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Evaluation of the Xinanjiang model structure by observed discharge and gauged soil moisture data in the HUBEX/GAME Project

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Abstract Based upon the sense that the use of an inadequate model structure may be more problematic than the use of sub-optimal parameter values, the experience and progress in the HUaihe River Basin EXperiment (HUBEX) during the intensified observation period from 1998 to 1999, as a component of the GEWEX (Global Energy and Water Cycle EXperiment) Asian Monsoon Experiment (GAME) Project, is reported in this paper. It focuses on the realism of the Xinanjiang model structure evaluated not only by discharge hydrographs observed upstream (Huangnizhuang station) and downstream (Jiangji station), but also by volumetric soil moisture data gauged at three sites, Meishan, Nianyushan, and Jiangji. The Xinanjiang model was applied to subcatchments derived from the digital elevation data for runoff generation. The Muskingum method was used for the routing of discharge from the outlet of each subcatchment to the outlet of the whole studied catchment. Soil tension water storage at each time interval computed by the Xinanjiang model, in millimetres is in good agreement with soil moisture data time series gauged in the field. Their correlation coefficients range from 0.810 to 0.867. The results show that the values of soil tension water storage in the Xinanjiang model can represent temporal variability of the soil moisture state variable within the subcatchments, reflecting wet or dry situations in the real world. That, to some extent, answers the question of how far the internal model state relates to real world variables.

Key words digital elevation model; discharge hydrograph; model structure; runoff generation; soil moisture; Xinanjiang model

INTRODUCTION

In general, a hydrological forecasting system includes three components: appropriate climatic and meteorological inputs from space-borne, air-borne and on-ground data sets or from computed models, such as GCM (General Circulation Model), QPE (Quantitative Precipitation Estimates, Vieux *et al.*, 2003) or HEP (Hydrological Ensemble Prediction, Schaake, 2004); the hydrological model structure; and the corresponding parameters (Sivapalan *et al.*, 2003). If a ranking is performed regarding those three components, climatic and meteorological inputs rank no 1. Well-defined spatiotemporal resolution of real data, such as precipitation, evapotranspiration, discharge, water level, groundwater table depth, and soil moisture, provide a significant basis for the development of hydrological models in simulation mode and for the implementation of hydrological forecasting systems in the real world. The hydrological model structure ranks second. The model structure should reflect real hydrological phenomena or basic hydrological laws. Hence, we must focus on principal and key aspects of hydrological processes at different spatiotemporal scales. For instance, the problem of how much runoff is to be generated from precipitation is more significant than how the runoff is to be routed, i.e. the problem is more what to route than how to route (Cordova & Rodriguez-Iturbe, 1983). Thus the priority should be given to the computation of runoff production. The Xinanjiang model is a semi-distributed conceptual hydrological model for use in humid or semihumid regions (Zhao, 1992; Zhao & Liu, 1995). It has the following advantages: (a) runoff depth computation over partitioned subcatchments: (b) evapotranspiration estimation by a three-layer method; (c) runoff components separation into surface, subsurface, and groundwater flows, according to flow velocity; and (d) relations between partial model parameters on different time scales, so as to conveniently transfer them across temporal scales, e.g. to derive the outflow coefficients of the free-water storage to groundwater and subsurface flow in an hourly model, from those in a daily model, based on the fact that daily hydrological data are more available than hourly data in the real world. Finally, the model parameters rank third. Parameters, especially sensitive ones, should have physical meaning. No matter what kind of objective function and what kind of optimization method is selected, the model structure is of great importance. A well-defined model structure plays a more significant role in the hydrological forecasting system than sub-optimal parameter values. The magnitude of a model parameter within a poor model structure would make less sense, even calibrated by very advanced optimization methods.

The space–time distribution of soil moisture is a key component in describing the transfer and distribution of mass and energy between the land and the atmosphere. It is a fundamental variable in biosphere–atmosphere transfers, biogeochemistry, ecosystem processes, and the rainfall–runoff process itself. The measurement of soil moisture is difficult, particularly if information is required over an area, at depth, and continuously in time. *In situ* measurement is accurate, but not able to cover a large area. Remotely sensed data give information over a large area, but can only penetrate a very thin surface layer. The soil layer may be divided into an aeration zone and a saturated zone from up to down. Soil water in the unsaturated zone can be categorized into non-active, active tension water, and free water. The active tension water is the most active portion of soil water that controls the runoff generation and evapotranspiration. As an initial condition, the estimation of watershed wetness has always been the central part of rainfall–runoff modelling. In the early stages, the API (Antecedent Precipitation Index) method was widely used. Later, many efforts were made to improve the simulation of soil moisture conditions in order to increase the accuracy of runoff prediction. As a result, an index of initial storage that is closely related to the active tension water in the effective soil layer was developed.

Based upon the assumption that the use of an inadequate model structure may be more problematic than the use of sub-optimal parameter values, the experience and progress in the HUaihe River Basin EXperiment (HUBEX) during the intensified observation period from 1998 to 1999, as a component of the GEWEX Asian Monsoon Experiment (GAME) Project, is reported here. The focus is on the realism of the Xinanjiang model structure, which is evaluated not only by discharge hydrographs observed upstream (Huangnizhuang station) and downstream (Jiangji station), but also by volumetric soil moisture data gauged at three sites, Meishan, Nianyushan, and Jiangji. The Xinanjiang model was applied to subcatchments derived from the digital elevation data for runoff generation. And the Muskingum method was used for the routing of discharge from the outlet of each subcatchment to the outlet of the whole studied catchment. Soil tension water storage at each time interval computed by the Xinanjiang model in millimetres will be compared with soil moisture data gauged in the real field.

STUDY AREA

The Shiguan River catchment within 31.2–32.3°N and 115.25–115.75°E is selected for this case study. Jiangji Station (see Fig. 1) is the outlet of this catchment with an area of 5930 km^2. The Shiguan River is a first-order southern tributary of the Huaihe River. There are two large reservoirs in the catchment. One, called the Nianyushan Reservoir that has 9.16×10^8 m^3 of total storage capacity, and controls 924 km^2 of drainage area. The other is the Meishan Reservoir with 2.338×10^9 m^3 of total storage capacity and 1970 km^2 of drainage area.

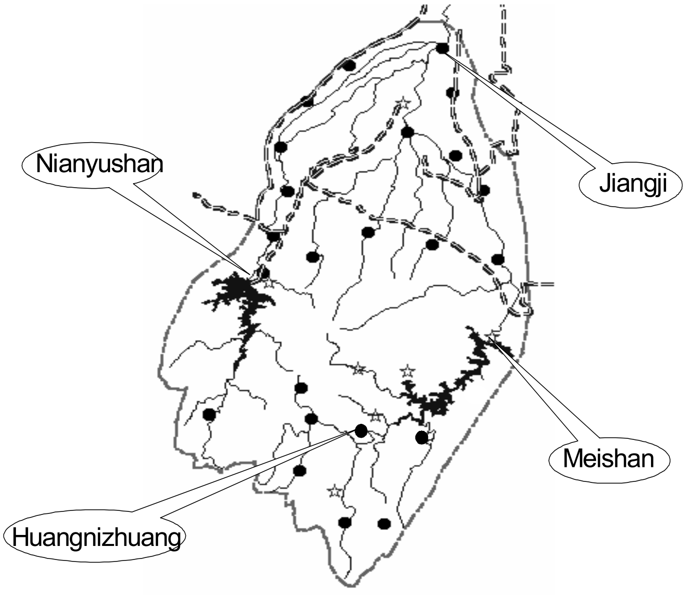

Fig. 1 Overview of the Shiguan River catchment.

There are various kinds of topographical situations, not only highly mountainous and hilly areas with the maximum elevation of 1576 m a.m.s.l., where the stream flows very fast, but also low alluvial plains where the drainage network is well developed. Therefore the Shiguan River catchment was selected as the intensified observation field for the HUBEX Project as the component of GAME supported financially from the National Natural Science Foundation of China.

GENERATION OF DIGITAL BASIN

The Digital Elevation Drainage Network Model (DEDNM) developed by Martz & Garbrecht (1992), or so-called TOpographical PArameteriZation (TOPAZ, Garbrecht & Campbell, 1997), was applied to the generation of the digital basin from the digital elevation model data, including raster-based flow-vector direction assignation over depressional and flat areas of the DEM, stream network generation, watershed divides delineation, and spatial topological evaluation of river network within a catchment. The relief imposition algorithm reported by Martz & Garbrecht (1992) was taken to generate a realistic, topographically consistent and convergent drainage network over the flat surfaces produced by depression-filling, as well as those inherent to the DEM, such as level valley floors or plateau at the watershed divide. On the basis of DEM pre-processing, the steepest downslope path method is applied to the determination of flow vectors on each grid. Then drainage area can be calculated in terms of the number of cells, watershed divide boundary delineated, drainage network generated and indexed step by step (Garbrecht & Campbell, 1997).

Both a Critical Source Area (CSA) and a Minimum Source Channel Length (MSCL) should be specified before the program of drainage network generation is run. Considering the specific topography, land cover, soil and rock of the Shiguan River catchment: the southern upstream part of two reservoirs is high mountain with a forest cover rate of 65%, while the northern area is smooth cropland, the catchment is partitioned into four subareas, each of which has been designated by different values of CSA and MSCL in order to reflect the spatial variability of factors affecting drainage network development (see Table 1).

The Horton-Strahler order of each channel link could be determined once a well-connected channel network is produced. An optimal executive sequence for cascade-type flow routing through the channel link may be determined according to the procedure described by Garbrecht (1988). Finally, the topological relationship amongst network nodes, channel links and subcatchments can be obtained, including the source drainage area of the first Strahler order channel, the direct contributing drainage area of left and right sides of each channel link, node elevation and slope of channel link, and related connected information.

DISCHARGE VERIFICATION

A rainfall–runoff model can be established over each subcatchment that is generated and numbered automatically by the DEDNM. Here, the Xinanjiang model (Zhao &

Table 1 Specified values of critical source area (CSA) and minimum source channel length (MSCL) designated to four subareas covering the Shiguan River catchment.

No.	North latitude	East longitude	CSA (km^2)	MSCL (km)
1	31–31.67°N	115–116°E	54	1.8
2	31.67–32°N	115–116°E	55	1.8
3	32–32.33°N	115.5–116°E	60	2.0
4	32–32.33°N	115–115.5°E	60	2.2

Liu, 1995) model (Zhao & Liu, 1995) is applied to each subcatchment, which is more or less homogeneous, for runoff production with different parameters in different subareas. These subareas are connected to the drainage network where runoff is routed by the Muskingum method from the outlet of each subcatchment to the specified outlet on the basis of the topological relationship of the river network structure produced by the DEDNM.

The Xinanjiang model is characterized by the concept of runoff formation on repletion of storage. That is to say, runoff is not produced until the soil moisture content of the aeration zone reaches field capacity, and thereafter runoff equals the rainfall excess without further loss. That concept could be understandable when applied to a point. The tension water storage capacity curve was introduced by Zhao in the 1960s while applied to a catchment. Three kinds of spatially heterogeneous distributions are taken into consideration in the Xinanjiang model: (a) uneven distribution of tension water storage capacity throughout the subcatchment is expressed by a parabolic curve for partial-area runoff generation; (b) non-uniform distribution of free water storage capacity over partial area where runoff has been produced, is expressed also in terms of a parabolic curve for separation of runoff into surface flow, interflow and groundwater flow; (c) the amount of free water storage is represented by the structure of linear reservoir for the sake of different velocities of different runoff components.

The Shihe catchment upstream of Huangnizhuang Station and the Shiguan River Basin upstream of Jiangji Station (see Fig. 1) are selected for discharge verification. Figures 2 and 3 show some simulated results. Further analysis will be made as follows.

It can be seen that the digital hydrological model (Ren & Liu, 2000) performs well for hourly flood hydrograph at Huangnizhuang Station in Fig. 2. And it simulates the peak values better than the low values of the daily discharge hydrograph at Jiangji Station (the outlet of the Shiguan River catchment) in Fig. 3 during the wet season of 1998. The reason is that there are several man-made irrigation channels upstream of Jiangji Station, which draw water from the Shiguan River when it does not rain. However, the amount of water drawn from the river is not available for inclusion in the simulation. Therefore, the simulated discharge is a little bit larger than the one observed in Fig. 3.

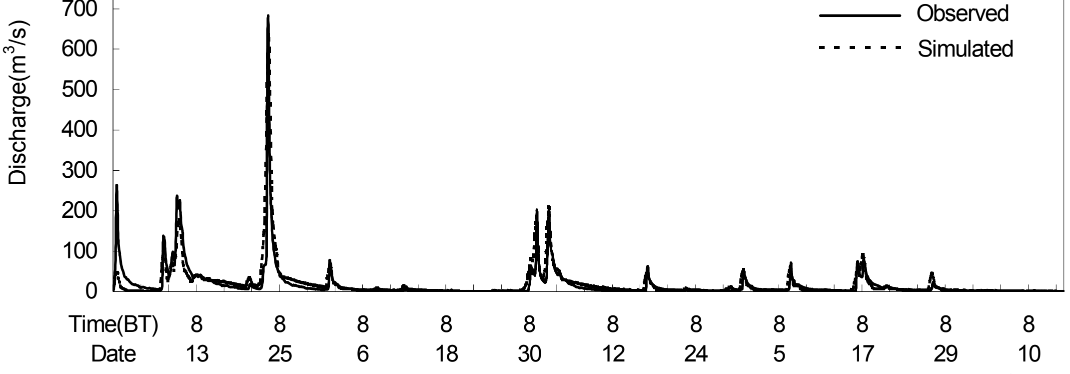

Fig. 2 Comparison between observed and simulated discharges at Huangnizhuang Station from 1 May to 15 September 1998.

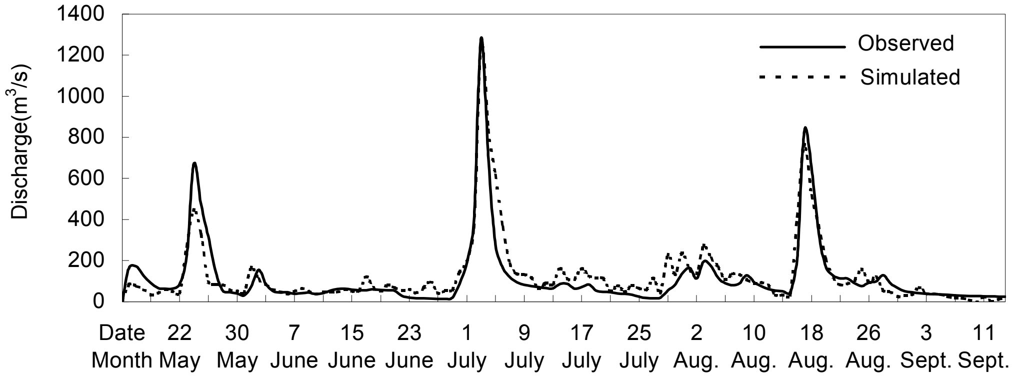

Fig. 3 Comparison between observed and simulated discharges at Jiangji Station from 15 May to 15 September 1998.

Because numbering of the drainage network nodes and segmented subcatchments, and generation of the topological relation of the drainage network are done automatically by the DEDNM, the digital hydrological model can operate very conveniently in the context of spatial positioning (Ren & Liu, 2000). That is to say, hydrographs and state variables at any site within a catchment are provided by the digital model. Meanwhile, discharge component parts at any station from its upstream tributaries might be simulated by the digital model. Figure 4(a) and (b) show the spatial distribution of rainfall over the Shiguan River catchment on 2–3 July 1998. Figure 4(c) and (d) show the spatial distribution of corresponding runoff depth over the Shiguan River catchment on 2–3 July 1998. Figure 5 shows the comparison between discharges from the upstream tributaries of Jiangji Station during the wet season of 1998. It can be seen from Fig. 5 that the peak discharge at Jiangji Station on 2 July 1998 resulted mainly from the Shicaohe River and the Jiliujian River, which corresponds to the darker area in Fig. 4(c).

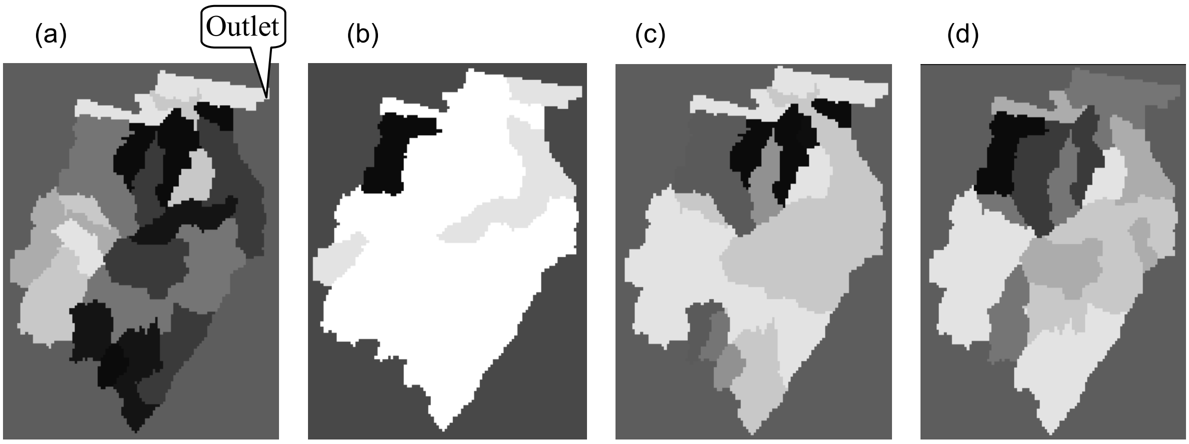

Fig. 4 Spatial distribution of rainfall and runoff over the Shiguan River catchment. The darker the grey, the larger the value of rainfall or runoff. (a) Rainfall distribution, 20:00–23:00 h, 2 July 1998; (b) rainfall distribution, 17:00–20:00 h, 3 July 1998 when the discharge peak appeared; (c) spatial distribution of runoff depth, 20:00–23:00 h, 2 July 1998; (d) spatial distribution of runoff depth, 17:00–20:00 h, 3 July 1998.

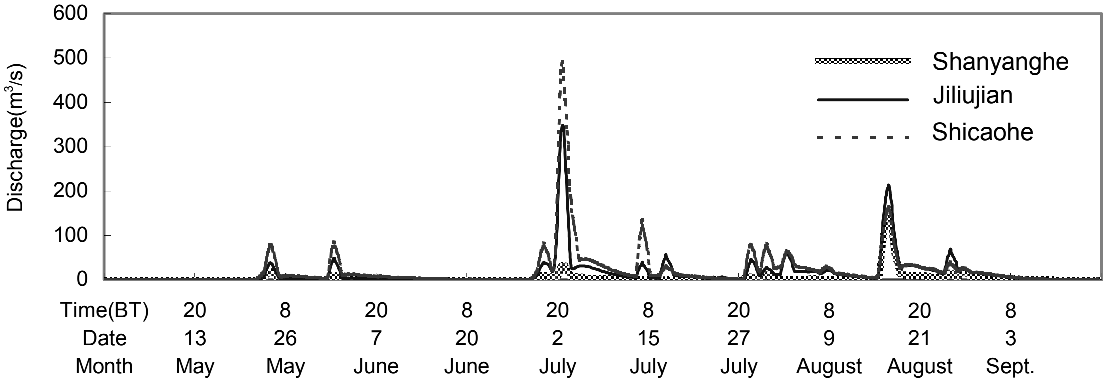

Fig. 5 Comparison between discharges from the upstream tributaries of Jiangji Station from May through September of 1998.

SOIL MOISTURE COMPARISON

During the Intensified Observation Period (IOP) of HUBEX from May to September in 1998/1999, besides observation of rainfall, evaporation, and runoff, soil moisture content was measured in terms of volumetric percentage using time domain reflectometry (TDR) probes so-called Type MP-406, at Nianyushan, Meishan, and Jiangji stations (see Fig. 1). The measurement was made at the land surface, 15 cm, 30 cm, 45 cm, 60 cm, and 90 cm below the surface. The values of soil tension water storage can be obtained in terms of depth (millimetre) from the hourly or daily Xinanjiang model on the basis of water balance. Table 2 shows the regression analysis between measured soil moisture and soil tension water data computed by the Xinanjiang model during IOP of HUBEX in 1998. Due to volumetric percentage of soil moisture measured at 08:00–09:00 h each day, the correlation coefficient is higher for the hourly model than that for the daily model, and the error sum of squares is less for the hourly model than that for the daily model for the three stations (Table 2). As shown in Fig. 1, three points, Nianyushan, Meishan, and Jiangji stations, at which soil moisture was measured in 1998 and 1999, make up a triangle. Nianyushan and Meishan stations near two large reservoirs, lie in the upper part of two main tributaries within the studied area. Jiangji station is situated at the outlet of the studied catchment. They are more than 60 km apart. Also they are on the top of hillocks, far from the river channel. So they are not correlated in space. The soil moisture data measured at three points can be taken as independent events.

Table 2 Correlation analyses between soil moisture content measured in the depth of 90 cm and soil tension water storage computed by the Xinanjiang model during IOP of HUBEX in 1998.

Statistical element	Nianyushan station		Meishan station		Jiangji station	
	Hourly model	Daily model	Hourly model	Daily model	Hourly model	Daily model
Correlation coefficient	0.867	0.822	0.851	0.820	0.839	0.810
Sample number	118	118	118	118	118	118
Error sum of squares	2.328	2.779	2.576	2.805	2.617	2.973

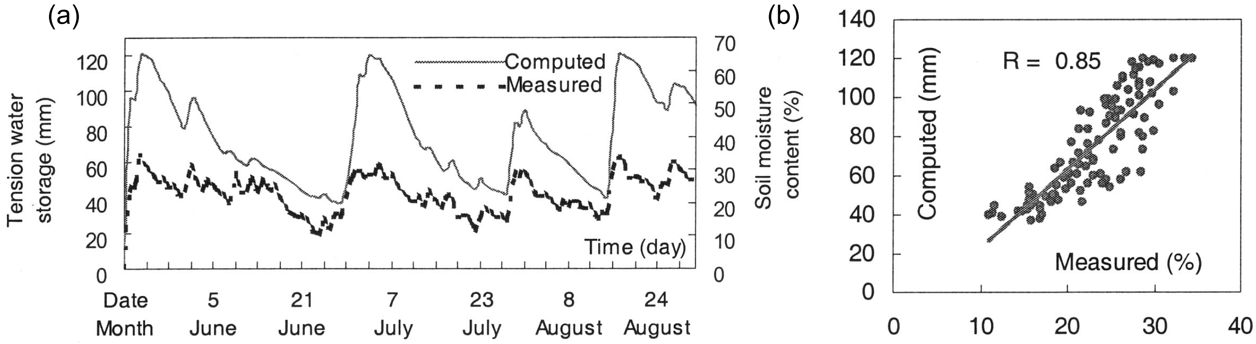

Fig. 6 Comparison and correlation between computed soil tension water and soil moisture content measured in the depth of 90 cm at Meishan Station during IOP in 1998. (a) Time series; (b) correlation analysis.

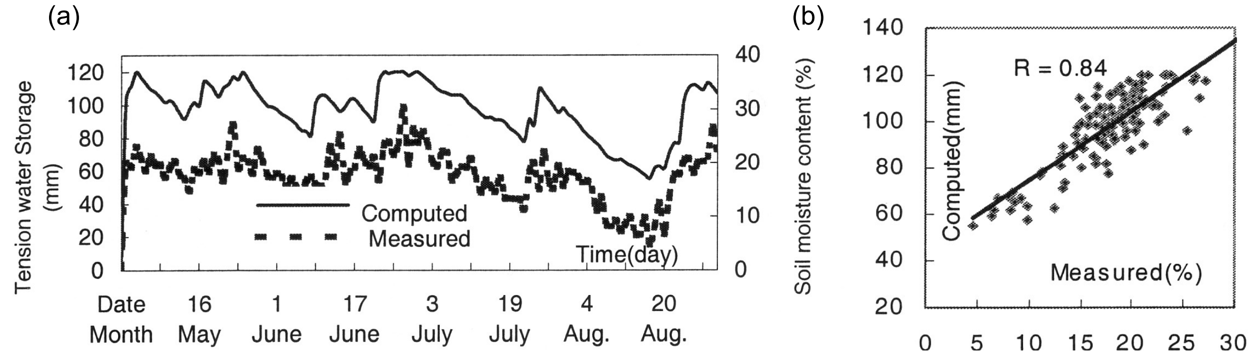

Fig. 7 Comparison and correlation between computed soil tension water and soil moisture content measured in the depth of 90 cm at Nianyushan Station during IOP in 1999. (a) Time series; (b) correlation analysis.

Figure 6 shows comparison and correlation between computed and measured soil moisture at Meishan station during the IOP in 1998. Figure 7 shows comparison andcorrelation between computed and measured soil moisture at Nianyushan station during the IOP in 1999, which corresponds to the situation expressed in Fig. 8. Their correlation coefficients are 0.85 and 0.84, respectively. It can be seen that the temporal variation of computed tension water storage is almost in agreement with that of the

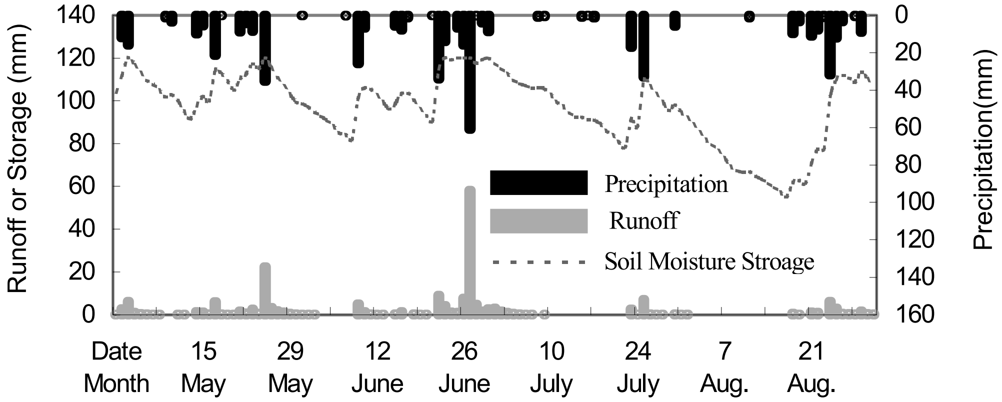

Fig. 8 Precipitation, runoff and tension water storage within the subwatershed nearby Nianyushan Station during IOP in 1999.

measured soil moisture content. It is shown that the values of tension water storage in the Xinanjiang model can represent the temporal variability of the soil moisture state variable, i.e. reflecting wet or dry situations within the catchment. Soil water storage can indeed stand for the index of soil moisture.

CONCLUSIONS AND SUGGESTIONS

In this research, both modelled discharge hydrographs and soil moisture state variable are verified by comparison with measured data in the real world. From one aspect, that justifies the structure of the soil moisture module in the Xinanjiang model when it is applied to the Shiguan River catchment. To some extent that answers the question regarding how far the internal model state relates to real world variables.Soil moisture is a state variable representing the volume of water stored in the relevant layer of the aeration zone. This volume of water is a component of the water balance of the land surface. Therefore the modelling of land surface water balance may be considered as an approach to the simulation of soil moisture variation and distribution. This approach gives the total quantity of soil water over a certain area and across a certain depth. It is believed that an integration of *in situ* measurement, remote sensing, and land surface water balance modelling may provide a methodology for the simulation of the space and time distribution of soil moisture over a large area.

The main concern raised is how to deal with interactions among multiple land surfaces, and relationships among single sensor measurements, statistical averages and the definition of spatial heterogeneity. Among the above issues, many are related to rainfall–runoff models. The main land surface processes, like evapotranspiration, surface runoff, groundwater recharge and discharge are all strongly soil moisture dependent. To improve the efficiency of runoff modelling, efforts should be made regarding the simulation of soil moisture variation and its spatial distribution. In return, the progress in rainfall–runoff modelling may increase our ability of soil moisture prediction and provide a sound base for the assimilation of soil moisture data. This significant relation between the simulated watershed storage and the observed soil moisture proved in this research that if the runoff simulation is more realistic, the index of watershed wetness as a by-product of the rainfall–runoff model is more meaningful and therefore closer to the real soil condition.

It should be pointed out that the volumetric soil moisture content was gauged at three observation points while soil tension water storage obtained by the Xinanjiang model, used for the above comparison, refers to the magnitude over subwatersheds in which the Nianyushan, Meishan, and Jiangji stations lie. After a catchment is segmented spatially as grid elements by the DEDNM, a grid element on the ground within the catchment matches the atmospheric input, such as precipitation and evapotranspiration. The grid-based hydrological model could provide a good platform for the computation of runoff and soil tension water, especially when radar-measured rain data are available as the input to the hydrological model (Ren *et al.*, 2003), so as to avoid the distinction of spatial ranges between point-gauged soil moisture and computed soil tension water.

Figure 9 gives an example of a a soil water profile measured at the Nianyushan station from 10 June to 24 August. It can be seen from Fig. 9 that the range of variation

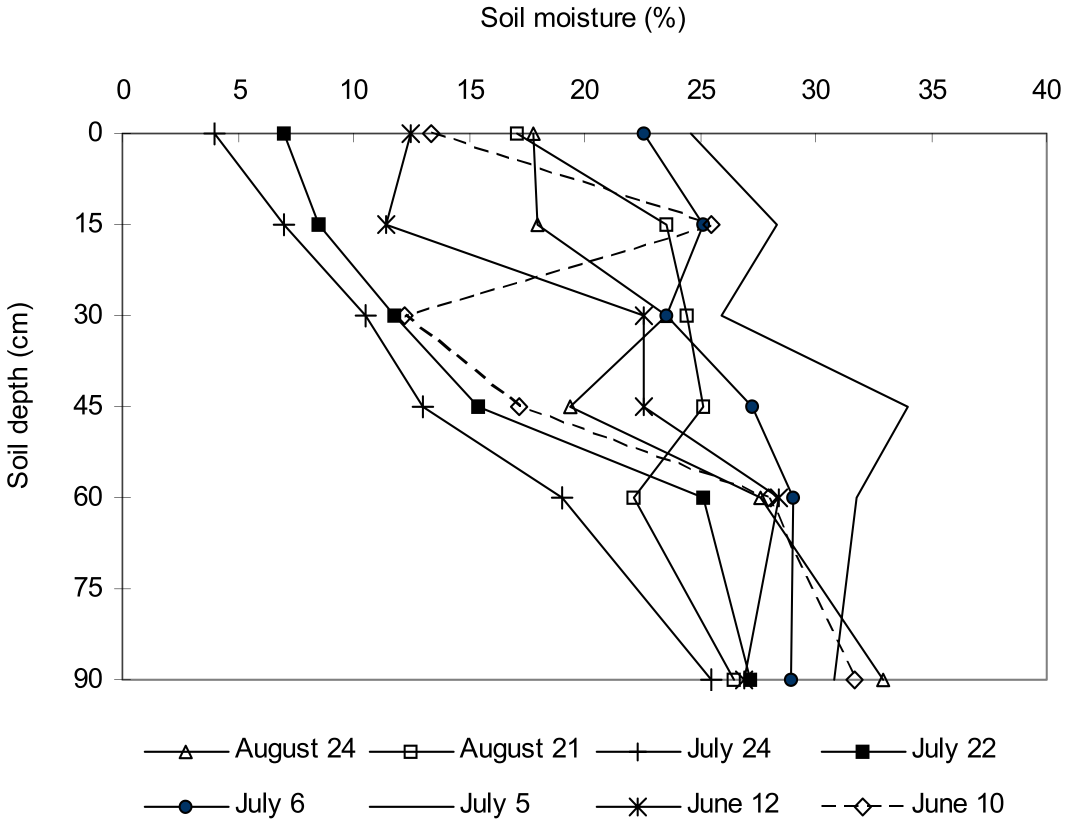

Fig. 9 Soil water profile measured at the Nianyushan station from 10 June to 24 August 1998.

of soil moisture content decreases with soil depth. In fact, the values of soil moisture content measured at three points, used for the above comparison, were averaged along the layer of soil depth. It is speculated that the depth over which soil moisture measurements are available should be more than 1.0 m in humid areas such as the Shiguan River catchment for data assimilation in the land surface schemes. As regards the location of soil moisture measurement, it is suggested that the gauged points would be set up over the different topographical characteristics with various types of vegetation and soil.

Soil moisture is a key component in the land surface schemes in GCMs, since it is closely related to evaporation and thus to the apportioning of sensible and latent heat fluxes. Soil moisture is pivotal in the formation of runoff and hence riverine flows. Further, soil moisture is an important determinant of ecosystem structure and hence a primary means by which climate regulates ecosystem distribution. Finally, adequate soil moisture is an essential resource for human activity. Consequently, accurate prediction of soil moisture is crucial for simulation of the hydrological cycle, of soil and vegetation biochemistry (including the cycling of carbon and nutrients), of ecosystem structure and distribution, and of climate (Berrien Moore III, 1999). Therefore it is of great significance to couple the module of soil moisture to the land surface schemes in GCMS.

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