# MODELING WATER MOVEMENT BETWEEN THE GLACIAL, AGRICULTURAL OASIS AND DESERT IN THE HEIHE WATERSHED, NORTHWEST CHINA[1]

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**ABSTRACT.** Irrigated farming accounts for more than 80 percent of the total water uses in arid Northwest China. Over the past few decades, rapid population growth, agricultural irrigation expansion, and industrial development have led to groundwater depletion, river flow reduction, and farmland salinization, and ecosystem deterioration in the region. In the context of climate change, how much water will be available to support domestic, irrigation, and industrial supplies while satisfying the needs for maintenance of ecosystems in Northwest China? This paper describes the preliminary work of adapting the U.S. Department of Commerce's National Oceanic and Atmospheric Administration's Distributed Large Basin Runoff Model to the Heihe Watershed (the second largest inland river in arid Northwestern China, with a drainage area of 128,000 km²) for understanding 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.
**Keywords**: Glacial Recession, Distributed Large Basin Runoff Model, (DLBRM), Heihe Watershed in Northwestern China, and Water Shortage.

## 1. INTRODUCTION

Irrigated agriculture is essential to ensuring a stable food supply, particularly in arid and semi-arid regions. Although representing only about 17 percent of the world's cultivated land, irrigated land produces about one third of the world's grains (World Resources Institute 1996; Postel 1999). However, inappropriate development and management of irrigation systems has also resulted in numerous problems worldwide, including poor food security, increased human diseases, conflicts between different users, limitations on economic development and human welfare, desertification, salinization, sand storms, water pollution, and so forth (United Nations World Water Development Report 2003; Reynolds et al. 2007). In India, large scale overexploitation of groundwater for irrigation has caused water table decline across the country and many aquifers in the nation are depleted (Postal 1999). 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 (Micklin 1994). 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 (Micklin 1994). 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. For example, as the second largest inland river (or terminal lake) in the nation, the Heihe (black river) has a drainage area of 128,000 km² in Northwest China. From its headwaters in the south to the middle and lower reaches in the north, it flows through Qinghai, Gansu, and Inner Mongolia (Figure 1). Glacial and mountain, agricultural oases, and desert cover 21.9, 43.6, and 34.5 percent of the watershed respectively (Pan and Tien 2001). While glacial/snow melt in the Qilianshan Mountain contribute about 8 percent of the total annual water supply in the watershed, the glacier had shrunk by 29 km² from 1960 to 1995 (Feng et al 2002). 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 reaches (below Zhengyixia as shown in Figure 1), shrinking

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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 (figure 1). To mitigate the water conflicts and rehabilitate West Juyan Lake, the State Council of China issued a "Water Allocation Plan for the Heihe Watershed Mainstream" in 1997, mandating water allocation to the lower reaches each year (Pan and Tien 2001; Feng 2002). 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 (Feng 1999; Feng et al. 2002; Pan and Tien 2001; Cheng 2002), the magnitude, spatial and temporal distribution, and transfer mechanism of the Heihe hydrological 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.

To address this problem, this study takes an integrated approach of hydrologic modeling and crop simulation to address two key research questions facing the Heihe Watershed: 1) 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? And 2) How will application of water conservation programs and technologies affect water uses in the study area?

This paper describes the preliminary work of adapting 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 hydrological processes of the Heihe Watershed. We first describe the physical features of the Heihe Watershed, then introduce the structure, input, and output of the DLBRM, and subsequently the Geographical Information System (GIS) interface to process and analyze multiple variables to the DLBRM. Finally we discuss its application to the Heihe Watershed. Since the research is still in progress, the paper reports climate change and irrigation management scenarios to be used in the DLBRM for assessing the impacts of glacial recession and water shortage on the hydrology and agricultural production in the watershed.

## 2. METHODS

### 2.1. The Study Area

From the headwaters in the south to the lower reaches in the north, the Heihe Watershed can be physically divided into the Qilianshan Mountain, the Hexi Corridor and the Alashan Highland (Figure 1) (Feng et al. 1999). The Qilianshan Mountain is situated at the south of the Watershed, with a peak elevation of 5,584 m. It is covered by ice and snow all year round above 4,500 m. Between 3,600 to 4,500 m are the mixed alpine meadow and permafrost. 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 (Feng et al. 1999). Located in the middle reaches of the Heihe Watershed, the Hexi Corridor covers 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 mainly from 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 (He et al., 2007).

Water shortage is a chronic problem in the Heihe Watershed. The total annual mean water supply in the watershed is approximately 3.48 billion ($10^9$) $m^3$ and nearly 90 percent of the flows are generated in the Qilianshan 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 ha of farmland mainly located in the Hexi Corridor (Pan and Tien 2001). 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 (Pan and Tien 2001). Water conflicts have been high between water users in the Hexi Corridor and those in Alashan Highland in the lower reaches, particularly in implementing the State Council's water allocation plan to deliver water to the lower reaches for rehabilitation of the West Juyan Lake (Pan and Tien 2001).

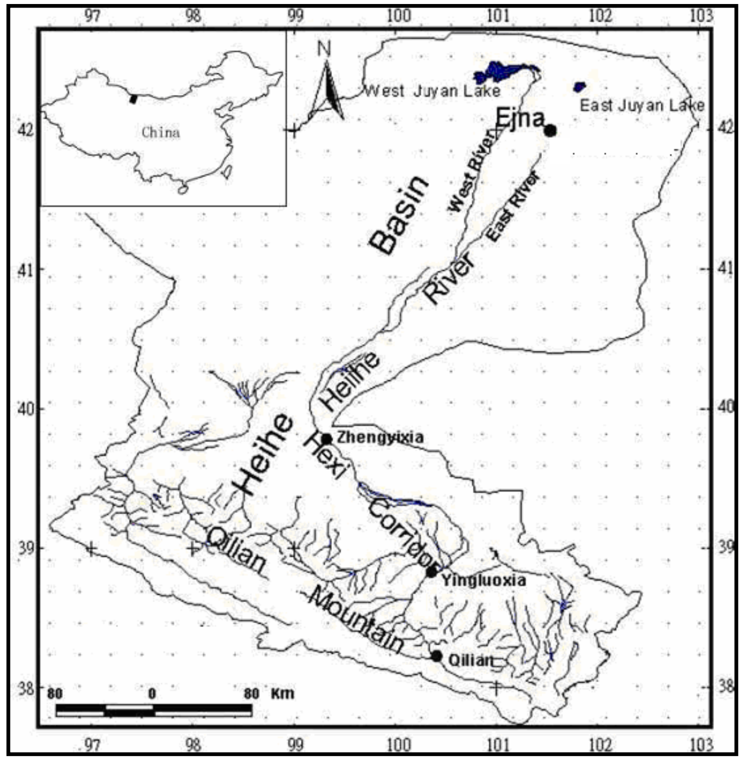


Figure 1. The boundary of the Heihe Watershed (Source: J.H. Si of CAREERI 2007)

## 2.2. Description of the DLBRM

The DLBRM represents a watershed by using 1-$km^2$ 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 (Figure 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. The model computes potential evapotranspiration from a heat balance, indexed by daily air temperature, and calculates actual evapotranspiration (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 (Croley and He 2005; 2006; Croley et al. 2005; He and Croley 2007). The unique features of the DLBRM include: 1) use of readily available climatological, topographical, hydrological, 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 Croley and He 2005; 2006; He and Croley 2007).

DLBRM inputs include, for each cell, flow direction, slope, land use, Manning's coefficient (*n*) values, soil texture, and 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.

As the DLBRM considers surface and subsurface interactions and is particularly suitable for continuous simulation of large scale hydrological systems over the long term, it is used to simulate the hydrological system of the Heihe over the period of 1978-2000 at daily intervals. Since the Heihe is regulated at the upper and middle reaches and discharges a small amount of water to the lower reaches at certain times, the upper and middle reaches of the Heihe Watershed is divided into 36,000 cells at resolution of 1 km by 1 km for hydrologic simulation. The databases of land use/cover (2000), DEM (100 m resolution), and watershed hydrography were provided by The Chinese Academy of Sciences (CAS) Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI). Meteorological databases from 22 weather stations for the period of 1978 to 2000 were used to interpolate precipitation and temperature using one of several methods: Thiessen polygon, inverse distance, inverse squared-distance, and linear interpolation over a triangular irregular network (TIN). Daily surface insolation estimates are generated by two methods: (1) from temperature databases by empirical formulae, and (2) reversed-engineered from an available weather generation model as a function of location, day of the year, air temperature and precipitation (Croley and He 2005; He and Croley 2007). Slope and flow direction are extracted from the DEM database. The soil database of 1999 (1:250,000) from the Gansu Province only contains soil types and texture at the soil association level, and attribute information on the depths, water capacity, and permeability of the USZ and LSZ was compiled from soil surveys and samples and then joined with the soil spatial database. Manning's coefficient values are derived for each grid based on the combination of land use, slope, and soil texture. Four streamflow gauge stations located along the main channels of the Heihe River are used in calibration of the DLBRM as a systematic search of the parameter space to minimize root mean square errors between actual and simulated daily outflow volumes at the watershed outlet. Currently, we are working to calibrate the DLBRM.

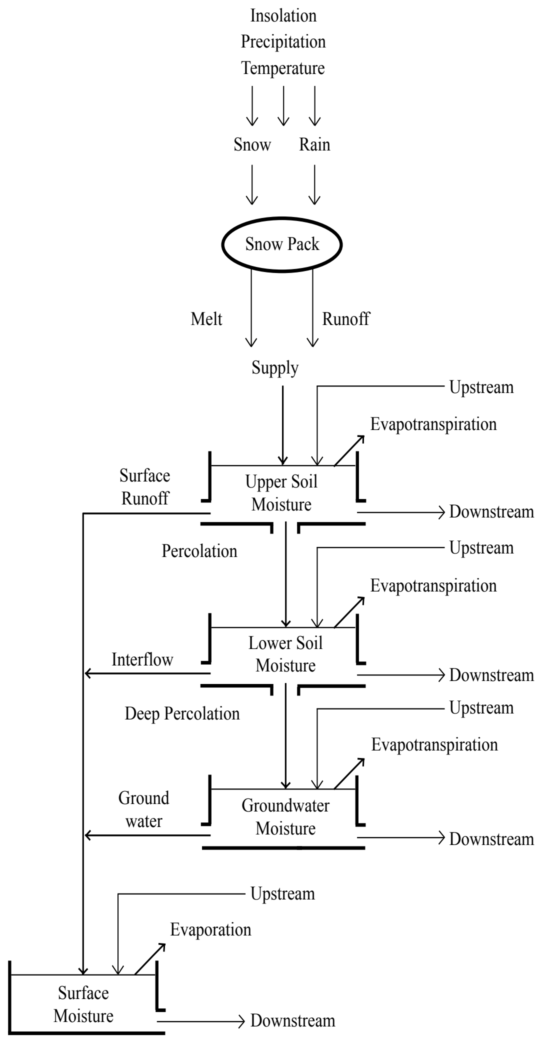


Figure 2. Tank cascade schematic of Distributed Large Basin Runoff Model

## 2.3. GIS-Model Interface

The DLBRM divides a watershed into a 1-km$^2$ grid network and simulates hydrologic processes for the entire watershed sequentially. It requires 16 input variables for each of the 1-km$^2$ grid cells. Since the DLBRM was designed for hydrologic modeling of large scale (>$10^3$ km$^2$) watersheds, development of the 16 input variables for each grid cell from multiple databases over large watersheds is a challenge. 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). 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, digital elevation model (DEM), land use/cover, and hydrology and hydrography are used by the interface to derive input variables for the DLBRM (He and Croley 2007c). The derived variables for each of the 1-km² cells nclude: elevation, flow direction, slope, slope length, land use, depth of upper soil zone (USZ) and lower soil zone (LSZ), available water capacity (%) of both USZ and LSZ, permeability (cm/hour) of both USZ and LSZ, soil texture, and Manning's coefficient values.

The interface determines appropriate Manning's coefficient values for each of the grid cells. It first defines the hydrologic response units (HRUs) based on combinations of land use, slope, and soil texture (i.e. dividing the watershed into different HRUs) for the entire watershed. Since the Manning's coefficient values are mainly determined by land use/cover categories and then adjusted by slope and soil texture, the interface allows the user to reclassify land cover (e.g. 22 categories), slope (e.g. 4 categories: <0.249%, 0.250 – 1.999%, 2.000-4.999%, and >4.999%), and soil texture (e.g. 4 categories: sand, peat, loam, and clay), and then define the HRUs for the entire watershed by using the "Define HRUs" (based on map calculation function of the ArcView) in the Parameter Generator module. A look-up table has been created to determine appropriate Manning's coefficient values for each HRUs. The user can then run "Manning *n"* icon to assign to each HRU an appropriate Manning's coefficient value automatically and at the same time, the interface also assigns Manning's coefficient values from each HRU to each grid cell (He and Croley 2007b).

## 2.4. Simulating Impacts of Glacial Recession on Streamflow

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 (UN World Water Development Report 2003). 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 (Varis and Vakkilainen 2001; Fu et al. 2004; Huang and Zhao 2004; Yang et al. 2004). 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) and the increase in evaporation (+52 mm/10 yr for pan evaporation) (Yang et al. 2004). Since glacial/snow melt contributes about 8 percent of the total annual discharges in the Heihe Watershed and the glacier has shrunk significantly during the past few decades, we will simulate the impacts of glacial recession on water supply of the Heihe River. Upon calibrating the DLBRM, we will incorporate scenarios of 10 and 20 percent reduction in glacial/snow melt into the model and assess how that reduction would affect the magnitude and distribution of surface runoff, groundwater, evapotranspiration, and basin outflow throughout the Heihe Watershed. Since the simulation results can be examined over individual cells in map format, we will be able to track the spatial distribution of hydrological variables to better understand the partitioning of river flows between the Hexi Corridor of the middle reaches and the Alashan Highland of the lower reaches. Such information will support implementation of the State Council's water allocation plan to rehabilitate the West Juyan Lake.

In addition, as irrigated agriculture uses over 86 percent of total water withdrawals in the Heihe Watershed (Pan and Tien 2001), it is crucial to evaluate crop water requirements under different management scenarios. We will evaluate the water requirements of wheat and corn (two major crops account for more than 60 percent of the total harvest areas) in the Heihe Watershed using two widely used crop-growth models of CERES MAIZE and WHEAT (He 1997) to: 1) simulate water requirements of corn and wheat, and 2) compare the differences in the crop water requirements under different irrigation practices (e.g. traditional flood irrigation vs. conservational sprinkler and drip irrigation) in the agricultural oases. The simulation results will allow us to determine the amount of irrigation water that can be saved by 1) reducing irrigation area; and 2) by using water saving irrigation technologies.

# 3. SUMMARY

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 reaches have depleted river flows to the lower reaches, drying up West Juyan Lake and endangering aquatic and terrestrial ecosystems downstream. 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. 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 hydrological system, and for exploring the effects of water saving practices and technologies in water conservation by using crop simulation models. The DLBRM requires multiple databases of climate, land use/cover, topography, and soil but some of the databases such as soil are either not readily available or incomplete. Collaborating with Chinese researchers, we have processed and generated necessary databases for the DLBRM and are working to simulate the impacts of reduction in glacial/snow melt on the magnitude and spatial and temporal distribution of hydrological components in the Heihe Watershed. Results from the simulations of the coupled Heihe hydrological and crop production system will shed light on how water saving programs may mitigate the chronic water shortage problems in arid and semi-arid regions of China.

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