Water Science and Engineering, 2010, 3(1): 14-22
doi:10.3882/j.issn.1674-2370.2010.01.002

http://www.waterjournal.cn
e-mail: wse2008@vip.163.com

Application of HEC-HMS for flood forecasting in Misai and Wan'an catchments in China

James Oloche OLEYIBLO*, Zhi-jia LI

College of Hydrology and Water Resources, Hohai University, Nanjing 210098, P. R. China

Abstract: The hydrologic model HEC-HMS (Hydrologic Engineering Center, Hydrologic Modeling System), used in combination with the Geospatial Hydrologic Modeling Extension, HEC-GeoHMS, is not a site-specific hydrologic model. Although China has seen the applications of many hydrologic and hydraulic models, HEC-HMS is seldom applied in China, and where it is applied, it is not applied holistically. This paper presents a holistic application of HEC-HMS. Its applicability, capability and suitability for flood forecasting in catchments were examined. The DEMs (digital elevation models) of the study areas were processed using HEC-GeoHMS, an ArcView GIS extension for catchment delineation, terrain pre-processing, and basin processing. The model was calibrated and verified using historical observed data. The determination coefficients and coefficients of agreement for all the flood events were above 0.9, and the relative errors in peak discharges were all within the acceptable range.

Key words: *hydrologic model; HEC-HMS; catchment delineation; DEM; terrain pre-processing; Misai Catchment; Wan'an Catchment*

1 Introduction

HEC-1 is a mathematical watershed model that contains several methods with which to simulate surface runoff and river/reservoir flow in river basins. The hydrologic model, together with flood damage computations (also included in the model), provides a basis for evaluation of flood control projects. The HEC-1 hydrologic model was originally developed in 1967 by Leo R. Beard and other staff members of the Hydrologic Engineering Center, with the U. S. Army Corps of Engineers, to simulate flood hydrographs in complex river basins (Singh 1982). Since then, the program has undergone a revision: different versions of the model with greatly expanded capabilities have been released. This study used the HEC-HMS Version 2.2.1. The HEC model is designed to simulate the surface runoff response of a catchment to precipitation by representing the catchment with interconnected hydrologic and hydraulic components. It is primarily applicable to flood simulations. In HEC-HMS, the basin model comprises three vital processes; the loss, the transform and the base flow. Each element in the model performs different functions of the precipitation-runoff process within a portion of the catchment or basin known as a sub-basin. An element may depict a surface runoff, a stream

*Corresponding author (e-mail: *evangjamesa1@yahoo.com*; *evangjamesa1@gmail.com*)
Received Nov. 3, 2009; accepted Dec. 23, 2009

channel, or a reservoir. Each of the elements is assigned a variable which defines the particular attribute of the element and mathematical relations that describe its physical processes. The result of the modeling process is the computation of stream flow hydrographs at the catchment outlet.

2 What necessitates hydrologic modeling

The design, construction and operation of many hydraulic projects require an adequate knowledge of the variation of the catchment's runoff, and for most of these problems it would be ideal to know the exact magnitude and the actual time of occurrence of all stream flow events during the construction period and economic life of the project. If this information was available at the project planning and design stages, it would be possible to select from amongst all alternatives a design, construction program, and operational procedure that would produce a project output with an optimized objective function. Unfortunately, such ideal and precise information is never available because it is impossible to have advance knowledge of the project hydrology for water resources development projects; it is necessary to develop plans, designs, and management techniques using a hypothetical set of future hydrologic conditions. It is the determination of these future hydrologic conditions that has long occupied the attention of engineering hydrologists who have attempted to identify acceptable simplifications of complex hydrologic phenomena and to develop adequate models for the prediction of the responses of catchments to various natural and anthropogenic hydrologic and hydraulic phenomena. In view of these, a number of hydrologic models have been developed for flood forecasting and the study of rainfall-runoff processes (Crawford and Linsley 1966; Burnash et al. 1973; Sugawara 1979; Beven and Kirkby 1979; Sivapalan et al. 1987; Zhao 1992; Todini 1996). In recent times, GIS (geographic information systems) has become an integral part of hydrologic studies because of the spatial character of the parameters and precipitation controlling hydrologic processes. GIS plays a major role in distributed hydrologic model parameterization. This is to overcome gross simplifications made through representation by lumping of parameters at the river basin scale. The extraction of hydrologic information, such as flow direction, flow accumulation, watershed boundaries, and stream networks, from a DEM (digital elevation model) is accomplished through GIS applications. This study combined GIS with HEC-HMS, and analyzed the model's suitability for the studied catchments.

3 Methodology

The methodology can be divided into four major tasks: (1) obtaining the geographic locations of the studied basins; (2) DEM processing, delineating streams and watershed characteristics, terrain processing, and basin processing; (3) importing the processed data to HMS; and (4) merging the observed historical data with the processed DEM for model simulations.

4 Study areas and data processing

4.1 Study areas

The model was applied to two catchments: the Misai and Wan’an Catchments. The Misai Catchment is in Zhejiang Province, in southern China. It has a total of six rain gauge measurement stations: Qixi, Majin, Yanxi, Daxibian, Huanglinkang, and Misai. The catchment has a total area of 797 km^2. The Wan’an Catchment is in Anhui Province, in southern China. It has a total of four rain gauge measurement stations: Xiuning, Yixian, Yanqian, and Rucun. The catchment has a total area of 869 km^2. The region is very similar to the Misai Catchment; in fact, they are neighboring catchments, both mountainous with thick vegetation cover, very fertile with a highly permeable upper layer soil profile, and humid.

4.2 Data processing

30" × 30" resolution DEMs were generated from data provided by the U. S. Geological Survey (USGS) (NGDC 2009), from the website. The hydrologic models were generated with the help of HEC-GeoHMS (USACE 2000a, 2000b) using DEMs of the study areas (Fig. 1 and Fig. 2). Using DEM terrain data, HEC-GeoHMS produces HMS input files, a stream network, sub-basin boundaries, and connectivity of various hydrologic elements in an ArcView GIS environment via a series of steps called terrain pre-processing and basin processing. The physical representation of catchments and rivers was configured in the basin models, and hydrologic elements were linked.

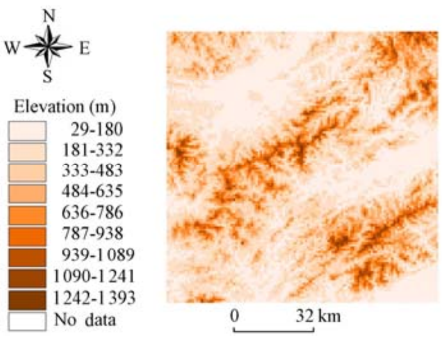

Fig. 1 Misai Catchment raw DEM

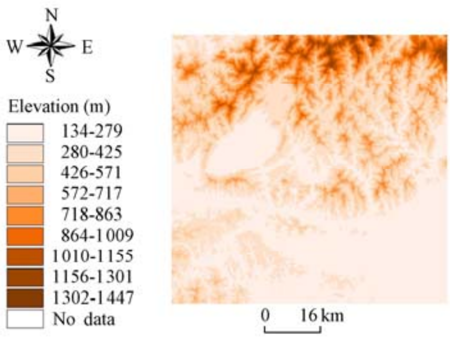

Fig. 2 Wan’an Catchment raw DEM

4.3 Terrain pre-processing

Determination of a hydrologically correct DEM and its derivatives, mainly the flow direction and flow accumulation grids, often demands some iteration of drainage path calculations in order to precisely depict the flow of water through the catchment, the hydrologically correct DEM must have a resolution sufficient to capture the details of surface flow. Problems often arise when the drainage area has a coarse resolution. These problems can be overcome if proper care is taken in the terrain pre-processing stage to produce a fine resolution of the drainage area. To obtain the DEM used to delineate various components of the catchments used for this study, the following steps were taken.

4.3.1 Filling sinks

A sink is a cell with no clear or defined drainage direction; all surrounding cells have higher elevation, resulting in stagnation of water. To overcome this problem, the sink has to be filled by modifying the elevation value. Once the sinks in a DEM are removed by breaching and filling, the resulting flat surface must still be interpreted to define the surface drainage pattern, because there is no flow on flat areas by definition, so the next step in the procedure requires that flow direction be assigned. The elevation of pit cells is simply increased until a down-slope path to a cell becomes available, under the constraint that flow may not return to a pit cell.

4.3.2 Flow direction

The flow direction was derived from the filled grid based on the premise that water flows downhill, and will follow the steepest descent direction. It provides the flat filled surface with a slope to enable water flow freely downward without having to be impounded or trapped. This was done by the assigned gentle slope to the filled grid DEM until the steepest descent direction was achieved. Water can flow from one cell to one of its eight adjacent cells in the steepest descent direction.

4.3.3 Flow accumulation

Based on the derived flow direction grid, the flow accumulation was calculated. A flow accumulation grid was calculated from the flow direction grid. The flow accumulation records the number of cells that drain into an individual cell in the grid. The flow accumulation grid is essentially the area of drainage to a specific cell measured in grid units. The flow accumulation grid is the core grid in stream delineation.

4.3.4 Stream definition

The threshold area was assigned to the flow accumulation grid in order to obtain the stream flow path. The stream flow path is defined by a number of cells that accumulate in an area before they are recognized.

5 Model application and calibration

In this study, 16 flood events that occurred during the seven-year period of 1982-1988 in the Misai Catchment and 15 flood events from 1987 and 2002 (there were no data from the period of 1998-2001) in the Wan’an Catchment were used for model testing. These data were obtained from the *Chinese Hydrological Year Book*. HMS uses a project name as an identifier for a hydrologic model. An HMS project must have the following components before it can be run: a basin model, a meteorological model, and control specifications. The basin model and basin features were created in the form of a background map file imported to HMS from the data derived through HEC-GeoHMS for model simulation (Fig. 3 and Fig. 4). The observed precipitation and discharge data were used to create the meteorological model using the user gauge weighting method and, subsequently, the control specification model was created. The control specifications determine the time pattern for the simulation; its features are: a starting date and time, an ending date and time, and a computation time step. To run the system, the basin model, the meteorological model, and the control specifications were combined. The observed historical data of six precipitation stations representing each sub-catchment and one stream gauge station in the Misai Catchment, and four precipitation stations representing each sub-catchment and one stream gauge station in the Wan'an Catchment, were used for model calibration and verification. An hourly time step was used for the simulation based on the time interval of the available observed data.

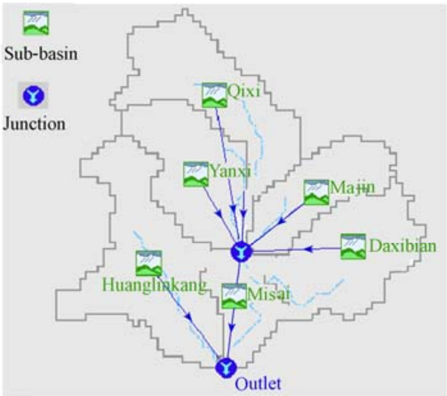

Fig. 3 Processed results for Misai Catchment imported to HMS for simulation

Fig. 4 Processed results for Wan'an Catchment imported to HMS for simulation

The initial and constant method was employed to model infiltration loss. The SCS (Soil Conservation Service) unit hydrograph method was used to model the transformation of precipitation excess into direct surface runoff. The exponential recession model was employed to model baseflow. The Muskingum routing model was used to model the reaches.

The trial and error method, in which the hydrologist makes a subjective adjustment of parameter values in between simulations in order to arrive at the minimum values of parameters that give the best fit between the observed and simulated hydrograph, was employed to calibrate the model. The criterion used to evaluate the fit was the determination coefficient (*DC*). Although the model was calibrated manually, the HEC-HMS built-in automatic optimization procedure was used to authenticate the acceptability and suitability of the parameter values and their ranges as applicable to their uses in HEC-HMS. The choice of the objective function depends upon the need. Here, percentage error in peak flow and volume were employed during the optimization and implementation of the univariate gradient search method. The recession constant was 0.70.

As stated earlier, ten flood events that occurred over four years in the Misai Catchment were used for model calibration, and six flood events that occurred over three years in the

Misai Catchment were used for model verification. In the Wan'an Catchment, nine flood events that occurred over eight years were used to calibrate the model and six flood events that occurred over four years were used for model verification.

6 Results and discussion

As described in the introduction, each component of HEC-HMS models an aspect of the precipitation-runoff process within a portion of the basin, commonly referred to as a sub-basin. Representation of a component requires a set of parameters that specify the particular characteristics of the component and mathematical relations that describe the physical processes (Singh 1982). Tables 1 and 2 below show the calibrated parameter values of each of the components represented in this model. Apart from the sub-areas, which are fixed, parameters were calibrated simultaneously through adjustment of their values until a good agreement between the observed and simulated hydrographs was achieved.

Table 1 Calibrated parameter values of Misai Catchment

Sub-basin	Area (km^2)	SCS lag (min)	Recession constant	Threshold discharge (ratio to peak)	Muskingum coefficient	
					X	K (h)
Qixi	207.22	510	0.7	0.12	0.2	1
Majin	162.59	400	0.7	0.12	0.2	1
Yanxi	130.71	518	0.7	0.12	0.2	1
Daxibian	131.51	391	0.7	0.12	0.2	1
Huanglinkang	89.26	450	0.7	0.12	0.2	1
Misai	75.71	240	0.7	0.12	0.2	1

Table 2 Calibrated parameter values of Wan'an Catchment

Sub-basin	Area (km^2)	SCS lag (min)	Recession constant	Threshold discharge (ratio to peak)	Muskingum coefficient	
					X	K (h)
Xiuning	106.51	450	0.7	0.12	0.2	1
Yixian	271.53	500	0.7	0.12	0.2	1
Yanqian	246.85	500	0.7	0.12	0.2	1
Rucun	240.91	450	0.7	0.12	0.2	1

The calibration and validation graphs of the two catchments are shown below. Figs. 5 through 8 show good agreement between observed and simulated graphs. Also, Tables 3 and 4 show observed and simulated values, as well as *DC* values, for both calibration and validation of the two catchments.

Q_s is the simulated discharge, Q_o is the observed discharge, and *DC* is defined as follows:

$$DC = 1 - \frac{\sum_{i=1}^{n}\left[y_c(i) - y_o(i)\right]^2}{\sum_{i=1}^{n}\left[y_o(i) - \bar{y}_o\right]^2} \tag{1}$$

where $y_o(i)$ is the observed discharge for each time step *i*, $y_c(i)$ is the simulated value at time step *i*, $\bar{y}_o$ is the mean observed discharge, and *n* is the total number of values within the time period.

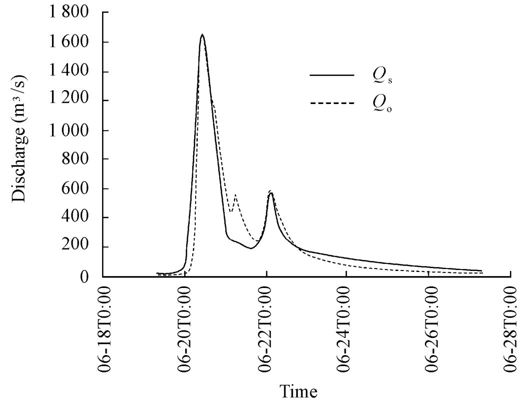

Fig. 5 Observed vs. simulated discharge in 1982 for calibration

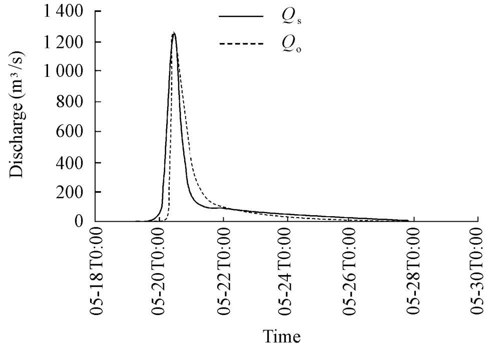

Fig. 6 Observed vs. simulated discharge in 1986 for validation

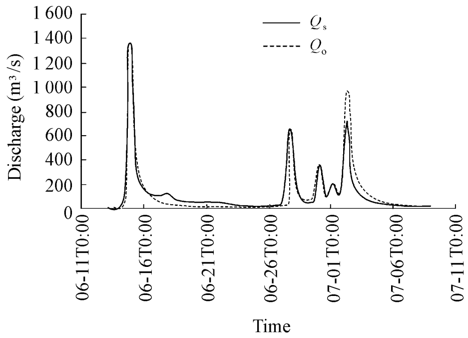

Fig. 7 Observed vs. simulated discharge in 1990 for calibration

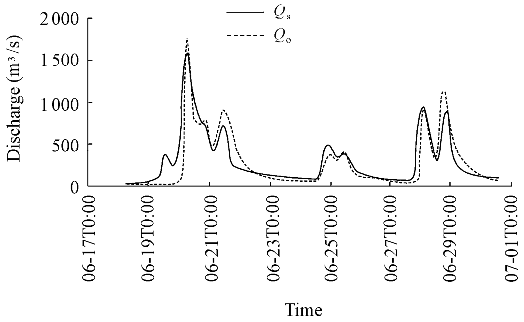

Fig. 8 Observed vs. simulated discharge in 2002 for validation

Table 3 Calibration and validation results for Misai Catchment

Period	Date	Q_s (m^3/s)	Q_o (m^3/s)	ΔQ (m^3/s)	Relative error (%)	Δt (min)	*DC*
Calibration	1982-04-02	344.99	345	–0.01	0	0	0.99
	1982-06-19	1 642.30	1 650	–7.70	–0.46	0	0.99
	1983-05-29	1 728.00	1 820	–92.00	–5.10	–60	0.92
	1983-06-14	942.27	942	0.27	0.03	0	0.99
	1983-06-20	1 447.60	1 420	27.60	1.94	60	0.98
	1984-04-02	798.05	795	3.05	–1.38	10	0.99
	1984-05-12	269.36	279	–9.64	–3.25	0	0.99
	1984-06-07	287.01	287	0.01	0	–60	0.99
	1985-05-04	758.76	745	13.75	1.85	0	0.99
	1985-07-03	398.25	398	0.25	0.06	60	0.99
Validation	1986-05-19	1 251.50	1 240	11.50	0.93	0	0.99
	1986-07-04	275.37	267	8.71	3.30	10	0.95
	1987-04-25	284.00	271	12.61	4.64	0	0.99
	1987-05-26	201.10	207	–5.70	–2.85	30	0.99
	1987-06-20	1 371.90	1 370	1.90	0.14	0	0.99
	1988-06-21	1 211.00	1 220	–9.00	–0.74	10	0.97

Note: ΔQ is error in peak discharge and Δt is peak time error.

Table 4 Calibration and validation results for Wan'an Catchment

Period	Date	Q_s ((m^3/s)	Q_o (m^3/s)	ΔQ (m^3/s)	Relative error (%)	Δt (min)	*DC*
Calibration	1987-07-02	723.16	780	–56.84	–7.30	60	0.95
	1988-06-16	731.28	727	4.28	0.58	0	0.99
	1989-05-20	553.72	526	27.72	5.26	0	0.99
	1990-06-13	1 350.30	1 260	90.30	7.20	0	0.99
	1991-06-30	1 656.30	1 840	–183.70	–9.98	0	0.89
	1992-06-20	790.04	797	–6.96	–0.87	–10	0.99
	1993-05-27	870.21	888	–17.79	–2.00	5	0.99
	1993-06-28	1 164.90	1 920	755.10	19.30	20	0.83
	1994-05-01	1 192.10	1 290	–97.90	–7.60	40	0.74
Validation	1995-05-15	1 657.40	1 814	–156.60	–8.63	40	0.99
	1995-06-30	1 576.10	1 480	96.10	6.49	60	0.95
	1996-06-01	798.60	803	–44.00	–0.55	60	0.83
	1996-06-23	2 850.10	2 970	–119.90	–4.04	0	0.76
	1997-07-05	759.66	779	–19.34	–2.50	0	0.97
	2002-06-18	1 785.00	1 720	65.00	3.80	60	0.99

It can be seen in the above graphs that the simulated and observed peak discharges occurred on the same day, and their maximum time difference was one hour, which is acceptable for flood forecasting. The entire *DC* for the Misai Catchment was above 0.9, while in the Wan'an Catchment there were two *DC* values below the acceptable value: 0.74 and 0.76. Li et al. (2008) applied the Xin'anjiang model to the Misai Catchment with the same data set and obtained almost the same results.

7 Conclusions

As shown in the results above, the model predicted peak discharge accurately based on the available historical flood data. Both the flood volume and timing were fairly accurate. This shows that HEC-HMS is suitable for the studied catchments. From the results, we can conclude that the complexity of the model structure does not determine its suitability and efficiency. Though the structure of HEC-HMS is simple, it is a powerful tool for flood forecasting. A further application of HEC-HMS should be encouraged to confirm its suitability for the Chinese catchments.

Acknowledgements

The author would like to acknowledge the use of observation data from the *Chinese Hydrological Year Book*, and to thank Hohai University in Nanjing, P. R. China, for supporting this study.

References

Beven, K. J., and Kirkby, M. J. 1979. A physically based variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin*, 24(1), 43-69.

Burnash, R. J., Ferra, R. L., and McGuire, R. A. 1973. *A General Stream Flow Simulation System Conceptual Modeling for Digital Computer*. Sacramento: Joint Federal State River Forecasts Center.

Chow, V. T., Maidment, D. R., and Mays, L. W. 1988. *Applied Hydrology*. New York: McGraw-Hill.Clarke, R. T. 1975. Prediction in catchment hydrology. Chapman, T. G., and Dunin, F. X., eds., *Proceedings of a National Symposium on Hydrology*, 482. Canberra: Australian Academy of Science.

Crawford, N. H., and Linsley, R. K. 1966. *Digital Simulation in Hydrology*: *The Stanford Watershed Model IV Technical Report.* Palo Alto, CA: Stanford University.

Li, S. Y., Qi, R. Z., and Jia, W. W. 2008. Calibration of the conceptual rainfall-runoff model's parameters. *Proceeding of 16th IAHR-APD Congress and 3rd Symposium of IAHR-ISHS*, 55-59. Beijing: Tsinghua University Press.

National Geophysical Data Center (NGDC). http://www.ngdc.noaa.gov/cgi-bin/mgg/ff/nph-newform.pl/mgg/topo/customdatacd/ [Retrieved Oct. 6, 2009]

Singh, V. P. 1982. *Applied Modeling in Catchment Hydrology*. Littleton, CO: Water Resources Publications.

Sivapalan, M., Beven, K. J., and Wood, E. F. 1987. On hydrologic similarity 2: A scale model of storm runoff production. *Water Resources Research*, 23(12), 2266-2278.

Sugawara, M. 1979. Automatic calibration of the tank model. *Hydrological Sciences Bulletin*, 24(3), 375-388.

Todini, E. 1996. The ARNO rainfall-runoff model. *Journal of Hydrology*, 175(1-4), 339-382. [doi: 10.1016/S0022-1694(96)80016-3]

U. S. Army Corps of Engineers (USACE). 2000a. Geospatial modeling extension. *HEC-GeoHMS*, *User's Manual*. Davis, CA: U.S. Army Corps of Engineers, Hydrologic Engineering Center.

U. S. Army Corps of Engineers (USACE). 2000b. *Hydrologic Modeling System: Technical Reference Manual*. Davis, CA: U.S. Army Corps of Engineers, Hydrologic Engineering Center.

Zhao, R. J. 1992. The Xin'anjiang model applied in China. *Journal of Hydrology*, 135(1-4), 371-381. [doi: 10.1016/0022-1694(92)90096-E]