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Hydrologic Model of the Vermilion River Watershed for Streamflow Simulations

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Abstract

In continuation of the efforts made by the Illinois State Water Survey to develop a detailed hydrologic and water quality simulation model of the entire Illinois River Basin, a hydrologic simulation model was developed for the Vermilion River Watershed (one of the major tributaries of the Illinois River) to simulate streamflows using available climatic data. The model was developed using Hydrologic Simulation Program – FORTRAN (HSPF, version 12) under the BASINS (Better Assessment Science Integrating Point and Nonpoint Sources, version 3.0)**,** a multipurpose environmental analysis system developed by the U.S. Environmental Protection Agency (USEPA). The watershed was sub-divided into 25 smaller, hydrologically connected sub-watersheds and their stream reaches. Hydrologic Response Units (HRUs) were created within each sub-watershed based on landuse and hydrologic soil groups. Streamflow data from two USGS streamflow gaging staions in the watershed and climate data from six representative staions for 1970-1995 was used. Model was calibrated using data for 1987-95 at the USGS gage at Pontiac, IL and then verified using 1972-1986 data from the same station, and using 1972-1995 data from the USGS gage at Leonore, IL. Model simulated the monthly streamflows with correlation coefficients and Nash-Sutcliffe Efficiency (NSE) of close to or greater than 0.8 during calibration as well as verification periods. Flow-duration curves of the daily observed and simulated streamflow data indicated good simulation for all flow conditions, except for some very low flow periods. The flood year of 1993 was under-simulated by the model whereas some very low flow years were generally over-simulated.

Introduction

Most of the significant rivers in the State of Illinois, including the Vermilion River, drain into the Illinois River. Illinois River carries the runoff, sediment, nutrient, and pollutants from these tributaries down to the Mississippi River. The Illinois State Water Survey (ISWS) has adopted a modular modeling approach for development of a hydrologic simulation model for the entire IRB to characterize its hydrology and compute streamflows into the Illinois River. In previous work, a preliminary hydrologic simulation model for the entire Illinois River Basin was developed by the Illinois State Water Survey with the objective of assessing restoration needs in the basin. The model will not only be useful in assessing flow and water quality characteristics throughout the basin, but also for evaluating the effects of land use change and various management alternatives on water resources and water supply. The model was developed using Hydrologic Simulation Program – FORTRAN (HSPF, version 12) under the BASINS (Better Assessment Science Integrating Point and Nonpoint Sources, version 3.0), a multipurpose environmental analysis system developed by the U.S. Environmental Protection Agency (USEPA).

The initial development of the Illinois River BASINS-HSPF model included parameter calibration to match observed and simulated streamflows for three separate watersheds in the basin using available climatic data as input into the model. The three initial watersheds were the Spoon, Iroquois, and Kankakee watersheds. For continued model development, the model needs to be calibrated to additional watershed areas, not only to improve the simulated flow values for the additional portion of the basin but also to better understand the relationship between model parameters and watershed characteristics. The results presented here describe the calibration of the model to streamflow data from the Vermilion River Watershed (VRW). Various steps involved in the development of the hydrologic simulation model of this VRW are explained in the following sections.

Watershed Description

The Vermilion River watershed (8-digit USGS Cataloging Unit 07130002) is located in the east central Illinois and covers an area of 1330 square miles. The Vermilion River merges with the Illinois River near Oglesby (LaSalle County, IL). Average annual precipitation in the watershed for the period of this study is 970mm. Most of the land in this watershed is under agriculture (97%) and forest and urban land use share the remaining area. Fourteen different soil associations, mainly silty-clay and silt loams, exist in the watershed. Silty-clay loam soil associations Bryce-Swygert (MUID=IL018) and Ashkum-Chenoa-Graymont (MUID=IL081) together cover over 36% area of the VRW.

Input Data and Sub-watershed Delineation

The HSPF requires spatial information about watershed topography, river/stream reaches, land use, and climate to accurately simulate the streamflow. Most of this data was extracted from the database provided by USEPA with the BASINS software, as shown in Table 1. The climatic inputs for the HSPF include hourly precipitation, potential evapotranspiration, cloud cover, air temperature, dew point temperature, evaporation, solar radiation and wind speed data. Since the BASINS database had only one climate station in the entire VRW with hourly precipitation data, 5 more daily precipitation stations maintained by Midwestern Climate Center (MCC) were identified within the VRW (Figure 1). Details of these daily precipitation stations are given in Table 2. The daily data at these 5 stations was disaggregated into hourly data using the methodology available in BASINS. The hourly precipitation data from 3 BASINS stations and 3 NOAA-NCDC stations in the vicinity of the VRW was used as reference data for disaggregating daily data into hourly data. Other climatic time series for the 5 MCC stations were imported from the closest BASINS climate station.

The “Automatic Delineation” tool of BASINS was used to subdivide VRW into 25 smaller, hydrologically connected sub-watersheds and their stream reaches, and respective outlets (Figure 1). Representative climate stations were assigned to each sub-watershed based on Thiessen Polygon method. Watershed outlets were defined in the model corresponding to two USGS streamflow gaging stations – USGS05555300 (at Leonore, IL) and USGS05554500 (at Pontiac, IL) – used for model calibration or verification purpose. Landuse in the model was divided into pervious and impervious areas. Agricultural, forest and urban grassland areas were considered pervious, whereas built-up urban areas were under impervious landuse types. Thirteen types of HRUs were created in the watershed based on various combinations of landuse and hydrologic soil groups of type A, B, C and D. Some examples of these HRUs are – agricultural area on soil B, forest on soil C, urban built-up area on soil A.

Model Parameters, Calibration and Verification

The hydrologic component of HSPF was calibrated for the VRW using historical streamflow data for 9 years (1987-1995) from USGS05554500 gage (G4500) at Pontiac, IL. This period was chosen because it represents a combination of dry, average, and wet years (annual precipitation 610mm to 1260mm). The model was run for 11 year period of 1985-1995 but the first two years (1985 and 1986) were used for stabilization of model runs only and data for 1987-1995 was used for comparison purposes. A stepwise approach was used for model calibration in which first an acceptable match was obtained between annual and monthly streamflow values. Model parameters were then further adjusted to obtain a satisfactory agreement between daily observed and simulated streamflow hydrographs and flow-duration curves. This approach was supported by the hierarchical structure in HSPF in which annual streamflow values are affected by one set of parameters (e.g. LZETP, DEEPFR, LZSN, and INFIL parameters), monthly flows by another set (UZSN, BASETP, KVARY, AGWRC, and CEPSC), and storm flows by a third set (e.g. INFILT, INTFW, and IRC). Snowmelt and freezing phenomena in the watershed were simulated by changing the values of SNOWCF, TSNOW, and CCFACT parameters associated with the snow simulation component of the HSPF.

Different values of these parameters may be specified to different HRUs based on the physical characteristics of each HRU. Detailed description of various parameters values assigned to various parts of the watershed is stored in the *.UCI file of the model (not included here). Definition and values of various HSPF model parameters used in this study are given in Table 3. During calibration values of these model parameters were adjusted within reasonable limits until optimal agreement between simulated and observed streamflows was obtained. This agreement was determined objectively by calculating coefficient of correlations (r) and Nash-Sutcliffe Efficiency of model fit (NSE) for daily and monthly flow comparisons. The NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. Based on other studies using the HSPF model (Chew et al., 1991; Price, T.H., 1994; and Duncker et al., 1995), calibration of HSPF was considered satisfactory when the NSE and r values for monthly flow comparisons exceeded 0.80. For the overall and annual streamflow comparisons only the percent error was considered (10 and 25 percent were used in this study for the annual flows). Donigian et al. (1984) state that in HSPF simulations, the annual and monthly fit is very good when the error is less than 10 percent, good when the error is between 10 to 15 percent, and fair when the error is 15 to 25 percent. The fit between daily observed and simulated streamflows was checked graphically also by plotting the runoff-duration curves and time series. General agreement between observed and simulated runoff-duration curves indicates adequate calibration over the range of the flow conditions simulated. Calibrated watershed model was verified using streamflow data for 15-year period of 1972-1986 at the same gage as calibration (i.e. G4500), and also using 24-year data (1972-1995) from the USGS05555300 gage (G5300) at Leonore, IL. During model verification, calibrated model parameters were used without any change.

Results and Discussion

Model calibration and verification statistics are presented in Table 4 for daily, monthly, and annual time scales. Model simulated the mean monthly streamflows satisfactorily during model calibration with r=0.90 and NSE=0.81 (Figure 3a). Runoff-duration curves of daily streamflows for this period (Figure 2a) indicated that model simulated the streamflows well for all flow conditions, except that some low-flow (<0.04mm or 25 cfs) periods were over-simulated. This was mainly because of water withdrawal (~ 3 cfs) from the river upstream of USGS gage at Pontiac and can be corrected by subtracting this amount from the simulated streamflow values. Simulated low flows were most sensitive to values of parameters that affect evapotranspiration, e.g. LZSN, UZSN, and BASETP as well as parameter AGWRC. High daily NSE (=0.75) and r (= 0.87) and low RMSE (= 0.75 mm) also indicate that shape and timings of daily streamflow hydrographs were simulated satisfactorily by the model. The shape of the recession limb of simulated hydrograph, which is affected by the delayed response related to interflow and ground-water flow, was affected most by the parameter that determines the relative amounts of interflow (INTFW) and surface runoff, and the interflow recession rate constant (IRC), which regulates the rate at which water is released from interflow storage to the stream. Over the nine year simulation period of 1987-1995 model undersimulated the streamflow only by 8.3%. Annual streamflow volumes were also simulated fairly well with seven out of nine years having percent error under 25%.

During model verification using 1972-1986 streamflow data from the gage at Pontiac (G4500), an r=0.86 and NSE=0.74 were obtained for mean monthly flows (Table 4 and Figure 3b). Based on criteria of Donigian et al. (1984) model simulated annual streamflows were in ‘very good’ category for 7 and ‘good to fair’ category in 5 years (Table 4). Analysis of daily flow-duration curve for this period (Figure 2b) indicated that for the most part curves of observed and simulated values match very closely. Only some very low flows were oversimulated which could be due to the same reason as stated above. Overall the calibrated model simulated the range in magnitude of daily streamflows reasonably well during the validation period as evidenced by high daily NSE and r values, low RMSE, and only -6% error over the 15 year period (Table 4).

Better agreement (than that obtained during model calibration period) between observed and simulated mean monthly streamflow values was obtained during model verification based on streamflow data for 1972-1995 from a downstream gage at Leonore. For this period observed and simulated mean monthly streamflows were closely correlated with an r=0.94 and NSE=0.88 (Figure 3c), both values higher than those obtained during model calibration, indicating that calibrated parameter set is applicable to the entire watershed. Daily flows were also simulated satisfactorily during this 24 year period as indicated by close match between flow-duration curves (Figure 3c), low percent error of only 2.2%, and high daily NSE (= 0.70) and r (= 0.85) (Table 4). Overall, comparison of annual flows during model calibration and verification periods showed that some very low-flow years were oversimulated whereas flood year of 1993 was undersimulated by the model.

References

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Table 1. HSPF Model Input Data Type and Sources for Hydrologic Modeling of the Vermilion River Watershed

Data type	*Scale*	*Source*
Topography	1:250,000	USGS
Landuse/Landcover	1:250,000	USGS GIRAS spatial data
Reach File ver.1 (RF1)	1:500,000	USEPA
National Hydrography Dataset (NHD)	1:100,000	USEPA – USGS[+]
Daily Streamflow	--	USGS[**]
Meteorology –		
Hourly weather data	--	- USEPA WDM Weather Stations - NOAA-NCDC Weather Stations
Daily precipitation data	--	NCDC - Midwest Climate Center

Note: Unless otherwise noted, data derived from BASINS 3.0 database
[+] from http://nhd.usgs.gov/
** from http://Water.usgs.gov/

Table 2. Precipitation Data Stations in the VRW that were Used in the Model

Coop ID	*Station Name*	*State*	*Latitude, DD*	*Longitude ,DD*
111475	Chenoa	IL	40.71667	-88.71670
115712	Minonk	IL	40.90000	-89.05000
6711	Peoria WSO AP*	IL	40.66670	-89.68330
116910	Pontiac	IL	40.86667	-88.61670
118353	Streator	IL	41.08333	-88.81670
118756	Utica StarvRD	IL	41.31667	-88.96670

Note: *Only station with hourly data.

Table 3. Model Parameters and their values used for the VRW model

Parameter	*Definition*	*Values used*
KVAR (1/in)	Variable ground water recession flow	1.5
INFILT (in/h)	Index to soil infiltration capacity	0.04-0.50
AGWRC (1/d)	Basic ground water recession rate	0.88-0.92
LZSN (in)	Lower zone nominal storage	4.0-8.0
UZSN (in)	Upper zone nominal storage	0.4-2.0
BASETP	Baseflow evapotranspiration	0.12
DEEPER	Fraction of inactive ground water	0.10
NSUR	Manning's n for overland flow	0.06-0.1
CEPSC (in)	Interception storage capacity	0.01-0.20
INTFW	Interflow inflow parameter	5.0-6.0
IRC	Interflow recession constant	0.34-0.64
LZETP	Lower zone evapotranspiration	0.3-0.7
TSNOW (°F)	Temp. at which precip is snow	33
SNOWCF	Snow gage catch correction factor	1.10
CCFACT	Condensation/convection melt factor	1.10

Table 4. Model Comparison Statistics for Daily, Monthly and Annual Basis during Calibration and Verification Periods at Two Different Gages - G4500 and G5300

	G4500		*G5300*
	Calibration 1987-1995	*Verification 1972-1986*	*Verification 1972-1995*
Daily basis			
Observed mean, mm	0.83	0.88	0.88
Simulated mean, mm	0.76	0.83	0.90
Percent error,%	-8.28	-5.96	2.22
NSE	0.75	0.66	0.70
r	0.87	0.82	0.85
RMSE,mm	0.75	0.96	0.86
Monthly basis			
NSE	0.81	0.74	0.88
r	0.90	0.86	0.94
Annual basis			
Years with % error < 10	0	7	10
Years with % error < 25	7	12	20

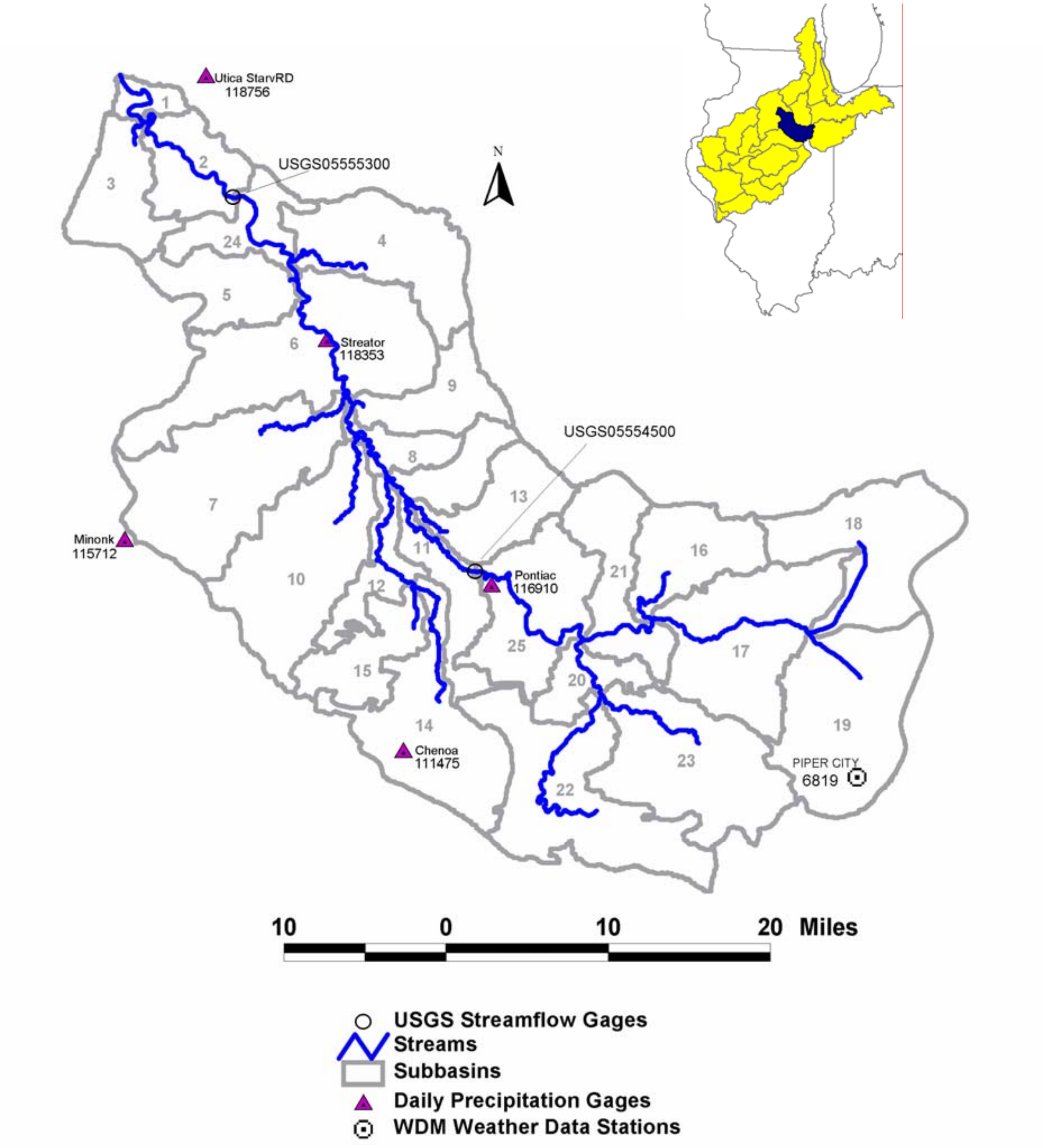

Figure 1. Sub-basins and USGS streamflow and climate gages in the watershed

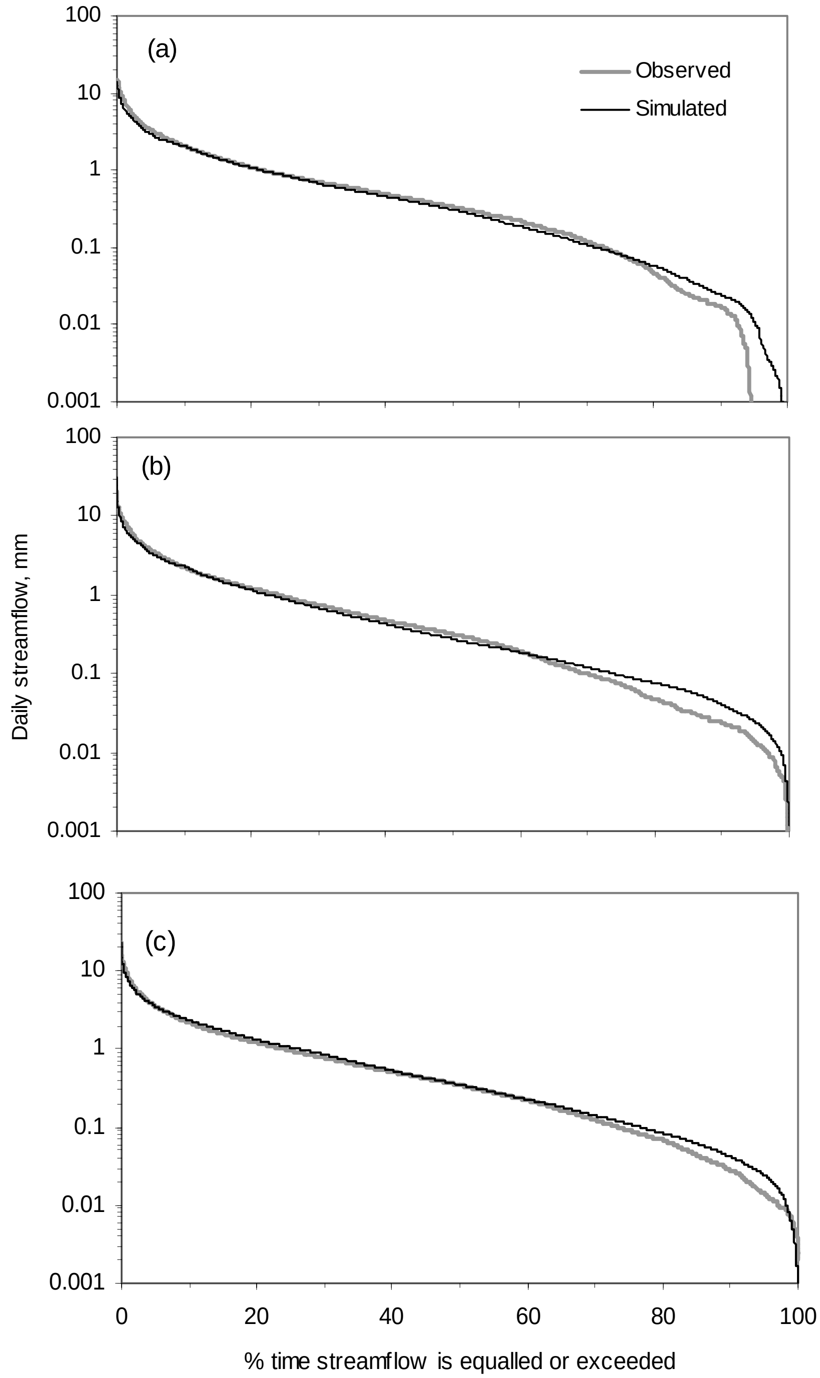

Figure 2. Flow-duration curves of observed and simulated daily streamflows for (a) model calibration at G4500 for 1987-1995, (b) model verification at G4500 for 1972-1986, and (c) model verification at G5300 for 1972-1995

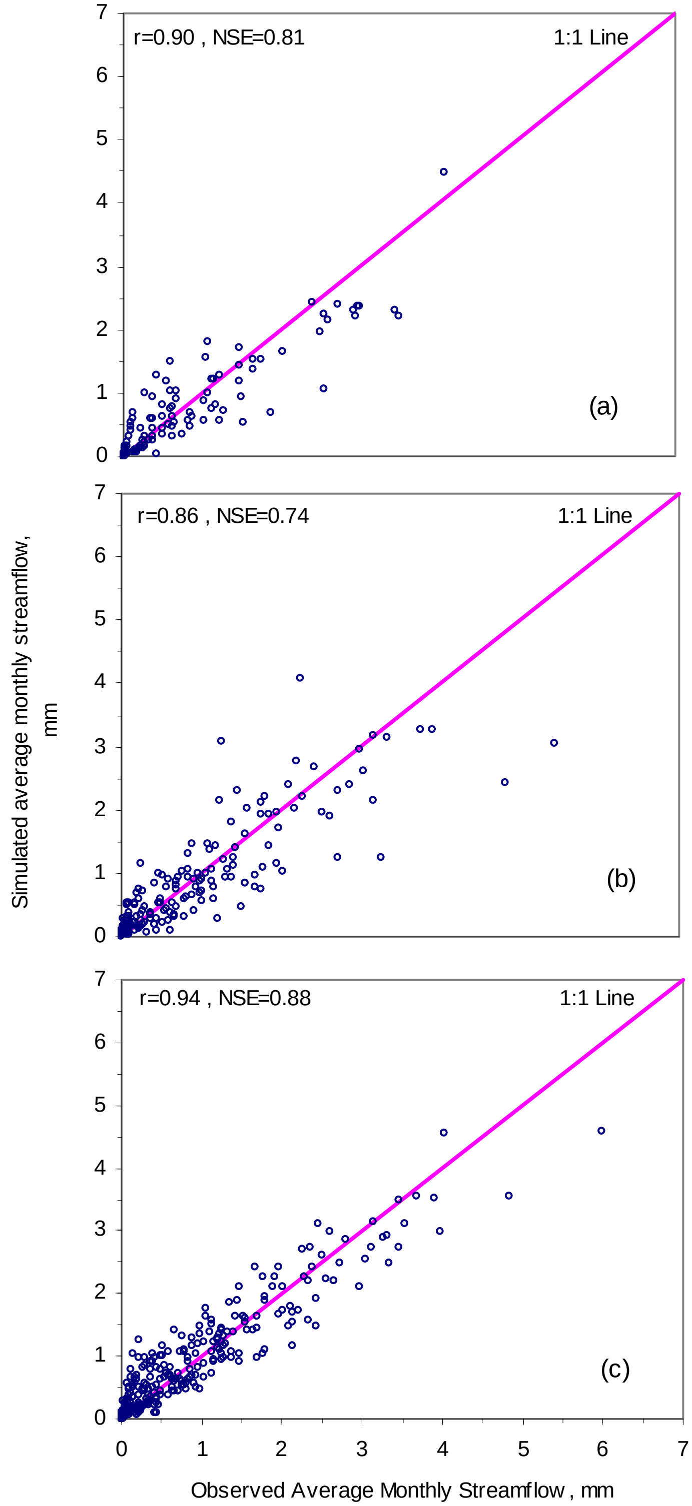

Figure 3. Scatter plots of observed and simulated average monthly streamflows for (a) model calibration at G4500 for 1987-1995, (b) model verification at G4500 for 1972-1986, and (c) model verification at G5300 for 1972-1995