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Integrated hydrologic modeling in the inland Heihe River Basin, Northwest China

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ABSTRACT

As a typical inland river basin in arid Northwest China, having distinct hydrological characteristics and severe and representative water problems, the Heihe River Basin (HRB) has attracted considerable research interest worldwide and in 2007 became a pilot basin of the G-WADI network of UNESCO/IHP. Many research programs have been conducted in the HRB since the 1980s, producing rich knowledge and data about the basin, which will be very helpful to further studies. This paper reviews research efforts related to hydrologic modeling and ongoing model integration studies performed in the HRB in recent years. Recently, an observation network covering the whole area and a Web-based data-sharing system have been established which can greatly improve data acquisition. This paper tabulates modeling activities in past years, including model applications, model modifications and enhancements, and model coupling efforts. Also described is a preliminary modeling integration tool designed to quickly build new models, which has been developed for hydrologic modeling purposes. Challenges and issues confronted in current studies are discussed, pointing toward key research directions in the future.
Keywords: hydrologic modeling; water resources management; Heihe River Basin

1 Introduction

The Heihe (literally meaning "black river") River Basin (HRB), the second largest inland river basin in arid Northwest China, is located in a transition zone between a semi-arid zone (the Qinghai-Tibet Plateau) and an arid zone (the Mongolian Plateau). As such, it is one of most water-stressed basins in China (Cheng, 2002). The situation is becoming more severe as a result of increasing population and socioeconomic development in the area. Water shortages and irrational allocation have caused a number of ecological problems and social conflicts in the HRB (Feng *et al.*, 2001; Feng *et al.*, 2002; Su *et al.*, 2002; Xiao *et al.*, 2006; Zhang *et al.*, 2006).

As a typical inland river basin, the HRB has several distinct topographic characteristics, encompassing alpine periglacial zones, forests and grasslands, piedmont oases, and deserts in the tail region (Lu *et al.*, 2001). The HRB differs, however, from river basins in wet regions with respect to hydrologic characteristics. For example, in the HRB, infiltration excess runoff, hydrologic impacts from glaciers, snow, and permafrost, as well as subgrid variability and appropriate spatial discretization due to its complex terrain must be considered when modeling water and heat cycles, whereas these aspects are generally ignored in warm and rainfall-rich areas (Hayashi *et al.*, 2003; Chen *et al.*, 2007; Al-Houri *et al.*, 2009; Wang *et al.*, 2009). Even more problematic is the lack of hydrometeorological observation sites in the HRB; the limited existing sites are concentrated in the middle reach area, while only few are distributed in upper and lower reach areas. These facts bring great challenges for hydrological simulations in the HRB.

For more than 2,000 years, residents of the HRB have battled against water scarcity and have accumulated many water-use and allocation experiences (Zhong *et al.*, 2011). For example, the water transfer scheme now in effect in the HRB, and its series of water-saving policies aiming to balance water uses and improve water-use efficiency, could be adopted by other areas that face similar water problems. Therefore, in 2007 the HRB was selected as a pilot basin within the framework of the Global Network of Water and Development Information for Arid Lands (G-WADI) of the United Nations Educational, Scientific and Cultural Organization (UNESCO). The objectives outlined by G-WADI are extremely relevant in the HRB.

A large number of research programs have been conducted in the HRB since the 1980s, from a variety of disciplines such as hydrology, physical geography, ecology, land surface study, economic geography, and remote sensing and geographic information systems (Ding *et al.*, 1999; Wang *et al.*, 2002; Wang *et al.*, 2006). Those studies produced rich knowledge and data about the HRB, which will be very valuable for further studies. The research history can be roughly divided into three stages (Li *et al.*, 2010a). The first stage began in the 1980s and featured basic field investigations. The second stage started in the mid-1990s and was supported by a number of large, state-level research projects, focused on key issues involving water capacity and regional planning on a macro level. Beginning in 2000, the latest stage is an integrated modeling stage which tests numeric models in the HRB, and is also a research framework coupling ecologic, economic, and hydrologic subsystems (Li *et al.*, 2008a; Ma *et al.*, 2009; Wang *et al.*, 2009; Li *et al.*, 2010a; Li *et al.*, 2010b; Li *et al.*, 2010c; Li *et al.*, 2010d). In 2009 the National Natural Science Foundation of China (NSFC) launched an 8-year research program (Li *et al.*, 2012), titled An Integrated Study of Ecological and Hydrologic Processes in the Inland Heihe River Basin, marking a new era in HRB hydrologic studies.

This paper reviews relevant advances of hydrologic modeling in the HRB. The next section briefly introduces the study basin as well as key issues and concerns. Section 3 introduces the past and current observation systems, data sharing systems, and data processing techniques. Model application, enhancement, and integration are presented in Section 4. Modeling environments are discussed in Section 5, followed by a discussion of existing issues and challenges in Section 6, which also point toward the key research directions in the future. Section 7 summarizes the paper.

2 Study area

The HRB, bounded by 96°42′E–102°00′E and 37°41′N–42°42′N, includes the middle range of the Qilian Mountains, the Hexi Corridor, and the vast Ejina Desert, with an area of approximately 140,000 km^2. The average elevation is 3,600 m with an altitude difference of 3,000 m. The basin can be divided into three topographic units: from the south to north, the Qilian Mountains as the upper reach, the Hexi Corridor as the middle reach, and the Alashan High Plain as the lower reach (Figure 1). Each unit has distinct geological and topographic characteristics and hydrometeorological conditions. The climate is primarily controlled by westerlies circulation and polar cold air. Consequently, the climate is arid with scarce but concentrated precipitation, strong solar radiation, and large diurnal temperature differences. Between 2,000- and 5,500-m elevation, the upper area is characterized by a distinct vertical zonality, that is, from low to high, forest steppe, scrub meadow, alpine desert, to permanent cold zone. The primary soil type is frigid desert soil. The mean annual precipitation is 300–500 mm, relative humidity is about 60%, and evaporation is approximately 700 mm. In the middle reach area, altitudes decline from 2,000 m to 1,000 m and the precipitation decreases from 250 mm in the south to less than 100 mm in the north. The middle area is mainly covered by arid Gobi and oases are nourished by rivers coming from the southern mountains. There is a large area of irrigated lands, well known in China for its productive crop yields, which also forms an artificial vegetation landscape. It is extremely arid in the lower reach area, having predominantly grey-brown desert soil, where the mean annual precipitation is about 42 mm and potential evaporation is up to 3,755 mm. In a flat elevation of 1,000 m, the lower area is primarily desert with only a small oasis area, where the vegetation is desert riparian forests, shrub woods, and meadows (Wang *et al.*, 1998).

Multiple-year average water resources in the HRB total 4.173 billion cubic meters, of which mountainous runoff is 3.683 billion cubic meters (Ning *et al.*, 2008). The eastern sub-water systems account for 2.475 billion cubic meters. Due to its rich precipitation, the upper area is the major runoff generation area. In contrast, the middle and lower areas do not produce runoff because of their strong potential evaporation and scarce precipitation. The runoff completely disappears near the lowest tail of the river in the Ejina Desert (Wang *et al.*, 2007). Glacier melt accounts for 4% of stream runoff and the remaining 96% is supplied by precipitation that is concentrated in summer and autumn. More than two-thirds (68.5%) of an entire year's stream runoff occurs in June through September.

Water uses in the HRB are uneven; the middle area utilizes up to 82.6% of entire basin's water resources. Agriculture consumes the most water, up to 95%, while industry uses 4% and domestic use comprises 1% (Ning *et al.*, 2008). Water consumption keeps increasing as more agriculture and industries develop in the middle area, where in the 1990s it reportedly increased by 0.2 billion cubic meters or so (Qu *et al.*, 2000). This has led to a deteriorated ecosystem downstream (Su *et al.*, 2004) due to lessened water supplies. In the 1950s there were 1.05 billion cubic meters of available water, but this had declined to 0.2–0.3 billion cubic meters in 2008 (Guo *et al*., 2010). As reported by He *et al*. (2005), 0.948 to 1.158 billion cubic meters of water are required downstream to maintain its ecological use. There are currently 98 reservoirs at various scales within the basin, most of which are plain reservoirs. Canal systems to divert water for irrigation use are fully developed and their utilization ratios range from 0.49 to 0.57, with an average of 0.55, while those of the western sub-water system can reach 0.6.

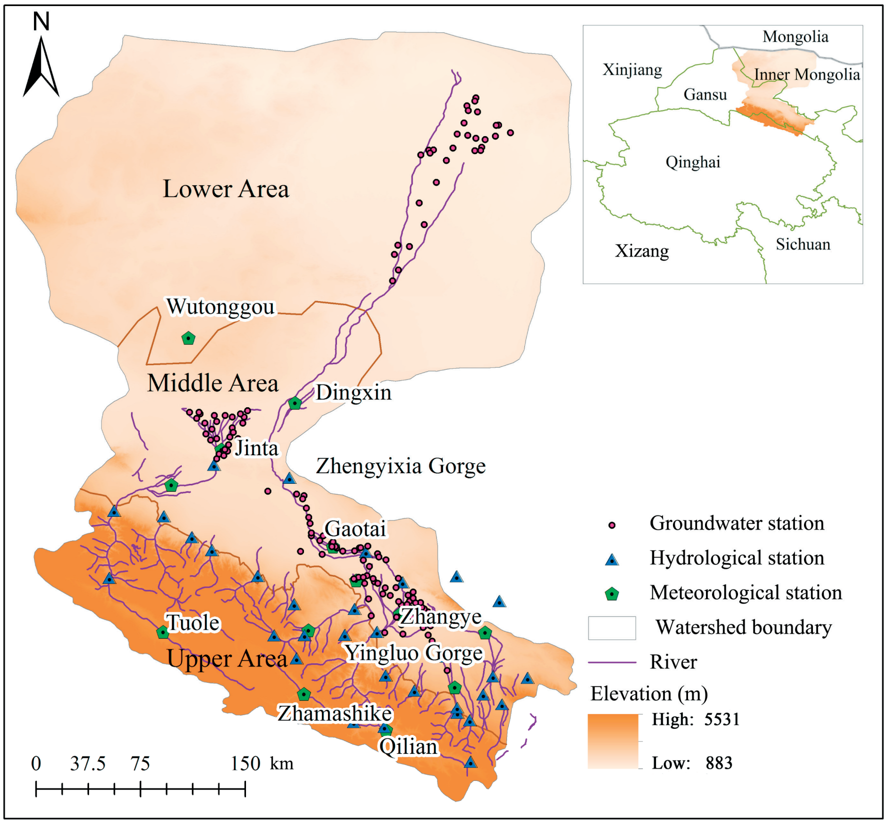


Figure 1 Location map of the Heihe River Basin (HRB)

In 2010 there were 1.97 million people in the HRB, of which 0.51 million were living in urban areas. The GDP was 23.7 billion Chinese Yuan (12,030 Yuan per capita) (Zhao, 2010). The population and economy are mainly developed in oasis agricultural areas in the middle reaches, accounting for more than 95% of the population and 87.93% of the GDP. About 75% of the population engages in agriculture and animal husbandry, predominantly mountain-pasture animal husbandry in the Qilian Mountains in the upper HRB, and irrigated agriculture in the Hexi Corridor oasis in the middle reach. The latter is also an important grain and vegetable production region in Northwest China. The Ejina and Jinta counties in the lower HRB are dominated by desert-steppe animal husbandry (Zhou *et al*., 2005).

Water resources are important in maintaining ecosystem health in arid Northwest China. Water scarcity is the most prominent challenge to local economic development. Lan *et al*. (2000) reported that there is great uncertainty in the response of local water resources to global climate change in the arid region. The temperature records in the HRB show that the temperature has increased at a rate much higher than average in the Northern Hemisphere over recent years (Zhang *et al*., 2007). Because the ecology of alpine cold deserts is very fragile, sparse vegetation and low-temperature microorganisms are extremely sensitive to temperature rise (Zhang *et al*., 2007). Also, rising temperature affects ablation of mountain glaciers in upper areas, the snow line, summer precipitation and evapotranspiration, sectional water consumption, and river/lake mineralization, and may result in degradation of the ecological environment.

Along with continued increases in the population and economic development, anthropogenic impacts on local water resources and the ecology in the HRB are becoming more severe, as presented in following aspects: (1) industrial and agricultural developments use more water, leaving insufficient amounts for ecological needs; (2) in water-stressed areas, overexploitation of water resources leads to groundwater-level decline, ground subsidence, and mass vegetation death; (3) irrational water conservancy engineering causes large water losses due to evaporation and leakage; and (4) lack of effective and uniform management measures induce water utilization conflicts and great waste.

A direct consequence of these natural and human impacts is ecosystem deterioration in the HRB. A long time-series study by Wang *et al*. (2000) showed a four-fifths reduction of the natural forest in the Qilian Mountains and an increase in occurrence of low-flow years from 50% to 70% in the past 2,000 years. In middle oasis areas, lands degraded by salinization and desertification account for 3.8% and 9.3%, respectively, of the total land area. In the lower reach, most terminal lakes have dried up; some began to be refilled only after the implementation of a water transfer project since 2000. The 32×10^3-km^2 oasis surface area in the lower reach has rapidly declined to 6.4×10^3 km^2 (Wang *et al*., 2000), and the Alexa area in the lower reach has become one of the major sandstorm sources in northern China.

Many studies in the past 50 years have been conducted across multiple fields, including hydrology and water resources, physical geography, ecology, land surface processes, economic geography, and remote sensing and geographic information systems. Those efforts accumulated valuable knowledge about the HRB and large amounts of research data. The following sections will review hydrological modeling efforts in the HRB from three perspectives: established data and observation systems, modeling activities, and modeling methodologies.

3 Data and observation systems

Observation networks are essential for hydrological modeling studies. However, there are insufficient eco-hydro observation sites in the HRB because the upper HRB is mountainous and the lower part is desert, making it difficult to build or maintain enough sites. In recent years the situation has improved due to the support of the Chinese Academy of Sciences West Action Plan project titled Watershed Allied Telemetry Experimental Research (WATER) (Li X *et al*., 2009), and the successor NSFC research plan known as Ecological and Hydrological Integrated Research in the Heihe River Basin (Leng *et al*., 2011). A comprehensive observation network as well as a data-sharing system have finally begun to form.

3.1 Observation systems

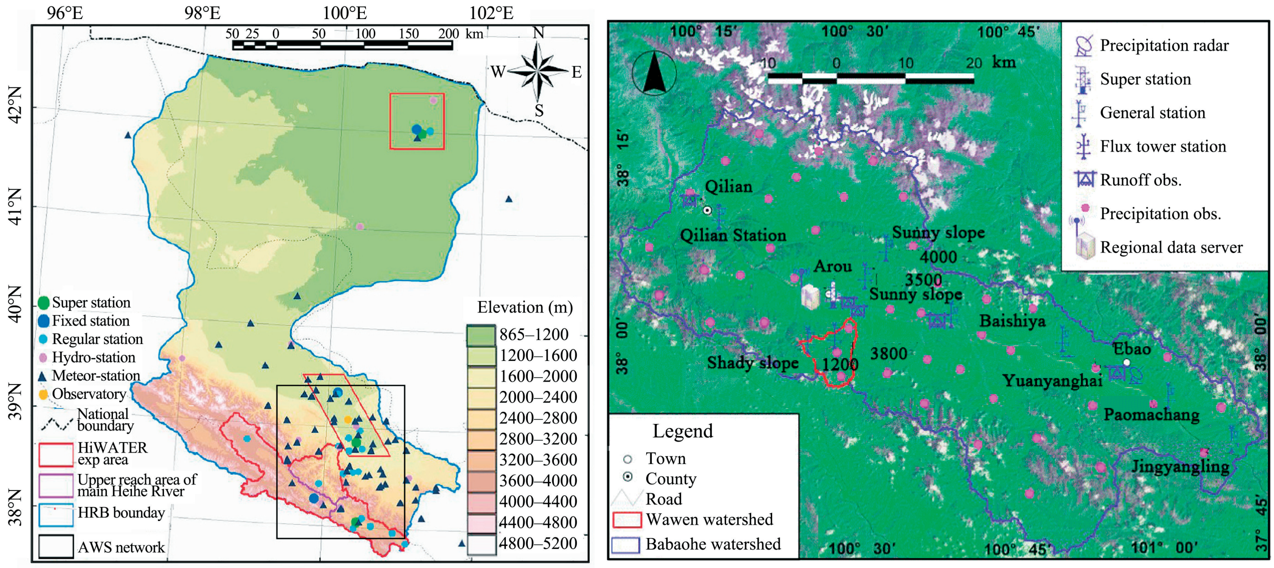
Obviously, the development of a watershed observation system (WOS) is an essential component of watershed science. In the 1940s two control hydrological sites, namely, the mountainous outlet Yingluoxia station to control the upper Heihe River and the Zhengyixia station to control the middle riverway, were established. To date, there are a total of eight hydrological control stations and nine regional representative stations. Since 2000 the WOS has been extended to include more sites which were originally designed for other purposes, such as for ecology monitoring. Several fixed stations, such as the Linze comprehensive observing station, several mountainous water conservation comprehensive observing stations, some Ejinaqi ecological stations, and a couple of hydrological sites were set up in recent years. Those originally maintained by research projects, such as the Dayekou-Guantan forest site, the Yeniugou permafrost observing site, and the hydro site in the Binggou sub-basin, provide hydrological records as well as ecological observations, making the whole WOS able to support integrated hydro-ecological study. The location map of the HRB WOS is shown in Figure 2a.

Launched in 2007, the three-year Watershed Allied Telemetry Experimental Research (WATER) project (Li X *et al*., 2009) greatly enriched the WOS by adding many remote sensing instruments such as microwave radiometers, imaging spectrometers, thermal imagers, laser radars, and others. Sponsored by this project, a set of multi-scale evapotranspiration observing experiments over inhomogeneous underlying surfaces have been carried out, using an observation matrix consisting of an intensive eddy covariance system, large-aperture scintillometers, and automatic weather stations (AWSs) to observe snow and permafrost hydrology, irrigation water balance, crop growth, and ecological water consumption.

Currently, in the HRB a simultaneous remote sensing and ground-based experiment platform has been established (Figure 2b). The missions of this platform are to: (1) observe the major components of water cycles in cold regions, forest areas, and arid regions by carrying out simultaneous airborne, satellite-borne, and ground-based remote sensing experiments; (2) develop scaling methods using airborne, high-resolution remote-sensing data and intensive in situ observations, and improve remote-sensing retrieval models and algorithms for water-cycle variables and corresponding ecological and other land surface parameters; (3) validate, improve, and develop catchment-scale hydrological and ecological models by using available data, as well as develop decision support tools for water resource management; (4) develop a catchment-scale land/hydrological data assimilation system that is capable of merging multi-source and multi-scale remote-sensing data to generate high-resolution and spatiotemporally consistent datasets in order to improve the predictability of water cycles and their response to environmental changes; and (5) establish a public experimental field and develop open, free, multi-scale, and integrated datasets for the enhancement of watershed science.

A more extensive, multi-scale integrated observation experiment known as HiWATER (successor to WATER) was launched in 2012. The goals of this experiment are to enhance the observation capabilities pertaining to watershed ecological and hydrological processes, to establish a leading international observing system in a watershed scale, and to improve the ability of remote-sensing applications in ecology-hydrology integrated research and water resources management (Li *et al*., 2012).

Especially in the upper mountains of the HRB and the deserts of the lower HRB, the physical conditions are extremely hard. Traditional manual observations are challenged by difficult maintenance and consequent large costs. Wireless sensor networking is regarded as one of the most promising technologies in the 21st century, having outstanding advantages such as simple and easy deployment, long-term monitoring capabilities, less human intervention, and small, controllable, efficient, and energy-saving systems (Hart *et al*., 2006). Wireless sensor networks (WSNs) have been experimentally deployed in the Mafenggou Basin and the Babaohe Basin, located in the upper mountainous area (Zhu *et al*., 2011). An automatic, intelligent, and remote-controllable eco-hydrological WSN has been established in the Daman/Yingke irrigation area in the middle reach (Jin *et al*., 2012), and reliable and continuous data have been produced.



(a) (b)

Figure 2 Observation network in the HRB (a) and present observational instruments in the Babaohe watershed (b)

3.2 Data sharing systems

Part of the data insufficiency in the HRB is related to past lack of data sharing, but now there are two data-sharing systems for geoscience research in the HRB. One is known as the Digital Heihe (http://heihe.westgis.ac.cn), sponsored by the Cold and Arid Regions Environmental and Engineering Research Institute of Chinese Academy of Sciences (CAREERI/CAS). The online Digital Heihe holds more than 1,000 GB of dedicated data for HRB studies and insists on a full and open data-sharing policy (Li *et al*., 2010a). The other is the Ecological and Environmental Science Data Center for West China (abbreviated as WestDC, http://westdc.westgis.ac.cn). This was initially supported as a key research project by the NSFC and is now operated by CAREERI. WestDC holds science data for greater western China in space, with the objective of data sharing as well as knowledge and research exchange and cooperation (Li *et al*., 2008b; Nan *et al*., 2010).

WestDC includes rich datasets for HRB studies, categorized as follows (Li *et al*., 2011):

(1) *Background geographical data*. These are defined as the fundamental data used in land surface modeling, hydrology, ecology, environment sciences, and other sciences. These data were collected from research institutions or individual scientists and partially digitized from existing paper maps. Generally, they cover the entire land territory of China.

(2) *Regional dataset subsets* from popular global datasets, usually of two types, one for western China and the other for the entire land territory of China.

(3) *Data for cold and arid regions in China*. The areal coverage includes the Qinghai-Tibet Plateau, the mountain cryosphere in western China, and arid regions (particularly the deserts). These data are usually derived from the results of scientific research in those regions and are among the most innovative data within WestDC. All the data are supplemented with elaborated metadata and necessary documentation.

(5) *A thematic HRB database*, which is actually imported from the Digital Heihe database.

(6) *Data submitted by NSFC West Plan projects*. Because WestDC was initially an NSFC project, it was authorized to archive data for NSFC West Plan projects. So far, 26 out of the total 66 West Plan projects have submitted their data to WestDC. Associated documentation was completed by a joint effort of data authors and data center staff, and its quality was ensured by a peer review process similar to that of scientific journals.

3.3 Data techniques

Various data techniques can be used to improve data quality and to meet research needs. For example, data assimilation is a good option for bringing modeled estimates and observational records together. A watershed-scale land data assimilation system has been established to assimilate data coming from different sources and in different resolutions. An example of this system is to use a land surface model to assimilate passive microwave remote-sensing observations such as from SSM/I, TMI, and AMSR-E (Huang *et al*., 2006). By this system, high-resolution assimilation data about soil moisture, soil temperature, and snow cover ranging from 1991 to 2010 have become available in the arid regions of Northwest China and the Qinghai-Tibet Plateau. These data have laid a solid foundation for the future research of water cycles in a basin and even finer scale.

With respect to data assimilation theory, a number of studies on issues such as nonlinearity and discontinuity of models, error estimation, and calculation efficiency enhancement have been carried out. For example, a data assimilation method was developed for calibrating a hydraulic conductivity field and improving solute transport prediction with an unknown initial solute source condition (Huang *et al*., 2009). A variety of major ensemble Kalman filters have been investigated (Zhang *et al*., 2005), and an experimental assimilation system based on simulated annealing has been developed which assimilates soil moisture observations into the land surface model SiB2 (Li *et al*., 2003; Pathmathevan *et al*., 2003). Soil moisture profiles can now be reverse estimated from soil temperature observations using adaptive Kalman filters (Zhang *et al*., 2004a,b).

4 Modeling activities

Because water scarcity is of greatest concern in the HRB, studies regarding hydrology and water resources management in that area have been conducted since the 1950s. The following summarizes past and current hydrologic modeling activities in terms of model application, model enhancement, and model integration.

4.1 Model applications

There are many applications of existing hydrological models, groundwater models, and land surface models in the HRB. Because the HRB consists of several distinctly different landscapes, the modeling activities in the upper, middle, and lower HRB have different objectives. The upstream studies focus on the energy-water cycle, especially the trends and periods of runoff at the mountain outlet simulated by hydrological models. Interactions and coupling mechanisms between climate, soil, vegetation, snow, and permafrost are also of great concern in the upper area. The core of the midstream studies is to couple the water resources, the ecology, and the economy in order to, for example, develop sustainable strategies to rationally and efficiently utilize water resources so as to assist governmental decision making. Due to intensive irrigation in the middle area, the strong interaction between surface water and groundwater is another hot topic. The downstream area is desert/Gobi and oasis, and therefore assessment of its ecosystem and the development of adaptive measures are of greatest concern (Li *et al*., 2010c). Table 1 presents hydrologic (Table 1a), groundwater (Table 1b), and land surface modeling (Table 1c) activities conducted in the HRB in past years.

In recognition of the significant impact of mountain runoff on the socioeconomic and environmental conditions in the middle and downstream areas, it is very important to improve predictability of runoff simulation to implement rational water resources management and thus promote local socioeconomic development. Almost all of the popular hydrological models, such as TOPModel, SWAT, and VIC, have been applied to the upper mountainous area of the HRB, as outlined in Table 1a. Most of those studies focused on mountain runoff forecasting, while some simulated the hydrological processes in the middle and lower areas. Among them, a model named Distributed Water-Heat Coupled Model for Mountainous Watershed of an Inland River Basin (DWHC), designed to model watersheds with complex snow and permafrost hydrology, has been developed by Chen *et al*. (2006a). The model fully describes the soil frozen state by establishing a continuous water and heat equation on the freezing front edge, and also features improvements in vegetation interception and infiltration.

Another important feature of the water cycle in an inland river basin like the HRB is frequent complex interaction between surface water and groundwater due to intensive irrigation. Not surprisingly, there have already been a number of studies addressing the interaction and groundwater dynamics in the middle and lower HRB (Table 1b). Wen *et al*. (2007), Li *et al*. (2009), and Zhou *et al*. (2009) employed FEFLOW to simulate groundwater changes. Wu *et al*. (2003) established a three-dimensional numerical model to study the groundwater system in the downstream area in Ejina, by which groundwater table dynamics were predicted with four scenarios of surface water delivery. Wang X *et al*. (2010) developed a nonlinear infiltration model by taking streamflow level changes and agricultural water use into account, reporting a more reasonable monthly infiltration simulation in the HRB.

Unlike hydrological and groundwater models, the land surface model (LSM) usually includes water balance as well as the energy budget balance and vegetation photosynthesis. The physically explicit LSM is capable of simulating energy exchange, the water budget, and the carbon cycle in a vertical profile from the atmosphere of the near surface to the subsurface. LSM simulation in the HRB began from a remote-sensing experiment known as the HEIFE Experiment, and has strengthened in following 20 years (Table 1c). Those studies elaborated the freezing-thaw process in cold regions and ET estimation in arid regions that are of great concern in water-stressed watersheds. These efforts provided a good basis for further model integration.

Table 1a Summary of hydrological modeling studies in the Heihe River Basin [modified from Li *et al*. (2010c) and annotated]

Model	Settings and study area	Modeled variables	Main inputs*	Main parameters	References
HBV	Monthly time step, upstream	ET and runoff in mountainous area	Monthly air temperature and precipitation	Lapse rate of temperature and precipitation, threshold of ice and liquid rainfall, and degree-day indices	Kang *et al*. (1999); Kang *et al*. (2002)
TOPModel	Gridded 1,500-m resolution, monthly or daily, upstream	Runoff	DEM, precipitation, ET	Five parameters related to hydraulic conductivity, interception, soil moisture deficiency	Chen *et al*. (2003)
SRM	Elevation zoning, daily, upper mountainous area	Runoff	DEM, meteorological data, snowpack area obtained from remote sensing	Runoff coefficient, degree-day indices, temperature lapse rate, recession coefficient	Wang *et al*. (2005)
DWHC	Gridded with 1-km, daily, upstream	Temperature, soil liquid, soil ice content, sensible heat, latent heat, soil water potential gradient, infiltration, capillary rise content	DEM, vegetation, soil, meteorological data	Parameters related to soil and vegetation types, threshold of ice and liquid, degree-day indices, unified coefficients for soil evaporation and transpiration adjustment, convergence parameter	Chen *et al*. (2006a,b,c)
SRM	Daily, upstream	Runoff	DEM, meteorological data, snowpack area obtained from remote sensing	Runoff coefficient, degree-day indices, temperature lapse rate, recession coefficient	Wang *et al*. (2011)
DTVGM	Gridded in 500-m, daily, upstream	Runoff	DEM, land cover, hydraulic, and meteorological data	Threshold of ice and liquid, critical temperature (snow-rain), temperature lapse rate, runoff-producing parameters, soil water discharge coefficient	Xia *et al*. (2003); Xia *et al*. (2004)
SWAT	157 hydraulic response units, daily, upstream	Runoff and other components of water cycle	DEM, land cover, soil, and meteorological data	Parameters related to soil and land cover, snowmelt runoff coefficient, groundwater coefficient	Huang *et al*. (2004)
SWAT	36 hydraulic response units, daily, upstream	Runoff (focused on parameter calibration)	DEM, land cover, soil, and meteorological data	Parameters related to soil and land cover, snowmelt runoff coefficient, groundwater coefficient	Li Z *et al*. (2009)
SWAT	4 sub-basins, daily, upstream	Runoff	DEM, land cover, soil, and meteorological data	Parameters related to soil and land cover, snowmelt runoff coefficient, groundwater coefficient	Wang *et al*. (2003)
SWAT	Daily, upstream	Runoff	DEM, land cover, soil, and meteorological data	Parameters related to soil and land cover, snowmelt runoff coefficient, groundwater coefficient	Yu *et al*. (2012)
VIC	Gridded with 1/64-degree cells, daily, upstream	Runoff, soil evaporation, vegetation transpiration, evaporation of canopy intercepted water, total ET, soil moisture, sensible heat flux, latent heat flux, soil heat flux	DEM, land cover, vegetation, soil, and meteorological data	Parameters related to soil and vegetation type, convergence parameter	Wang (2006)
VIC-3L	3 sub-basins, daily, upstream	Runoff	DEM, land cover, vegetation, soil, and meteorological data	Parameters related to soil and vegetation type, convergence parameter	Zhao *et al*. (2012)

* Initial conditions excluded

Table 1b Summary of groundwater modeling studies in the Heihe River Basin [modified from Li *et al.* (2010c) and annotated]

Model	Settings and study area	Modeled variables	Main inputs*	Main parameters	References
FEFLOW	Triangle-gridded, 35×760 units, aquifer depth 200–500 m, monthly, midstream (5,024.4 km^2)	Groundwater table	Hydrogeological data	Hydrogeological parameters (*e.g.*, hydraulic conductivity)	Wen *et al.* (2007)
FEFLOW	Finite elements, monthly, downstream Ejina delta (11,545 km^2)	Groundwater table	DEM, hydrogeological data, meteorology and irrigation data, groundwater recharge and withdraw	Hydrogeological parameters	Li S *et al.* (2009)
FEFLOW/MIKE11	Finite elements (66,073 units), daily, midstream	Groundwater table, groundwater and river recharge and discharge	DEM, land cover, vegetation, soil, hydrogeological data, drainage, meteorology, irrigation, river diversion, groundwater exploitation	Parameters related to soil and land cover type, groundwater coefficient	Zhou *et al.* (2009)
Groundwater model of Heihe midstream	Finite elements (1,421 units), single layer, monthly, midstream	Groundwater table	Hydrogeological data, boundary conditions, source/sink	Hydrogeological parameters	Zhang G *et al.* (2004)
Groundwater model of Heihe downstream	Irregular polygons, double layers, monthly, downstream Ejina delta (33,987.5 km^2)	Groundwater table	Hydrogeological data, boundary conditions, source/sink	Hydrogeological parameters (*e.g.*, hydraulic conductivity, unsaturated soil water flow parameter)	Wu *et al.* (2003)
Nonlinear Leakage Model	Finite difference, monthly, midstream Zhangye City	Hydrogeological dynamics, river percolation, recharge and discharge relationship of groundwater, river, and wells	Hydrogeological data, spring water, groundwater withdraw	Hydrogeological parameters	Wang X *et al.* (2010)

* Initial conditions excluded

Table 1c Summary of land surface modeling studies in the Heihe River Basin [modified from Li *et al*. (2010c) and annotated]

Model	Settings and study area	Modeled variables	Main inputs*	Main parameters	References
One-dimensional land-surface process model (derived from SiB)	Soil layer (15 layers), vegetation, and atmospheric reference layer, 10-min time step, HEIFE experimental site	Components of water balance, components of energy balance	Meteorological data, soil parameters, crop type	Parameters related to soil and crop type, leaf area index (LAI)	Niu *et al*. (1992)
SHAW	Vegetation, residual layer, soil layer, daily time step, upper stream grassland and spruce forest sites	Water cycle components, soil moisture, ET, energy balance components (*e.g.*, short-wave and long-wave radiation, sensible heat, and latent heat)	Meteorological data, site information	Parameters related to soil and vegetation type, roughness, snow and residue parameters	Kang *et al*. (2004)
NCAR/LSM	Hourly, the Ejina site in downstream	Surface temperature, soil moisture, energy balance components	Meteorological data, site information, vegetation and soil type	Parameters related to soil and vegetation type, aerodynamic parameter	Feng *et al*. (2008)
HYDRUS-1D	Daily, downstream (*Populus euphratica* forests)	Root zone hydraulic lift (interaction between vegetation and groundwater)	Meteorological data, plant growth	Hydraulic parameters related to soil type, root distribution	Zhu *et al*. (2009)
Soil water migration model of irrigated field with growth of spring wheat	Daily for spring wheat growth model, variable time step (1–60 min) for soil moisture model, the Linze site in midstream	Daily crop growth states, rootzone intake profile, profile distribution of soil moisture for each layer, input and output of field moisture balance	Meteorological data, soil parameters, crop type, LAI	Soil hydraulic parameters, crop parameters, and root parameters	Ji *et al*. (2006)
Irrigation field water balance model	Extension of former model, Linze site in midstream	Soil moisture, rootzone hydraulic lift, evaporation, and ET	Meteorological data, soil parameters	Soil parameters, root distribution, vegetation parameters (*e.g.*, stomatal conductance)	Ji *et al*. (2007)
TSEBPS	Yingke site in midstream oasis	Sensible and latent heat flux	Meteorological data, thermal infrared range remote sensing, LAI	Soil and aerodynamic parameters	Xin *et al*. (2010)

* Initial conditions excluded

In past years, all of these models were applied and their applicability was validated. Their major contribution has been the information provided by cold-region hydrological simulation of snow, permafrost, and glacier effects. The focus of the next stage is to strengthen the current hydrological models by considering frozen soil hydrology, snow hydrology, and forest hydrology. Study of the impacts of climate change and human intervention on mountain ecosystems and hydrological processes will also be strengthened. The new trend of groundwater modeling is to consider the interaction between groundwater, river water, well water, and irrigation, and to further study the complex interaction between surface water and groundwater. For LSM studies, simulation of land surface energy budgets with various underlying surfaces is the primary focus.

4.2 Model enhancement

The runoff-generating area in the HRB is located in the alpine area, where snow and permafrost create a series of challenges to the simulation of the hydrological and land surface processes (Ding *et al*., 2000). In order to improve the simulation accuracy, existing models need to be enhanced by specifically considering boundary conditions, soil and vegetation parameters, and additional processes such as snow and permafrost. Relevant works are summarized in Table 2.

In terms of hydrologic model enhancement, a customized water cycle system for the HRB, based on the WEP model, has been developed to further separate artificial water processes from the natural water cycle (Jia *et al*., 2006a,b). Gao *et al*. (2006) improved the Noah LSM and coupled it to the mesoscale climate model MM5 to simulate typical precipitation processes in the upper HRB. Yu *et al*. (2012) realized that simulation accuracy of the river runoff with SWAT is lower because SWAT is insufficient in estimating snowmelt in springs; they proposed a coupling approach to improve the simulation of snowmelt by integrating FASST snowmelt into SWAT. Their work confirmed the applicability of the SWAT-FASST coupled approach in cold and alpine watersheds where snowmelt should be taken into account, and suggested its significance in improving the simulations in such areas.

Wang L *et al*. (2010) simulated the short-term hydrothermal conditions in the Dadongshu Pass site located in the upper reach by adopting an enhanced WEB-DHM land surface model, which optimizes permafrost parameterization. Their study confirmed that a suitable frozen soil parameterization scheme is able to improve the accuracy of water thermal simulation in alpine areas. Ji *et al*. (2004) modified the often-used Penman-Monteith equation by combining parameters from the Shuttleworth-Wallace model to more accurately estimate evaporation from sparse crops. In that method, a combination equation is derived to calculate plant transpiration and soil evaporation of an agriculture field, and then a one-dimensional soil-vegetation-atmosphere transfer model is employed to simulate the process of soil evaporation, plant transpiration, and total evapotranspiration during the growing seasons of spring wheat in irrigated farmlands, located in an oasis close to the mountains of the upper HRB.

No matter which strategy is used, whether building a new special model for the HRB or modifying existing models, it offers the capability to further understand the interaction between heat and water in cold alpine areas. Such studies lay solid foundations for further researches in order to improve numerical simulation accuracy and strengthen forecasting capabilities.

4.3 Model integration

Considering the existence of interactions of water, soil, air, ecosystems, and human activities in the HRB, Li *et al*. (2010c) suggested the necessity of developing integrated models and using high-resolution remote-sensing data to comprehensively depict thermal and water characteristics in the HRB. The essential objective of an integrated model is to couple different models which might be derived from different disciplines and have their own advantages and also disadvantages. Recent model integration efforts in the HRB are summarized in Table 3.

Gao *et al*. (2004) coupled the distributed hydrological model DHSVM and the mesoscale climate model MM5 to describe a watershed-scale climate-hydrology interactive process. With this coupled model, a July 2002 flood event in the upstream could be well simulated. Hu *et al*. (2007, 2008) established a surface and groundwater coupled model to forecast the dynamics and streamflow level more accurately. Zhou *et al*. (2008) proposed a coupling scheme that linked a vadose zone hydrological model and a land surface model through their boundary condition inputs. Tian *et al*. (2012) attempted to link the land surface model SiB2 and the groundwater model AquiferFlow; they successfully obtained a more precise description of the land surface dynamic processes because the coupled approach provides a better formulation of the ET estimation. In an attempt to couple multidisciplinary models, Liu *et al*. (2012) presented a case study of coupling a hydrological model with a socioeconomic model where SWAT was used to the simulate soil moisture contents of each sub-basin, which were then input into the minimum data (MD) method as "ecosystem service." That study shows a promising potential to link a physical model to a socioeconomic model in the socioeconomics field, because the physical model usually has a better quantitative capability than the latter. Compared to building a large and very complicated model that has all kinds of functionality, the lightweight integration approach offers an applicable and effective way to address complex watershed problems.

5 Modeling methodologies

Integrated modeling environment (IME) is a computer software platform which supports the efficient development of model integration. It is capable of easy linkage of existing models or functional modules which usually represent physical subprocesses, model management, parameter calibration, and data visualization. More than three decades of IME development worldwide has proven its effectiveness and efficiency in model integration. Feng *et al.* (2008) initially developed a prototypical IME for the HRB in which two hydrological models, Xinanjiang and TOPMODEL, were modularized. On basis of that work, Nan *et al.* (2011) implemented a fully functional integrated modeling environment (HIME) for hydrological and land surface modeling purposes in a very extendable, efficient, and easy-to-use manner. In its design, a physical process is incorporated as a module, and a new model can be generated in an intuitive way by linking module icons together and determining their relationships. Using XML-based meta-information, modules with either source codes or in binary form can be used in HIME. As demonstrated in Figure 3, HIME holds about 70 functional modules from existing hydrological, land surface, ecological, and socioeconomic models, ready to establish new model when given region-specific requirements.

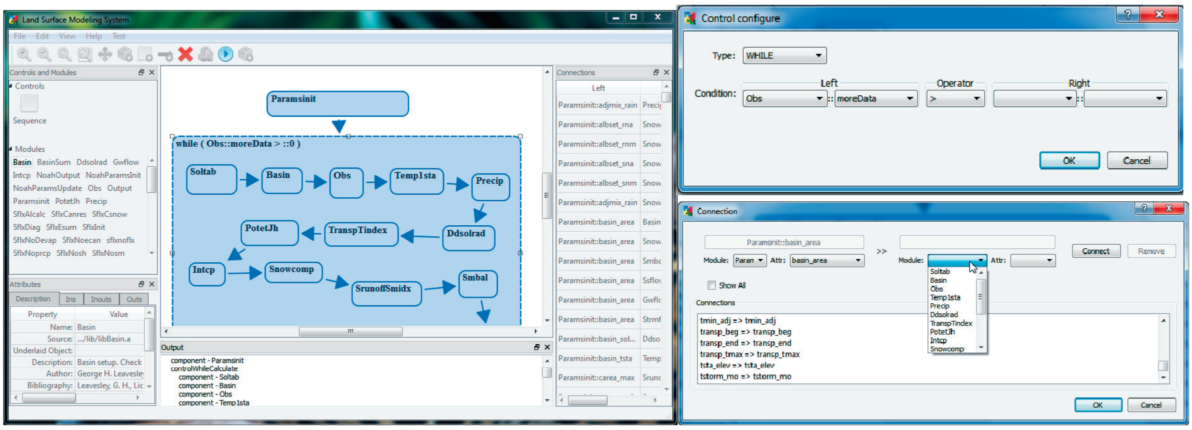


Figure 3 Screenshots of the HIME user interface by which subprocess modules can be assembled into a new model

Having more hydrological and land surface models incorporated into HIME will significantly enhance its functionality. The highest priorities are for snow and permafrost modules for the upstream research, and surface and groundwater modules for the middle oasis research, all with various time steps and spatial discretization schemes. Because running a computationally complex model for a large, high-resolution study area incurs high computation costs, IME should support high-performance computing and cloud computing in the future.

6 Discussion

Data are undoubtedly the foundation of all hydrological research. Due to the HRB's location in the northwest arid area of China, its current sparse observation sites cannot meet the research needs for data (Kang *et al.*, 2007). In modeling activity, it is therefore necessary to resort to interpolation methods to obtain the required resolution. However, it should be pointed out that because of strong landscape heterogeneity in the HRB, data validity and the true parameter representativeness after downscaling or interpolation should be carefully evaluated. Intuitively, the best response to this situation is to set up more observing sites. Therefore, in recent decades, in addition to conventional hydrometeorological sites, advanced remote-sensing instruments have been installed and special sites for observing permafrost and snow have been established to form a more representative watershed observation system. At the same time, data techniques, including interpolation algorithms and data assimilation, are being further strengthened. Although many significant achievements have been obtained in HRB case studies, there is still much improvement to be made in data assimilation and data mining analysis. The heterogeneous biophysical parameters of the HRB usually preclude accurate modeling.

As a newly emerged and promising technology, wireless sensor networks (WSNs) seem applicable and have great potential in cold alpine areas, especially in areas that have extreme physical conditions and are hard to reach. However, there are still some improvements that need to be made in WSNs, including time synchronization, power consumption, and cost control.

Despite the wide application of existing hydrological and groundwater models in the HRB, they cannot yet adequately describe the hydrological characteristics of permafrost and snow layers. There are some difficulties in snow simulation, such as snow drift and snow decay under strong solar radiation (Li *et al.*, 2008; Che *et al.*, 2012). Therefore, the remote sensing approach seems feasible to get more accurate snow data by means of airborne microwave radiometers. The permafrost hydrological cycle involves complex water and heat flux dynamics. Because a complete description of this process is still difficult to obtain, current studies are mainly concentrated on the simulation of hydrothermal processes. Especially under global warming, permafrost degradation should be taken into account when modeling eco-hydrological processes. Such studies are still in the early stage of empirical and semi-empirical descriptions.

Table 2 Summary of model enhancement studies in the Heihe River Basin [modified from Li *et al*. (2010c) and annotated]

Model type	Model	Settings and study area	Modeled variables	Main inputs*	Main parameters	References
Hydrological model	WEP-Heihe	Gridded in 1 km, daily, upper and middle watershed area	ET and evaporation, infiltration and runoff, groundwater flow, groundwater discharge and overflow, slope confluence and river confluence, artificial collateral circulation	DEM, land use, soil, meteorology, irrigation water information, domestic water, population	Parameters related to soil and vegetation type, aquifer, convergence, and snowmelt parameter	Jia *et al*. (2006a,b)
	Noah+MM5	Gridded in 1 km, 9 s, midstream	Precipitation, soil temperature and moisture, latent heat flux	Meteorological data, vegetation, soil	Parameters related to soil and vegetation type	Gao *et al*. (2006)
	SWAT+FASST	Daily, upstream	Runoff	DEM, land cover, soil, and meteorological data	Parameters related to soil and land cover, snowmelt runoff coefficient, groundwater coefficient	Yu (2012)
Land surface model	WEB-DHM (SiB2+GBHM+frost soil parameter)	Hydraulic response unit, hourly, Binggou sub-basin in upstream	Runoff, water cycle components (*e.g.*, soil moisture, soil ice content, energy balance component, carbon cycle)	DEM, land cover, soil, remote sensing data, meteorological data	Parameters related to soil and land cover, LAI and photosynthetic active radiation ratio extracted from remote sensing data	Wang L *et al*. (2010)
	Improved Shuttleworth-Wallace evapotranspiration	Two-layer canopy, daily, Linze site in midstream	ET	Meteorological data, soil parameters, LAI	Aerodynamic resistance, canopy leaf boundary layer resistance, turbulent exchange resistance between surface and canopy, soil resistance, stomatal resistance of canopy	Ji *et al*. (2004)

* Initial conditions excluded

Table 3 Summary of model integration studies in the Heihe River Basin

Type	Coupled models	Settings and study area	Modeled variables	Inputs*	Parameters	References
Climate model, hydrological model	MM5/DHSVM	3-km grids, 10-s time step, upper and middle stream	Hydraulic variables (*e.g.*, runoff, surface energy balance)	DEM, land cover, soil, vegetation, vegetation cover, NECP reanalysis data	Parameters related to soil and vegetation type	Gao *et al.* (2004)
Surface water and groundwater coupled model	Integrated model for surface water and groundwater in arid inland river regions, based on PGMS	Finite difference, 8 vertical simulation layers, 3,755 cells for each layer, monthly, midstream (8,716 km^2)	Groundwater level, recharge and discharge relationship of groundwater, river and wells, spring flow	Hydrogeological data, spring water, water exploitation	Hydrogeological parameters (*e.g.*, hydraulic conductivity), river parameters (*e.g.*, Manning roughness coefficients)	Hu *et al.* (2007); Hu (2008)
Land surface model, groundwater model	SiB2+vadose infiltration model	Hourly, Linze site in midstream	Components for water balance, groundwater level	Meteorological, irrigation and soil data	Parameters related to soil and vegetation type	Zhou *et al.* (2008)
	SiB2+AquiferFlow model	Hourly, midstream	ET	Meteorological, irrigation, vegetation and soil data	Parameters related to soil and vegetation type	Tian *et al.* (2012)
Hydrological model, socio-economic model	SWAT+MD	31 sub-basins, upper stream	Monthly runoff, water content of soil, supply of water conservation services	DEM, land cover, soil, meteorological data	Parameters related to soil and land cover, snowmelt runoff coefficient, groundwater coefficient	Liu *et al.* (2012)

* Initial conditions excluded

As pointed out earlier, model integration is a good option to address complex multidisciplinary watershed problems. On the one hand, an existing model can be enhanced by adding the absent processes which are key for the study area. This is called as the "big model approach," by which the model will become more complex and difficult to learn and maintain. On the other hand, a unified modeling environment can be constructed to support rapid modeling by integrating the advantages of different models. Expert systems can be introduced into the modeling environment because the modeling process involves ample expert knowledge. Eventually, an integrated model able to fully and precisely describe the water and heat processes in the HRB is expected to be used in a decision support system to facilitate decision making and policy evaluation for this region. Along with the development of the HRB researches, such a model will produce much more accurate predictions.

7 Summary

This paper reviews key aspects of hydrological modeling, including data support, modeling practices, and methodology advances. In particular, past and current modeling efforts in the HRB are tabulated in terms of model application, enhancement, and model integration. The review shows that a wealth of data and research results have been accumulated, and initial efforts to systematically examine the interactions of water, ecology, and socioeconomics have been carried out. However, data acquisition and modeling in the HRB still need much improvement. Along with further HRB researches, an integrated model able to fully and precisely describe the water and heat processes in the HRB is expected to be developed. As a pilot basin of the Asian G-WADI/UNESCO framework, the modeling experiences and lessons learned from the HRB can be adopted by river basins elsewhere in the world having similar water-stress issues; similarly, given enhanced research collaboration and data sharing, the HRB can also benefit from those other works.

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