JOURNAL OF
ENVIRONMENTAL HYDROLOGY

The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com

VOLUME 12 2004

GIS-AIDED INLAND WATERSHED MODELING, SHIYANG RIVER BASIN, CHINA

He Chen
Zhen-yao Shen
Zhi-feng Yang

State Key Laboratory of Environment Simulation and Pollution Control Institute of Environmental Sciences, Beijing Normal University, Beijing, China

Geographic Information Systems (GIS) have been recognized as a powerful means to integrate and analyze data from various sources in the context of comprehensive watershed management. Hydrologic modeling plays a crucial role, and there is much to gain in incorporating these modeling capabilities in GIS. Interfacing between these models and GIS may be a very efficient way of overcoming the difficulties and getting very good results in terms of engineering practice. In this paper, GIS-aided watershed modeling is applied in a watershed in northwest China. The GIS is interfaced with a watershed modeling program, HSPF, to facilitate data storage, management and display; derivation of model input parameters; and effective presentation of results. Through interfacing programs and other GIS programs, a database is queried to derive model input parameters, and to visually present results in maps. We simulated a rainfall process in the Shiyang River Basin in northwest China. Results for current conditions and practices show that HSPF can be used successfully in similar inland watersheds.

INTRODUCTION

Geographic Information Systems (GIS) are increasingly being used to forecast effects related to the spatial and time variability of geographic data. These systems are expressly designed to store information about location, topology, and attributes of spatially referenced objects, and can also provide analysis of spatial properties of these objects. Due to their data handling capabilities, GIS is an effective tool in water resources management. Attribute and spatial data developed using GIS allow the user to overlay coverages, analyze and determine pollutant loadings, and prioritize and identify critical areas in a very efficient and economical manner (Debarry, 1991; Steffen, 1993; Sui, 1999).

Many researchers have used GIS-aided hydrologic models to study the hydrologic responses to rainfall. Moharana et al. (2000) used GIS to simulate the streams in the Thar desert, in which superimposition of data layers generated from remote sensing and secondary sources validated the simulation results, and suggested suitability of the method for application in similarly handicapped areas. Schumann et al. (2000) presented one approach on how statistical descriptions of distributed catchment characteristics could be used to consider spatial heterogeneity within conceptual models. Jain et al. (2000) estimated the soil erosion of a Himalayan watershed using GIS techniques. Carpenter et al. (2001) used GIS to estimate national threshold runoff in support of operational flash flood warning systems.

In some inland watersheds such as the Shiyang River watershed, much of the runoff volume is lost through infiltration. In such a topographical and runoff situation, watershed modeling becomes a difficult proposition. This difficulty is a major problem in the inland watersheds of northwest China, where the state is funding water conservation programs, as well as other related development activities.

STUDY AREA

This paper concentrates on the rainfall-runoff process in a tributary of the Shiyang River of Gansu Province. The river, named the Huangyang River, rises in the Qilian mountains, travels in a northeast direction and joins the Shiyang river. The study area lies between 102°15´E and 102°46´E and between 37°16´N and 37°38´N, and covers an area of 828 km^2. The climate of the region is arid with an average annual rainfall of about 400 mm. Most of the rainfall comes during the months of June, Stream networks rise in the high mountains, and exist in the form of variational streams in valleys. All of them gather together and flow into a reservoir. Water in the reservoir is used for irrigation, and almost no water flows to lower reaches of the river. For watershed modeling studies we simulated the hydrologic process of one rainfall process in the area above the reservoir.

METHODOLOGY

Preparation of the digital elevation model

To prepare a digital elevation model (DEM) of the area we first digitized the contour lines from the 1:250,000 scale topographical sheet. This was sufficient to explain the observed topographical variations. The vector data were then converted to a raster file for simulation of the channel network, and for comparison with other raster data on different land resources.

Preparation of thematic maps

Based on the interpretation of Landsat TM satellite images and one land use map made by the Gansu Administration of State Land and Resources, the land use map was constructed. It consisted of a fundamental map and an affiliated map. The land use map was the most important thematic map for watershed modeling.

Channel extraction from the DEM

Extraction of the channel network from the DEM is based on the principle that the basic structures of drainage basins/catchments are reflected in topographical variations and slope. A number of gullies formed in the upslope areas are joined together to form a drainage network, and the total runoff from the catchment is drained through a single outlet at the downslope end of the catchment with lowest elevation.

Hydrologic simulation

The Hydrologic Simulation Program Fortran (HSPF) is a lumped catchment model designed to simulate a broad range of hydrologic and water quality processes (Brun, 2000). Once land segments are defined, the user must define the percent pervious cover for each land use. This step produces pervious and impervious land segments for each sub-watershed (Goodchild, 1993; Bicknell et al., 1993). The amount of impervious cover for each type of land use was estimated, and daily precipitation and potential evapotranspiration (ET) records were used for model input. Initial model parameters were obtained from defaults and were subsequently modified during model calibration. Observed stream flow records in a rainfall process in 1988 from gaging stations were compared to simulated results for model calibration. The 1988 calibration parameters were then used for the rainfall process in 1987.

APPLICATION AND DISCUSSION

In order to validate the applicability of HSPF in the inland watershed, we simulated the rainfall process from June 7th to 17th, 1987 in the Huangyang River basin.

The DEM is obtained from digitized contour lines, and is shown in Figure 1. Based on this DEM, we delineated watershed and sub-basin boundaries and then converted it to a series of arcs and polygons. The basin was divided into three sub-basins based on shape of the streams (Figure 2). Flow directions and accumulations are determined using a program named TOPAZ. A flow direction grid

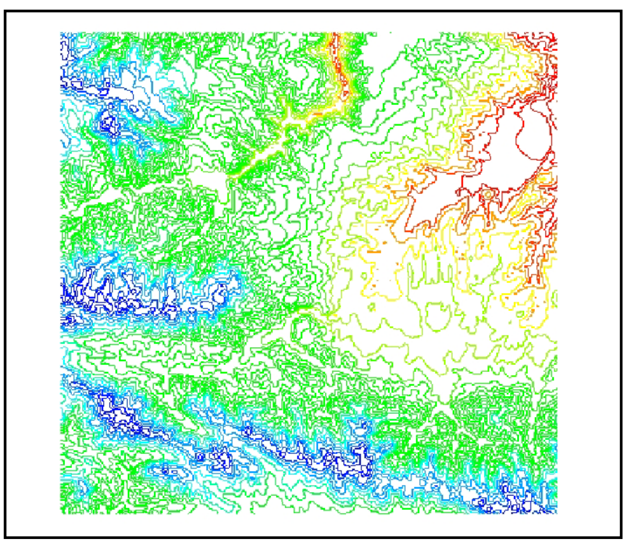


Figure 1. DEM of Huangyang River Basin.

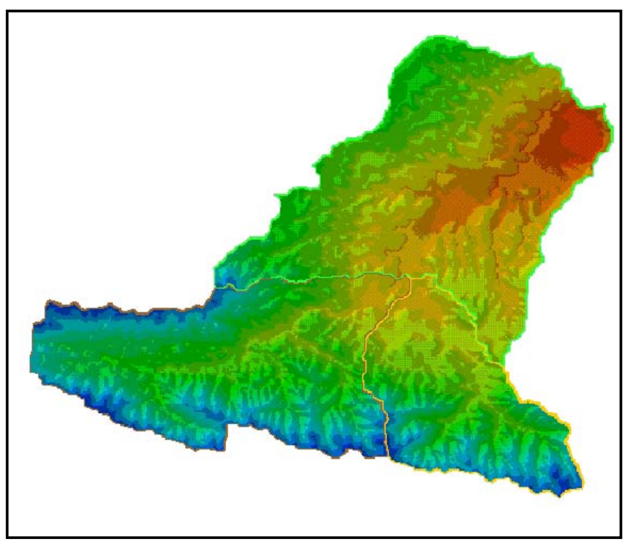


Figure 2. Sub-basins.

consists of a flow direction value for each DEM point (Figure 3). The flow direction identifies which neighboring point has the lowest elevation. A flow accumulation grid consists of an integer value for each DEM point that represents the number of upstream DEM points whose flow path passes through it. Different colors indicate different accumulation values. High accumulation values indicate points in the stream, whereas low values represent areas of overland flow.

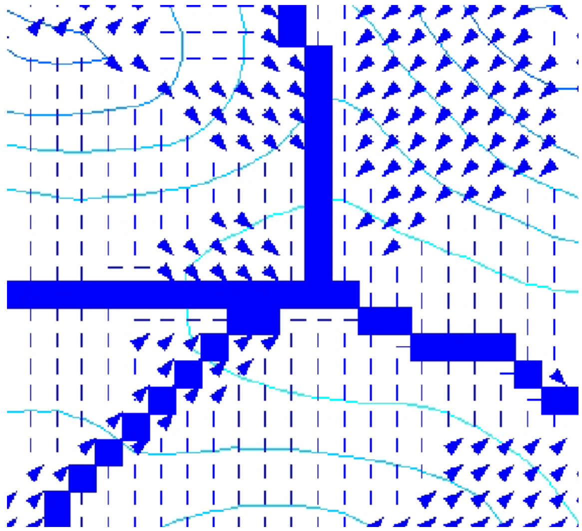


Figure 3. Flow direction grid.

Streams are shown in Figure 4, which are created from the DEM whose flow accumulation values are above a defined threshold. Consecutive stream DEM points are joined together as arcs with nodes created at junction points where the stream splits. Streams created from the DEM are similar to natural streams (Figure 4) except for some difference in lower reaches because of cultivation.

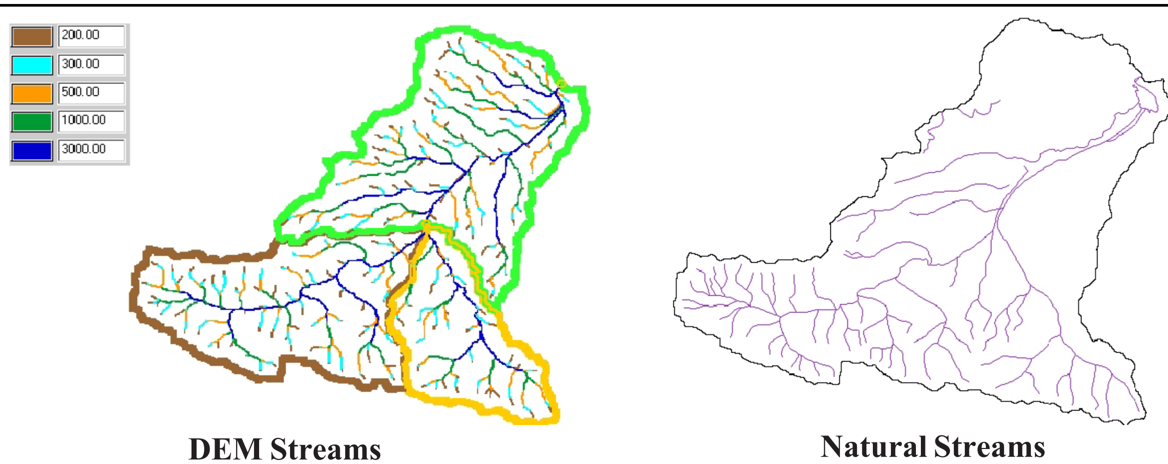


Figure 4. DEM-created and natural streams.

After defining basin boundaries, attributes such as basin areas and slopes, and stream lengths and slopes were computed by the aid of a Geographic Information System (GIS). Some geometric parameters are shown in Figure 5. CN,A,BS,AOFD,L, and P mean curve number, basin area, average basin slope, average overland flow distance, basin length, and basin perimeter respectively. These are all geometric parameters used in defining basins and routing networks in HSPF.

We generated a topologic tree that indicates basin delineation and a particular sub-basin configuration based on the DEM and feature objects. In the topologic tree, every icon denotes a basin

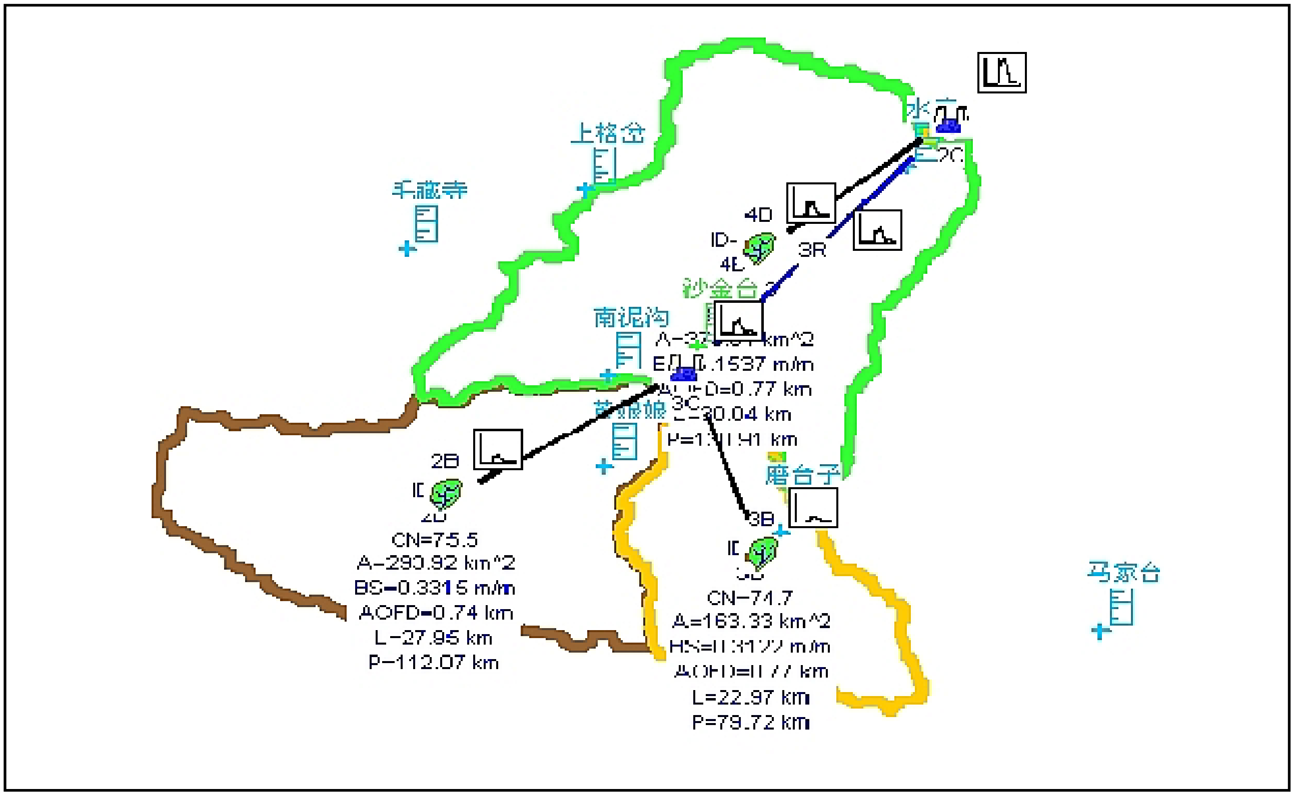


Figure 5. Topologic tree, gages, basin parameters and results.

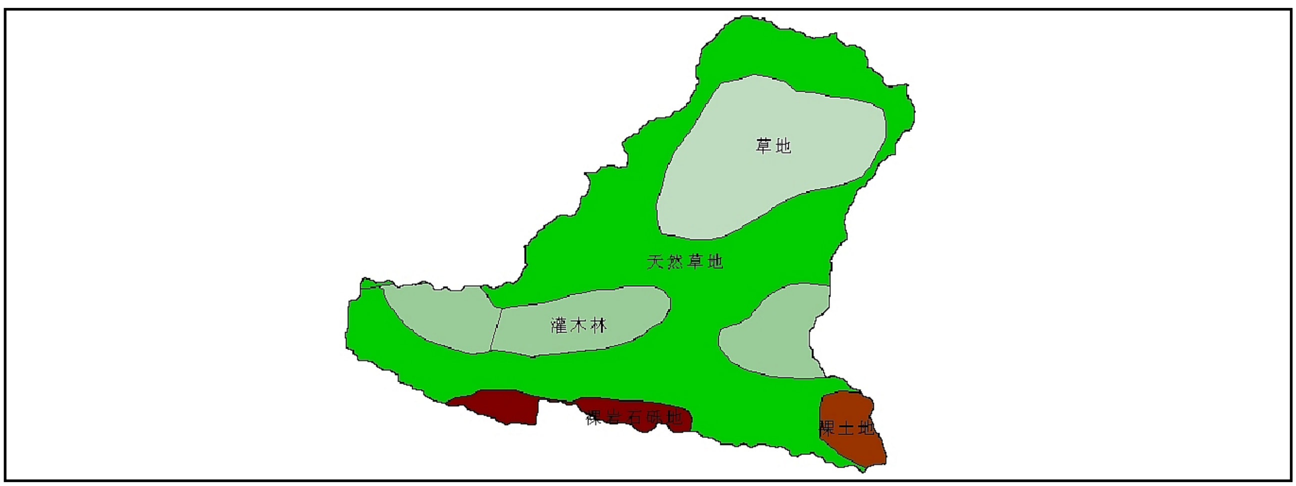


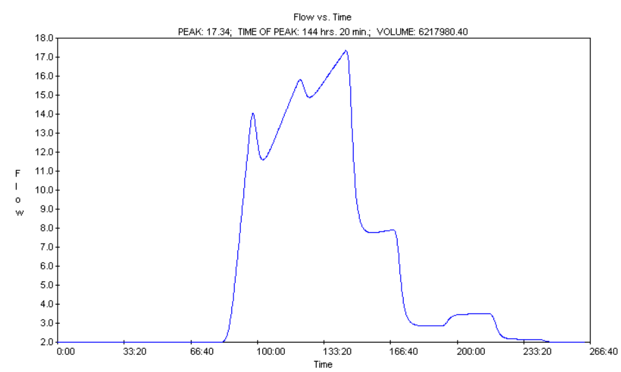
Figure 6. Land use types.

outlet or a basin. In Figure. 5, 2C and 3C are basin outlets, and 2B, 3B and 4B are sub-basins.

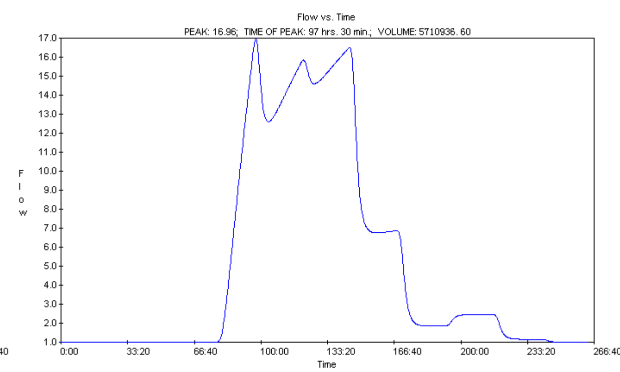
Transformed into feature objects, basin boundaries and streams and topologic trees make up a fundamental coverage named the watershed coverage. In addition, there is another coverage, the land use coverage, which is very important to the HSPF model (Figure 6). For this study, the land use coverage was generated from satellite images of Landsat TM and a thematic map.

There are eight valid rain gauges in this basin, which are the Huangniangniang, Motaizi, Nannigou, Huangyang Reservoir, Shajintai, Maozangsi, Shanggecha, and Majiatai (Figure 5). Because we simulated only two rainfall-runoff processes, accurate data are necessary. But the hydrologic data in the most useful gage, Huangyang River reservoir, is coarse. So we only validated the model with the total runoff data of the Huangyang River reservoir. Based on the basin parameters and thematic maps from the GIS, we calibrated the HSPF model with the rainfall and potential evapotranspiration (ET), and observed stream flow records from July 3 to 21, 1988. The initial 1988 simulation was run with uncalibrated model parameters and was found to underestimate baseflow. As a consequence, we changed the parameters of land segments until reasonable results were found between simulated and observed flow records.

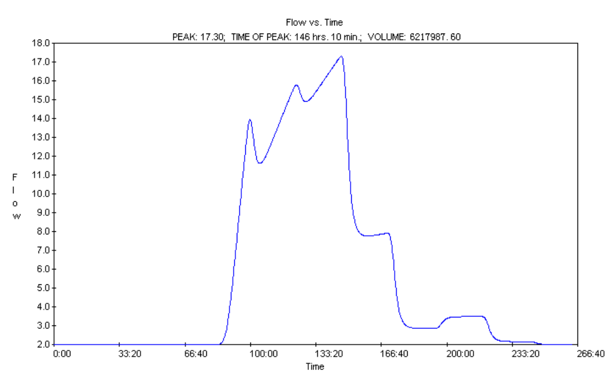
The calibrated parameters were then used to simulate the rainfall-runoff process from June 7 to 17, 1987. The time interval was 10 minutes. The results are shown in Figure 7. The x and y coordinate of the graph indicate time and flow respectively. The unit of time is hours and the unit of flow is m^3. In Figure 7(a) the curve indicates the hydrograph at the junction of basin 2B and 3B. The flow at this location is equal to the sum of that of basin 2B and 3B. The hydrograph at the outlet of basin 4B is shown in Figure 7(b). Water that comes from the junction of basin 2B and 3B flows through the streams in basin 4B and forms the hydrograph shown in Figure 7(c). The hydrograph curves in Figure 7(a) and Figure 7(c) are similar except that the peak in Figure 7(c) is lower and comes later.



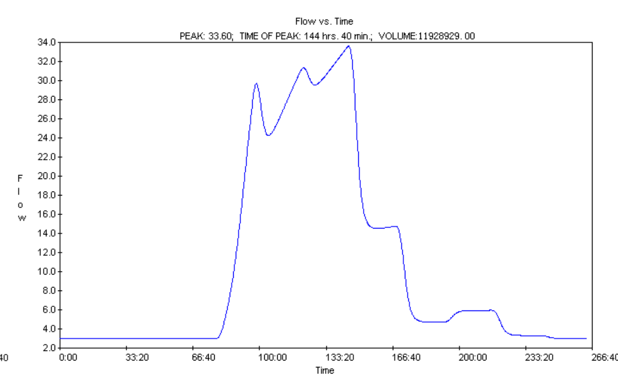
(a) Hydrograph at the junction of basin 2B and 3B



(b) Hydrograph at the outlet of basin 4B



(c) Hydrograph at stream 3R



(d) Hydrograph at the outlet of the watershed

Figure 7. Simulation results.

The hydrograph at the outlet of Huangyang River Basin is shown in Figure 7(d). The water at this outlet comes from the outlet of basin 4B and stream 3C. As we can see in this figure, the flow reaches a peak after 144 hours and 40 minutes, the value of which is 33.6 m^3/s. Every rainfall results in a maximum flow in the figure. The total runoff of this rainfall process at the outlet of the Huangyang River Basin is 119 x $10^7 m^3$.

There is only one stream gage in the Huangyang River Basin which lies downstream of the Huangyang Reservoir. The validation of the HSPF model can only rely on the data from this gage.

The total outflow from this reservoir isQ_{out}=9.21 x $10^6 m^3$ and the total inflow to this reservoir is Q_{in}=1.19x$10^7 m^3$. So the pure inflow isQ_{purein} =2.72 x $10^6 m^3$. We calculated the area of the reservoir based on satellite images of Landsat TM, which is A=1,821,455 m2.. From June 7 to 17 the water level measured h=1.19 m. .

The error of this simulation is $Q_{error} = Q_{in} - Q_{out} - Ah$ = 5.54 x $10^5 m^3$, and the relative error is

$$\sigma = \frac{Q_{error}}{Q_{in}} = \frac{5.54x10^5}{1.19x10^7} = 4.66\% .$$

CONCLUSION

Watershed modeling requires efficient management of large amounts of spatial and temporal datasets, which involves data acquisition, storage, and processing of model inputs, as well as the manipulation, reporting, and display of results. GIS has the capacity to manage large volumes of data in a common spatial structure. In this paper we integrated the HSPF model and GIS, which has shown the advantages of using a hydrologic model coupled with GIS. GIS was used to derive lumped basin characteristics, which describe the spatial heterogeneity within a basin. These characteristics were used directly in the HSPF model with the aim of making good and effective use of basin information.

In this paper, the application of GIS-aided watershed modeling in the inland watershed in Northwest China, Huangyang River Basin, consisted of using GIS to generate and manage basin parameters, and transfer these parameters to the HSPF model. The simulation of the 10- day rainfall-runoff process in 1987 proved that the GIS-aided watershed modeling method and the HSPF model can be used in an inland watersheds with similar characteristics.

ACKNOWLEDGMENT

This study was supported by the Ministry of Science and Technology of China (Contract No. 200IDIA1005).

REFERENCE

Bicknell, B.R., J.C. Imhoff, J.L. Kittle, A.S. Donigian, and R.C. Johanson; (1993). Hydrological Simulation Program -FORTRAN (HSPF): UsersManual for Release 10. EPA-600/R-93/174, U.S. EPA, Athens, GA, 30605.

Brun, S.E. and L.E. Band; (2000). Simulating runoff behavior in an urbanizing watershed. Computers, Environment and Urban Systems, (4):5-22.

Carpenter, T.M., J.A. Sperfslage, K.P. Georgakakos , T. Sweeney, and D.L. Fread; (1999). National threshold runoff estimation utilizing GIS in support of operational flash flood warning systems. Journal ofHydrology, 224, 21-44.

Debarry, P.A.; (1991). GIS applications in nonpoint sources pollution. Hydr. Engrg., Proc., 1991 Nat. Conf. ASCE, New York, N.Y.

Goodchild, M.F.; (1993). The state of GIS for environmental problem-solving. In: M.F. Goodchild, B.O. Parks, L.T. Steyaert (eds), Environmental Modeling with GIS. New York: Oxford University Press.

Jain, S.K., H. Chowdhary, S.M.Seth, and R.K. Nema; (1997). Flood estimation using a GIUH based on a conceptual rainfall-runoff model and GIS, ITC Journal 1997-1, pp. 20–25.

Jain S.K., S. Kumar and J. Varghese; (2001). Estimation of Soil Erosion for a Himalayan Watershed Using

GIS Technique. Water Resources Management, (15):41–54,.

Krahe P., K. Daamen, R. Muelders and K. Wilke; (1997). GIS-related baseflow simulation for water balance and precipitation-runoff modeling in the River Rhine basin. Remote Sensing and Geographic Information Systems for Design and Operation of Water Resources Systems. IAHS Publication.

Moharana, P.C and A. Kar; (2002). Watershed simulation in a sandy terrain of the Thar desert using GIS. Journal of Arid Environments, (51):489-500.

Sui D.Z., R.C. Maggiob; (1999). Integrating GIS with hydrological modeling: practices, problems, and prospects. Computers, Environment and Urban Systems, (23):33-51.

Schumann, A.H, R. Funke and G.A. Schultz; (2000). Application of a geographic information system for conceptual rainfall-runoff modeling. Journal of Hydrology, (240):45-61

Steffen P.; (1993). Geographic Information Systems in Urban Storm-Water Management. J. Water Resourc. Plng. and Mgmt., (2):206-228.

ADDRESS FOR CORRESPONDENCE
YANG Zhi-feng
State Key Laboratory of Environment Simulation and Pollution Control
Institute of Environmental Sciences
Beijing Normal University
Beijing 100875
China

E-mail : zfyang@bnu.edu.cn