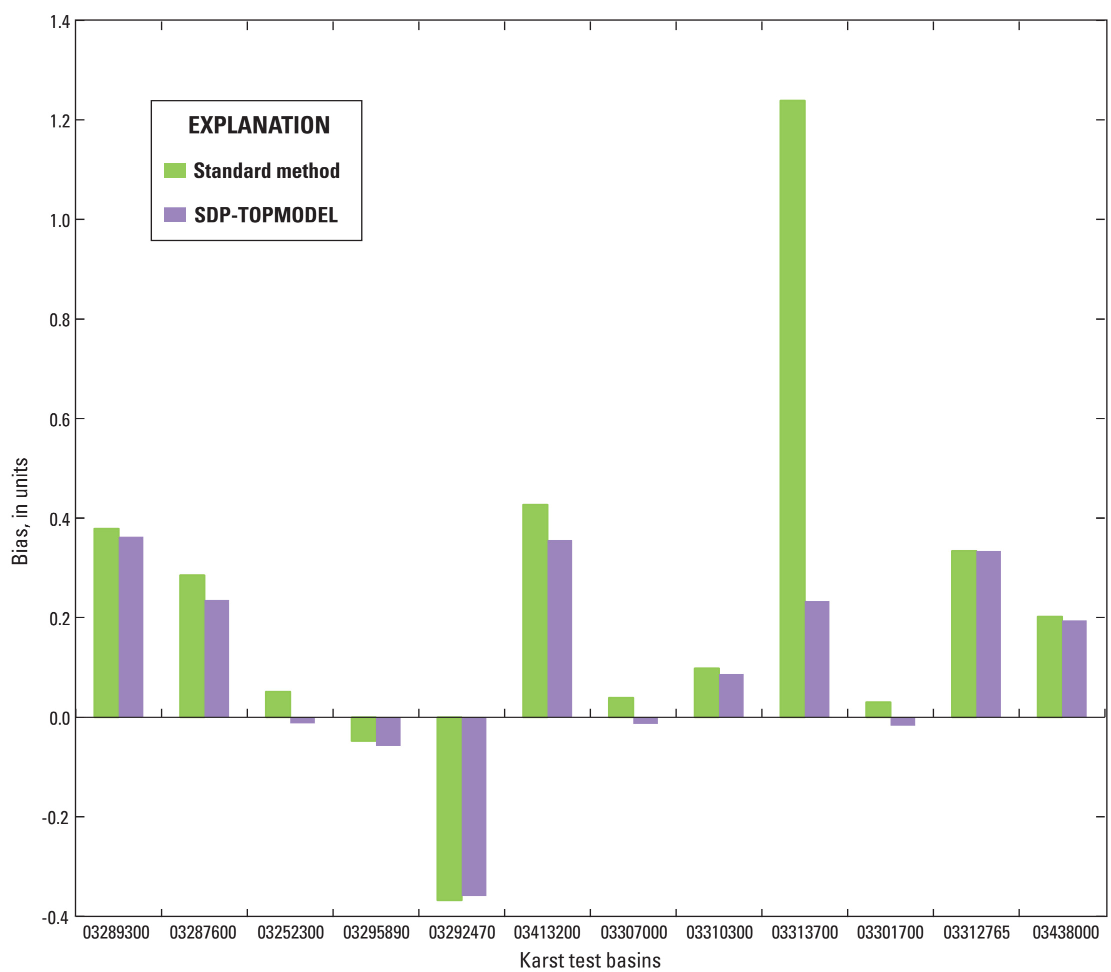

Figure 6. Bias statistics for karst test basins used in the study.

SDP-TOPMODEL approaches. The bias values obtained using the SDP-TOPMODEL approach were closer to zero than those obtained using the standard TOPMODEL approach in 10 of the 12 basins:

1. 03252300–Hinkston Creek,
2. 03287600—North Elkhorn Creek,
3. 03292470—Harrods Creek,
4. 03295890–Brashears Creek,
5. 03301700–Mill Creek,
6. 03307000–Russell Creek,
7. 03310300–Nolin River,
8. 03312765–Beaver Creek near Glasgow,
9. 03313700—West Fork Drakes Creek, and
10. 03438000–Little River.

Five basins simulated using the SDP-TOPMODEL approach yielded negative bias values, indicating that model output under-predicted stream discharge for these basins, probably because of local variability in basin characteristics that are not adequately accounted for in the simulations.

Relatively more consistency in the range of values was obtained for the RMSE and Correlation statistics (figs. 7 and 8, respectively) for both the SDP-TOPMODEL and standard TOPMODEL simulations. RMSE values varied slightly from basin to basin, but values ≤ 2 were obtained in 8 of 12 basins using both the standard TOPMODEL and SDP-TOPMODEL approaches (fig. 7). Among these, RSME was slightly closer to zero in 6 of 12 basins using the SDP-TOPMODEL approach:

1. 03289300–South Elkhorn Creek,
2. 03295890–Brashears Creek,
3. 03307000–Russell Creek,
4. 03312765—Beaver Creek near Glasgow,
5. 03313700—West Fork Drakes Creek, and
6. 03438000—Little River.

Correlation values (fig. 8) were consistently high and ≥ .7 using both the standard and SDP-TOPMODEL approaches for 11 of the 12 test basins. Of these, values closer to one were obtained using the SDP-TOPMODEL approach in 7 of 12 basins:

1. 03287600—North Elkhorn Creek,
2. 03295890—Brashears Creek,
3. 03301700—Mill Creek,
4. 03307000—Russell Creek,
5. 03312765—Beaver Creek near Glasgow,
6. 03413200—Beaver Creek near Monticello, and
7. 03438000—Little River.

In addition, the Correlation value of the SDP-TOPMODEL simulation for 03292470—Harrods Creek exceeded the .7 threshold and the value obtained for the standard TOPMODEL simulation of this basin.

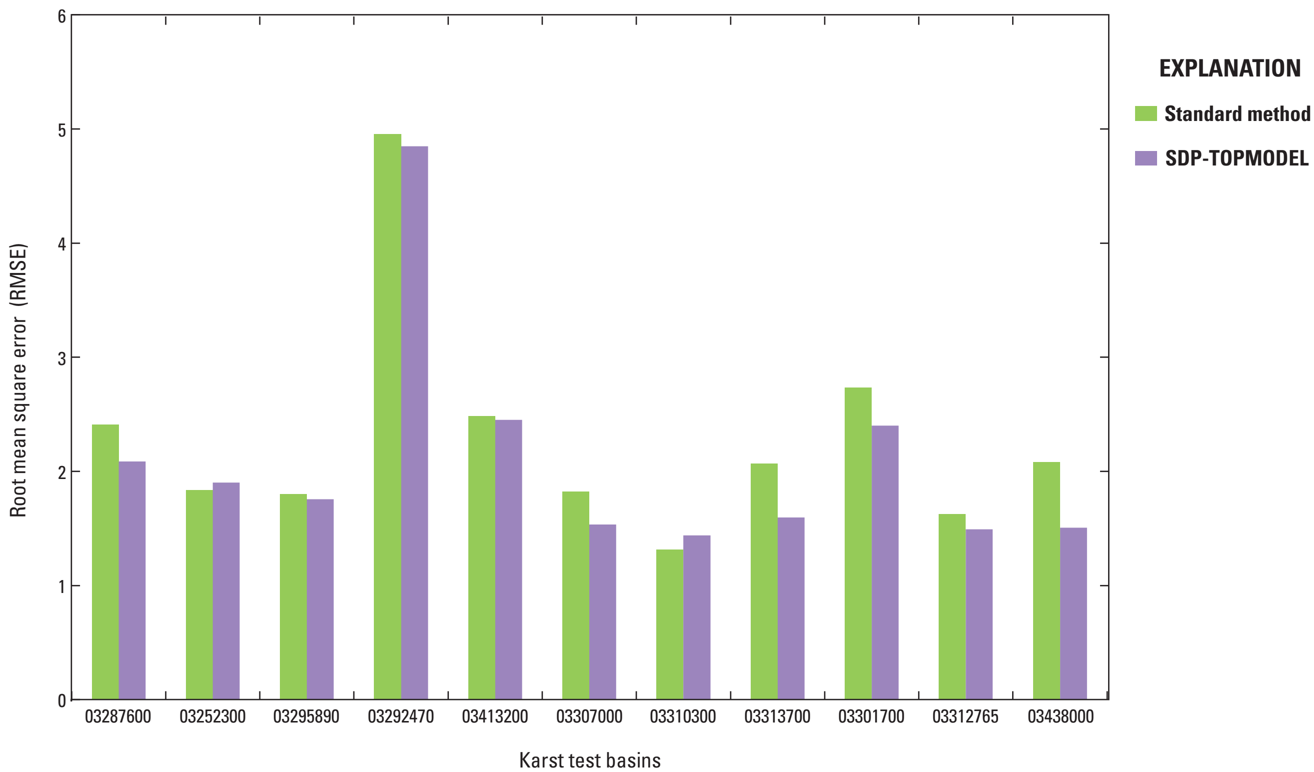

Figure 7. Root mean square error (RMSE) statistics for karst test basins used in the study.

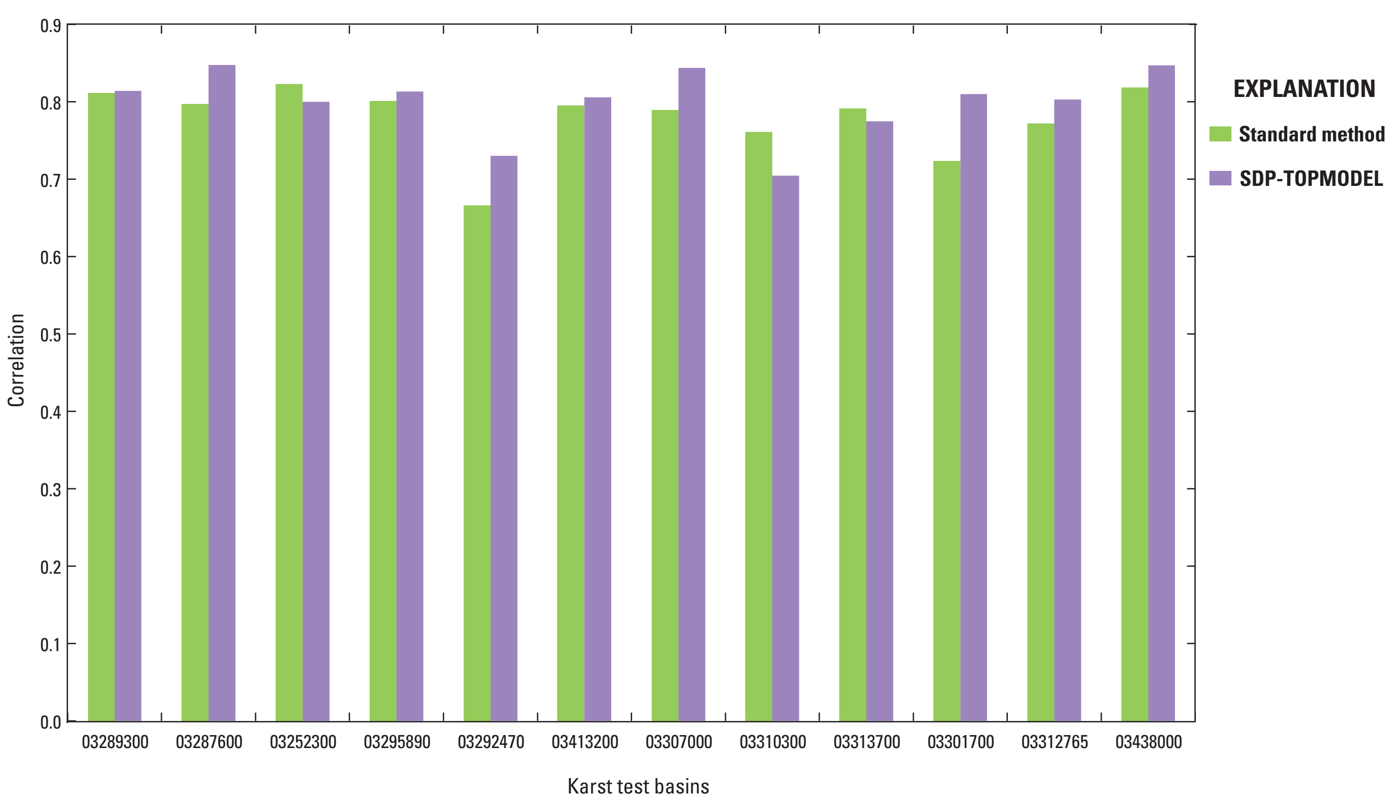

Figure 8. Correlation statistics for karst test basins used in the study.

Ef values (fig. 9) exceeded .4 in 9 of 12 basins using either the standard TOPMODEL or SDP-TOPMODEL approaches, and were ≥ .6 in 5 of 12 basins using both simulation techniques. Of the later, Ef values obtained for the SDP-TOPMODEL simulations were closer to one in 4 of the 5 basins, and overall, Ef values obtained for the SDP-TOPMODEL approach were ≥ .6 for 10 of 12 test basins:

8. 1) 03252300–Hinkston Creek,

9. 2) 03287600—North Elkhorn Creek,

10. 3) 03289300—South Elkhorn Creek,

11. 4) 03295890–Brashears Creek,

12. 5) 03301700–Mill Creek,

13. 6) 03307000–Russell Creek,

14. 7) 03312765–Beaver Creek near Glasgow,

15. 8) 03313700—West Fork Drakes Creek,

16. 9) 03413200—Beaver Creek near Monticello, and

17. 10) 03438000–Little River.

Ef values obtained using the SDP-TOPMODEL approach were lowest (<.5) for test basins 03292470–Harrods Creek, and 03310300–Nolin River (fig. 9). These test basins were used with reservations because of physical hydrologic characteristics that were anticipated to be problematic to modeling. For example, the basin for the Harrods Creek streamflow gage includes several developing suburban residential areas, and its hydrology is believed to be significantly affected by on-going land disturbance and changes in the percentage of pervious-to-impervious land-surface areas. The basin delineated for the streamflow gage on Nolin River (at White Mills, Kentucky) is located less than a few hundred feet from a large karst spring whose discharge, measured at approximately .2 m^3/s at base flow (Ray and Blair, 2005), is partly diverted to a public water supplier, and is partly recharged by a subsurface meander cutoff conduit that diverts water from the river by way of several known upstream swallow holes (Mull and others, 1988). Nevertheless, these two basins were included in the evaluation in order to bolster the total number of karst test basins in the study and to expand the range of percent area of sinkhole drainage in the Western Pennyroyal and Outer Bluegrass karst terrains.

Comparison of flow-duration curves for observed discharges and SDP-TOPMODEL simulated discharges (appendix 2) were visually evaluated to assess the relative accuracy of the SDP-TOPMODEL outputs over different flow regimes. The flow-duration curves are constructed by calculating the exceedance probability of the modeled daily flow values. The data points are arranged according to magnitude in a range of classes, and the percent of the time each class exceeds the total is computed; a curve then can be drawn through the points. The techniques used by the USGS are described by Searcy (1959). In general, peak flows (0–30 percent exceedance) appear to be most accurately simulated for the test basins, based on the relative visual match of the two curves. Results among the various basins vary somewhat in the moderate flow range (30–70 percent) and although there is a perceived tendency for the SDP-TOPMODEL simulated curves to slightly overestimate discharges in most basins, the overall results, based on the apparent relative differences between the two curves for each basin, fall within a generally acceptable range. Note that all hydrographs presented here

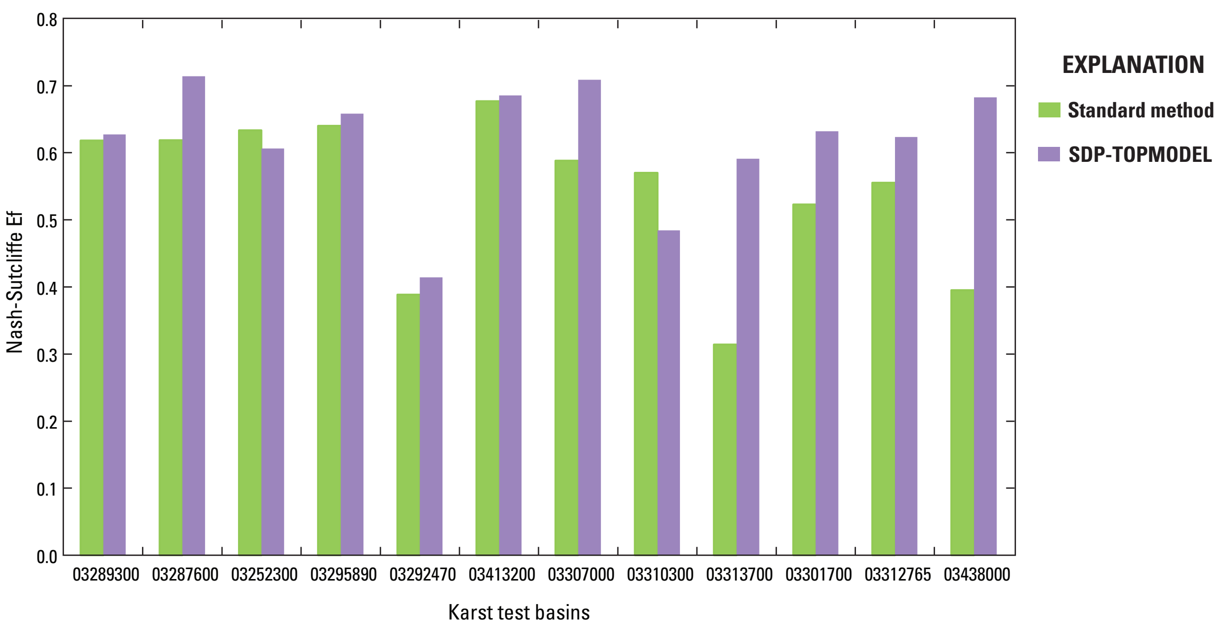

Figure 9. Nash-Sutcliffe efficiency (Ef) coefficient statistics for karst test basins used in the study.

are plotted at logarithmic scale, thereby visually exaggerating apparent differences (on the y-axis) between the simulated hydrographs at discharges less than 1 mm/d. Greater apparent uncertainties, and a more consistent tendency for modeled discharge to overestimate actual observed discharges, are apparent in the low-moderate to low-flow range (70 percent and greater probability of flow exceedance).

A more quantitative evaluation of the attributes of SDP-TOPMODEL simulated flow-duration curves is accomplished using boxplots (figs. 10, 11, and 12) in the manner described by Helsel and Hirsch (2002) that illustrate the median values (center point of the boxplot), the variation or interquartile range (the boxplot height), skewness (relative size of the two halves of the boxplot), and the presence or absence of extreme or outlier values (lower and upper "detached" values). Comparison of paired observed and modeled boxplots for each test basin illustrates that the hydrographs simulated using the SDP-TOPMODEL approach generally exhibit a slightly high overall bias compared to observed data. The bias is observed by comparing the relative positions of the 75th-percentile discharge, median discharge, and 25th-percentile discharge between each respective observed and modeled dataset. The bias is more pronounced for low-flow conditions (with respect for the graphical exaggeration resulting from the logarithmic plot), as it also appears to be on the flow-duration curves. However, overlap of the interquartile range (variability) and similarity of quartile skew indicate that overall model response generally falls within an acceptable range for most hydrologic applications, as also indicated by the Ef values, described previously.

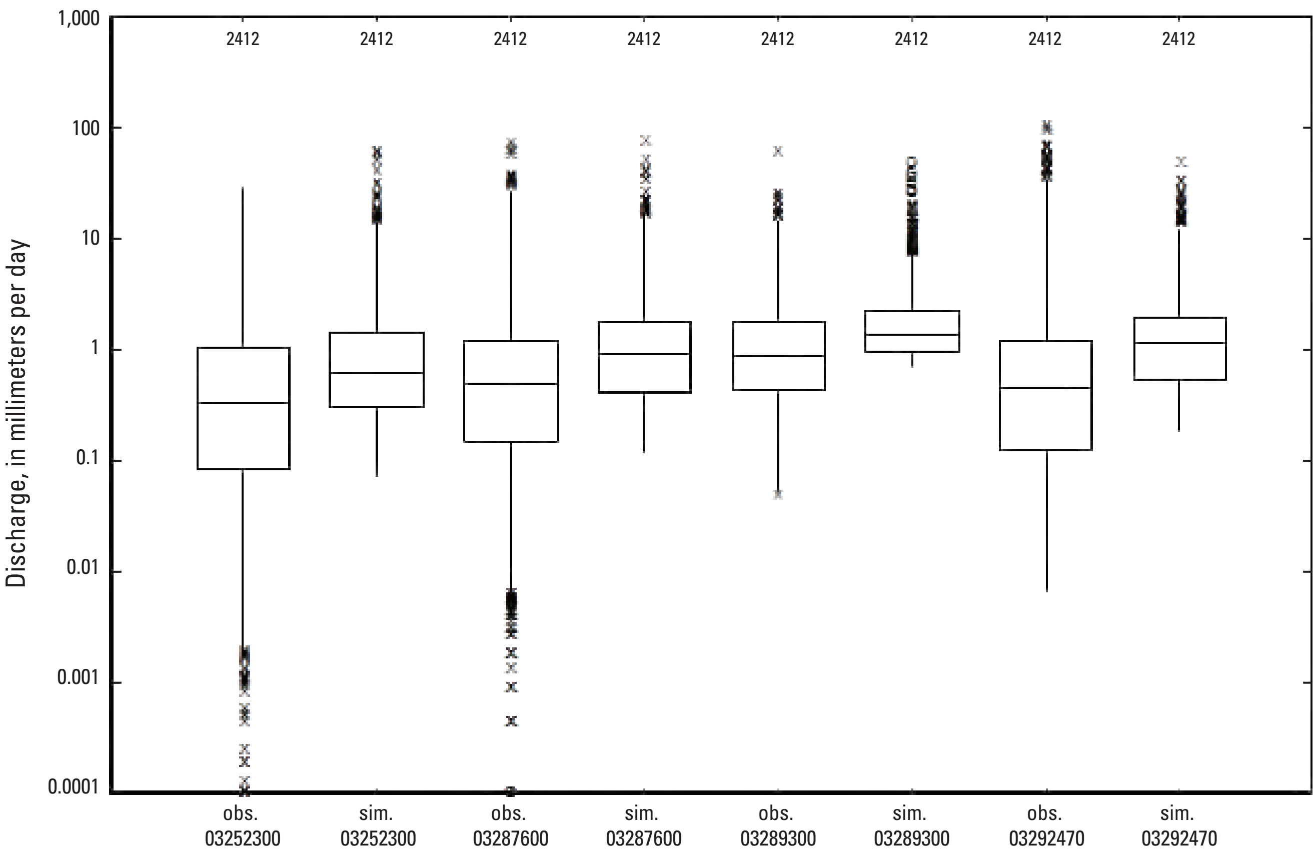

Figure 10. Statistical distribution for observed and simulated flow-duration data for karst test basins 0325300, 03287600, 03289300, and 03292470 [Explanation: obs.—observed discharge data; sim.— simulated discharge data].

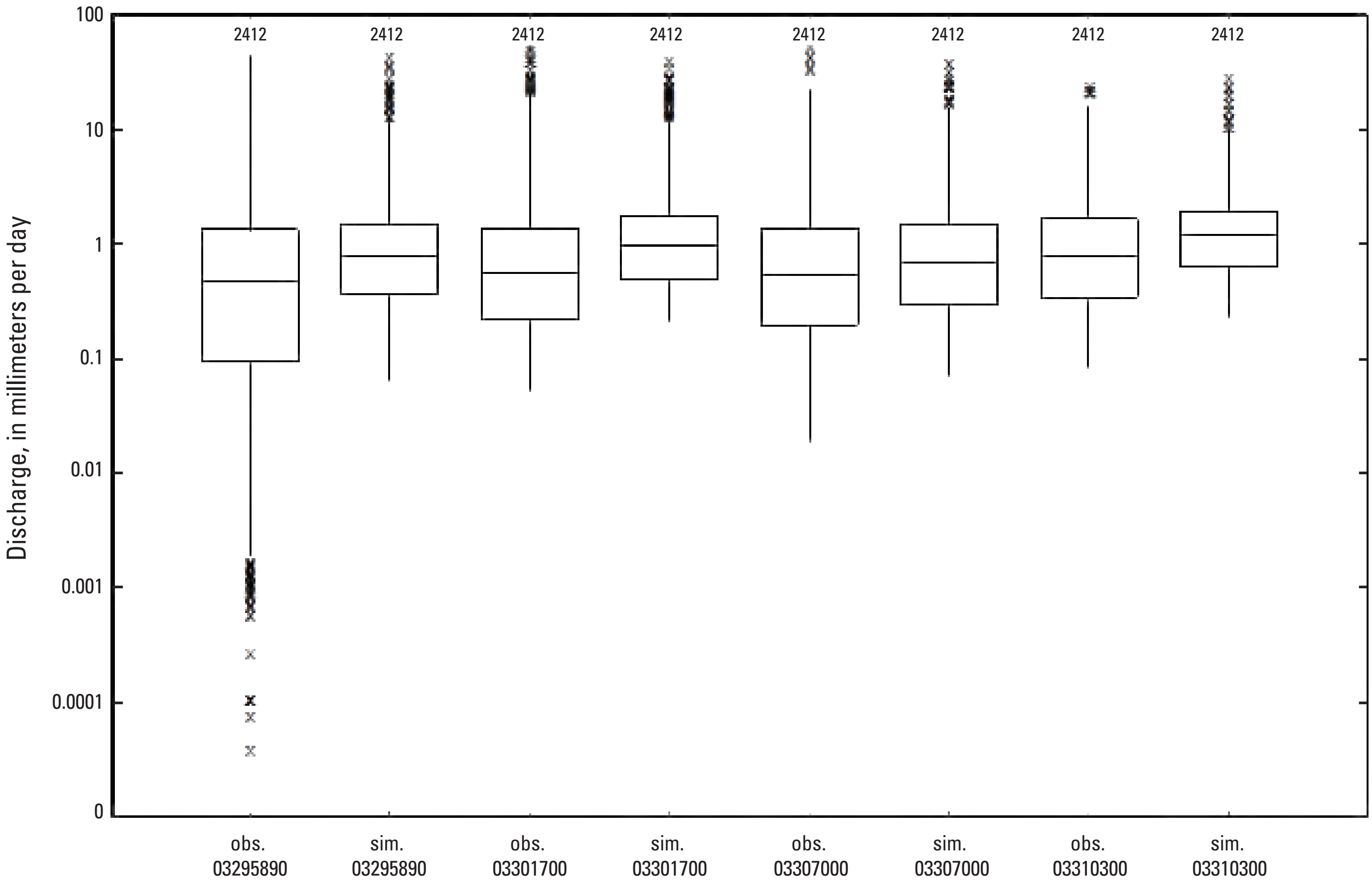

Figure 11. Satistical distribution for observed and simulated flow-duration data for karst test basins 03295890, 03301700, 03307000, and 03310300 [Explanation: obs.—observed discharge data; sim.— simulated discharge data].

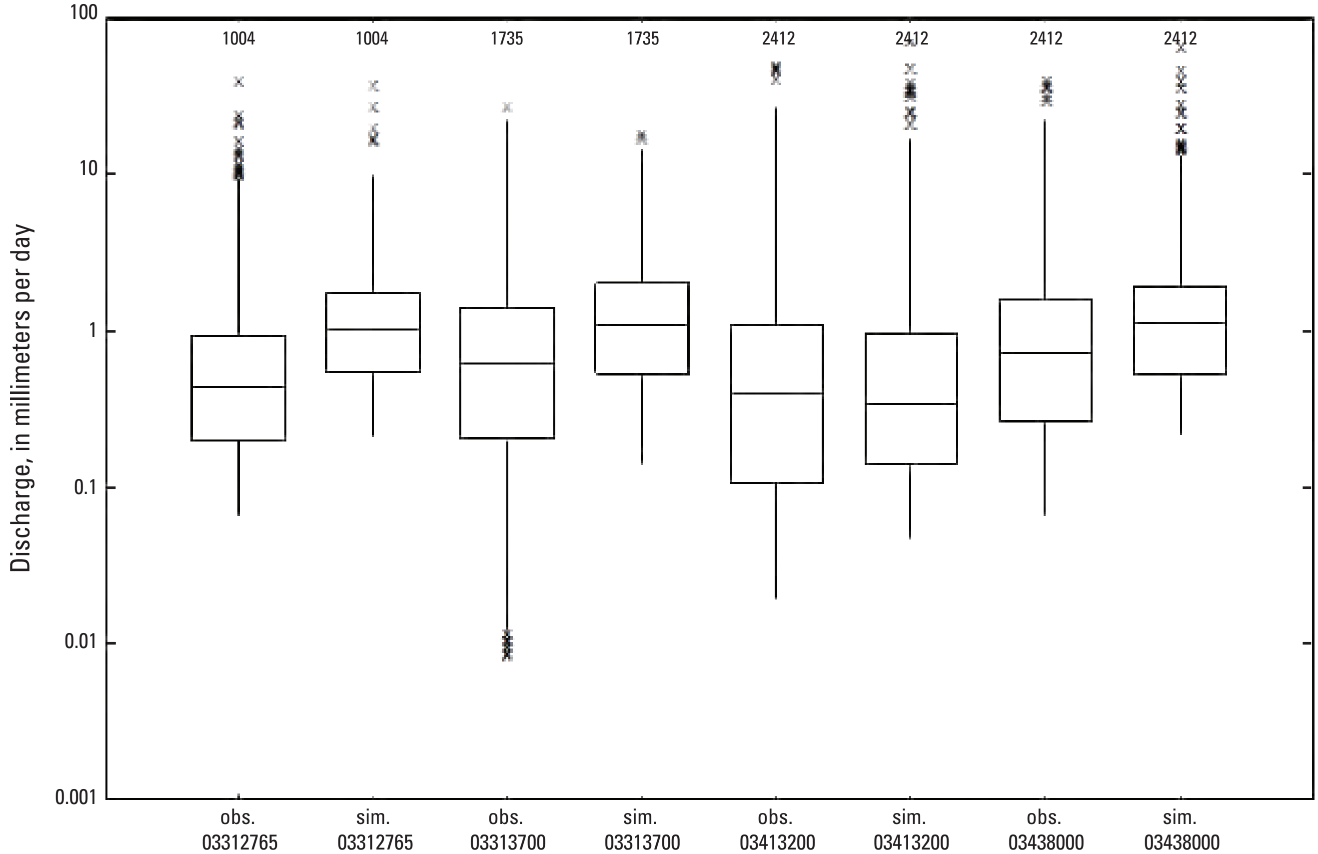

Figure 12. Statistical distribution for observed and simulated flow-duration data for karst test basins 03312765, 03313700, 03413200, and 03438000.

Limitations of the SDP-TOPMODEL Approach

Presently (2011), all basin or watershed boundaries are automatically delineated by the WATER program using topographic-data derived 10-m DEM datasets. Manual editing of these boundaries is not available as an option. Once the user-selected pour point is established, WATER automatically runs a basin-delineation routine to determine the topographic boundaries of the catchment area upstream of the pour point and begins to extract and compile the necessary climatic, topographic, and basin characteristics input data needed for the hydrologic modeling application. As part of this process, WATER automatically checks for the presence of sinkholes or sinking-stream catchments within the boundaries of the simulation basin and automatically employs the SDP-TOPMODEL approach if any such karst features are present.

The working assumption used in the present version of WATER for the SDP-TOPMODEL approach is that topographic-drainage divides automatically derived using the point-and-click GUI are accurate and represent the actual contributing area to a stream. However, in each of the karst terrains of Kentucky, water-tracer tests have demonstrated that subsurface solution conduits typically extend beneath local topographic-drainage divides, resulting in subsurface transfers of water into, or out of, many topographically defined drainage basins. As a consequence, in many karst areas the actual size of the contributing area of a stream may be larger or smaller than the area indicated by the topographic-basin boundaries of the stream (Ray, 2001). The user is advised to consult the series of 15-minute karst atlas maps published for Kentucky (Currens and Ray, 1999) to assess the accuracy of the delineated basin boundaries and to identify possible locations where sinkhole-dominated surface drainage may be misattributed to a particular basin because of the effects of subsurface-conduit piracy. However, at present, no capabilities exist within the WATER GUI to enable manual editing of basin boundaries to correct for misattributed sinkhole drainage areas. The addition of this capability may be the subject of future WATER programming revisions. It also should be noted that water-tracer test results and karst-mapping data may not be available for specific basins in many areas of Kentucky.

As described previously, visual inspection and boxplot statistical analysis of simulated flow-duration curves (appendix 2) indicates that simulations obtained using the SDP-TOPMODEL approach are most accurate at peak flows (0–30 percent flow duration), acceptable at most moderate flows (30–70 percent), and are acceptable but with comparatively less overall accuracy at low flows (>70 percent). Therefore, simulation of low-flow stream conditions should be anticipated as having the greatest chances of potential uncertainty or error. This may be a consequence of several factors, including the inability of the present TOPMODEL code to incorporate seasonal variability in evapotranspiration and soil-water storage owing to changes in vegetation growth, and longer-term storage and discharge of subsurface water in the epikarst zone. In well-developed karst watersheds, the lack of a water-budget component capable of accounting for storage in solutional conduits below the water table also may contribute to greater potential errors in low-flow simulations. Subsurface routing of flow from individual sinkholes and sinking streams through conduits is likely to be a major factor controlling the timing and volume of water discharged to streams in karst areas; however, these cannot be incorporated into karst-basin simulations because TOPMODEL is not a true distributed-deterministic model. Future work is needed to incorporate flow routing into TOPMODEL and to further modify water-budget calculations to improve the ability of WATER to simulate recessional hydrograph periods and low-flow conditions in both karst and non-karst watersheds. Currently (2011), the user is advised to anticipate greater potential errors and uncertainties when applying WATER to address water-management issues involving low-flow conditions.

An additional consideration when using the SDP-TOPMODEL approach in well-developed karst areas is this: no karstic basins having SD areas >50 percent of the total basin area were tested during this study because of the lack of suitable streamflow data. It is therefore unknown how the standard or SDP-TOPMODEL approaches perform in karstic basins largely dominated by internal drainage. It also should be emphasized that neither the standard nor SDP-TOPMODEL approaches include water-budget terms specifically for groundwater recharge and storage, or a routing or computational method that is capable of representing rapid flow through subsurface conduits. Therefore, the SDP-TOPMODEL approach is intended for the simulation of discharge from karst springs and should be used with caution in karstic basins characterized by extensive sinkhole development, multiple sinking or disappearing stream reaches, and discharge to multiple karst springs.

The standard and SDP-TOPMODEL approaches currently (2011) available in WATER are calibrated only for use in surface basins in Kentucky. With the exception of test basin 03313700—West Fork Drakes Creek, stream basins that cross the State line between Kentucky and Tennessee cannot be simulated using the Phase II version of WATER.

Summary and Conclusions

Modifications made to the Water Availability Tool for Environmental Resources (WATER)-TOPMODEL programming code during this project (Phase II) enable sinkholes and sinking-stream catchments to be physically simulated as hydrologic features in karstic basins of Kentucky. The practical effect of this programming modification—called the sinkhole-drainage process or SDP-TOPMODEL approach—enables WATER to more realistically simulate the internal drainage and flashy hydrologic responses that are characteristic of karstic watersheds in the State. The accuracy of stream-discharge estimates obtained using the SDP-TOPMODEL approach was evaluated using streamflow data collected during 2000–06 from 12 test basins located throughout each of Kentucky's four karst terrains: Inner Bluegrass, Outer Bluegrass, Eastern Pennyroyal, and Western Pennyroyal.

Visual and statistically based evaluations of simulated hydrographs and flow-duration curves indicate that most karstic basins in Kentucky can be modeled to an acceptable level of accuracy using either the standard (Phase I) TOPMODEL or the SDP-TOPMODEL approaches. However, the SDP-TOPMODEL approach physically incorporates contributions from digitally mapped, internally drained catchments in the simulation-basin model. Nash-Sutcliffe efficiency values, as well as bias, RMSE, and Correlation statistics indicate that relatively more accurate simulations typically can be expected using the SDP-TOPMODEL approach as compared to the standard TOPMODEL approach. Simulated flow-duration curves and boxplots of SDP-TOPMODEL estimated discharge data indicate that peak flows are most accurately simulated using the SDP-TOPMODEL approach, and that moderate- to low-flow ranges, though typically overestimated, are simulated with acceptable accuracy. Stream-discharge estimates in the mid-moderate to low-flow ranges were statistically acceptable, though slightly overestimated by SDP-TOPMODEL approach, and subject to greater potential uncertainties and errors.

The additional modifications made to WATER during this Phase II project included implementation of an improved point-and-click graphical user interface (GUI), which fully automates the delineation of simulation-basin boundaries and WATER input-data processing. The current (2011) version of WATER (Phase II) provides the user with the ability to select a pour point anywhere on a stream line of interest, and the program automatically delineates all upstream areas that contribute drainage to that point. Once the pour point is selected, WATER automatically delineates the boundaries of the simulation basin and extracts and compiles the necessary geospatial-input datasets needed to simulate the hydrologic response of the basin using the TOPMODEL application. WATER automatically checks for and identifies the presence of sinkholes or sinking-stream catchments within the boundaries of the simulation basin and automatically employs the sinkhole-drainage process if any such karst features are present. No special knowledge of local karst topographic or hydrologic characteristics or special geospatial data-processing actions are required by the user to simulate the hydrology of basins located in karst areas of Kentucky.

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Appendixes

Appendix 1. Hydrographs showing observed versus simulated discharge and residuals for the 12 karst test basins used in the study.

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Appendix 1. Hydrographs showing observed versus simulated discharge and residuals for the 12 karst test basins used in the study.

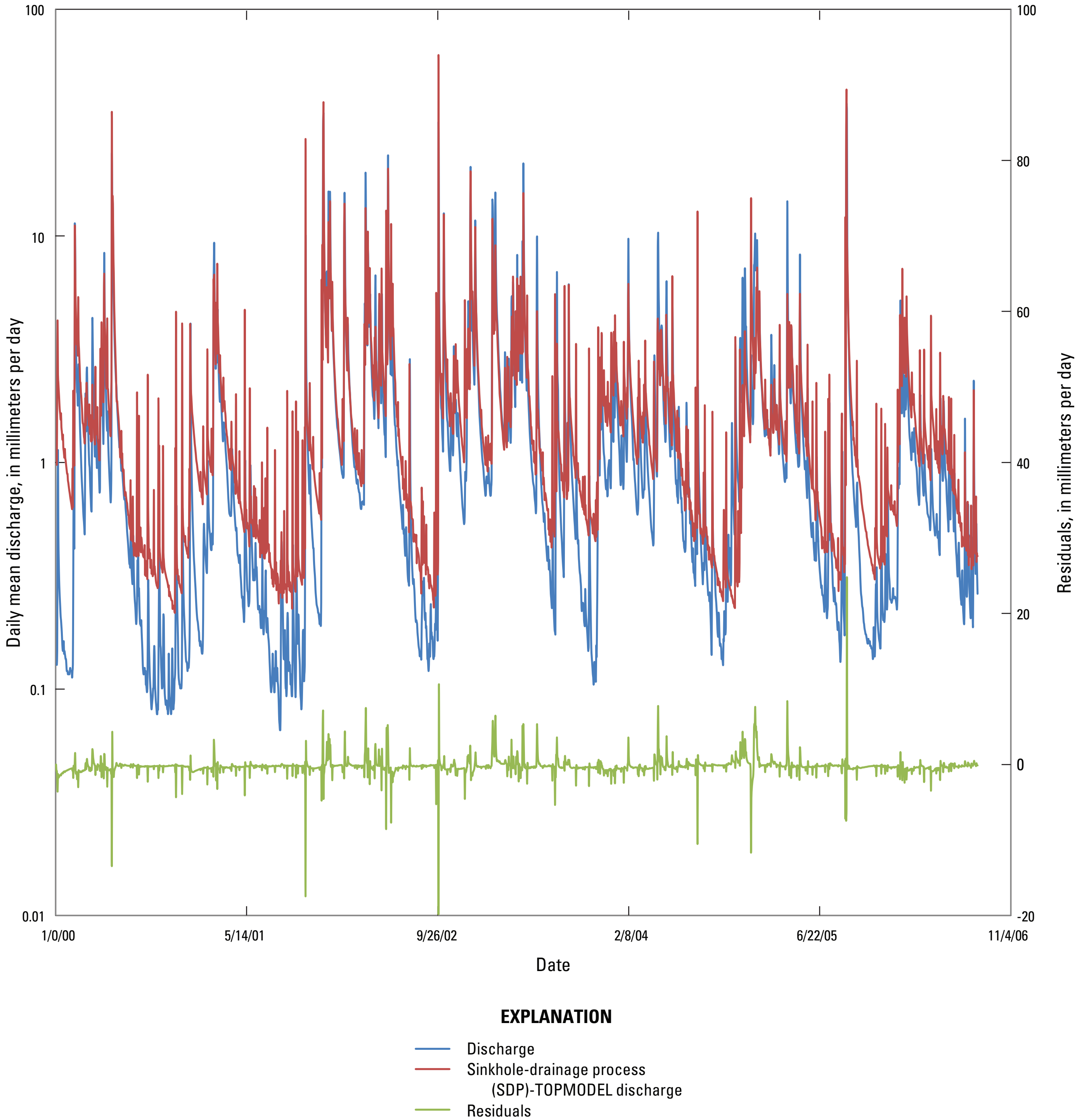

Figure 1–1. Observed versus simulated discharge and residuals for test basin 03252300.

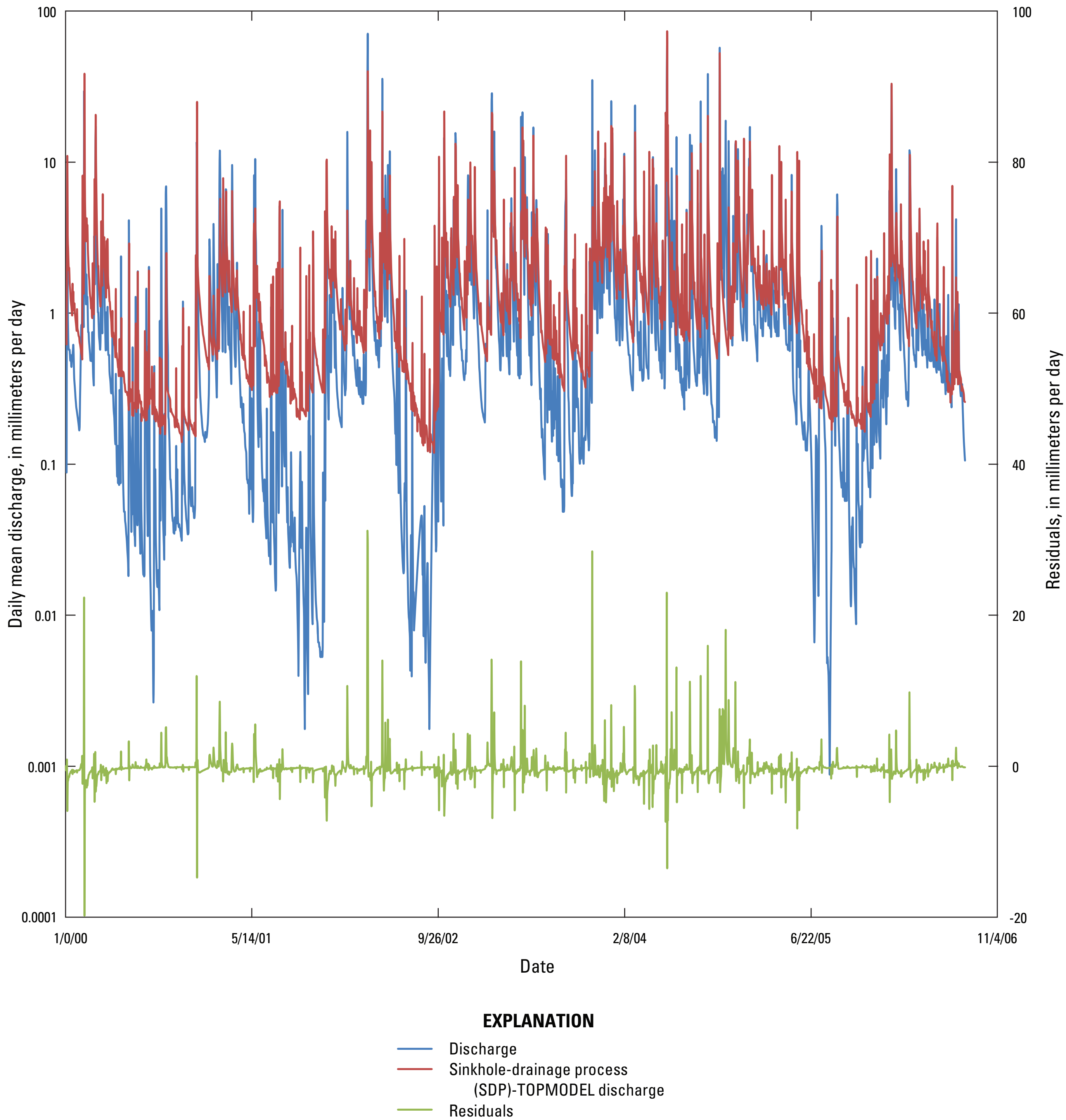

Figure 1–2. Observed versus simulated discharge and residuals for test basin 03289300.

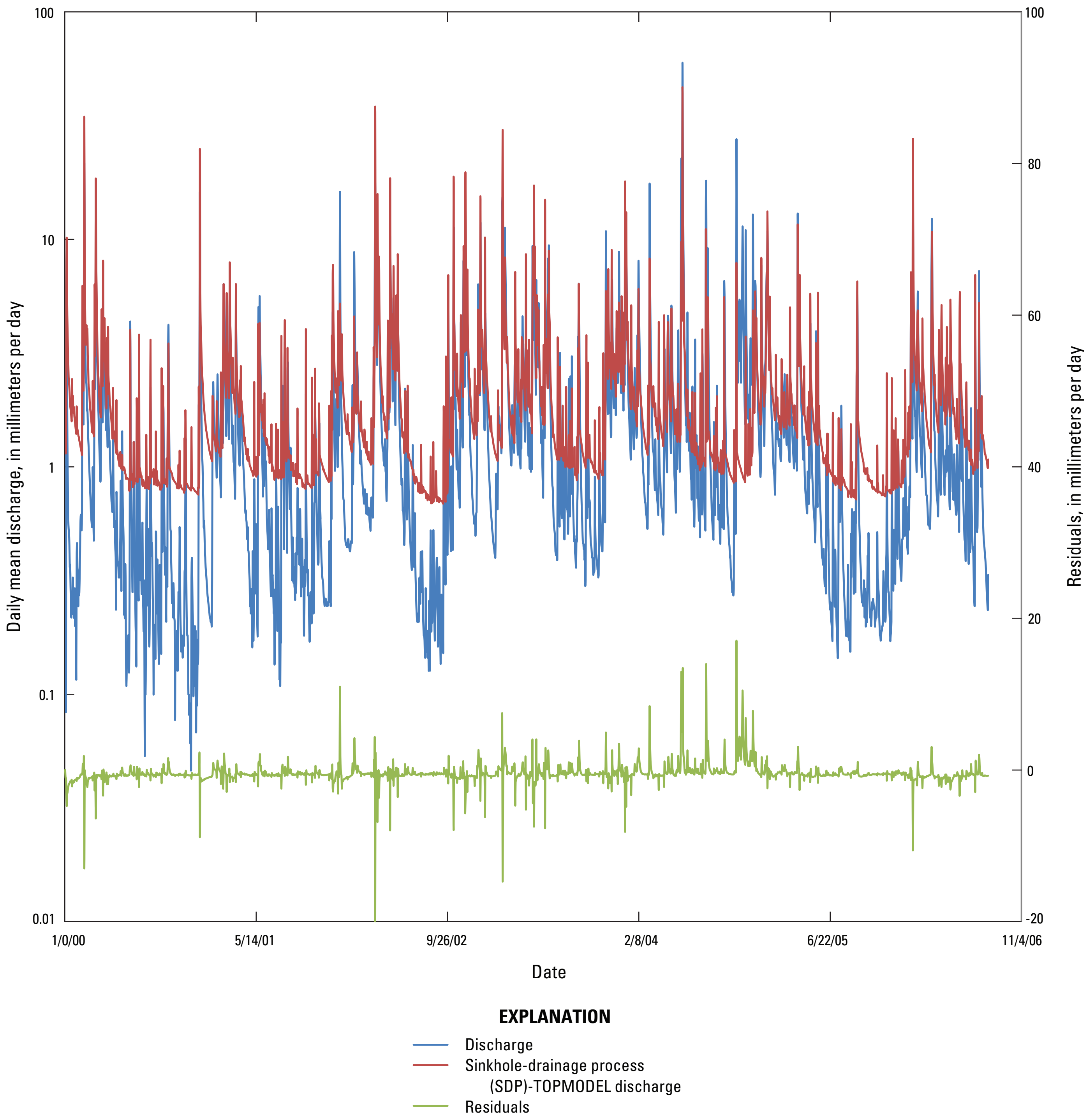

Figure 1–3. Observed versus simulated discharge and residuals for test basins 03289300.

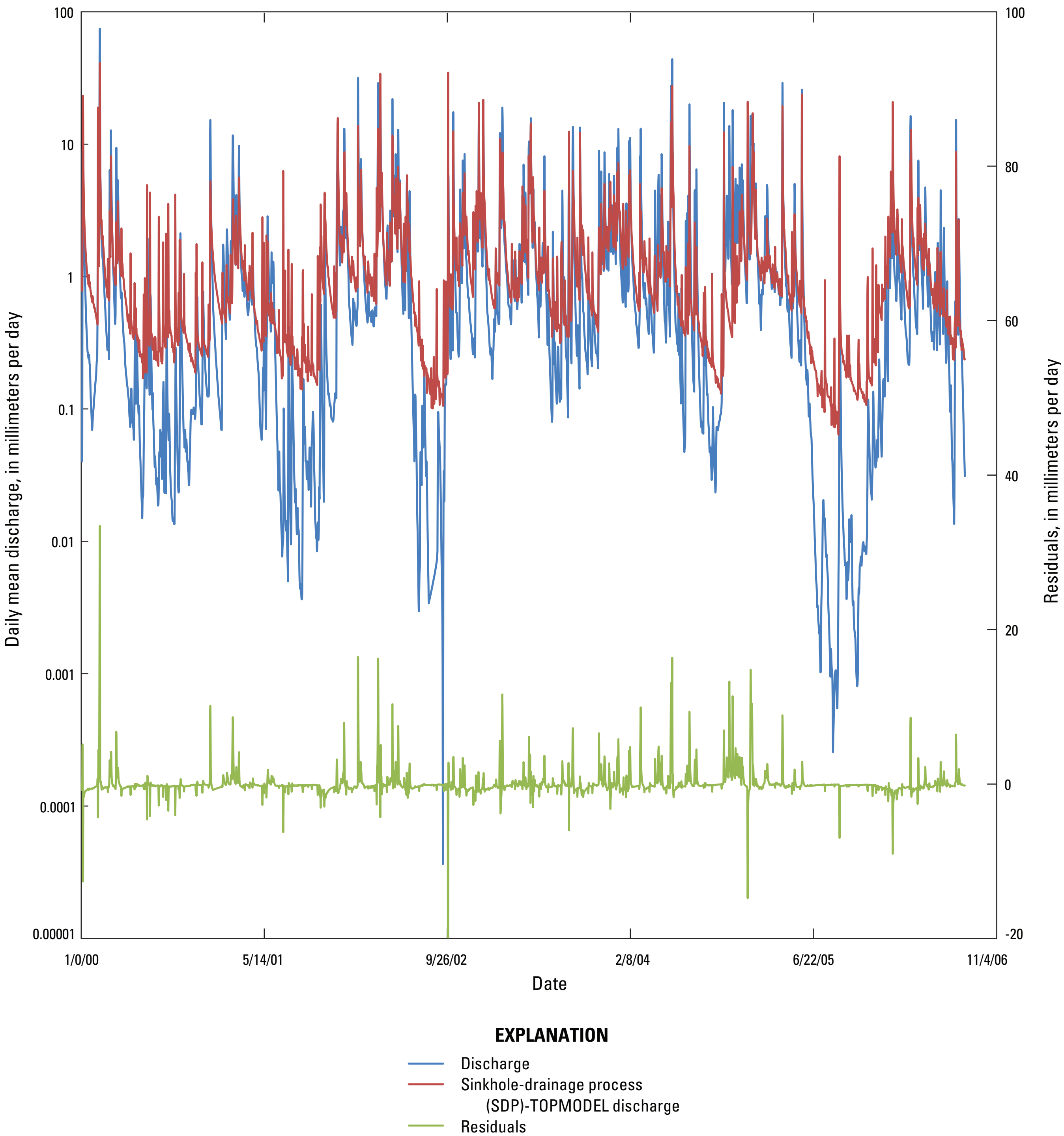

Figure 1–4. Observed versus simulated discharge and residuals for test basin 03292470.

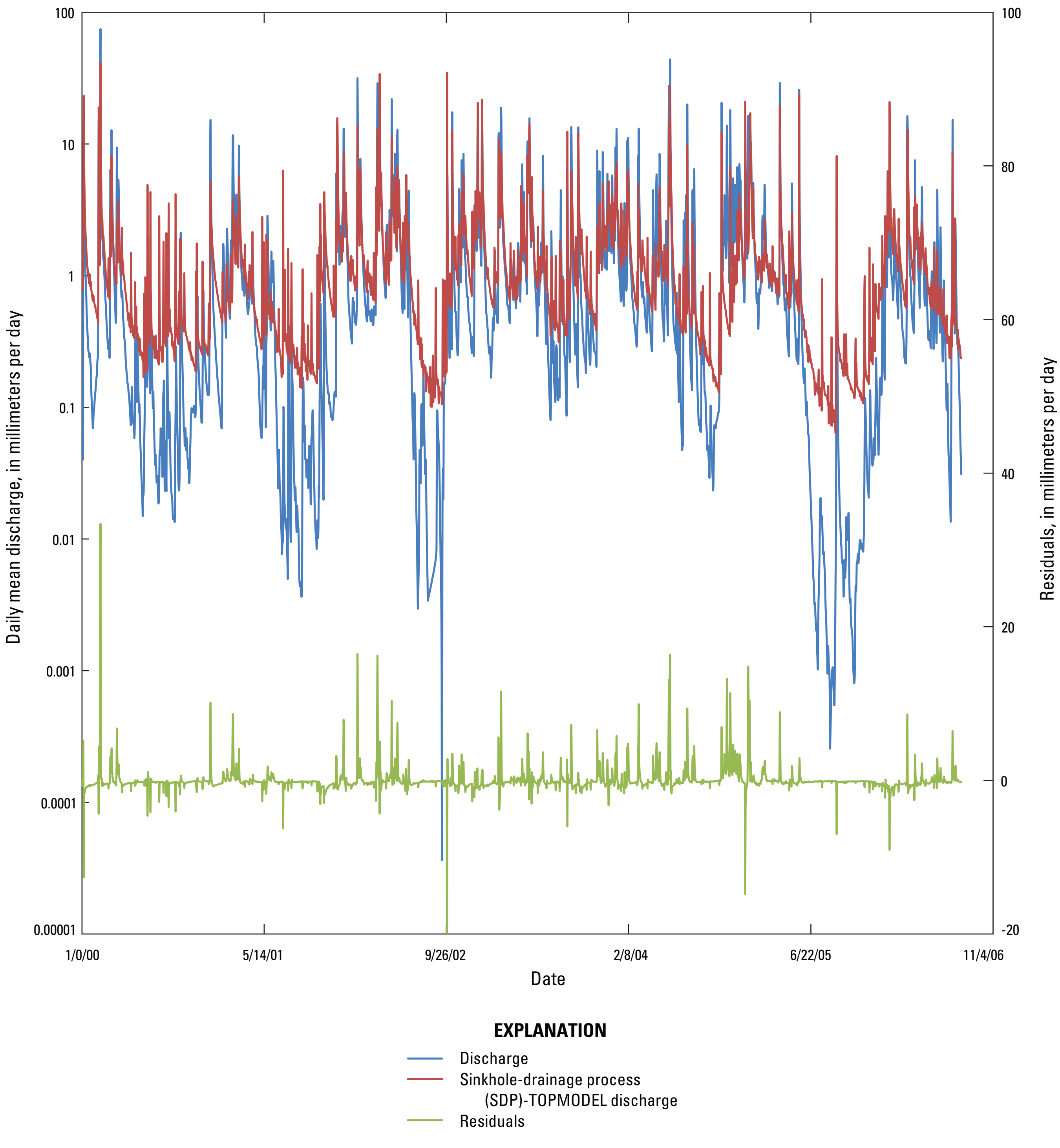

Figure 1–5. Observed versus simulated discharge and residuals for test basin 03295890.

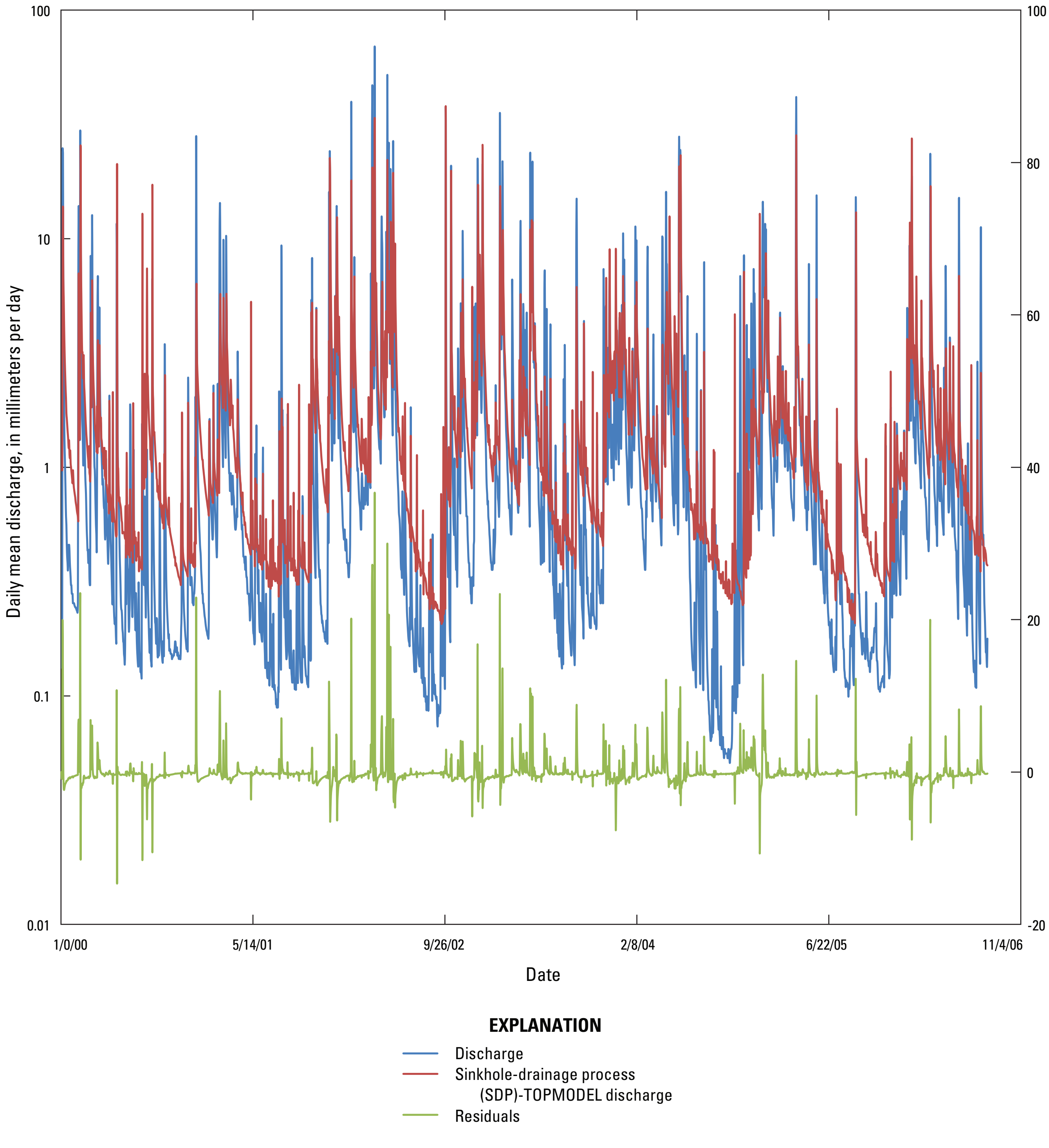

Figure 1–6. Observed versus simulated discharge and residuals for test basin 03301700.

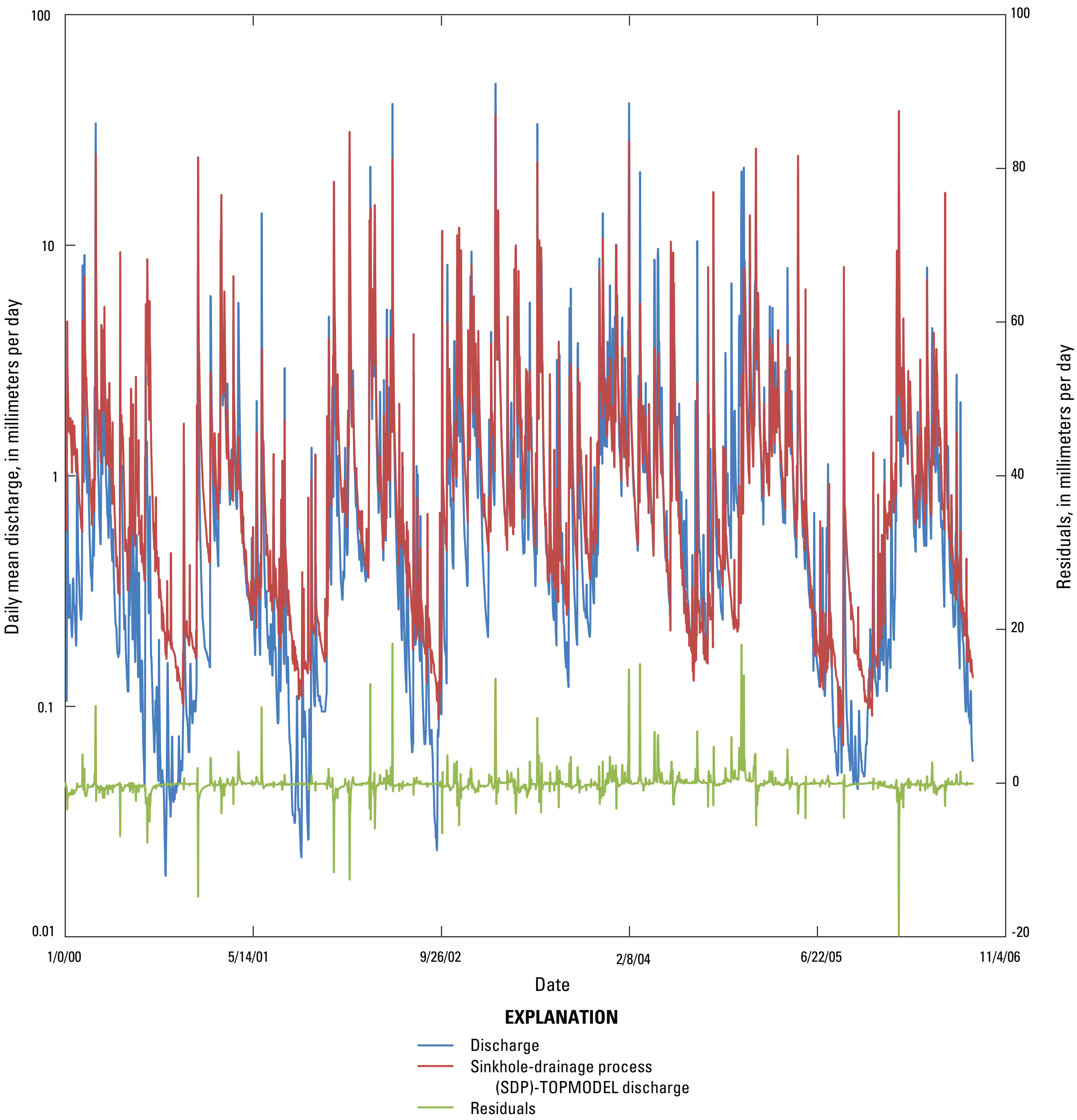

Figure 1–7. Observed versus simulated discharge and residuals for test basin 03307000.

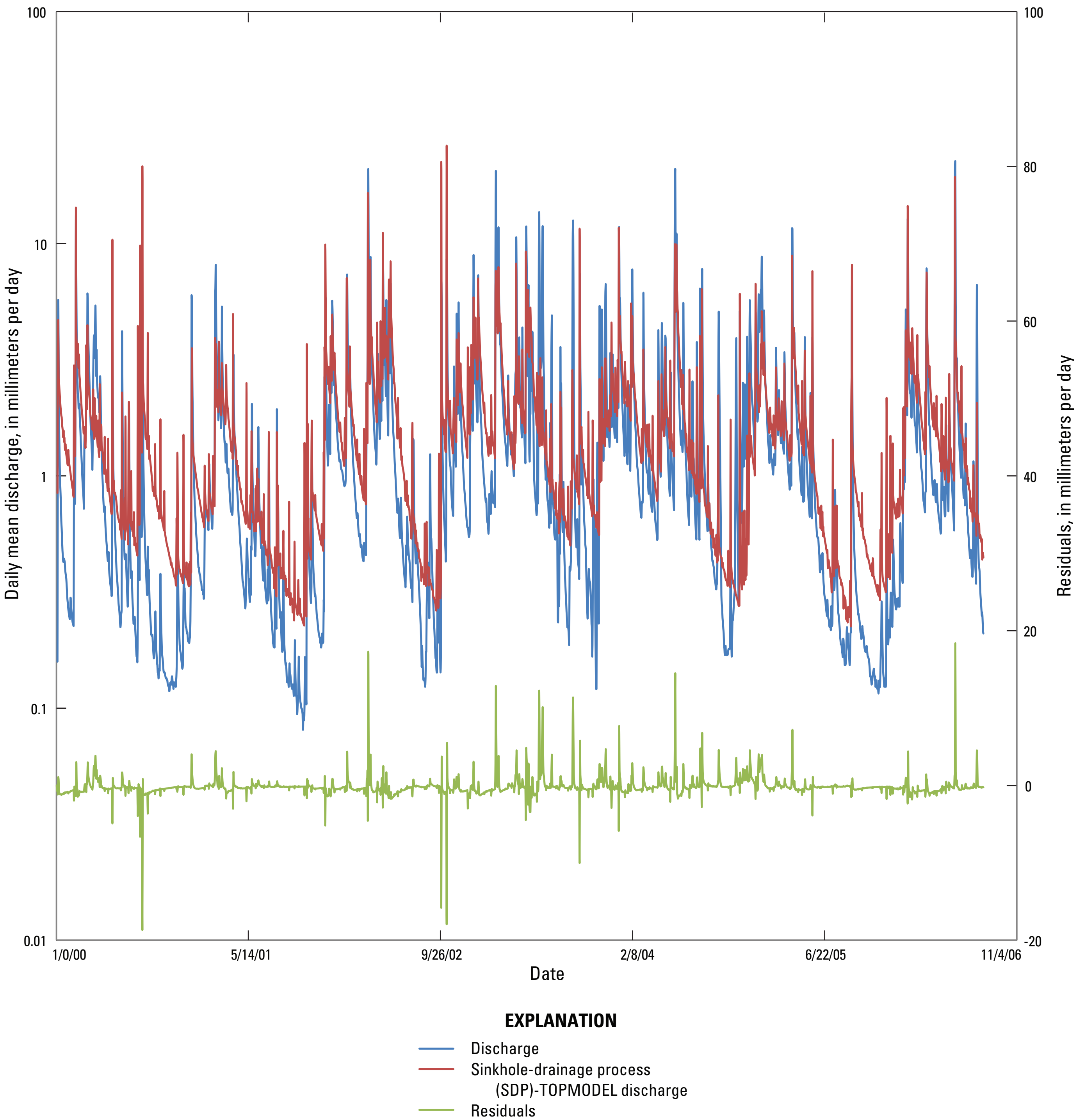

Figure 1–8. Observed versus simulated discharge and residuals for test basin 03310300.

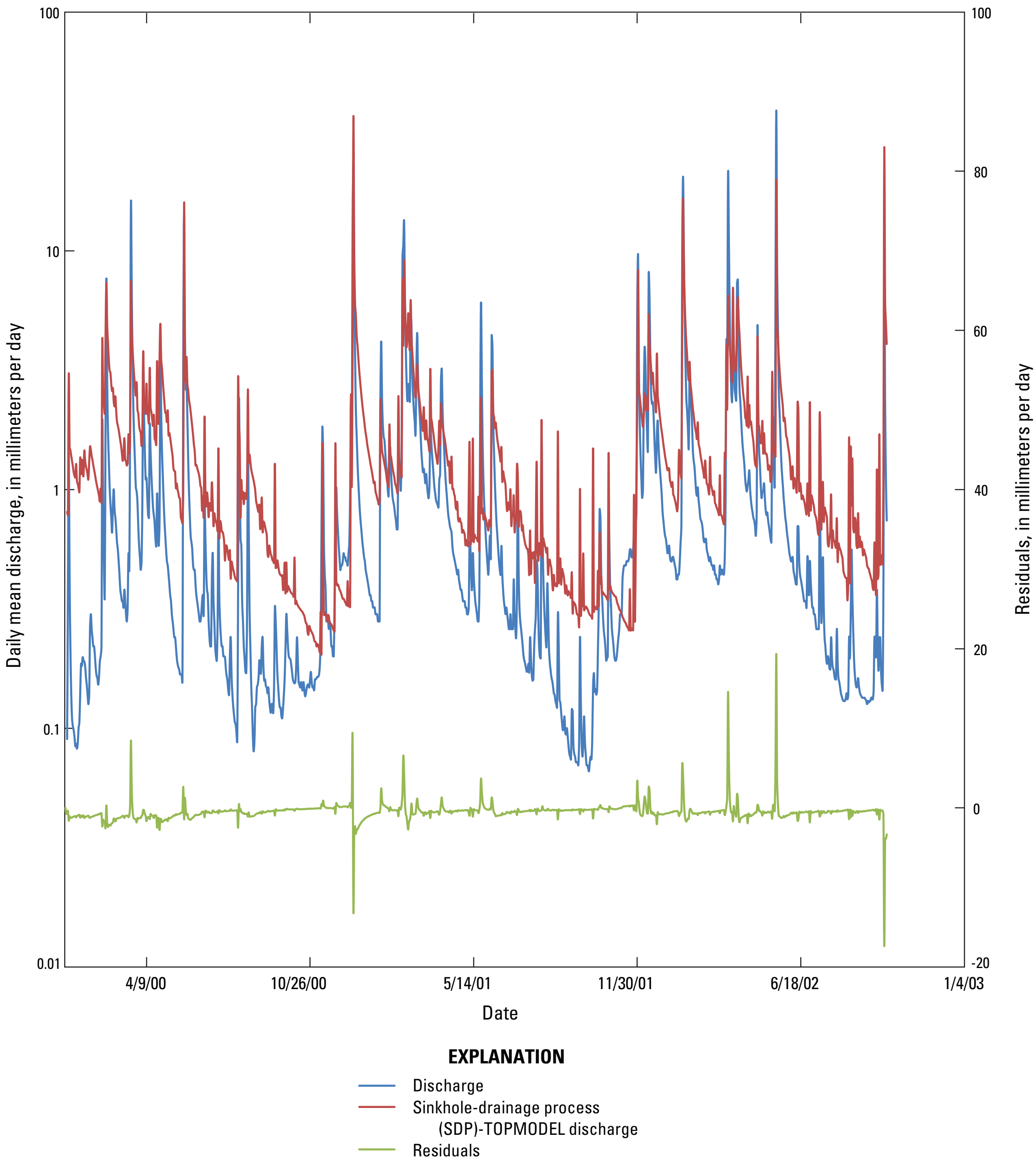

Figure 1–9. Observed versus simulated discharge and residuals for test basin 03312765.

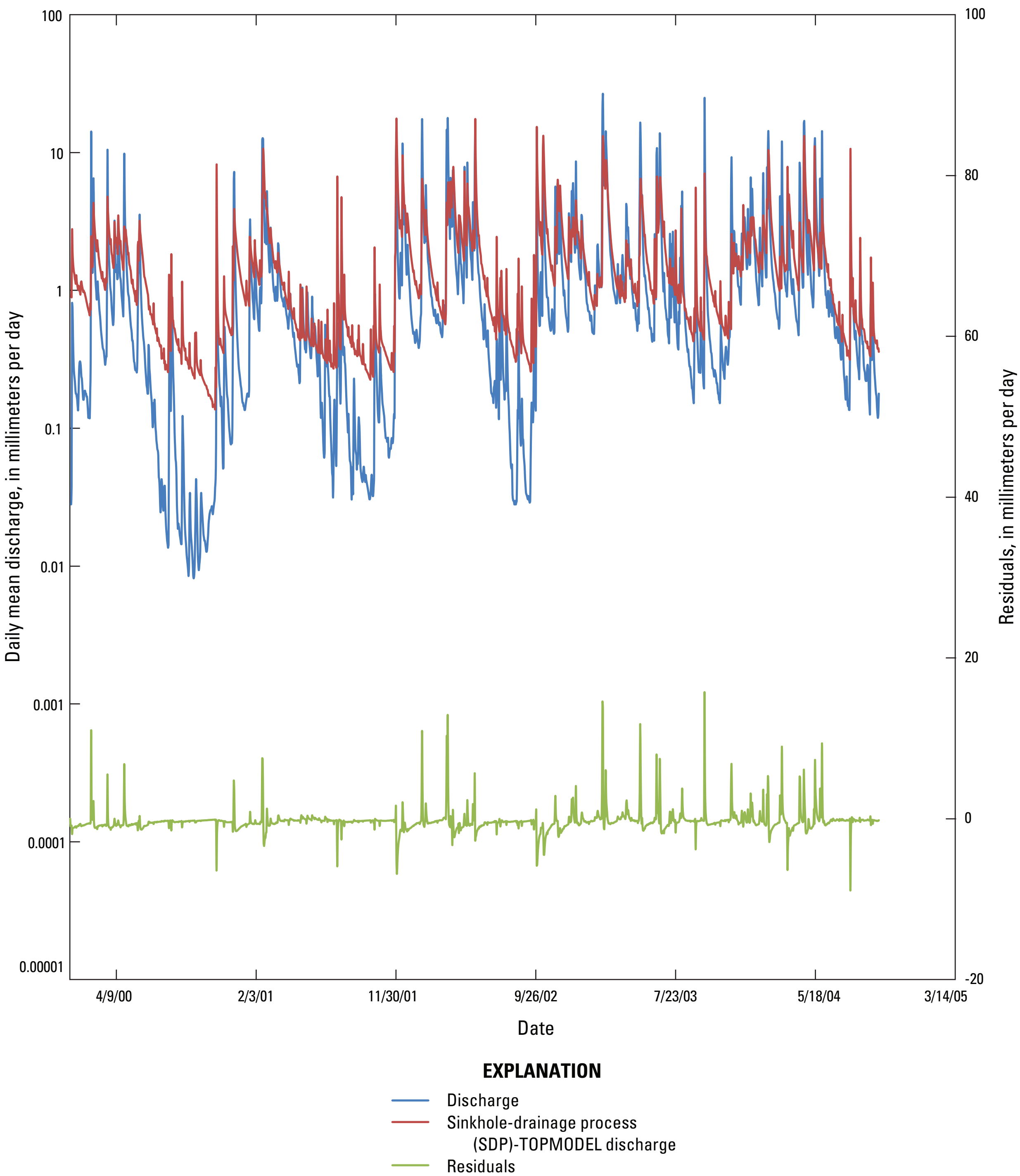

Figure 1–10. Observed versus simulated discharge and residuals for test basin 03313700.

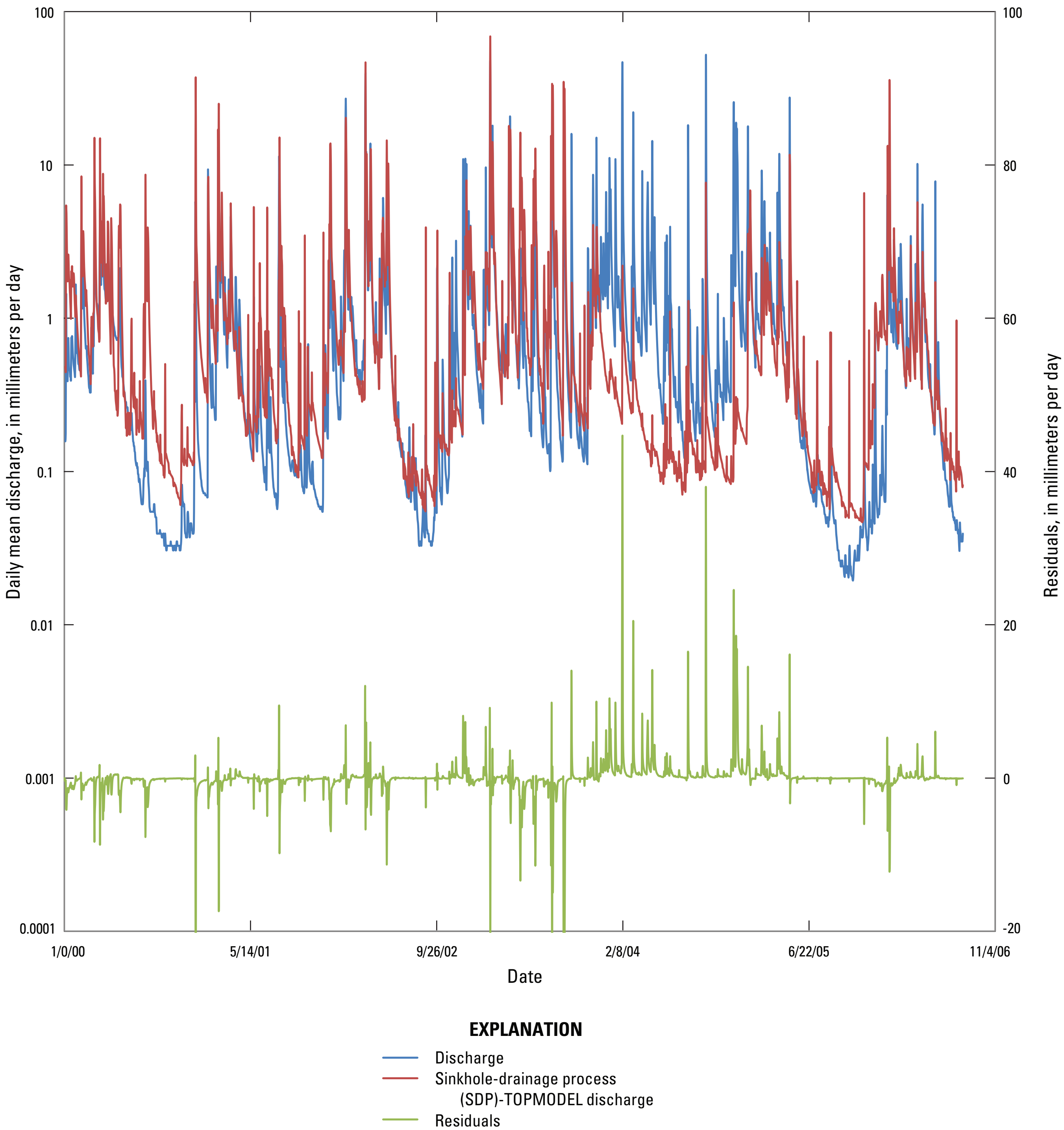

Figure 1–11. Observed versus simulated discharge and residuals for test basin 03433200.

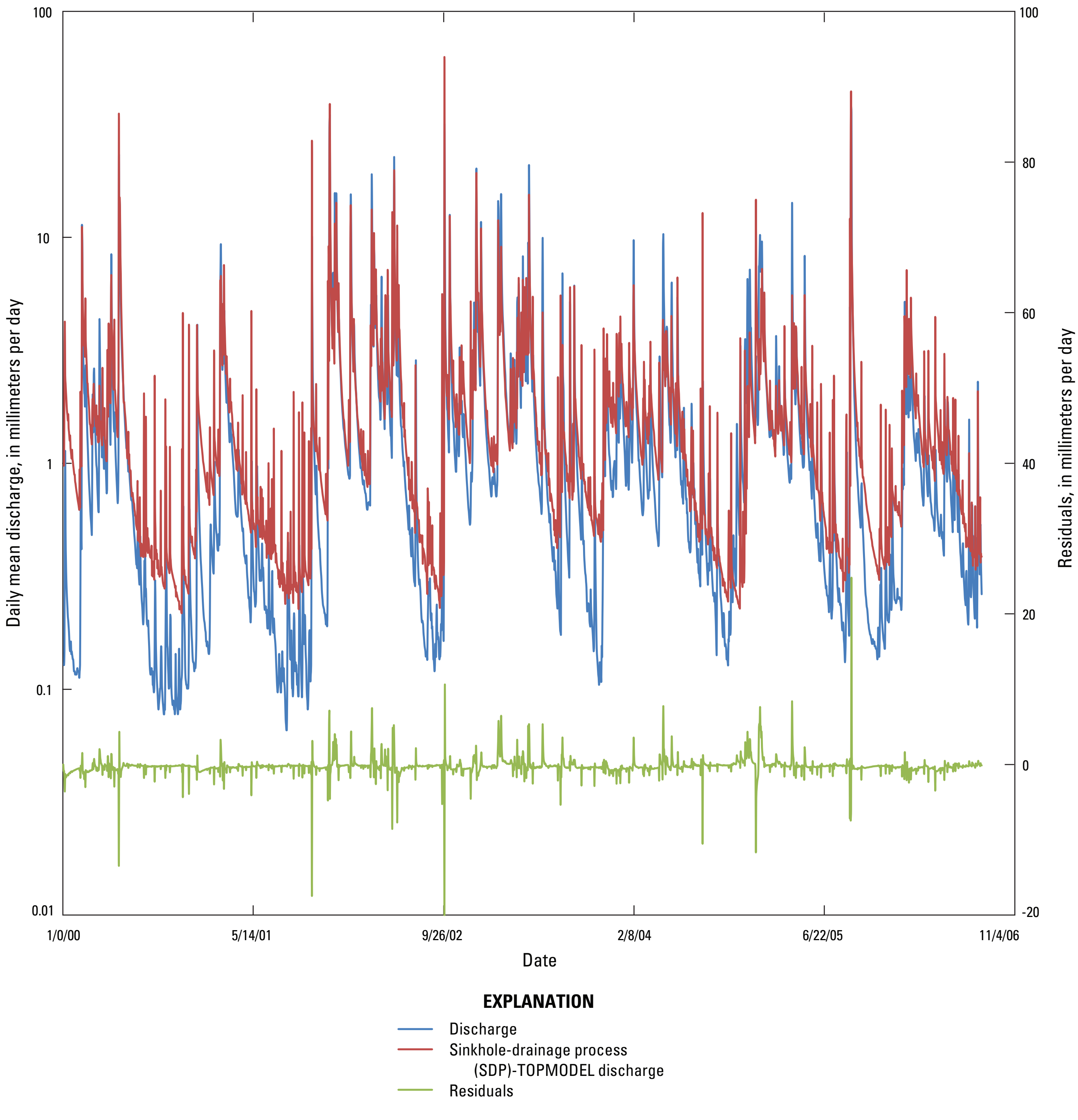

Figure 1–12. Observed versus simulated discharge and residuals for test basin 03438000.

Appendix 2. Flow-duration curves showing simulated versus observed discharge for the 12 karst test basins used in the study.

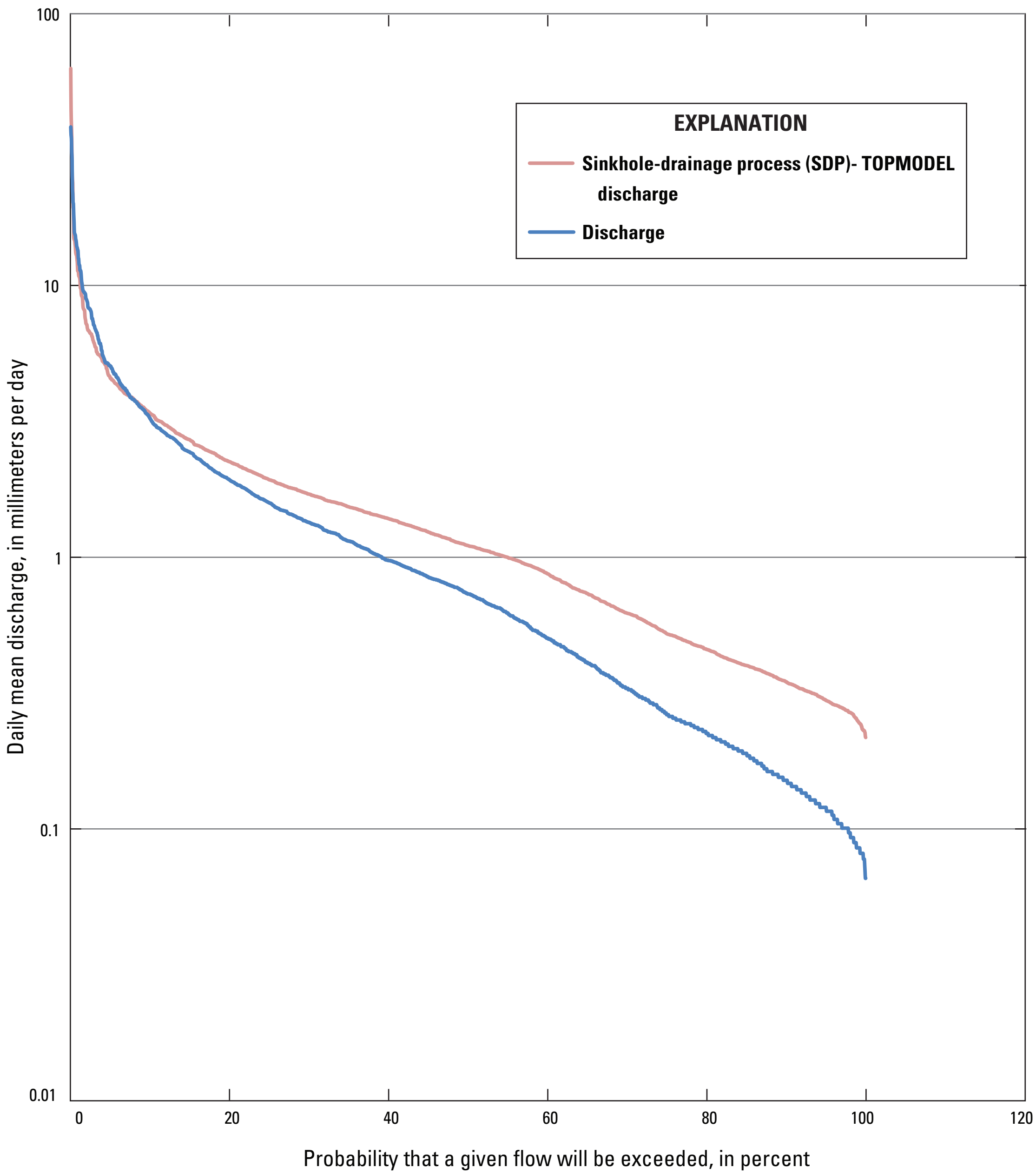

Figure 2–1. Flow-duration curves showing simulated versus observed discharge for test basin 03252300.

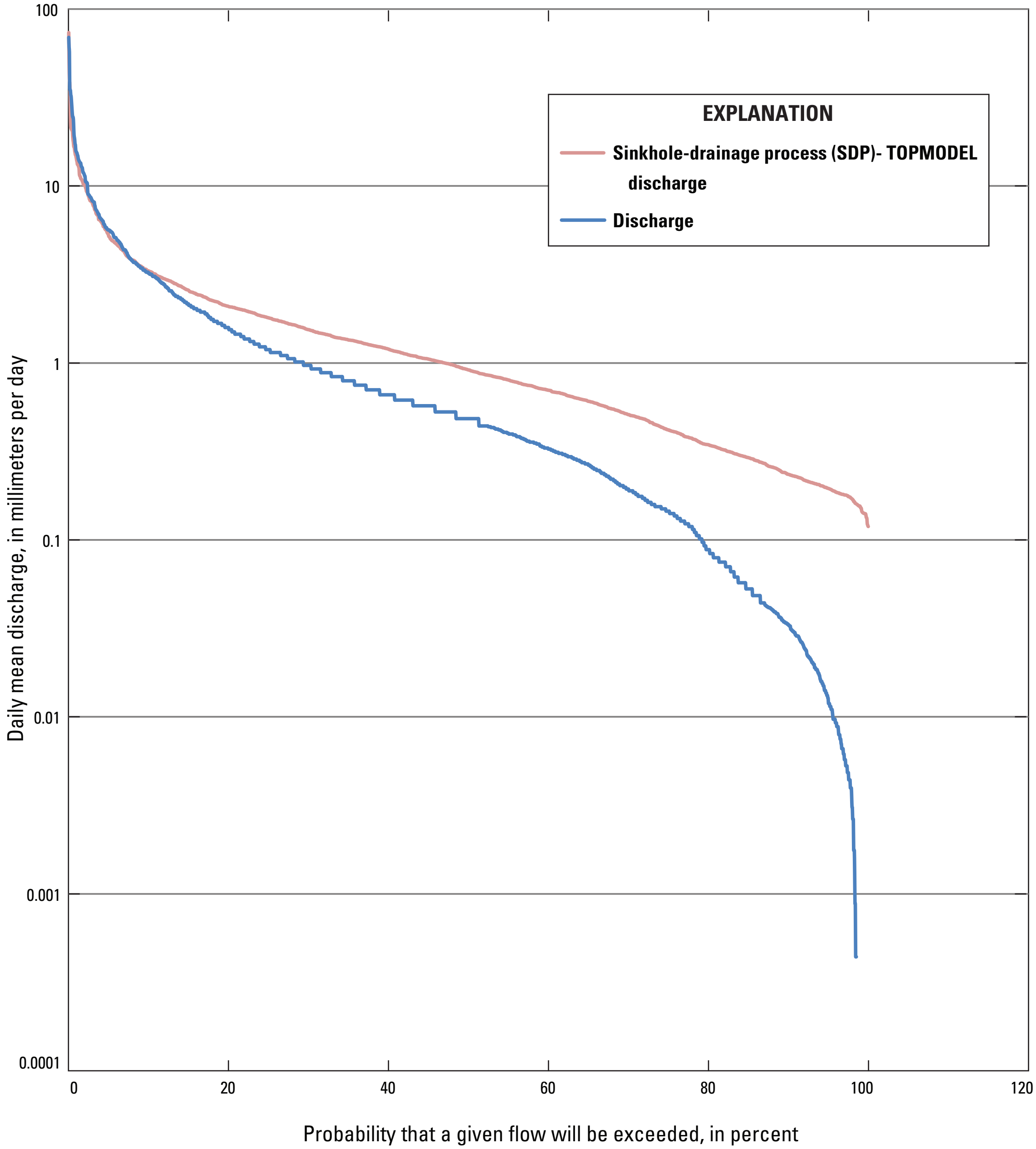

Figure 2–2. Flow-duration curves showing simulated versus observed discharge for test basin 03287600.

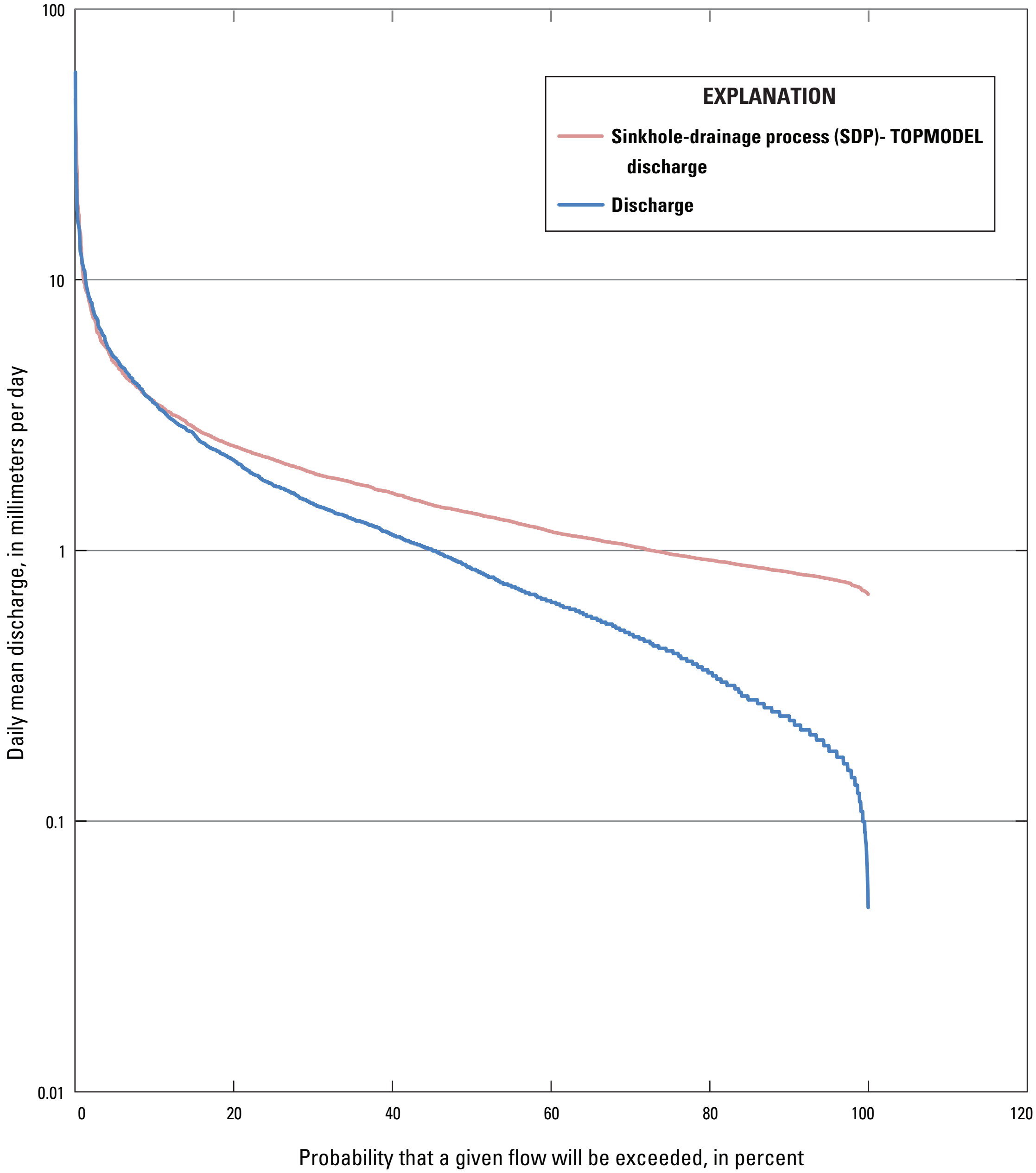

Figure 2–3. Flow-duration curves showing simulated versus observed discharge for test basin 03289300.

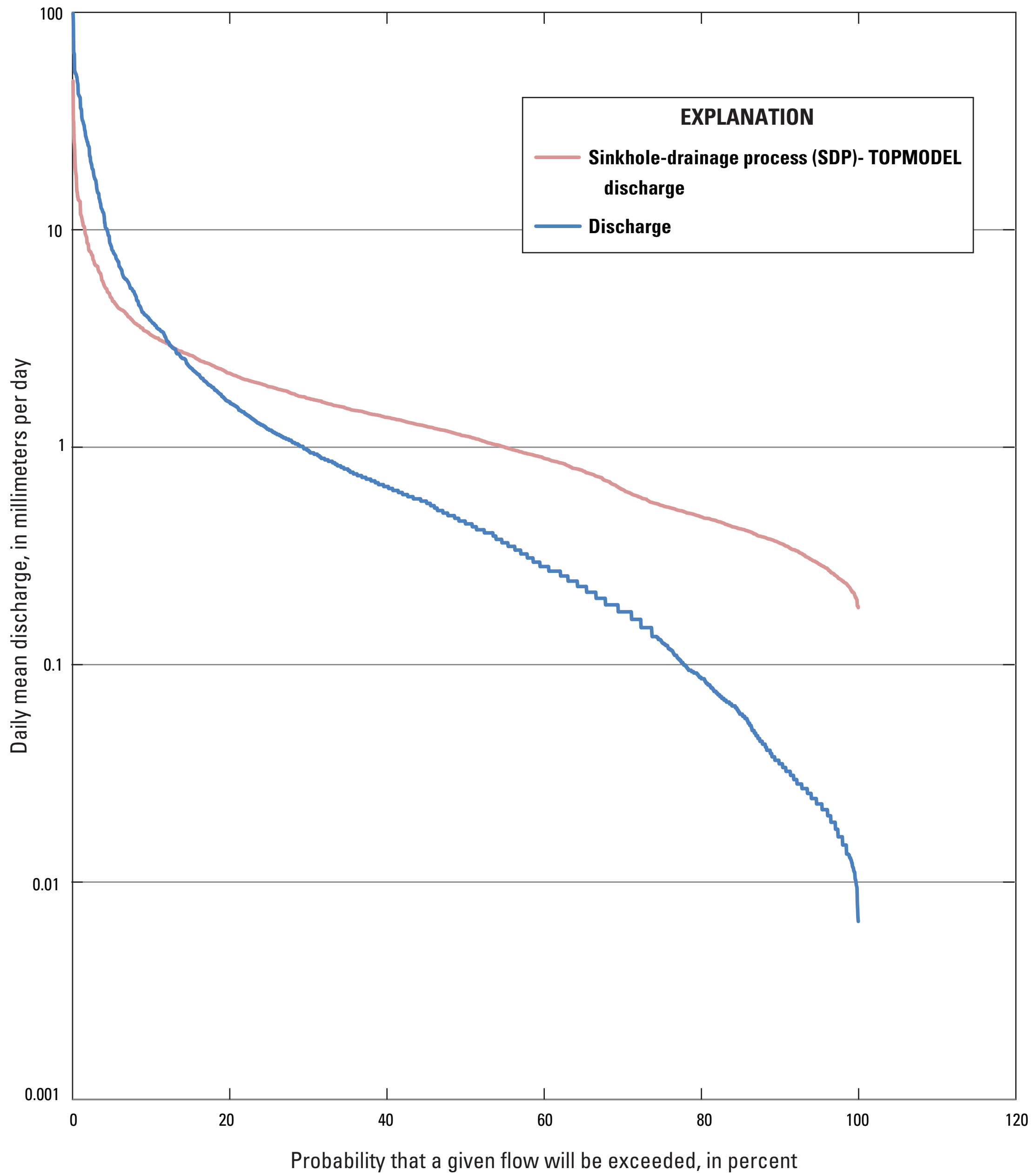

Figure 2-4. Flow-duration curves showing simulated versus observed discharge for test basin 03292470–

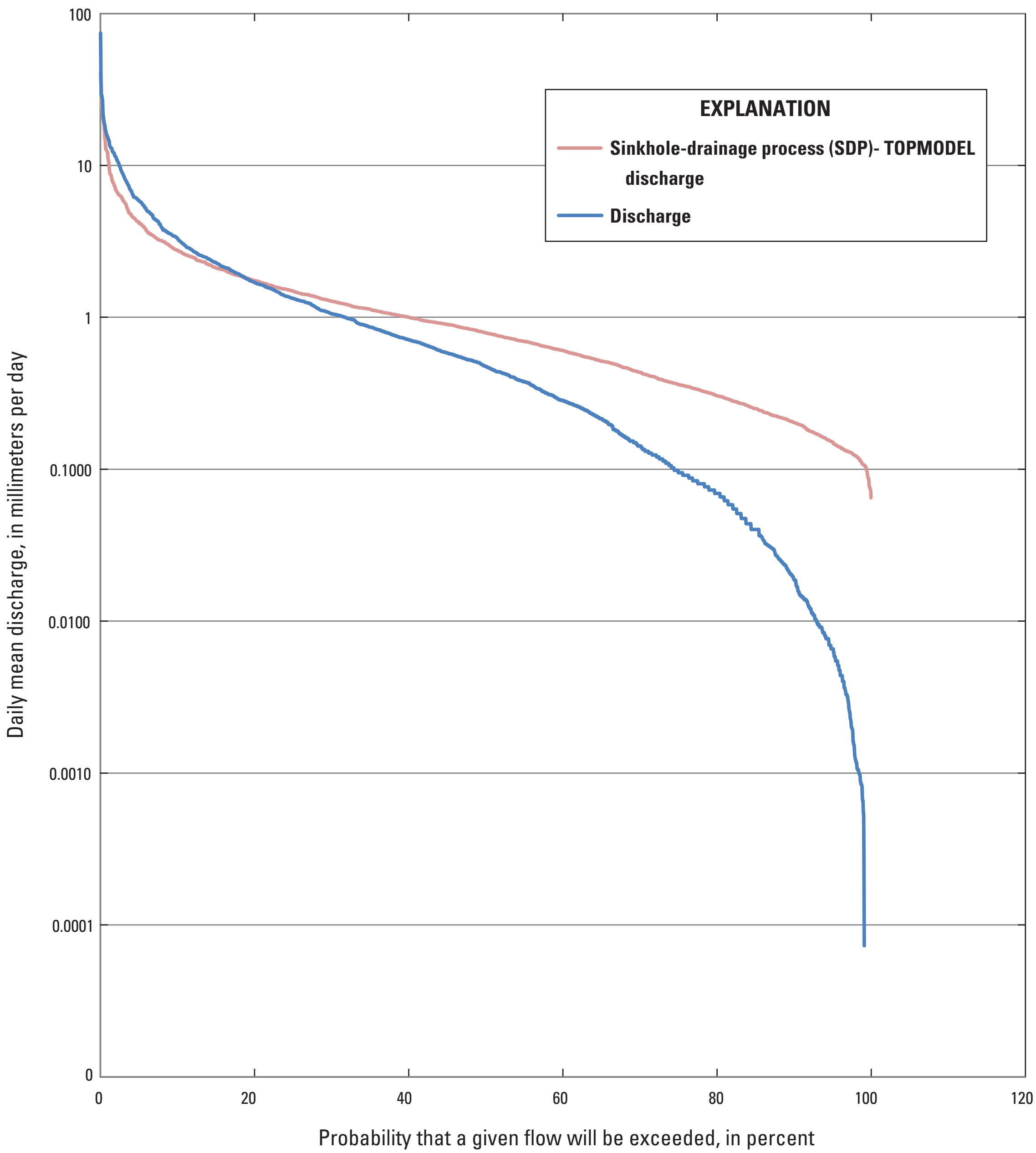

Figure 2–5. Flow-duration curves showing simulated versus observed discharge for test basin 03295890.

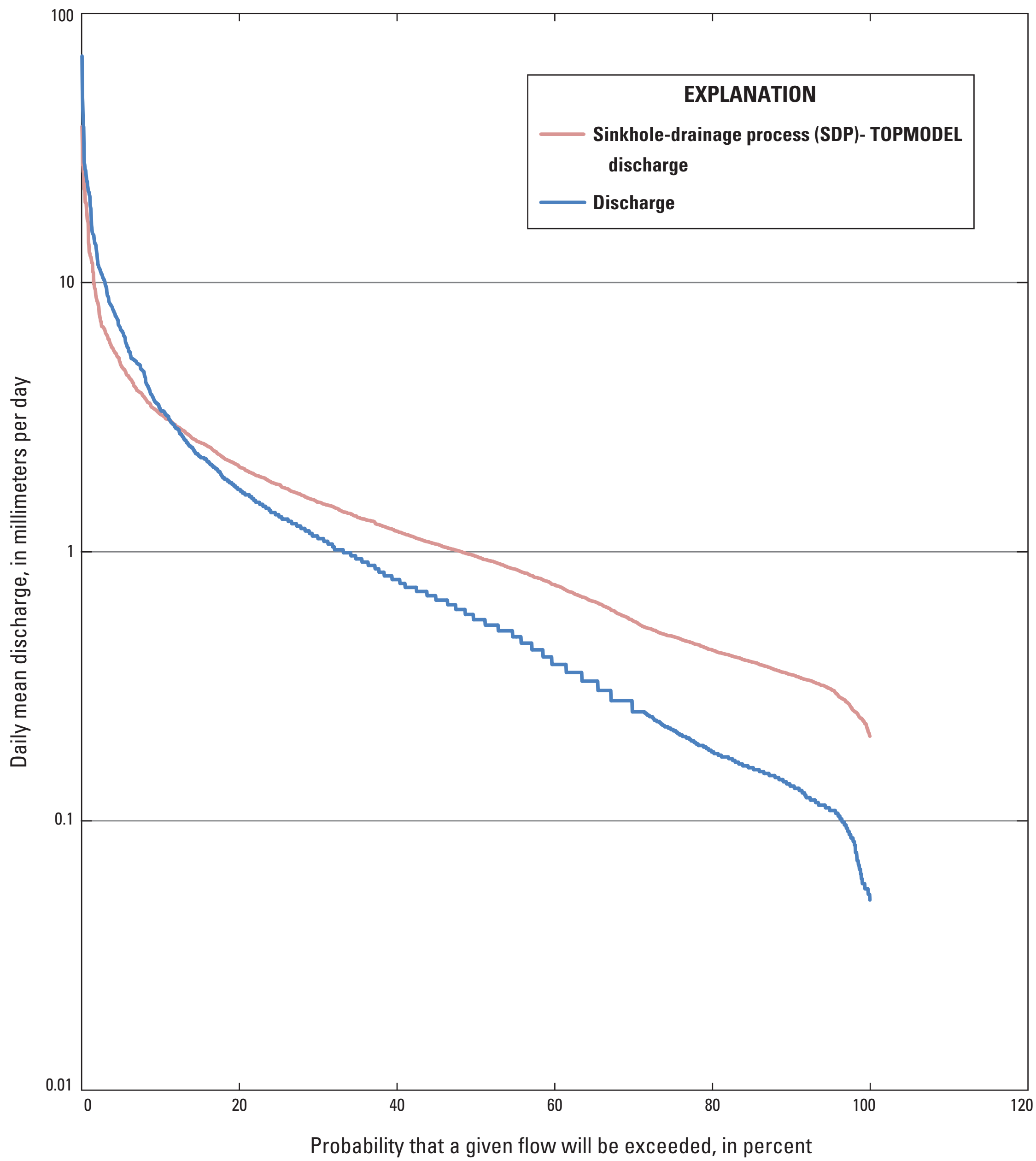

Figure 2–6. Flow-duration curves showing simulated versus observed discharge for test basin 03301700.

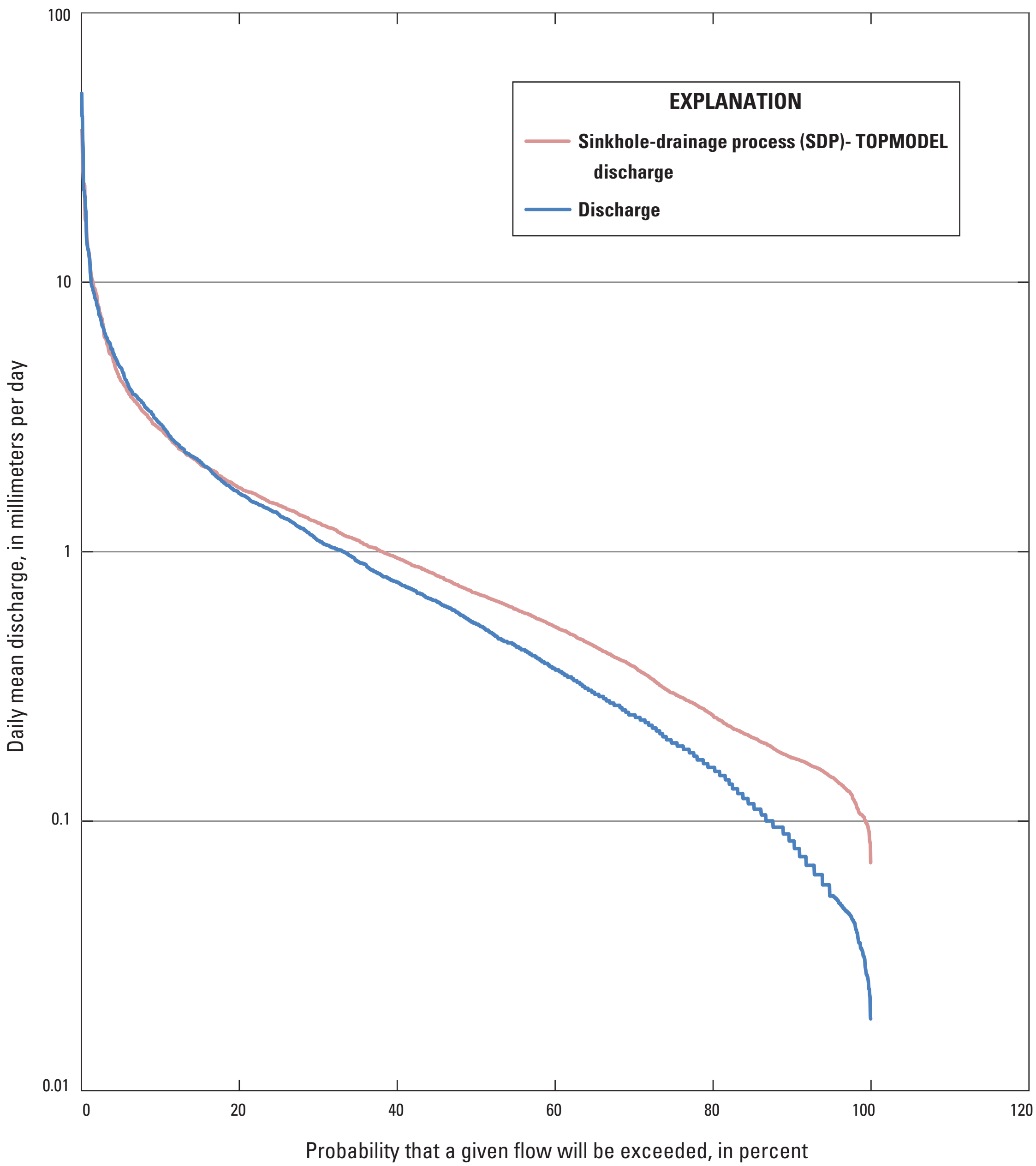

Figure 2–7. Flow-duration curves showing simulated versus observed discharge for test basin 03310300.

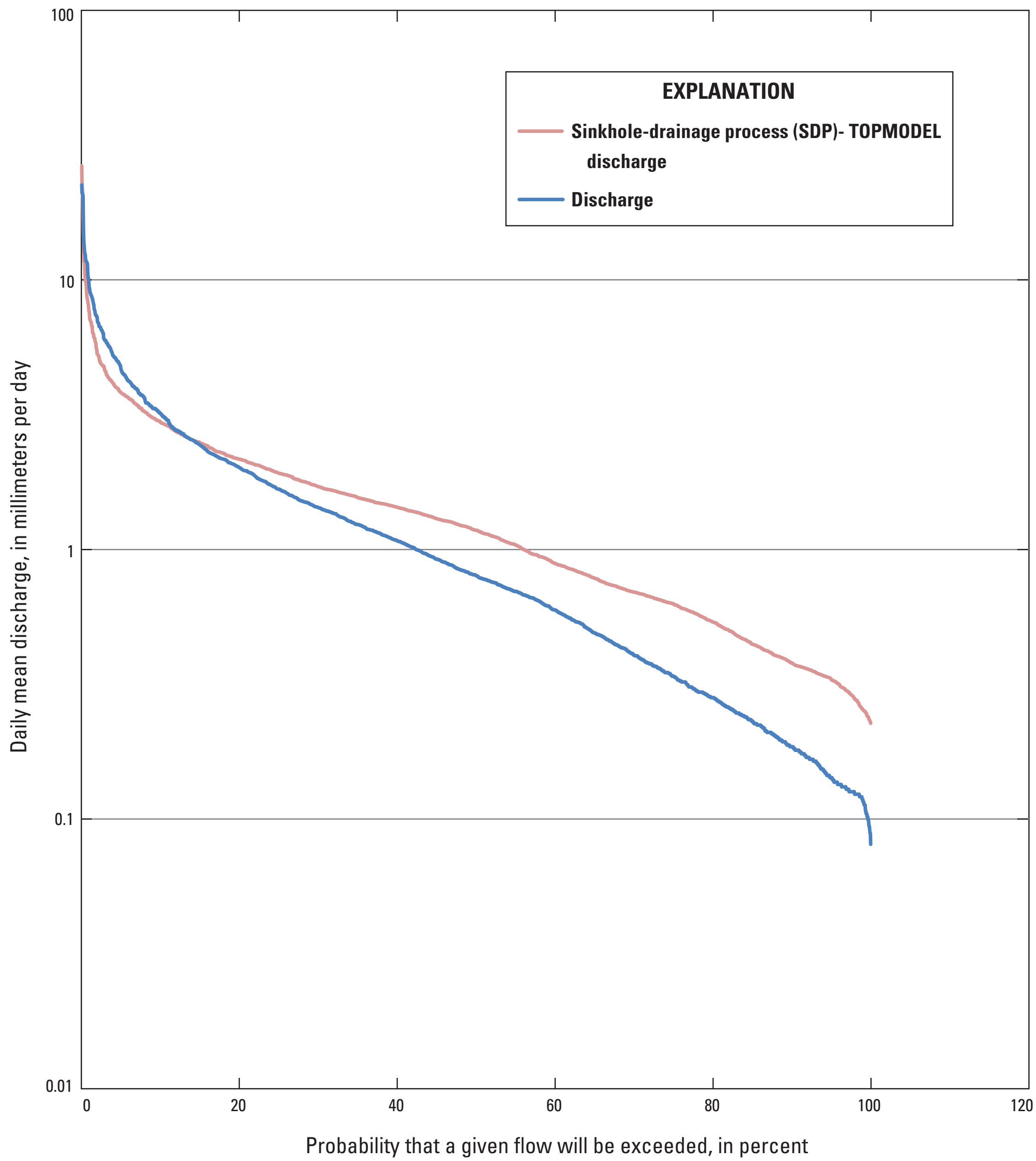

Figure 2–8. Flow-duration curves showing simulated versus observed discharge for test basin 03310300.

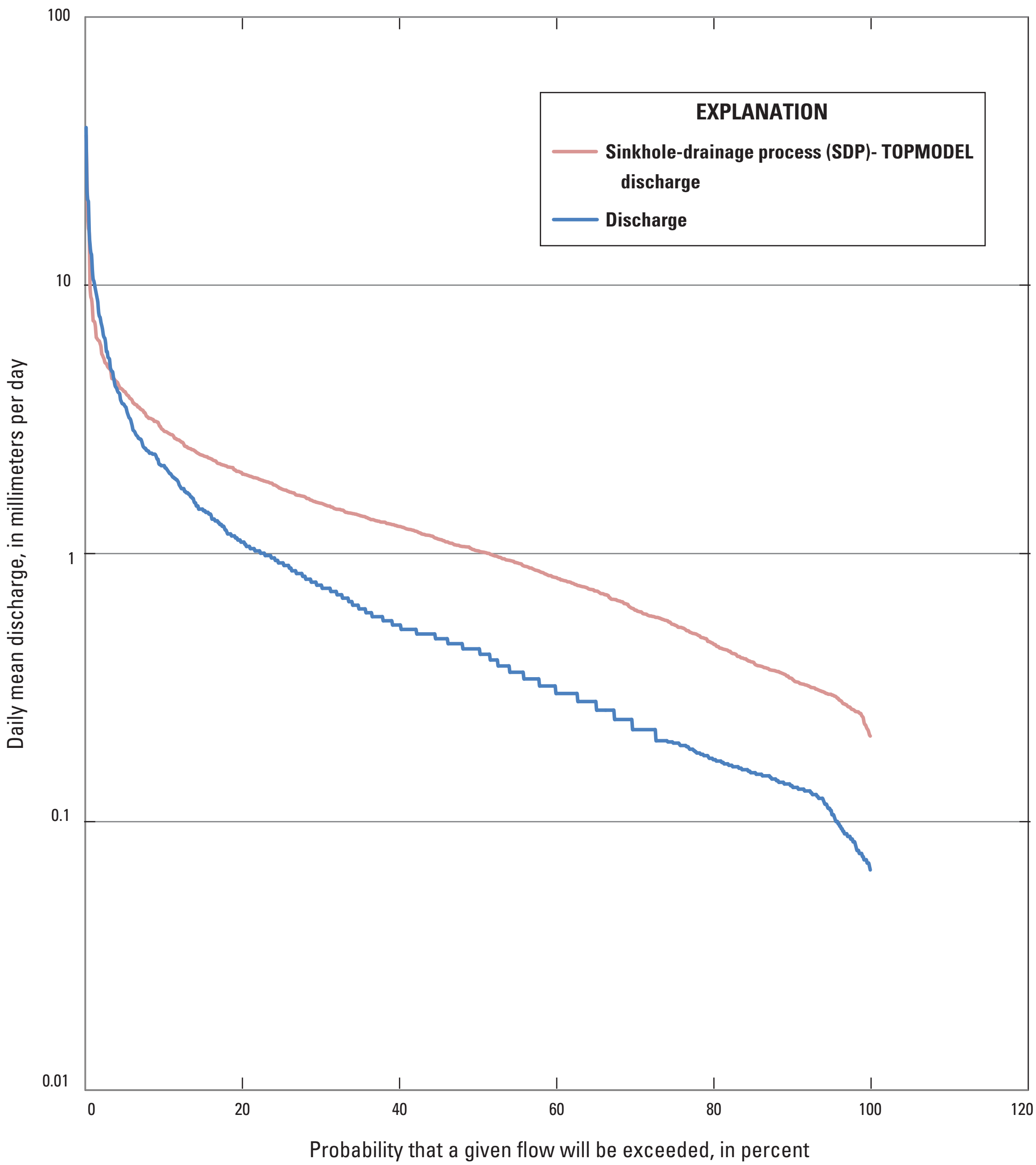

Figure 2–9. Flow-duration curves showing simulated versus observed discharge for test basin 03312765.

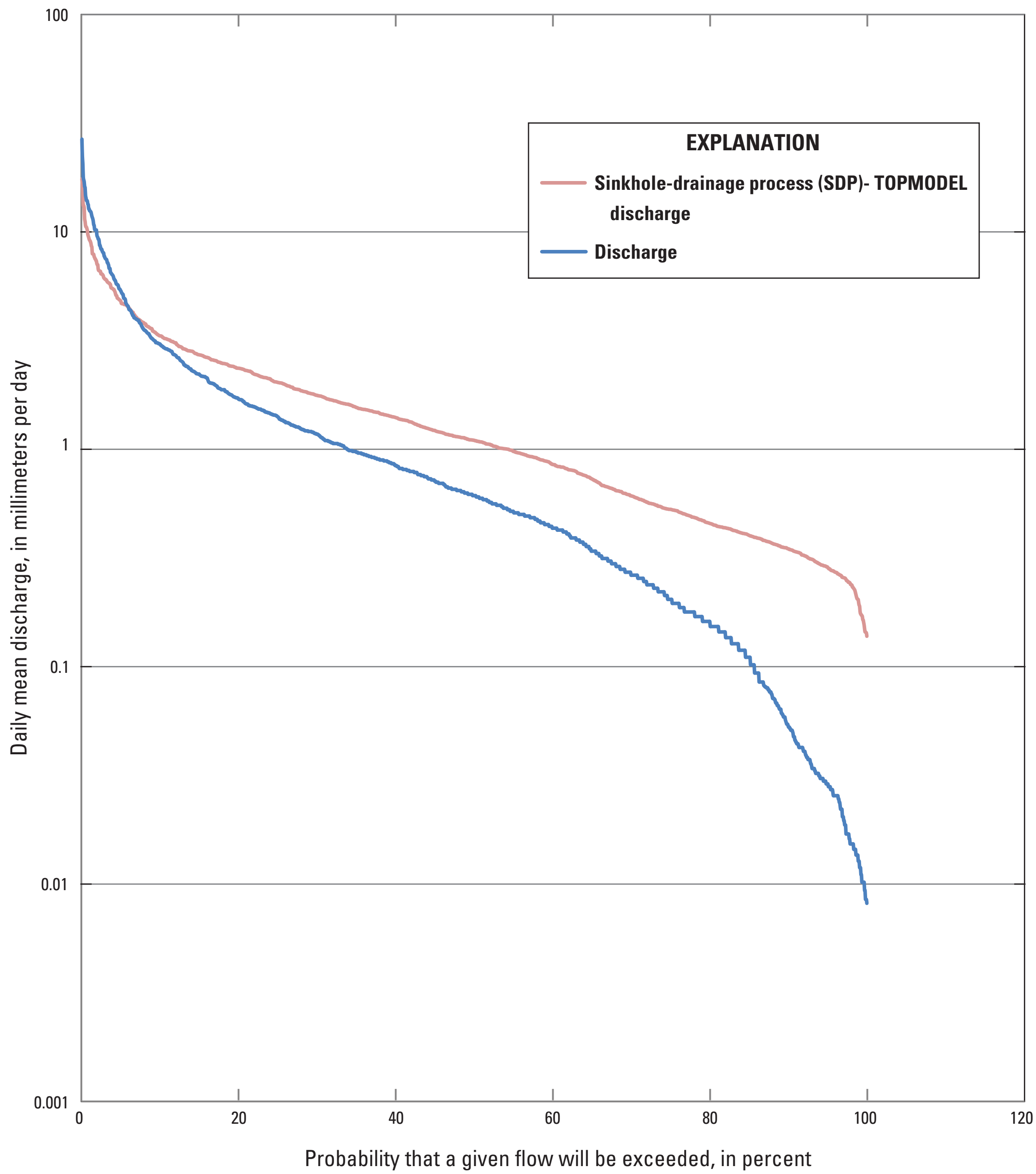

Figure 2–10. Flow-duration curves showing simulated versus observed discharge for test basin 03313700.

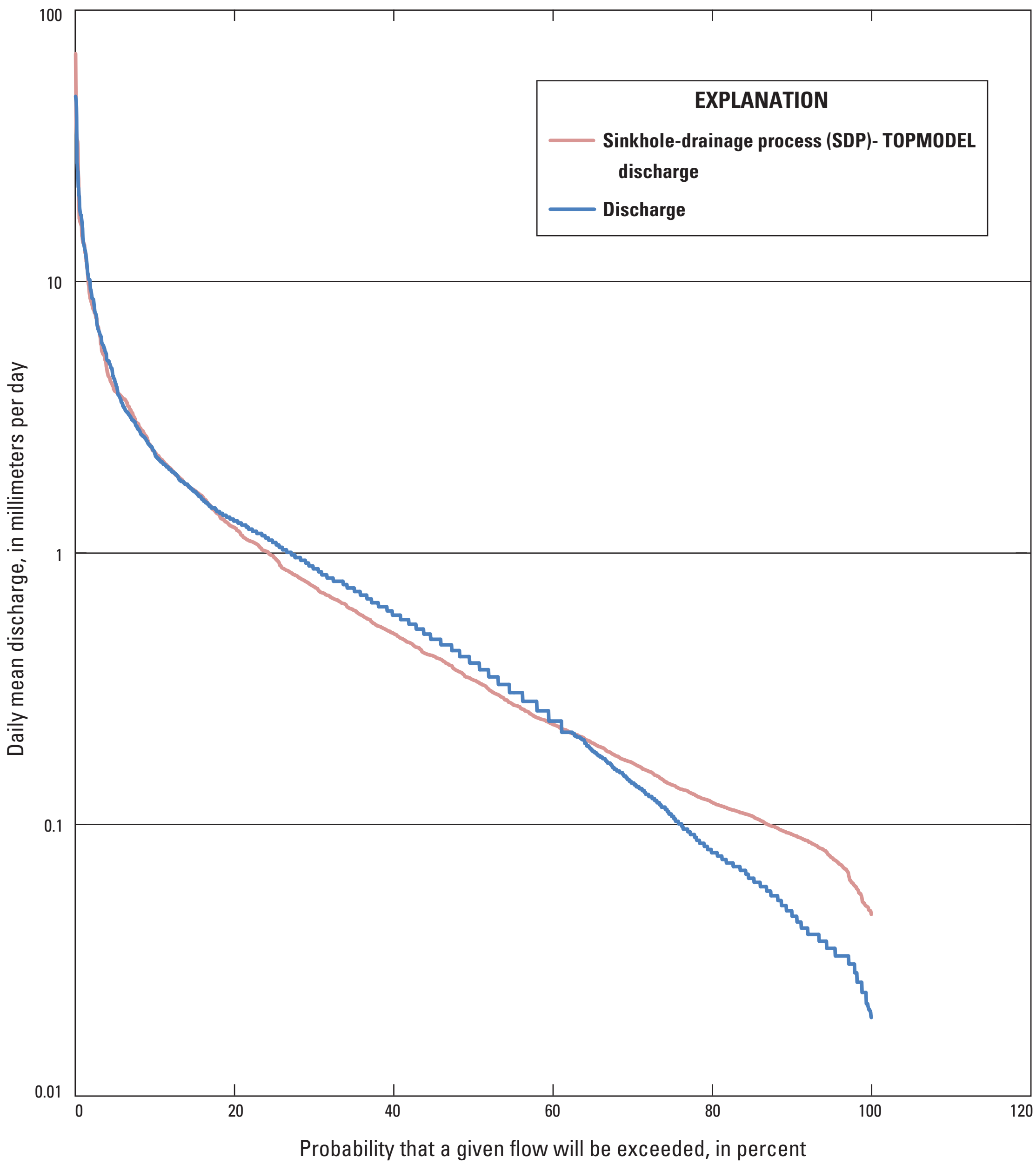

Figure 2–11. Flow-duration curves showing simulated versus observed discharge for test basin 03413200.

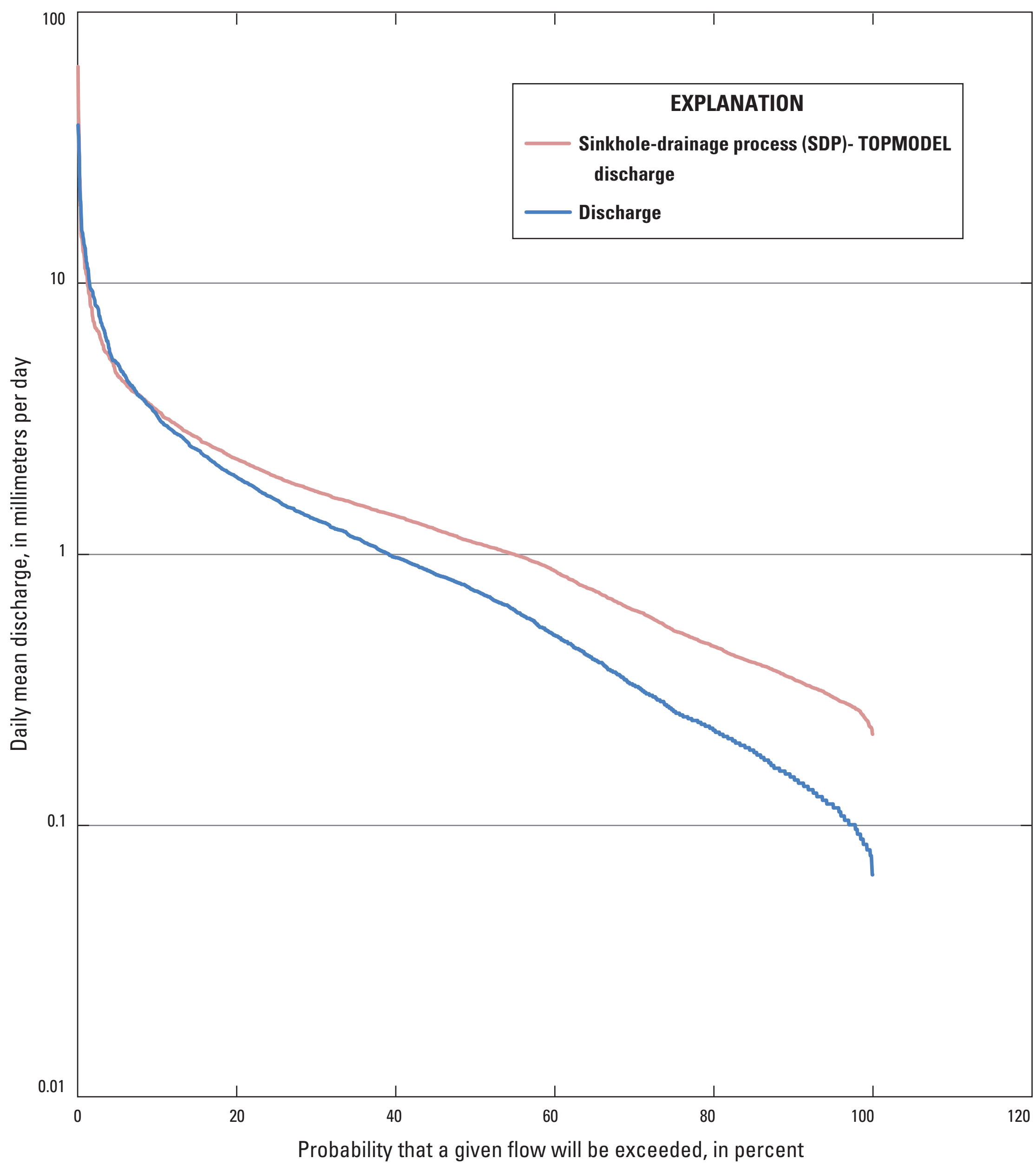

Figure 2–12. Flow-duration curves showing simulated versus observed discharge for test basin 03438000.

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Taylor and others—**Phase II Modification of the Water Availability Tool for Environmental Resources (WATER) for Kentucky**—Scientific Investigations Report 2012–5071