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Hydrologic Modeling of the Heihe Watershed by DLBRM in Northwest China

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Abstract: Water shortage is a chronic problem in arid Northwest China. The increasing population growth and expanding urbanization as well as potential climate change impacts are likely to worsen the situation, threatening domestic, irrigation, and industrial supplies and even the survival of the ecosystems in Northwest China. This paper describes the preliminary work of adapting the Distributed Large Basin Runoff Model (DLBRM) to the Heihe watershed (the second largest inland river in arid Northwestern China, with a drainage area of 128 000 km^2) for understanding distribution of glacial/snow melt, groundwater, surface runoff, and evapotranspiration, and for assessing hydrological impacts of climate change and glacial recession on water supply in the middle and lower reaches of the watershed. Preliminary simulation results show that Qilian Mountain in the upper reach area produces most runoff in the Heihe watershed. The simulated daily river flows of the 1990▮2000 indicate that the Heihe River discharges about 1 billion m^3 of water from the middle reach (at Zhengyixia station) to lower reach, with surface runoff and interflow contributing 51 and 49 percent respectively. The sandy lower soil zone in the middle reach has the highest evapotranspiration rate and also contributes nearly half of the river flow. Work underway focuses on the DLBRM model improvement and incorporation of the climate change and management scenarios to the hydrological simulations in the watershed.

Key words: Distributed Large Basin Runoff Model (DLBRM)▮Heihe watershed in Northwestern China▮water shortage▮climate change

1 INTRODUCTION

Irrigated agriculture is essential to ensuring a stable food supply, particularly in arid and semi arid regions. Although accounting for only 17 percent of the world s cultivated land, irrigated land produces about one third of the world's grains[1▮2]. However, inappropriate development and management of irrigation systems have also resulted in numerous problems worldwide, including poor food security, increased human diseases, conflicts between different users, limitations on economic devel▮opment and human welfare, desertification, salinization, sand storms, water pollution, and so forth[3▮4]. In India, large scale overexploitation of groundwater for irrigation

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has caused water table decline across the country and many aquifers in the nation are depleted[2]. In Central Asia, increasing irrigation demands have resulted in the reduction of the Aral Sea, once the world's fourth largest lake, by 50 percent in size and the lowering of its water level by 16 m[5]. The ecological and human health impacts resulting from the shrinking lake area include depletion of fisheries and wildlife habitat, floral and faunal extinction, increasing respiratory and digestive diseases from inhalation and ingestion of blowing salt and dust, and rising mortality and morbidity[5]. In arid Northwest China, irrigated farming accounts for more than 80 percent of the total water uses. Over the past few decades, rapid population growth, agricultural irrigation expansion, and industrial development have led to groundwater depletion, river flow reduction, farmland salinization and ecosystem deterioration. An example of this situation is the Heihe (Black River) in Northwest China, with a drainage area of 128 000 km^2, the second largest inland river (or terminal lake) in the nation. From its headwaters in the south to the middle and lower reaches in the north, the Heihe flows through Qinghai, Gansu, and Inner Mongolia (Fig.1). While glacial/snow melt in the Qilian Mountain still contributes about 8 percent of the total annual water supply in the watershed, the glaciers have shrunk by 29 km^2 from 1960 to 1995[6]. Since the 1970s, the increased withdrawals for agricultural irrigation in the oases have depleted much of the river flows (in some years, the river dries up completely for some time) to the lower reach (below Zhengyixia Station as shown in Fig.1), shrinking East Juyan Lake and drying up West Juyan Lake, endangering the aquatic ecosystem, accelerating desertification, and intensifying water conflicts between the middle (between Yingluoxia and Zhengyixia) and lower reaches (Fig.1). To mitigate the water conflicts and rehabilitate West Juyan Lake, the State Council of China (the executive branch of the central government) issued a "Water Allocation Plan for the Heihe Watershed Mainstream" in 1997, mandating water allocation to the lower reach each year[6−7]. A number of water saving initiatives such as water quota, water rights, and transfer have been initiated to make effective use of water resources in the Heihe watershed. While a number of studies have been done in the Heihe watershed[6−9], the magnitude, spatial and temporal distribution, and transfer mechanism of the Heihe hydrologic system are still not well understood, especially in the face of climate change and urbanization. This gap, together with the lack of a comprehensive implementation plan has slowed down implementation of the State Council's water allocation plan.

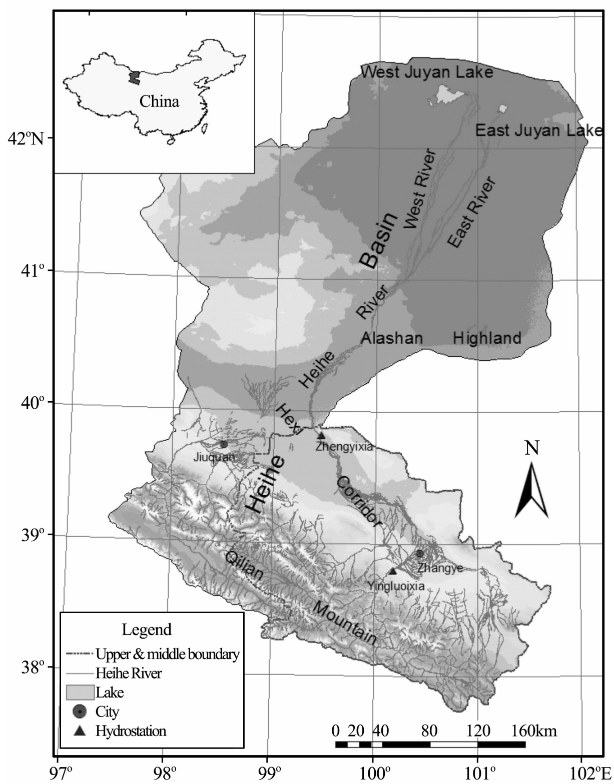

Fig.1 Boundary of the Heihe Watershed

To address this problem, this study uses a hydrologic modeling approach to address two key research questions facing the Heihe watershed: How does water distribute among glaciers, agricultural oases, and desert in the Heihe watershed? In the face of rapid population growth and climate change, how much water will be available to support competing demands for water for domestic, irrigation, industrial supplies and maintenance of the ecosystems?

This paper describes our collaborative work to adapt the US Department of Commerce's National Oceanic and Atmospheric Administration's (NOAA) Great Lakes Environmental Research Laboratory (GLERL) Distributed Large Basin Runoff Model (DLBRM) for understanding hydrologic processes of the Heihe watershed. We first describe the physical features of the Heihe watershed, then review the key factors in watershed modeling, and subsequently introduce the structure, input, and output of the DLBRM, and the Geographic Information System (GIS) interface to process and analyze multiple variables to the DLBRM. Finally we discuss its application to the Heihe watershed.

2 METHODS

2.1 The Study Area

From the headwaters in the south to the lower reach in the north, the Heihe watershed can be physically divided into the Qilian Mountain, the Hexi Corridor, and the Alashan Highland (Fig.1)[7]. The Qiliann Mountain is situated at the south of the watershed, with a peak elevation of 5 584 m. Ice and snow cover it all year round above 4 500 m. Mixed alpine meadow and permafrost dominate between 3 600 to 4 500 m. In the 1 900～3 600 m range, the mean annual precipitation is 250～500 mm and the main vegetation is forest and grassland. Below 1 900 m, the landscape is dominated by hilly desert or grassland desert with mean annual precipitation of 200～250 mm[7]. Located in the middle reach of the Heihe watershed, the Hexi Corridor hosts over 90% of the total agricultural oases in the watershed. More than 97 percent of the Heihe watershed's 1.8 million inhibits are concentrated in two metropolitan areas: Zhangye (population 1.25 million in 2000) and Jiuquan (population 0.49 million in 2000) in the Corridor. Irrigation supply is from both surface water withdrawals and groundwater pumping. North of the Hexi Corridor is the Alashan Highland (the area north of Zhengyixia with mean elevation 1 000 m), an extremely dry desert with an annual precipitation below 50 mm. Spotty oases appear intermittently along the streams, lakes, and irrigation ditches. Since it is extremely dry, the Alashan Highland is a large source of frequent sandstorms[8, 10-11].

Water shortage is a chronic problem in the Heihe watershed. The total annual mean water supply (both surface water and groundwater) in the watershed is approximately 4.11 billion (10^9) m^3 and nearly 90 percent of the flows are generated in the Qilian Mountain. The total annual water withdrawals in the Heihe in 1995 were about 3.36 billion m^3 and 86 percent of that was used to irrigate 288 000 hm^2 of farmland mainly located in the Hexi Corridor[7]. Water deficits range from 0.32 billion m^3 (normal years with 50% non-exceedance), to 0.57 billion m^3 (dry years with 75% non-exceedance), and 0.82 billion m^3 (drought years with 95% non-exceedance) respectively[7]. Water conflicts have been high between water users in the Hexi Corridor and those in Alashan Highland in the lower reach, particularly in implementing the State Council's water allocation plan to deliver water to the lower reach for rehabilitation of the West Juyan Lake[7].

2.2 Key Factors in Hydrologic Modeling

Hydrologic modeling, particularly distributed hydrologic modeling of large watersheds (usually > 10^3～10^4 km^2) involves four key factors: input digital databases, model structure, model calibration, and geographic information system (GIS) interfaces. This section gives a brief review of each of these factors (for detail, see Ref. [12]).

Input Digital Databases . Data availability is critical to successful hydrologic modeling. During the past three decades, rapid advances in remote sensing, GIS, digital databases, and computing technology have provided enormous opportunities for the hydrologic research community. For example, newly launched satellites, such as the Earth Observing System (EOS) PM-1, RADARSAT (space borne radar), LANDSAT 7 Enhanced Thematic Mapper (TM) Plus, Space Imaging, Inc's 1 m resolution of the IKONOS satellite, and others, enable the extraction of hydrologic parameters (e. g. areal estimates of precipitation, snow water equivalent and snow cover extent, vegetative cover, surface temperature, surface albedo, incoming solar radiation, soil moisture, and vegetation indices such as the Normalized Differential Vegetation Indices or NDVI) over multiple temporal and spatial scales. Digital Elevation Model (DEM) databases are widely used for deriving slope, aspect, drainage network, and flow direction for a watershed. Soil databases such as the State Soil Geographic Data Base (STATSGO) from the U. S. Department of Agriculture Natural Resource Conservation Service ensure the incorporation of spatial variation of soil characteristics into hydrologic models. Land cover databases allow the derivation of land use/cover related parameters such as leaf area index, and Manning's coefficient values to hydrologic models[12-14].

Despite the availability of a large number of digital databases makes, obtaining certain input variables for hydrologic models, especially for spatially-distributed models, remains a challenge. For example, precipitation is a key parameter in rainfall-runoff modeling. Estimates of the spatial distribution of precipitation are still inadequate due to a lack of spatial and temporal coverage of satellites and rain gauge stations, particularly in rural areas. Methods for estimating precipitation rates, such as cloud indexing, thresh-holding, and life history methods, by satellite remote sensing are still at an experimental stage. Microwave and geosynchronous orbiting satellites such as Geostationary Operational Environmental Satellite (GOES) can only provide limited types of observations. Ground-based radar is currently limited to a measurement circle with a radius of about 100 km and its distribution is mainly limited to densely populated areas[12]. Estimates of precipitation from those radar stations still need to be calibrated against measurements from nearby rain gauges. Application of satellite remote sensing is still at a research stage for estimating soil moisture and determining sediment load. No remote sensing methods have been found to measure streamflow in river basins, or infiltration of precipitation into the soil, deep soil moisture or groundwater, or the levels of chemical pollutants in water bodies[15]. Thus, hydrologic models for large basins must still rely on inadequately distributed rain gauges for estimates of precipitation. Therefore, development of large-scale hydrologic models need to take advantage of opportunities provided by remote sensing and GIS databases, and at the same time, to consider limitations of data availability in mathematical formulation and parameter specifications[12].

Structure of Hydrologic Models. Large-scale hydrologic models represent all the component hydrologic processes as a system of interconnected storages with mass continuity equations. Model components should include land surface, soil zones, and groundwater to produce realistic estimates of rainfall- runoff generation[16]. Variable-source-area concepts (runoff from a dynamically changing surface area) should be used in computing infiltration and saturation runoff as the variable-source models give a better representation of hydrologic processes and produce better estimates of overland flow and are less scale dependent[12, 16—18]. Soil layers and groundwater should be included in the model structure as water budget is very sensitive to the number of layers in the soil profile and omission of the subsurface-groundwater component in a runoff model can lead to an increase in model scale dependency[12, 16].

The Penman-Monteith (PM) method and the complementary relationship (CR) methods have both been widely used for estimating regional evapotranspiration (ET) over long periods of time. The PM method assumes that actual ET does not affect potential ET (the ET and potential ET are "independent"). It links the effects of vegetation to the ET process through aerodynamic and canopy resistance terms and may be more appropriate for small areas where detailed databases are available. The CR concept states that as water availability becomes limited then actual ET falls below its potential, and an excess amount of energy becomes available in the form of sensible heat and/or long-wave back radiation that increases the temperature and humidity gradients of the over passing air and leads to an increase in potential ET equal in magnitude to the decrease in ET. If water availability is increased, the reverse occurs, and ET increases as potential ET decreases. Thus, potential ET can no longer be regarded as an independent causal factor. Instead it is predicated upon the prevailing conditions of moisture availability[19]. The CR methods bypass complex and poorly understood soil-plant interactions, require fewer parameters for applications, and may be more applicable to large areas where detailed datasets are not available[19—20]. Dependent upon the data availability and the modeling scale, either method may be used in large-scale hydrologic models[12].

Spatial variations of climate and landscape have significant impacts on runoff modeling[17]. Large-scale hydrologic models should take advantage of available databases of DEM, vegetation, soil, climate, and hydrography to account for spatial variations of climate, soil, topography, and land use practices. While several approaches have been proposed as the fundamental scale for hydrologic modeling (e.g., representative elementary area, critical transitional area, and hydrologic response units or HRUs etc.), research on hydrologic scaling is evolving. Dependent upon the purpose of the study and data availability, the study watershed should be discretized into either grid network or hydrologic response units (HRUs), large-scale models applied to each cell or HRU, and output from each cell routed to the watershed outlet for identifying and understanding of both hydrologic responses and their spatial distribution in the study watershed[12].

Model Calibration and Uncertainty. Hydrologic models must be calibrated (model parameters estimated) to match observations with acceptable accuracy and precision[21-22]. Traditionally, hydrologic model calibration is done with split-sample testing by using streamflow data to find the "best" parameter set[21, 23]. This approach is practical, less data demanding, and easier to implement than dealing with multiple-response data. Recently researchers have explored different calibration approaches. Mroczkowski *et al*. (1997)[23] state that use of multiple-response data (e.g.streamflow, soil moisture, and chemical stream loads) in a watershed experiencing a change in hydrologic regime gives a better assessment of the model structure than the traditional split-sample testing using streamflow data alone in undisturbed watersheds. However, obtaining independent, multiple-response data may be very difficult, particularly over large watersheds. Others[22, 24] suggest use of a multiobjective approach in model calibration for better assessment of the limitations of model structure and confidence of model predictions when multiple objectives cannot be easily transformed into a single common objective due to a lack of quantitative comparison measures. But nonlinearity in parameters and multiple optima make calibration by multiple criteria very difficult. A residual-based approach is likely to have similar power but is easier to implement[12, 23].

The inherited uncertainties in model input data and parameters affect model performance even after calibration. Inadequate consideration of the spatial variability of precipitation data introduces greater uncertainty into parameter estimates than errors in runoff data[25] and inaccuracies in DEM and the DEM-derived drainage network affect estimates of runoff peaks, timing and volume[26]. Gan *et al*. (1997)[27] evaluate five conceptual rainfall-runoff models of different complexity (ranging from 9 to 21 parameters) and report that model performance is more associated with the model structure, the objective function in calibration, and data quality and less related to model complexity or calibration data length. Some researches state that performance of the spatially distributed models can only be assessed with spatially distributed observations that are technically not feasible, especially over large areas[28]. Considering the limitations of data, the criteria for model acceptability need to be carefully defined, since if the criteria are too strict, all models will be rejected[12, 17].

GIS-Model Interface. Development of hydrologic models, particularly distributed hydrologic models, requires integration of GIS, remote sensing, and other digital data bases for extracting the needed model variables, and for processing, analyzing, and visualizing the model results[29]. GIS-model interfaces serve this purpose by assisting users in data organization, parameter extraction, model execution, and output display, and by improving model applicability. Such interfaces include linkages between Geographic Resource Analysis and Support System (GRASS) and AGNPS (Agricultural Nonpoint Pollution Model)[13], and Arc/Info and HEC-HMS (Hydrologic Modeling System)[30]. He *et al*. (2001)[14] developed an interface to integrate the ArcView GIS and AGNPS for modeling and analysis of agricultural watersheds. Since the 1990s, the U. S. Environmental Protection Agency (2001)[31] has developed and updated Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) system to incorporate ArcView and ArcGIS and hydrologic models in support of water quality programs nationwide. To better represent hydrologic processes and facilitate model implementation and applicability, hydrologic models should incorporate linkages or interfaces to GIS for data integration, analysis and visualization.

2.3 Description of the DLBRM

Considering the availability of data, computing power, and the large size of the study watershed, this study uses the Distributed Large Basin Runoff Model to simulate the hydrology of the Heihe watershed at daily intervals over the period of 1978—2000. The DLBRM was developed by the Great Lakes Environmental Research Laboratory and Western Michigan University. It represents a watershed by using 1-km^2 (or other size) grid cells. Each cell of the watershed is composed of moisture storages of the upper soil zone (USZ), lower soil zone (LSZ), groundwater zone, and surface, which are arranged as a serial and parallel cascade of "tanks" to coincide with the perceived basin storage structure (Fig. 2). Water enters the snow pack, which supplies the basin surface (degree-day snowmelt). Infiltration is proportional to this supply and to saturation of the upper soil zone (partial-area infiltration). Excess supply is surface runoff. Flows from all tanks are proportional to their amounts (linear-reservoir flows). Mass conservation applies for the snow pack and tanks; energy conservation applies to evapotranspiration (ET). The model computes potential ET from a heat balance, indexed by daily air temperature, and calculates actual ET as proportional to both the potential and storage. It allows surface and subsurface flows to interact both with each other and with adjacent-cell surface and subsurface storages. The model has been applied extensively to riverine watersheds draining into the North America's Laurentian Great Lakes for use in both simulation and forecasting[12,32−34]. The unique features of the DLBRM include: 1) use of readily available climatological, topographical, hydrologic, soil, and land use databases; 2) applicability to large watersheds; and 3) analytical solutions of mass continuity equations, (mathematical equations are not shown here due to space limitations; for details, see[12, 32−33].

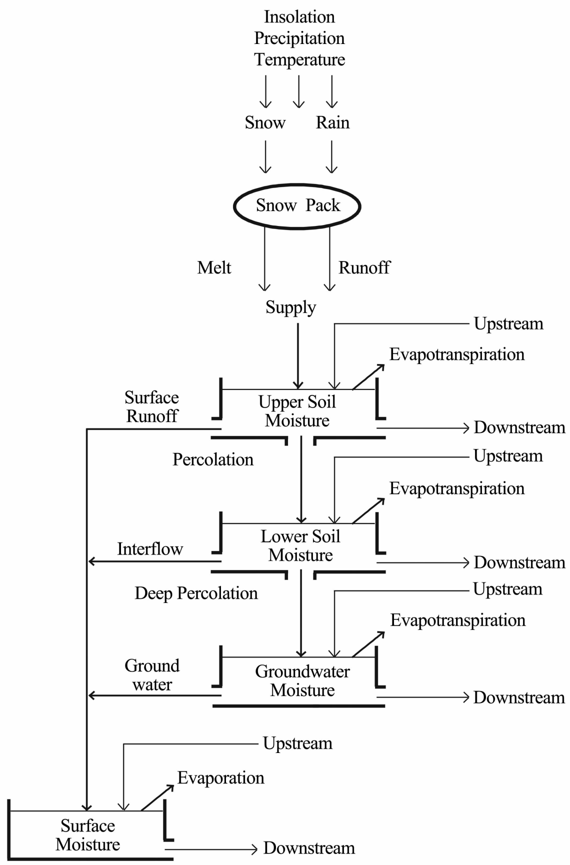

Fig.2 Tank cascade schematic of Distributed Large Basin Runoff Model

2.4 GIS-Model Interface

The DLBRM requires 16 input variables for each of the grid cells. To facilitate the input and output processing for the DLBRM, an ArcView-DLBRM (AVDLBRM) interface program has been developed to assist with the model implementation. The interface was written in ArcView Avenue scripts by modifying the ArcView Nonpoint Source Modeling interface by He (2003)[29]. It consists of six modules: 1) Soil Processor; 2) DLBRM Utility; 3) Parameter Generator; 4) Output Visualizer; 5) Statistical Analyzer, and 6) Land Use Simulator. Multiple databases of meteorology, soil, DEM, land use/cover, and hydrology and hydrography are used by the interface through the draw-down menu to derive input variables for the DLBRM[14, 29, 35]. The derived variables for each of the 4-km^2 cells include: elevation, flow direction, slope, land use, Manning's coefficient (n) values, soil texture, USZ and LSZ depths, available water capacity, and, permeability, as well as daily precipitation, air temperature, and solar isolation. DLBRM outputs include, for every cell, surface runoff, ET, infiltration, percolation, interflow, deep percolation, groundwater flow, USZ, LSZ groundwater, and surface moisture storages, and lateral flows between USZ, LSZ, groundwater, and the surface (Tables 1 and 2). The outputs can be examined either in tabular or map format using the interface.

Table 1 Input variables for the DLBRM

Variables	Databases
Elevation	Digital elevation model (DEM)
Flow direction	DEM
Slope	DEM
Land use	Land use database
Depth of upper soil zone (USZ)	Compiled soil database
Depth of lower soil zone (LSZ)	Compiled soil database
Available water capacity/% of USZ	Compiled soil database
Available water capacity of LSZ	Compiled soil database
Permeability of USZ	Compiled soil database
Permeability of LSZ	Compiled soil database
Soil texture	Compiled soil database
Manning's coefficient value	Land use, slope, and soil texture

Sources: All the databases were from the CAREERI.

Table 2 Time series meteorological and flow variables for the DLBRM

Variables	Databases
Daily precipitation	Gansu Bureau of Meteorology
Daily air temperature	Gansu Bureau of Meteorology
Daily solar isolation	Gansu Bureau of Meteorology
Daily flows	Gansu Bureau of Hydrology

Sources: All the databases were from the CAREERI.

2.5 Modeling the Hydrology of the Upper and Middle Reaches of the Heihe Watershed

Climate change will further intensify water stresses in areas that already suffer from water shortages such as northern China and the Middle East and sub-Saharan Africa countries, decreasing river flows in low flow periods and degrading water quality[3]. Studies have reported the observed significant increase in annual mean minimum temperature and the decrease in annual mean precipitation rates during the past 50 years in Northwestern China[36-39]. The drying-up of the Yellow River since the 1990s was reported as a result of the decrease in precipitation (-38.2 mm · (10 yr)$^{-1}$) and the increase in evaporation ($+52$ mm · (10 yr)$^{-1}$ for pan evaporation)[39]. In the face of climate change and rapid urbanization, water conflicts and stresses will further intensify between water users in the middle and lower reaches in the Heihe watershed. Addressing this chronic water shortage problem requires the understanding of distribution of water resources over both space and time. This study uses the DLBRM to simulate the hydrologic processes of the upper and middle reaches of the Heihe watershed. The selection of the upper and middle reaches for modeling is due to the following factors: 1) the upper reach (mountain area south of Yingluoxia) is the main runoff production area; 2) the middle reach (between Yingluoxia and Zhengyixia) is the main irrigated farming area and also hosts Zhangye City with over 1 million people, and 3) Heihe is heavily regulated and releases flow to downstream (north of Zhengyixia) only a few times a year, and the river channel downstream of Zhengyixia is dry most of the time[7-8].

2.5.1 Model input

The upper and middle reaches of the Heihe watershed were discretized into a grid network of 9,790 cells at 4 km^2 resolution. A DEM at 100 m resolution from The Chinese Academy of Sciences (CAS) Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI) was used to derive topographically related parameters (flow direction, receiving cell number, and slope) by the AVDLBRM interface. The land cover database of year 2000 was used to generate a land cover category (code) for each grid cell. Meteorological databases from 13 weather stations for the period of 1978 to 2000 were used to interpolate precipitation and temperature and to generate surface insolation estimates[12, 32]. Since the soil database of 1999 (1 ∶ 250 000) from the Gansu Province only contained soil types, we spent a significant amount of effort to compile relevant soil attributes for each of the soil types. First we used the soil sample data (unpublished soil depth, and mechanical composition data collected by Xiao and his group 2006) to determine soil texture and depth of USZ and LSZ for each of the 57 soil types. For those soil classes for which no soil survey data were available, we estimated texture and depth of USZ and LSZ based on the work of Chen and Xiao (2003)[40]. We used SPAW(Soil-Plant-Atmosphere-Water) Field & Pond Hydrology model developed by the U.S. Department of Agriculture Agricultural Research Service and Natural Resources Conservation Service (http://hydrolab.arsusda.gov/soilwater/Index.htm accessed Dec. 7, 2007) to estimate soil water holding capacity (%) and permeability (cm · h^{-1}) based on the texture for each of the soil types. Once the compilation of the soil database was completed, we used the AVDLBRM interface to derive the relevant soil parameters for each of grid cells. Manning's coefficients were assigned to each cell by the hydrologic response units (HRU), which was determined according to the combination of land use, soil texture, and slope[35]. Average daily river flow rates (in m^3 · s^{-1}) were converted into daily outflow volumes and were used to conduct a systematic search of the parameter space to minimize the root mean square errors (RMSE) between actual and simulated daily outflow volumes at the watershed outlet[33-34].

2.5.2 Model Calibration

The DLBRM was calibrated over the period of 1978—1987 for each of the 9 790 cells (4-km^2) at daily intervals. The calibration took over 61 days on a desktop personal computer (Intel Pentium[R] Processor @ 3.40 GHz). The calibration shows a 0.69 correlation between simulated and observed watershed outflows (0.48 coefficient of determination); a 0.072 mm · d^{-1} root mean square error. The ratio of model to actual mean flow was 1.011; and the ratio of model to actual flow standard deviation was 0.68 (Table 3). Over a separate verification period (1990—2000), the model demonstrated a 0.71 correlation between simulated and observed watershed outflows (0.52 coefficient of determination), a 0.006 mm · d^{-1} RMSE; the ratio of model to actual mean flow was 1.409; and the ratio of model to actual low standard

Table 3　DLBRM Heihe calibration statistics

Calibration Period	Correlation	RMSE/cm	μ_M/μ_A	σ_M^2/σ_A^2	Long-term average ration to surface net supply				
					Surface Runoff	Interflow	GW	USZ ET	LSZ ET
1978—1987	0.690	0.007	1.014	0.683	0.065	0.061	0.000	0.000	0.884
1978—1987* With glacial	0.690	0.007	1.011	0.682	0.065	0.061	0.000	0.000	0.885
1990—2000	0.710	0.006	1.409	0.717	0.070	0.000	0.000	0.000	0.870

Note: * A 10. 85 m of snow pack was assumed in about 305 km^2 of mountain area (elevation > 4 500 m) in the simulation; ET represents evaporation.

deviation was 0.72. To take into account surface water supply from snow and glacial melt, a 10.85 m of snow pack was assumed in about 305 km^2 of upper reach mountain area (elevation > 4 500 m) in the simulation. All the assumed snow was melted within 2 months in the simulation and the result was quite similar to the ones without added snow pack (Table 3).

Simulation results for the long term average annual water budget (1990—2000) are shown in Fig.3. Annual surface net supply from both rainfall and snow melt was about 8.92 billion (10^9) m^3, which mainly came from Qilian mountain in the upper reach area. The USZ (a simulated layer accounting for the upper few centimeters of the soil) stored about 391 billion m^3 of water, the largest storage among all the four storage tanks (USZ, LSZ, groundwater zone, and surface storage). Surface runoff from the USZ averaged about 0.54 billion m^3, while a much larger portion of water (8.37 billion m^3) percolated down to the LSZ. A majority (94%) of the percolated water evaporated to the atmosphere from the LSZ and the rest flowed to the stream in the form of interflow. There was hardly any deep percolation to the groundwater since the LSZ is up to 200 m deep in much of the middle reach area[7]. The annual outflow at the outlet (Zhengyixia) of the middle reach was about 1 billion m^3 to the downstream (Fig.3). Simulation results for 1990 are shown in Fig. 4. Compared to the observed daily discharge, DLBRM using parameters from both the 1978—1987 and the 1990—2000 calibration periods reasonably depicted the daily variations of the Heihe discharge at the outlet (near Zhengyixia Station), with the former performing better than the latter. The simulations underestimated the discharges during the cold season, when there was not much precipitation, and overestimated the discharges during the spring and summer, when there were more storms (except underestimating the discharge from the July 25, 1990 storm of 2.5 cm) (Fig.4).

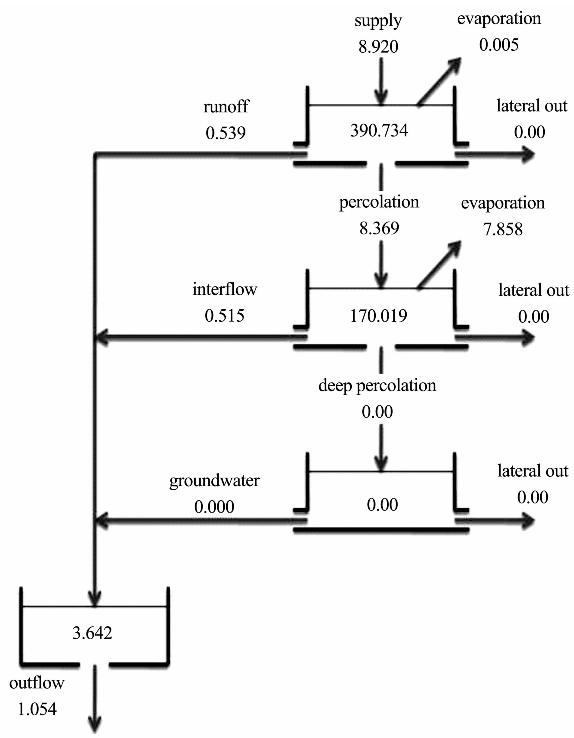

Fig.3　Annauwater budget (1990—2000 average in 10^3 m^3) of the upper-Middle Reaches of the Heihe Watershed

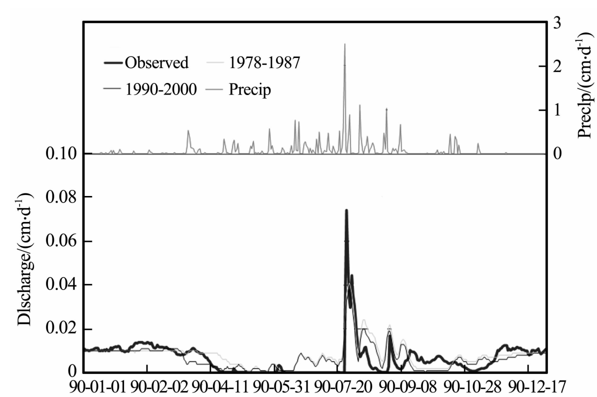

Fig.4　Comparison of the simulated discharges and observed discharge in the Heihe River for 1990

2.5.3　Discussions

The Qilian Mountain (up to 5 500 m above sea level) makes up the upper reach of the Heihe watershed. Vegetation in the area consists of mainly meadow, grassland, forest, and cold desert. Majority of the water supply and runoff in the entire Heihe watershed is produced from this area[7－9]. Due to the high altitude and steep slope of the mountain area, much of the snow melt and rainfall becomes surface runoff. Once reaching the mountain outlet (Yingluoxia Station), the water quickly percolates to the deep, coarse sandy and loamy soils in the allavial fan (up to 200 m deep). As annual precipitation in the middle reach (between the mountain outlet Yingluoxia and the middle reach outlet- Zhengyixia) is less than 200 mm, the river flow is used to irrigate crops like spring wheat, corn and rice in the oasis. As shown in Fig.3, nearly 94 percent of the net supply was simulated to percolate to the lower soil zone. Since the LSZ is up to a few hundred meters deep, there is hardly any deep percolation to the groundwater. Instead, a portion of the water in the LSZ flows to the river channels though interflow. This is similar to the findings by Cheng *et al*. (1999)[8] and Pan and Qian (2001)[7]. Between the mountain outlet (Zhengyixia) and the cities of Zhangye and Jiuquan lies the main agricultural oasis. The dry climate and deep, coarse and sand soils require large amount of water withdrawals for crop irrigation, nearly depleting river flow downstream of Zhangye City (Fig.1). A main portion of the irrigation water is returned to the atmosphere through ET and a small portion of it returns to the river channels through interflow. Pan and Qian (2001)[7] report that quite limited recharge from the precipitation to the groundwater is only observable in the middle reach area where groundwater level is less than 5 m deep and daily precipitation is more than 10 mm. But the irrigation return flows percolate to the groundwater zone and then flow to the river since the groundwater level is higher than the river water level in certain areas. This study simulated only interflow from the LSZ because the LSZ is several hundred meters deep and could be mixed with groundwater zone.

The simulation results show there was little ET from the upper soil zone. Instead, a very high ET rate occurred in the LSZ (Fig.3). This phenomenon is attributable to several factors. First, the USZ is a hypothetical storage layer with a simulated capacity of up to 100 cm. Second, between the mountain outlet (Yingluoxia) and middle reach outlet (Zhengyixia), soil is quite coarse and sandy and thus water from the USZ infiltrates to the LSZ quickly[8]. Third, consumption of groundwater is mainly through ET in the middle reach of the watershed and significant ET is observed not only in warm summer but also in cold winter when the soil water is frozen in the 1～2 m depth and water in the deeper layers moves up to the frozen layer[7].

The DLBRM simulations reasonably depicted the water movement processes in the Heihe watershed and reported similar findings by other researchers[7－9]. However, the simulated annual flows in this study were 20 to 30 percent lower than those simulated byJia et al (2005)[9] at Zhengyixia Station. This might be due to the fact that this study simulated the entire upper and middle reaches together, while Jia *et al*. (2005)[9] first simulated each subwatersheds separately and then added those flows together. Moreover, the uncertainty in this study may also be related to the following factors: 1) Absence of meteorological databases in the high elevation area (above 3 300 m). Daily precipitation and temperature input to the DLBRM were spatially interpolated from a network of 13 weather stations all located below 3 300 m elevation, corresponding to about 3 000 km^2/station. Such lack of detailed spatial representation of meteorological data leads to large uncertainties in parameter estimates and hence model output[25]. 2) Poor spatial coverage of streamflow gauge stations. Surface runoff from tributaries in the upper reach mountain area and middle reach accounts for nearly all the river flow in the Heihe watershed. However, hydrologic data from several major tributaries (e.g.Liyuan River) were not available to this study, causing inaccurate accounting of water budget. 3) Lack of detailed soil attribute database. The available soil database only contained spatial coverage of the 57 types of soils in the entire Heihe watershed. The related soil attributes such as texture and depths were estimated from a number of sources including literature. And 4) the spatial landscape data used in this study had multiple spatial resolutions. All those databases were aggregated to the 4 km^2 cell for use in this study. This aggregation process inevitably generates errors into the simulation results[12].

Future work includes adjustment of daily precipitation and temperature databases by elevation to account for the effects of the elevation in the study area, and use of finer grid cells (e.g.1 km^2) to represent the study watershed in the simulations. After improving the simulation accuracy of the DLBRM, we will incorporate climate change (from the General Circulation Model results) and management scenarios into the model and assess how climate change and irrigation management (e.g.drip irrigation) would affect the magnitude and distribution of surface runoff, groundwater, ET, and basin outflow in the study area. Since the simulation results can be examined over individual cells in map format, we will be able to track the spatial distribution of hydrologic variables to better understand the partitioning of river flows between the Hexi Corridor of the middle reach and the Alashan Highland of the lower reach. Such information will support implementation of the State Council's water allocation plan to rehabilitate the West Juyan Lake.

3 CONCLUSIONS

The Heihe watershed is the second largest inland river in China and is a microcosm of China's arid and semi-arid regions. While water shortage is a chronic problem in the Heihe watershed, the rapidly increasing water withdrawals for agricultural irrigation and urbanization in the populated middle reach have depleted river flows to the lower reach, drying up West Juyan Lake and endangering aquatic and terrestrial ecosystems downstream. With climate change and rapid urbanization, water conflicts and stresses will further intensify between water users in the middle and lower reaches in the Heihe watershed. This paper reports our collaboration with Chinese colleagues to adapt the DLBRM to the Heihe watershed for understanding water transfers between glaciers, snow pack, groundwater, surface runoff, and evapotranspiration, for simulating the impacts of reported glacial recession on the Heihe hydrologic system, and for exploring the effects of climate change and water saving practices and technologies on water supply . The preliminary DLBRM simulation results show that Qilian Mountain in the upper reach area is the main runoff production area for the entire Heihe watershed. On average, surface runoff and interflow contributed 51 and 49 percent of the river flow respectively for the period of 1990 to 2000. Annually the river was simulated to discharge about 1 billion m of water from the middle reach (Zhengyixia station) downstream to the lower reach. Overall, the DLBRM simulations reasonably depicted the hydrologic processes in the study area but lack of the comprehensive meteorological, soil, and hydrologic databases affected the accuracy of the simulations. Future work will focus on the model improvement and incorporation of the climate change and management scenarios to the simulations for better understanding the impacts of the climate change and human activities on the watershed processes and for support of sustainable use of water resources in arid and semi-arid regions of China.

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基于分布式大流域径流模型的中国西北黑河流域水文模拟

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摘　要: 水资源短缺是中国西北干旱地区长期的问题, 区域人口增加、城市化扩张,加之气候变化的影响进一步加剧了西北地区水资源短缺, 也使生活用水、灌溉用水、工业用水和维持生态系统稳定的用水危险加剧. 采用分布式大流域径流模型(DLBRM)模拟黑河流域水文(中国第二大内陆河,流域面积128 000 km^2)来理解区域的冰川和积雪融化水、地下水、地表水、蒸散发等方面的分布, 评估气候变化对水文的影响和冰川退缩对中游和下游来水量的影响. 模拟结果表明, 黑河流域的大部分产流那源于黑河上游地区的祁连山. 模拟 1990—2000 年黑河河流日流量变化结果认为, 黑河中游正义峡给下游的供水为 10×10^8 m^3,其中地表径流占 51%, 层间流占 49%. 中游地区沙土具有较高的蒸腾发能力, 近一半的地表水被蒸发掉. 模拟实践证明, 分布式大流域径流模型可以结合气候变化、水资源管理方面的成果, 改进流域水文模拟的精度.

关键词: 分布式大流域径流模型; 中国西北地区流域; 水短缺; 气候变化

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