INTEGRATED MODELING AND MANAGEMENT OF GROUNDWATER AND SURFACE WATER, ZHANGYE BASIN, NORTHWEST CHINA

by

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ABSTRACT

This dissertation consists of three self-contained, yet closely related, papers summarizing the results of a comprehensive study aimed at the development of a decision support system for sustainable water resources management for the Zhangye Basin in northwestern China. The first paper presents a 3D groundwater flow model to represent groundwater dynamics of the basin from 1999 through 2010 using MODFLOW-2005. The regional 3D groundwater model provides reliable information of the flow field and produces detailed water budgets for management purposes. It defines the intensive groundwater-surface water interaction zones, and reveals the increasing flux exchange due to both climate change and human activities.

The second paper presents an integrated 3D groundwater-surface water flow model using GSFLOW. The model calibration was done by first running PRMS and MODFLOW-2005 models separately, and then followed by the calibration of the integrated GSFLOW model. The model shows a detailed trend of water storage changes and their relationship with each inflow and outflow item. More importantly, this study demonstrates the applicability of integrated basin-scale models in characterizing the groundwater-surface water(GWSW) interaction, reproducing the flow system, and supporting sustainable water resources management while accounting for the effects of climate change in arid inland river basins.

The third paper presents an efficient decision support tool, taking into consideration the relevant complexities and interactions in different water resource components, to inform decision making for water resources management for the Zhangye basin. On the basis of data collection and data mining, incorporated with integrated hydrological conceptual models and numerical models, a Bayesian network (BN) has been developed and calibrated by K-fold cross validation. The trained BN model captures the important hydrological cycle characteristics and uncertainty of related factors to provide the optimal management solutions under consideration.

While this study is based on the Zhangye basin, the concepts and approaches developed in this study are of general applicability. The integrated GWSW modeling, coupled with a BN construct, provides an innovative tool to inform decision making in water resources management.

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LIST OF ABBREVIATIONS AND SYMBOLS

<	Less than
=	Equal
3D	Three dimensional
ArcGIS	Esri's geographic information system for working with maps and geographic information
basin_lat	Latitude of watershed centroid
BN	Bayesian Network
CAREERI	Cold and Arid Regions Environment and Engineering Research Institute, Chinese Academy of Sciences
CIGEM	China Institute for Geo-Environmental Monitoring
ddsolrad_hru_prms	PRMS Solar-Radiation Module
ddsolrad_hru_prms	PRMS Solar-Radiation Distribution Module
DAG	Directed acyclic graphical
DEM	Digital Elevation Model
DSS	Decision Support System
E (N&F)	Nash-Sutcliffe efficiency coefficient
ET	Evapotranspiration
FEFFLOW	Finite Element subsurface FLOW system
GIS	Geographic Information SystemGSFLOW Coupled Ground-Water and Surface-Water Flow Model
GWSW	Groundwater-surface water

HRB	Heihe River Basin
HRU	Hydrologic Response Units
hru_lat	Latitude of HRU centroid
hru_plaps	Identifier of lapse measurement station used in calculating precipitation lapse rate
hru_psta	Identifier of measurement station used as base in calculating precipitation lapse rate
hru_slope	HRU slope, specified as change in vertical length divided by change in horizontal length
hru_tlaps	Identifier of lapse measurement station used for air-temperature lapse rate calculations
hru_tsta	Identifier of base measurement station used for air temperature lapse rate calculations
HWDP	Heihe Water Diversion Project
jh_coef	Monthly air temperature coefficient used in Jensen-Haise potential evapotranspiration equation
jh_coef_hru	Air temperature coefficient used in Jensen-Haise potential evapotranspiration equation for each HRU
Kx	Horizontal hydraulic conductivity along the x direction
Ky	Horizontal hydraulic conductivity along the y direction
Kz	Vertical hydraulic conductivity
ME	Mean Error
MODFLOW	USGS's popular 3D Finite-Difference Groundwater Flow Model
PEST	Parameter Estimation Software
potet_jh_prms	PRMS Potential Evapotranspiration Module
potet_pan_prms	PRMS Potential Evapotranspiration Module

precip_laps_prms	PRMS precipitation module
PRMS	Precipitation-Runoff Modeling System
radj_sppt	Precipitation-day adjustment factor to solar radiation for a summer day
radj_wppt	Precipitation-day adjustment factor to solar radiation for a winter day
RMSE	Root mean square error
SFR2	Streamflow-Routing package
soilzone_gsflow	PRMS Soil-Zone Module
soltab_hru_prms	PRMS Potential Solar-Radiation Module
Ss	Specific storage
SWAT	Soil and Water Assessment Tool
Sy	Specific yield
t	Time
temp_laps_prms	PRMS Temperature Distribution Module
W	volumetric flow rate
x, y, and z	coordinate axes
θ	vertical hydraulic conductivity

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Any hydrogeological study of a regional scale inevitably requires many persons who occupy different positions to secure the essential information and data. Without their ready cooperation the study of this type could never have been completed.

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CHAPTER 1 INTRODUCTION

Water is essential to human substance and ecological system. Because of global climate change and the increasing intensity of human activity, water scarcity becomes an urgent issue globally, especially in arid and semi-arid regions (Grafton et al. 2012, Konikow and Kendy 2005). Decision making become extremely challenging in face of substantial uncertainties (Uusitalo et al. 2015).

The direct motivation of this research arises from the urgent needs to develop a decision support system using integrated approaches to address hydrological problems caused by uncertain climate change and to evaluate the impacts of implementation of Heihe Water Diversion Project (HWDP) on the hydrological system in the Zhangye Basin under uncertain climate change. It was proposed that linking the hydrological process model with the statistical model will provide a solution to solve above mentioned issues.

The Zhangye Basin is located in the arid region in northwest China, which refers to one of the most important agricultural bases for the country (Figure 1.1). The basin covers approximately 5000 km^2 in the middle reach of the Heihe River, it contains 90% of the population and consumes about 82% of the water resources of the whole inland Heihe River Basin. Like other inland river basins in arid and semi-arid northwest China, the Zhangye Basin faces severe problems of water scarcity and ecological deterioration (Cheng et al. 2006). This has involved the drying up of rivers and lakes, decline of water tables, deterioration of water quality, land salinization, desertification and other eco-hydrological problems (Mi et al. 2016, Wang et al. 2016, Xiao and Cheng 2006).

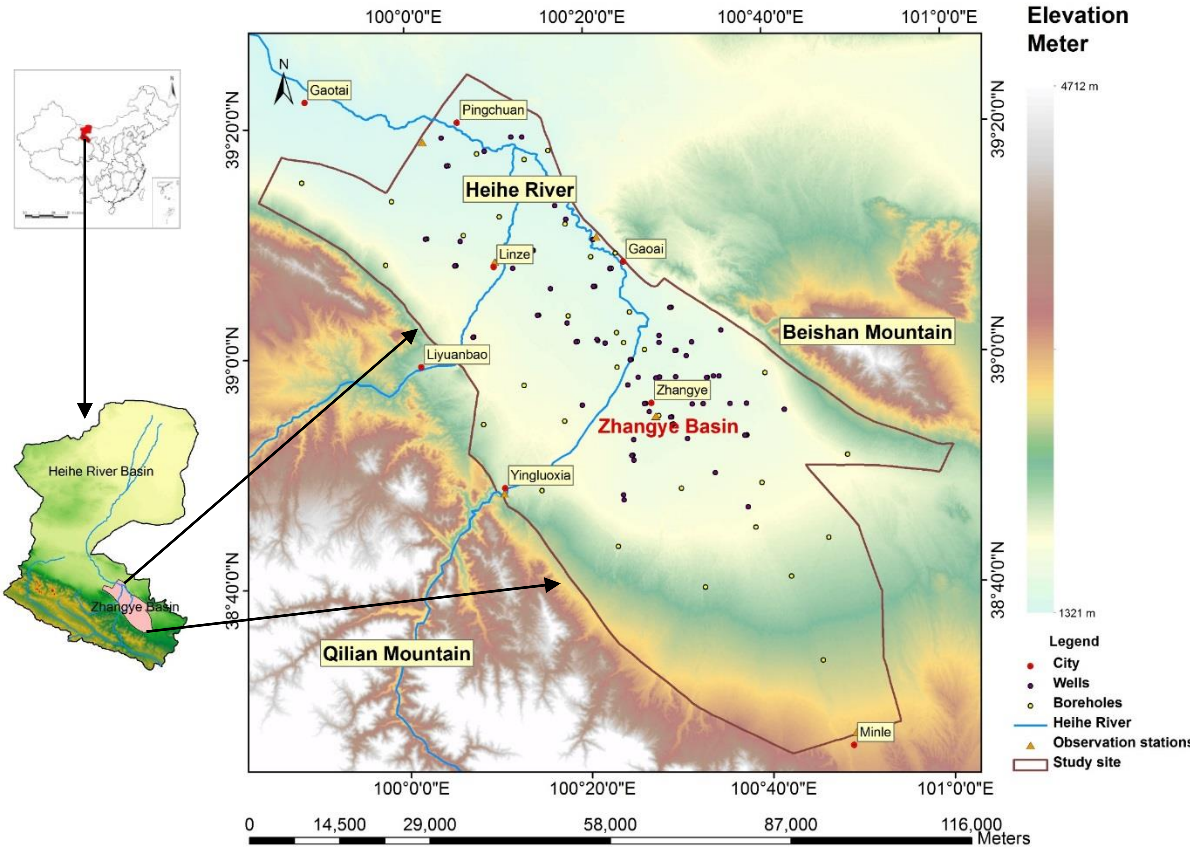

Figure 1.1. Location and topography of the Zhangye Basin.

In the past few decades, global climate change and the increasing intensity of human activity cause water scarcity to become an urgent issue in the basin. Additionally, the implementation of the HWDP established in 2000 (Chang 2003) – which stipulated that the middle reach deliver at least 0.95 billion cubic meters of surface water to the downstream annually when the inflow from Yingluoxia is not less than 1.58 billion m^3/a (Chang 2003) – resulted in a more complicated situation for the hydrogeological system in the Zhangye basin

(Figure 1.2). Due to the required reduction in the surface water supply, over 6000 wells were drilled in the middle-reach areas to pump groundwater for agricultural and industrial usage (Zhou et al. 2011).

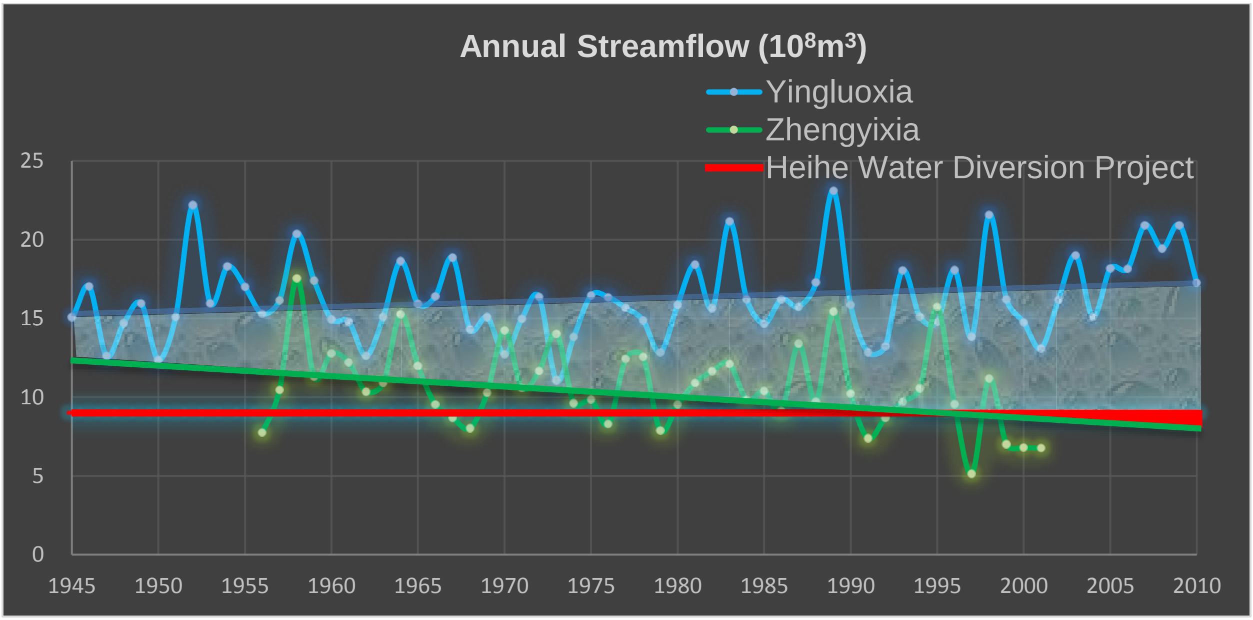

Figure 1.2. Annual streaflow of Yingluoxia Gorge and Zhengyixia Gorge.

No doubt that the implementation of HWDP has largely improved the ecological situation of the lower reaches of the Heihe River. The vegetation in 80.4% of Vegetation in oasis regions and 91.5% in desert regions presented an increasing or recovery trend (Zhang et al. 2011b) . Dry lakes in the desert regained water. Groundwater level reached it historical high since 1995 (Jiang and Liu 2009). The HWDP clearly had positive impacts on ecosystem in the lower reaches. However, the long term impacts of HWDP on water system of the Zhangye Basin in the middle reach of Heihe River had received continuous attentions from the police makers and local water authorities.

For the Zhangye Basin, its groundwater storage change is sensitive to human activities and long-term climate change. Human activities tend to affect the pumping rate, the distribution of runoff, and the irrigation and evapotranspiration rate in agriculture-dominated regions. On the other hand, temperature changes mostly affect the precipitation, evapotranspiration and runoff. In general, the direction and the magnitude of groundwater storage changes are synthetically affected by the above factors.

This study is a collection of several independent, yet closed related, papers summarizing the results of a systematic yet progressive study on the development of a decision support system for sustainable water resources management for the Zhangye Basin in northwestern China. In chapter 2 (the first paper) a method of developing groundwater flow model to capture the long-term characteristics of groundwater flow dynamics is presented. The simulation results for assessing the subsurface flow system are described.

Chapter 3 (the second paper) provides the application of the integrated groundwater-surface water (GWSW) model to further address the issues we found through the study we conducted in chapter 2. The integrated GWSW model sharpens our knowledge of specific interests. Its temporal and spatial precision has been improved to better demonstrate the groundwater-surface water interaction, to calculate the exchange fluxes across interfaces and to revise our knowledge of water budgets. The simulated results are presented with discussions of its applications to evaluate the implementation of the HWDP, and analyze the irrigation schemes.

The hydrological process model presented in the first two papers are calibrated to provide sound data of the hydrological processes. Those data are supplement to our very limited observation data. Chapter 4 (the third paper) documented the development of the Bayesian network (BN) model, and its usage to manage uncertainties both in nature process and decision making by linking the integrated process model and statistical tools. The BN was trained using observation data and supplement data. The calibrated BN model was not only able to emulate the numerical model, but also represent independencies and causal dependencies of linked variables explicitly. It provides great flexibility in capture the uncertainties both in nature processes and in decision making. The model has the ability to manage uncertainty and update conclusions to reflect new evidence, it allows us to get the prospective of future water allocation.

This study not only provides a valuable tool for evaluating the hydrological responses to climate change and human interventions, but also presents a solution to support decision making in water resources management.

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CHAPTER 2 MODELING THE IMPACTS OF WATER RESOURCES EXPLORATION AND CLIMATE CHANGE ON GROUNDWATER OF THE ZHANGYE BASIN

Abstract

The Zhangye Basin is one of the most intensely exploited and ecologically stressed inland river basins in the world. Additionally, global climate change and the increasing intensity of human activity cause water scarcity to become an urgent issue in the basin. However, the implementation of the Heihe Water Diversion Project (HWDP) results in a more complicated situation for the hydrogeological system in the basin. To refine our understanding of the impacts of such complexities, regional 3D groundwater flow models were built to represent groundwater dynamics of the basin using MODFLOW-2005. A steady state model simulated the flow regime in 1999 to represent the flow system pre-HWDP, followed by a transient model for 2000-2010. Models were reasonably calibrated to closely match the observed hydraulic heads in 75 monitoring wells and water level contours for 1999. Such a sophisticated regional groundwater model provides information of flow dynamics and produces water budget data which facilitates the regional water resource management strategy based upon scientific methodology. The model defines the intensive groundwater-surface water interaction zones, and reveals the increasing flux exchanging due to both climate change and human activities. The study enhances our understanding of watershed hydrology and provides the scientific basis for sustainable water resources management in arid inland river basins. In addition, the numerical groundwater flow model makes it possible to integrate all the available data to evaluate the impact of climate

change and water resources exploration on groundwater-surface water interactions in the Zhangye Basin.

1.Introduction

Groundwater is essential to human society in arid regions (Scanlon et al. 2006). Increasing demands on limited water supplies in arid and semi-arid regions under climate change result in critical status of groundwater resources. Groundwater storage change is sensitive to human activities and long-term climate change. Human activities tend to affect the pumping rate, the distribution of runoff, and the irrigation and evapotranspiration rate in agriculture-dominated regions (Figure 2.1). On the other hand, temperature changes mostly affect the precipitation, evapotranspiration and runoff. Increasing temperatures lead to earlier runoff in the absence of changes in precipitation (Barnett et al. 2005). In general, the direction and the magnitude of groundwater storage changes are synthetically affected by the above factors.

The study site, the Zhangye Basin, is situated in the central part of the Heihe River Basin (HRB) in the arid region of northwest China. As one of the most intensely exploited and ecologically stressed inland river basins in the world, the Zhangye Basin contains 90% of the population and consumes about 82% of the water resources of the whole inland HRB as a regional agricultural and industrial center (Zhang et al. 2004a). During the past several decades, the hydrological cycle in the Zhangye Basin has become more complex. This has involved the drying up of rivers and lakes, decline of water tables, deterioration of water quality, desertification and other eco-hydrological problems (Wang and Cheng 1999a) . Better understanding the groundwater system in the Zhangye Basin became an urgent issue for regional sustainable development.

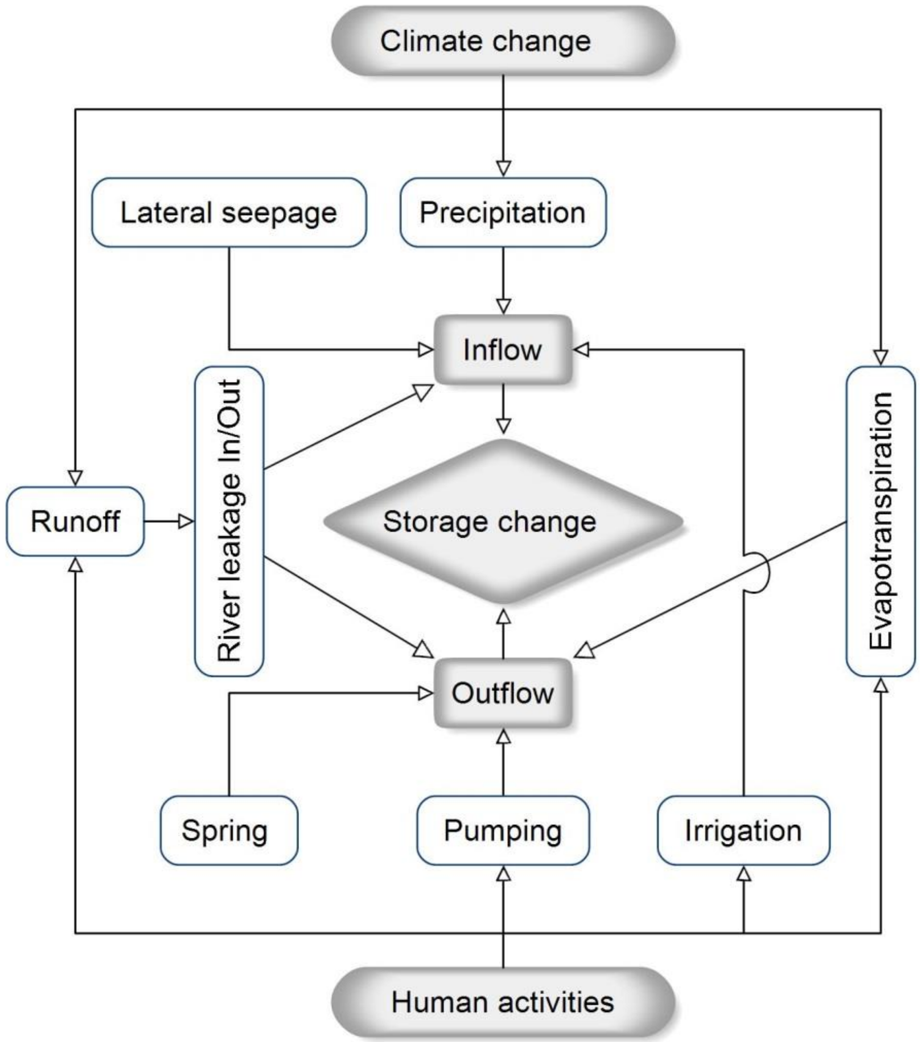


Figure 2.1. Schematic diagram of factors affecting groundwater system.

Studies conducted in the Zhangye Basin may be divided into three stages. The first stage, before 1995, involved mostly basic data gathering and geological mapping; the outcome included 1:200,000 hydrogeological maps, aquifer system characterization, and regional discharge and recharge estimation. The second stage, from 1995-2000, involved more focused investigations, including the ecological carrying capacity of the Heihe River Basin (Wang et al. 2000), land-cover and land-use changes (Kai et al. 1997, Zhang and Li 2000), and prediction of future water demands by 2050 (Xu and Cheng 2000). The third stage, since 2000, has involved more comprehensive studies of hydrology, ecology and economics on the basin scale (Chen et al. 2006, Feng et al. 2004, Li and Zhao 2010, Liu et al. 2010, Qi and Luo 2006, 2007, Wang et al. 2007, Wang et al. 2009, Zhang 2007, Zhu et al. 2008).

Previous studies indicated the increasing trend of precipitation and runoff in the Zhangye Basin as the temperature increases (Ding et al. 2009, Wang and Meng 2008). Taken together, these impacts should result in more recharge to the groundwater system. However, the intense exploration of groundwater resources – which included increasing of pumping from aquifer, expanding of irrigation area, and the Heihe Water Diversion Project (HWDP) established in 2000 (Chang 2003), which stipulated that the middle reach deliver at least 0.95 billion cubic meters of surface water to the downstream annually when the inflow from Yingluoxia is not less than 1.58 billion m^3/a (Chang 2003) largely affected the groundwater discharge. To reveal joint effects of these comprehensive processes, groundwater modeling has been considered as a very powerful tool. In 1990, Zhou et al.(1990) built a 2D finite-different model of the middle stream of the Heihe Basin in which they considered the aquifer system as one single unconfined aquifer layer, in order to represent the flow system in the middle reach of Heihe Basin (Zhou et al., 1990b). Zhang et al. (2004a) constructed a multi-layer finite-element groundwater flow model to characterize the water circulation and groundwater evolution pattern in HRB. Su et al. (2005) built a three-dimensional finite-element groundwater model to simulate solute transport and groundwater quality in the Zhangye Basin. Hu et al. (2006) used a 3D finite-different groundwater model to simulate the vadose zone recharge process. Wen et al. (2007) constructed a 3D model using FEFLOW to assess and evaluate planned groundwater development from 2000 to 2030. Cheng et al. (2008) used model simulations to address seepage from thick unsaturated zones. Wang (2010) developed a nonlinear leakage model to calculate the leakage of the Heihe River considering river stage changes and irrigation rate variations. Wang (2011) developed a 3D groundwater model to analyze the trend of groundwater level changes.

Most previous models focused on the period pre-HWDP. Few studies reveal effects of climate change and human activities on groundwater dynamics and evolution. Thus, the main objective of this study to represent the evolution of flow system in the Zhangye Basin during the implement of HWDP.

2.Site Descriptions

The Zhangye Basin lies in the middle reach of the Heihe River, connecting the Qilian Mountains to the south and the Gobi Desert to the north (Figure 2.2). The basin contains 90% of the population of the whole inland Heihe River Basin and consumes about 82% of water resources as a regional agricultural and industrial center (Wang and Cheng 2002). The Zhangye Basin covers approximately 5000 km^2, extending between latitudes 38º15′-39º45′ N and longitudes 99º30′-101º30′ E.

The Zhangye Basin has a typical temperate continental semiarid climate, with a mean annual temperature of about 3-7 ℃ (ranging from lows around -16.2℃ in the winter to highs around 29.3℃ in the summer). The mean annual precipitation ranges from ~50 to ~280mm from southeast to northwest, with the majority (~80%) falling from June to September. The potential evaporation rate ranges from ~1000 to ~2200mm from northwest to southeast (Wang et al. 2011, Wen et al. 2007). The Heihe River is the dominant surface runoff in the Zhangye Basin, originating in the Qilian Mountains and merging with its tributary Liyuanhe River in Zhangye wetland and enters the desert.

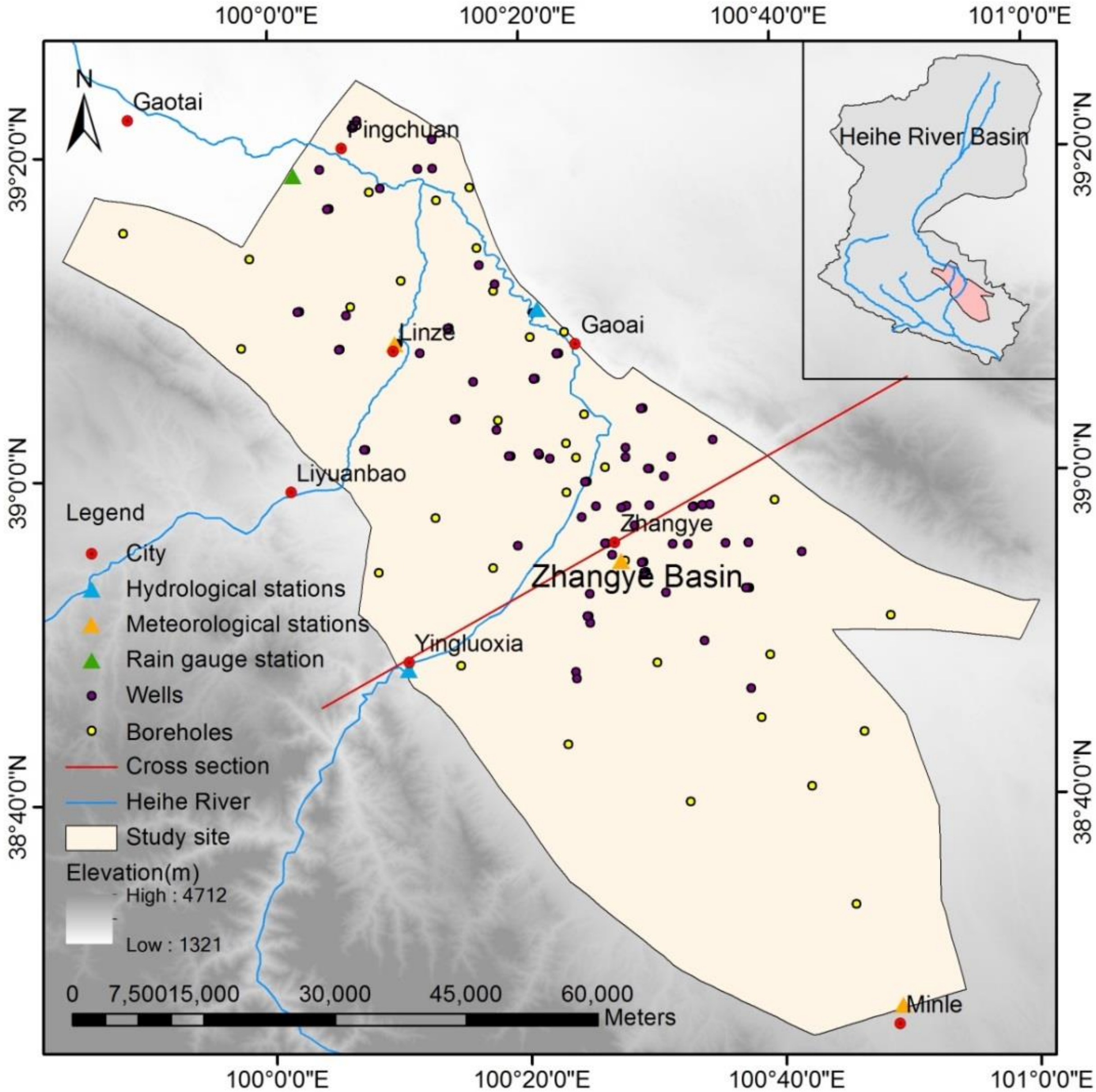
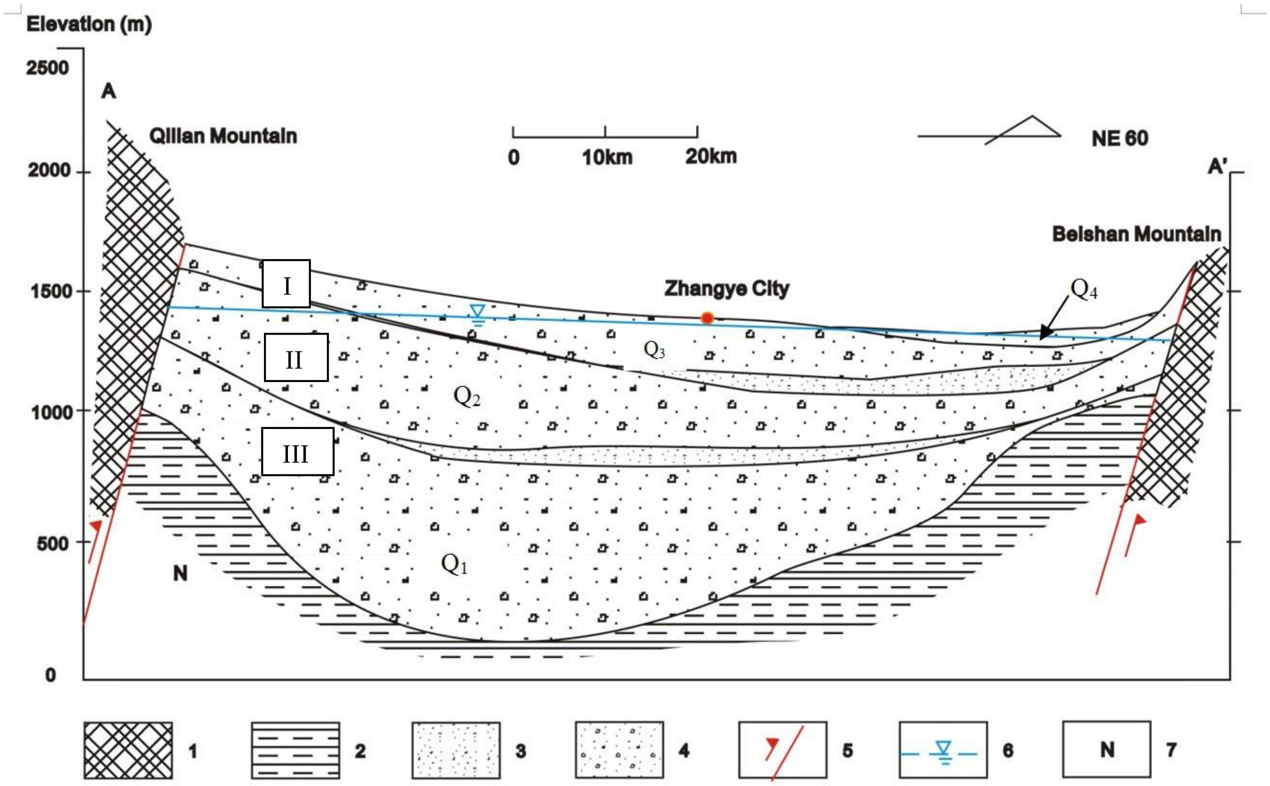


Figure 2.2. Location and topography of the Zhangye Basin. (1) Boreholes used in 3D hydrostratigraphy model construction; (2) A-A' line of cross section in Figure 3; and (3) Locations of hydrogeological monitoring stations, meteorological stations and observation wells used in model construction and calibration.

The Zhangye Basin is a north-south trending basin, caused by the uplift of Qilian Mountains. It consists of three discrete geomorphologic units, alluvial fan, floodplain, and desert. The basin is filled with unconsolidated Quaternary sediments with a depth of tens to thousands meters. Sediments vary gradually from coarse-grained gravel to medium- and fine-grained sand, from the south to north.



1 Bed rock, 2 Mudstone, 3 Sandy loam, 4 Sand and gravel, 5 Fault, 6 Water table, 7 Lithology.

Figure 2.3. Hydrogeological cross section of the Zhangye Basin along A-A' in Figure 2.2. Aquifer units I and II correspond to the unconfined aquifer and confined aquifer refers to aquifer unit III.

In the southern part of the basin, the aquifer is composed of highly permeable cobble and gravel deposits with a thickness of 300-500 m. In the northern edge, the aquifer becomes confined or semi-confined, with a thickness of 100-200 m, comprised of inter-bedded cobble, gravel, and fine sand and clay. Groundwater in the basin generally flows from the piedmont area towards the center of the basin, and discharges at the edge of the alluvial fan in the middle and north parts of this basin by upward seepage and springs. The depths to the water table gradually become shallow from south to north, and range from 50-200 m in the upper alluvial fan to 3-5 m in the north part of the floodplain (Figure 2.3).

3.Hydrogeological Setting

The hydrostratigraphy considered in this study was established based on the previous hydrogeological investigations conducted by the Hydrogeological Group II of Gansu in the 1980s, and the Cold and Arid Regions Environment and Engineering Research Institute, Chinese Academy of Sciences (CAREERI) in the 1990s, respectively. Investigation work to estimate the hydraulic parameters across the Heihe began in the 1970s, and most of the parameters were estimated in the 1980s (Zhou et al. 1990).

Values and distributions of these hydraulic parameters in the study were summarized from the hydrogeological mapping zonation modified in the 1990s by Hydrogeological Group II of Gansu. Horizontal hydraulic conductivity of gravel generally ranges from 1-40 m/d. Horizontal hydraulic conductivity of sand generally ranges from 0.2-10 m/d. Horizontal hydraulic conductivity of loam and sandy loam generally ranges from 0.1-0.001m/d. Specific yield ranges from 2-5% in loam to 10-20% in sand. The storage coefficient in confined aquifers decreased from 0.001-0.005 in the alluvial plain to 0.00005-0.0005 in the flood plain (Table 2.1).

Main recharge sources in this area are lateral seepage, precipitation and irrigation return. The precipitation data was obtained from five hydrological stations (Pingchuan, Gaoai, Yingluoxia, Mingle and Zhangye), as well as historical rainfall isoline. The mean annual precipitation ranges from 50-280mm from southeast to northwest as the latitude increases and elevation decreases. The basin contains two major irrigation regions: Zhangye and Linze irrigation districts. Those two districts consume 98% of the total annual average irrigation rate of the whole basin, which is about 0.43 billion m^3/a.

Table 2.1. Summary of input parameters for the groundwater flow model.

Model Layer	Aquifer Units	Hydraulic Conductivity (m/d)	Storage Parameters	Thickness (m)	Lithology
1	Aquifer I	1-40	0.03-0.2	15-30	Sand, gravel
2	Aquifer II	1-35	0.00005-0.005	50-300	Sand, gravel
3	Aquifer III	1-25	0.00005-0.005	30-400	Sand, gravel

The Liyuanhe River and the Heihe River originate in the Qilian Mountains, merge at the Zhangye wetland and flow through the Hexi Corridor. Those rivers are losing water to the aquifer in the piedmont area and gaining water from groundwater in the flood plain. Springs are widely distributed at the edge of this alluvial fan and in the flood plain.

Major drainage basins in the model area contain the Zhangye wetland and the Linze wetland. Most of the flow in the aquifer that is not pumped by wells eventually discharges to the Heihe River and springs.

Most of the flow in the aquifer discharges to springs and the Heihe River, with a lesser amount discharged by evapotranspiration. Reliable discharge measurements are only available for several major springs located in the study area.

4.Groundwater Modeling

4.1. Conceptual Model

The Zhangye Basin is surrounded by the Alashan uplift in the north, the Gaotai-Nanhua divide in the west, the Qilianshan Fault in the south, and the Minle-Yonggu uplift in the east. The Quaternary aquifer system underlain by Jurassic basement in the basin traditionally has been considered an independent hydrogeological unit. The flow system is conceptualized as a saturated (constant density) flow system. In the 1990s, the Quaternary aquifer was simplified to one single unconfined layer in a 2D finite-different model. The model estimated the impact of Yingli water conservancy project to groundwater in the Zhangye Basin (Zhou et al. 1990). In the last 10 years, double-layer, multi-layer 3D groundwater models were built using finite-different, finite-element models to simulate groundwater flow system in the Zhangye Basin (Hu and Chen 2006, Su 2005, Wang et al. 2011, Zhou et al. 2011). The single layer model cannot reflect the groundwater downwelling in the mountain front and upwelling in the floodplain. The use of multi-layer models, however, imposes significant additional field data and computational requirements and can cause uncertainty.

In this study, the Quaternary aquifer is classified into 3 aquifer units, corresponding to Holocene series (Q_4) and late (Q_3), middle (Q_2) and early (Q_1) Pleistocene series. Aquifer units I and II correspond to the unconfined aquifer and the aquifer unit III refers to confined aquifer. Thicknesses range approximately from 15-30 m, 50-300m, and 30-400m, respectively (Table 1).

The aquifer sediments are mainly composed of pebble, coarse and medium grained sand. According to water level records gathered from 75 monitoring wells in the Zhangye Basin combined with historical groundwater contour maps, the vertical hydraulic gradient is considered ranging from 0.001 to 0.01, which allows us to assume that the groundwater flow are horizontal in each layer.

The south and north boundaries are no flow boundaries. Previous studies reported that the Zhangye Basin and the Mingle Basin is hydraulically connected, with negligible annual seepage rates, so most of the east boundary is considered a no flow boundary in this study. Both on the south and east edges of the simulation area, we use injection wells to represent the gully flow and deep lateral seepage from the Qilian Mountain and the Mingle Basin. The no flow boundary is also defined along the west edge, which is a groundwater divide. The same boundary conditions apply to all six layers.

Precipitation and irrigation return flow are considered as the main recharge terms in flow models. The entail study area has been divided into five recharge zones. The recharge rate is assumed to be distributed uniformly to each recharge zone. The recharge rate of the zone covering major irrigation units is determined by both irrigation rates and precipitation amounts. The recharge rate of other zones is set up based on historical rainfall isoline data. It has been noticed that in the lower basin, there are intense groundwater-surface water interactions through irrigation, river leakage and spring discharge. The gully flow and deep lateral seepage from the south boundary are estimated as 0.2 billion m^3/a, and 0.3 billion m^3/a, they enters into the Zhangye Basin from the east boundary. There are over 6000 production wells drilled in to aquifers since the 1990s with an increasing pumping rate of 0.27 billion m^3 annually (Zhang et al. 2004a).

For each of the six numerical layers, model parameters include (1) elevations of the top and bottom of the layer, (2) horizontal and vertical hydraulic conductivities, (3) specific yield (for unconfined conditions), and (4) specific storage (for confined conditions). Specific yield and specific storage are required only for the transient simulations. Elevation of the saturated surface is modified from the DEM data of Zhangye Basin. Elevations of the top and bottom of each layer are modified from previous studies of Su (2004) and Wang (2010). The zonation of hydraulic conductivities is decided by hydrogeological maps of the Zhangye Basin. Based on borehole logging data and pumping test results, the basin was classified in to 24 individual hydrogeological units. Each one has a unique Kx, Ky and Kz. For three low permeable layers, the K was set to be smaller in the flood plain and to be larger in the piedmont area to represent the typical aquifer. In this model the Sy and Ss had the same zonation as K due to the hydrogeological setting.

4.2. Numerical Model

A multi-layer, heterogeneous and anisotropic model was built to simulate the flow system in the Zhangye Basin using MODFLOW-2005 (Harbaugh 2005, Harbaugh and Geological Survey (U.S.) 2000) (Table 2.2). This model utilizes a 120x120 grid system with a cell size of 1×1km for each of the six numerical layers (Figure 2.4). However, flow only occurs in the grid cells identified as active. In the three-dimensional reconstruction of the aquifer system, the model grid was discretized into three layers, each corresponding to one aquifer units. A steady state model which simulates the flow regime in 1999 as a representative flow system before the HWDP was followed by a transient model simulating the flow field from 1999 to the present (including the time period in which the HWDP was implemented). The initial head for the steady-state simulations was based on the groundwater contour map of 1999. After calibration was achieved, however, the calibrated heads were saved as the new starting heads for transient simulations.

Table 2.2. MODFLOW-2005 Packages and files used for flow model simulation.

MODFLOW-2005 Packages and Files	
Basic Package	.BAS
Output Control Option file	.OC
Discretization file	.DIS
Layer-property Flow Package	.LPF
Preconditioned Conjugate-Gradient Solver Package	.PCG
Streamflow-Routing Package	.SFR
Well Package	.WEL
Drain Package	.DRN
River Package	.RIV
Recharge Package	.RCH
Time-Variant Specified-Head Package	.CHD
Evapotranspiration Package	.EVT

Natural discharge occurs as evapotranspiration (simulated by EVT package), springs (simulated by DRN package) and river leakage outflow (simulated by RIV package). The evapotranspiration rate is estimated to be around 0.3m/year, and ET was simulated with a uniform extinction depth of 6.5 m across the Zhangye Basin (Unpublised report).

The recharge rates are functions of precipitation and irrigation. The total amount of lateral seepage, gully flow, irrigation and pumping rate for the steady-state model are assumed to be equal to the long-term (1950 through 1999) average values. The precipitation and evapotranspiration amounts are estimated from observation data of 1999. The initial head for the steady-state simulations was based on the groundwater contour map of 1999.

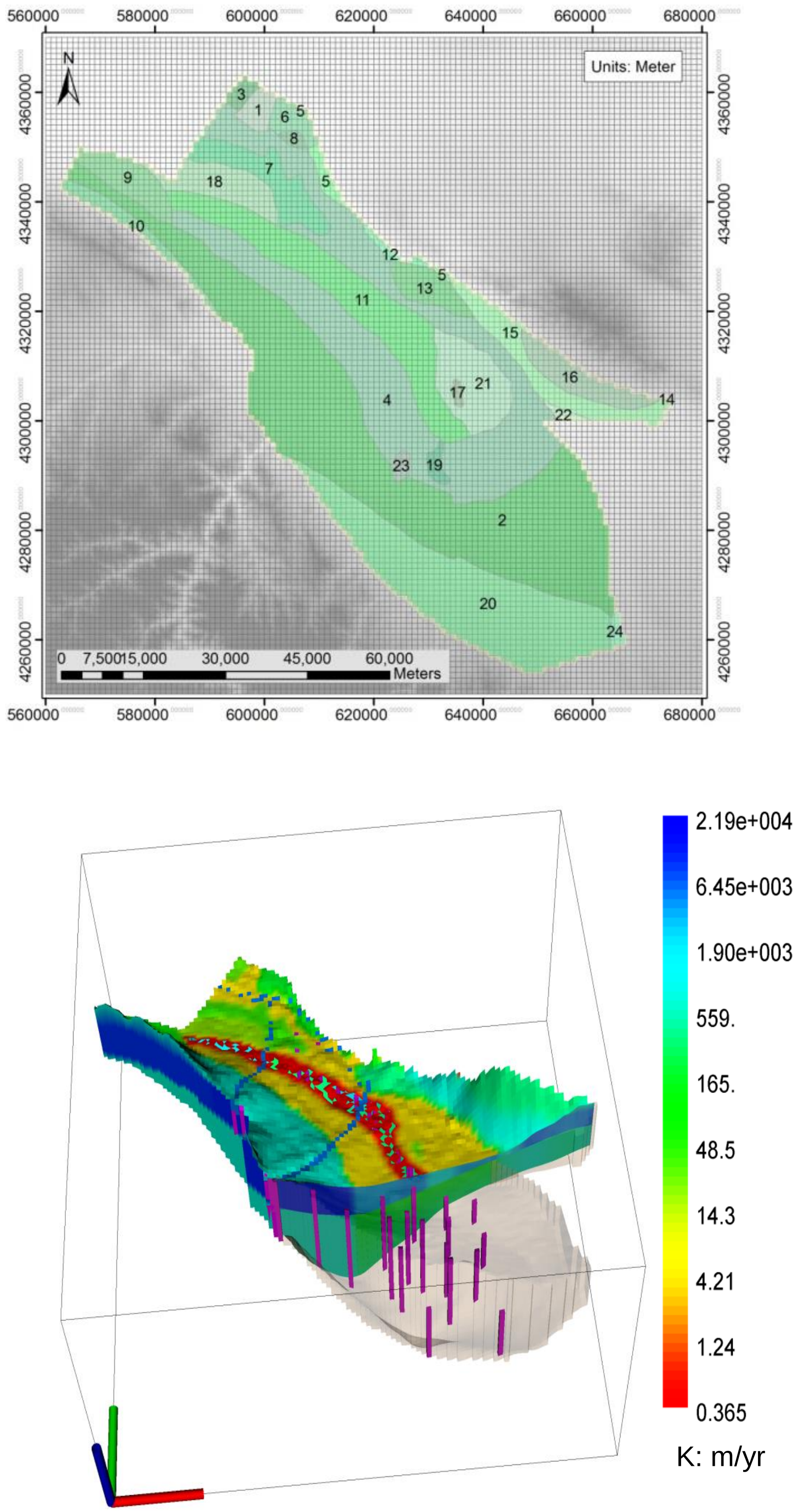


Figure 2.4. Calibrated spatial distribution of hydraulic conductivity parameters.

For the transient simulations, the model solution is divided into 11-years stress periods with varying recharge and discharge conditions to reflect the annual precipitation, evapotranspiration and pumping amount from 2000 to 2010. Daily precipitation and evaporation values gathered from 5 hydrogeological stations and 3 meteorological stations were summed to obtain yearly totals. Well pumping rates used in this model are estimated based on data provided by CAREERI and groundwater evolution investigations (Zhang et al. 2004a). The calibrated heads for steady-state simulations were saved as the new starting heads for transient simulations.

4.3. Model Calibration

The steady-state model simulates the flow regime in 1999 as a representative flow system of the year before the implementation of HWDP. Hydraulic head observations obtained from 75 monitoring wells from January to December 1999 were used as calibration targets. This time period was selected to approximately reflect average conditions throughout the model domain. Values of hydraulic conductivity and storage parameters for the six layers are varied using a trial-and-error approach and then PEST code to obtain the best match to observed hydraulic heads. In this study, the recharge estimates come from infiltration of precipitation and irrigation return flow, the recharge values were assumed to be representative and were not adjusted during model calibration. The goal of the calibration was to minimize the root-mean-square of the residual error between simulated and observed water levels. Figure 2.4 shows the calibrated spatial distribution of hydraulic conductivity parameters.

Hydraulic head observations of the 75 monitoring wells from 2000-2007 were used as calibration targets for the transient model. The ratio between vertical and horizontal hydraulic conductivity (Kv/Kz) was also adjusted in calibration and estimated to be 4-8 for all layers.

Table 2.3. Calibrated hydraulic conductivity values. Units: m/d.

Zone	Layer 1 Kx, Ky	Layer 1 Kz	Layer 2 Kx, Ky	Layer 2 Kz	Layer 3 Kx, Ky	Layer 3 Kz	Layer 4 Kx, Ky	Layer 4 Kz	Layer 5 Kx, Ky	Layer 5 Kz	Layer 6 Kx, Ky	Layer 6 Kz
1	1.500	0.300	40	8	0.010	0.002	20	4	0.010	0.002	5	1
2	0.080	0.020	15	3	0.050	0.010	15	3	0.005	0.001	15	3
3	0.010	0.002	5	1	0.100	0.020	20	4	0.001	0.000	8	2
4	0.400	0.100	8	2	0.010	0.002	15	3	0.010	0.002	10	2
5	0.500	0.100	1	0	0.001	0.000	5	1	0.008	0.002	4	1
6	0.060	0.015	2	0	0.500	0.100	5	1	0.500	0.100	5	1
7	0.050	0.010	15	3	0.200	0.040	5	1	0.100	0.020	5	1
8	0.200	0.040	5	1	0.050	0.010	5	1	0.005	0.001	5	1
9	1.800	0.400	10	2	0.200	0.040	10	2	0.200	0.040	10	2
10	0.001	0.001	0	0	18.000	3.600	15	3	8.000	1.600	18	4
11	0.008	0.002	20	4	0.001	0.000	20	4	10.000	2.000	10	2
12	0.800	0.200	0	0	0.400	0.080	4	1	0.008	0.002	8	2
13	0.001	0.000	25	5	1.500	0.300	15	3	0.001	0.000	10	2
14	1.000	0.200	35	7	0.200	0.040	15	3	2.000	0.400	8	2
15	1.200	0.250	35	7	2.000	0.400	15	3	2.000	0.400	8	2
16	0.080	0.002	30	6	1.500	0.300	20	4	1.500	0.300	1	0
17	0.050	0.001	0	0	0.080	0.016	20	4	2.000	0.400	8	2
18	0.050	0.010	15	3	0.005	0.001	15	3	0.005	0.001	5	1
19	0.020	0.004	1	0	0.020	0.004	5	1	0.010	0.002	2	0
20	2.000	0.400	40	8	20.000	4.000	15	3	10.000	2.000	10	2
21	0.050	0.010	6	1	0.005	0.001	6	1	0.005	0.001	20	4
22	0.050	0.010	5	1	0.020	0.004	15	3	0.010	0.002	2	0
23	0.050	0.010	5	1	0.050	0.010	18	4	0.050	0.010	1	0
24	2.000	0.400	15	3	20.000	4.000	15	3	10.000	2.000	10	2

Table 2.4. Calibrated storage parameter values.

Zone	**Aquifer I**	**Aquifer II**		**Aquifer II**	
	Sy	Sy	Ss	Sy	Ss
1	0.12	0.14	0.00060	0.14	0.00030
2	0.20	0.03	0.00005	0.08	0.00125
3	0.12	0.14	0.00060	0.15	0.00060
4	0.11	0.16	0.00700	0.12	0.00050
5	0.05	0.06	0.00010	0.15	0.00060
6	0.10	0.03	0.00005	0.14	0.00030
7	0.12	0.06	0.00010	0.14	0.00030
8	0.10	0.03	0.00005	0.14	0.00010
9	0.15	0.01	0.00016	0.12	0.00050
10	0.20	0.12	0.00250	0.08	0.00125
11	0.02	0.16	0.00480	0.12	0.00050
12	0.11	0.16	0.00070	0.12	0.00050
13	0.18	0.12	0.00250	0.12	0.00050
14	0.18	0.12	0.00250	0.01	0.00010
15	0.18	0.12	0.00250	0.01	0.00010
16	0.18	0.18	0.00300	0.12	0.00050
17	0.05	0.03	0.00005	0.15	0.00060
18	0.08	0.08	0.00123	0.14	0.00030
19	0.12	0.06	0.00010	0.01	0.00010
20	0.20	0.18	0.00300	0.12	0.00050
21	0.03	0.12	0.00050	0.12	0.00050
22	0.11	0.08	0.00013	0.03	0.00005
23	0.12	0.12	0.00030	0.12	0.00050
24	0.2	0.18	0.00300	0.12	0.00050

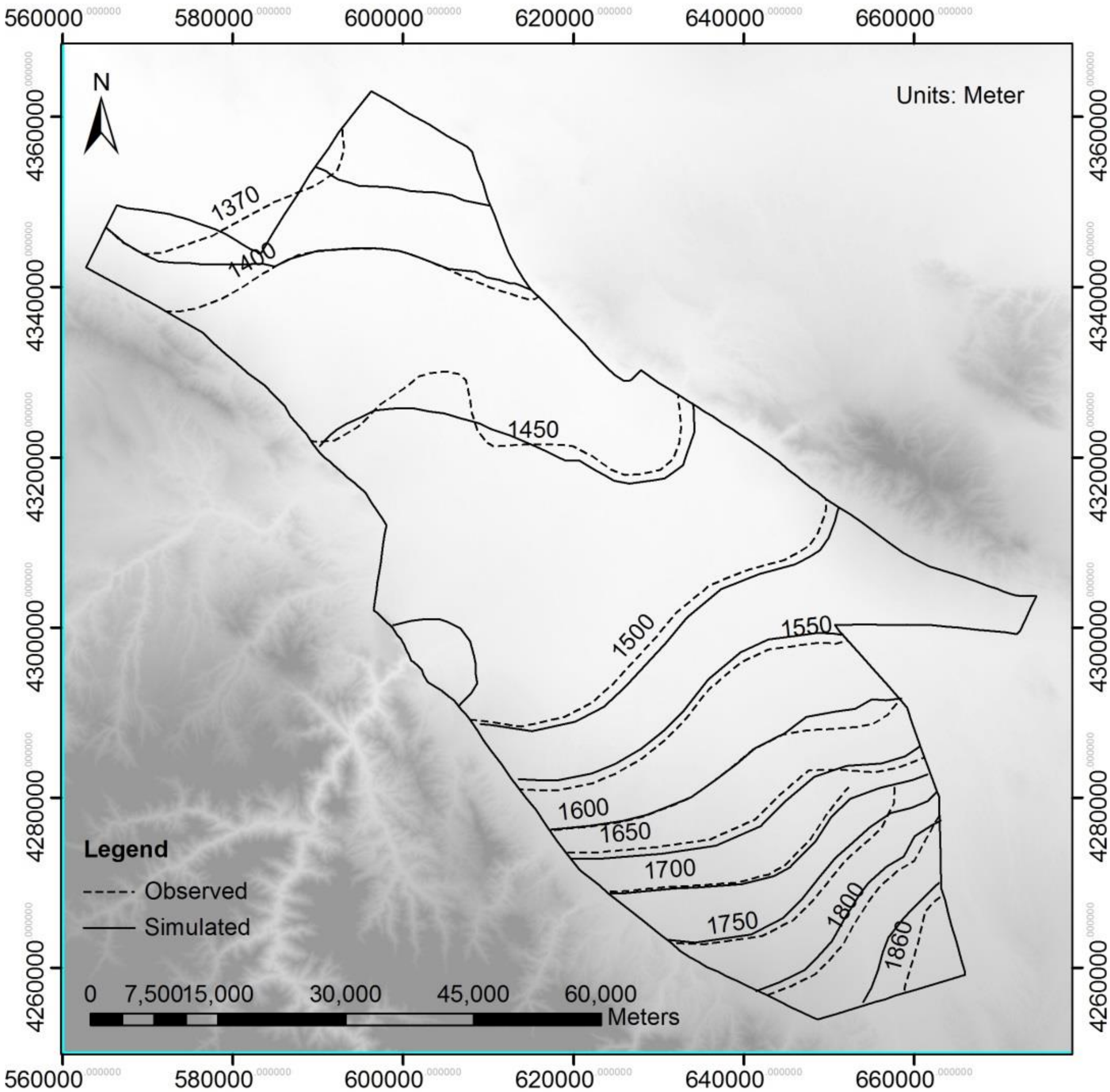
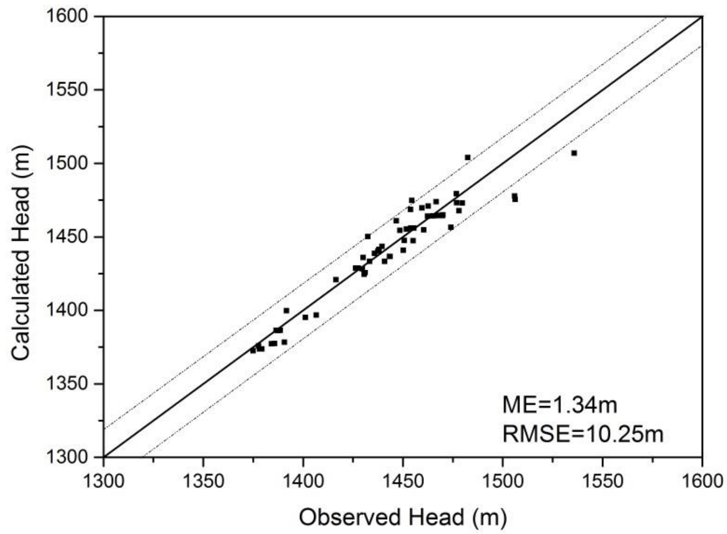


Figure 2.5. Comparison of observed and simulated water level contours in unconfined aquifer layers in 1999. Solid lines represent simulated water level contours, and dash lines represent observed water level contours. (Units: m).

The specific yield and specific storage parameters were important to the model's ability to match hydraulic head fluctuations in observation wells. Increasing the aquifer storage capacity has the effect of reducing the amplitude and spreading out the time response of discharge peaks.



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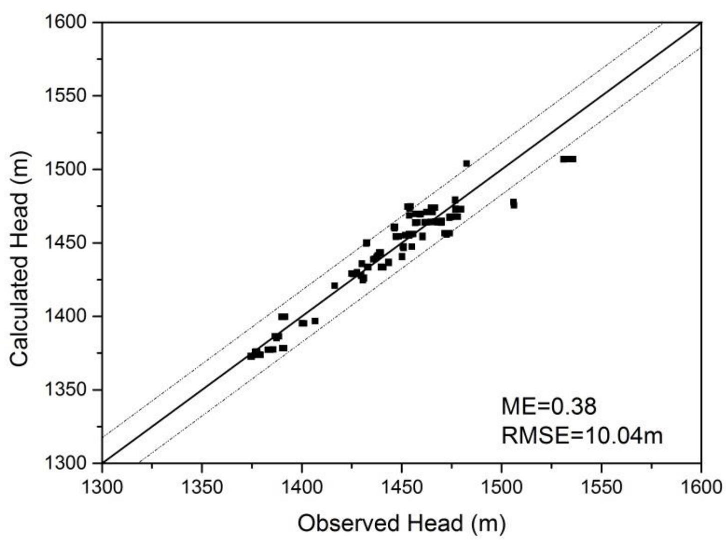


b,

Figure 2.6. Comparison between observed and simulated annual water levels from 1999 to 2007 at 75 observation wells. (a) Steady state; (b) Transient model. Dotted lines indicate 95% confidence level.

Table 2.3 and Table 2.4 lists all the calibrated values of hydraulic conductivity and storage parameters for 24 zones.

Figure 2.5 shows simulated and measured annual average groundwater level contours in 1999.

Figure 2.6 shows the calibration statistics and residual error plots for both steady-state and transient calibrations. The mean error (ME) and root mean square error (RMSE) are 1.34m and 10.25m for steady state. The ME and RMSE are 0.38m and 10.04m, respectively, for the transient model.

Table 2.5. Comparison of calculated water budgets for the Zhangye Basin. Units: 10^8 m ^{3}/ year.

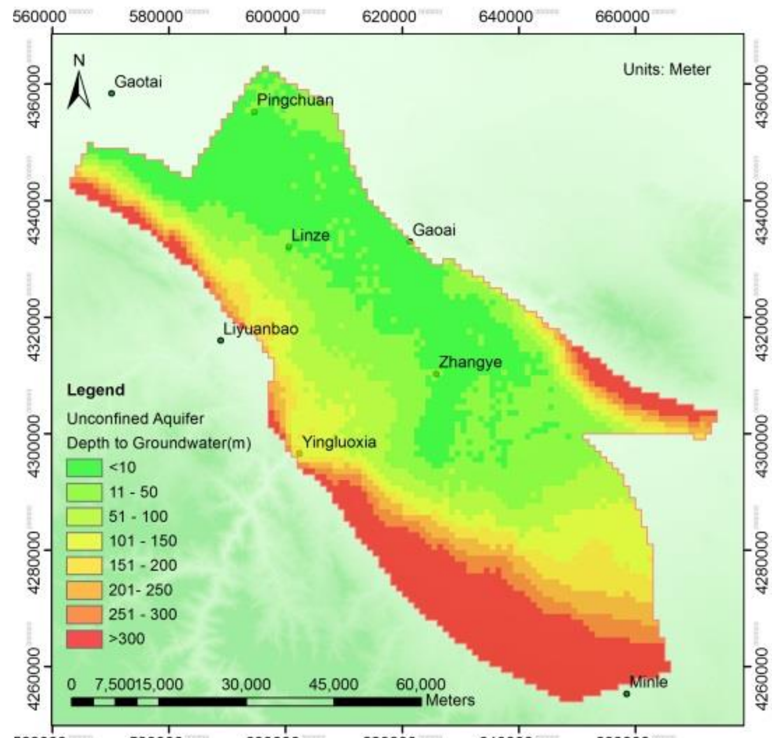
	Calculated	**Zhang (2004)**	**Calculated**	**Wang(2011)**	**Trend**
	1999	Average annual	2009	2009	Comparison of 1999 and 2010
Lateral Seepage	3.43	3.50	3.00	1.78	-12.59%
Recharge	3.86	3.81	3.90	6.37	5.02%
River Leakage In	3.74	4.20	3.72	4.01	-0.34%
River Leakage Out	-1.24	-1.53	-1.24	-4.10	0.08%
ET	-2.48	-1.52	-2.11	-2.66	-15.40%
Spring Discharge	-4.67	-5.90	-4.45	-4.13	-5.68%
Pumping	-2.64	-2.55	-4.28	-2.76	70.52%
Total In	11.02	11.51	10.64	12.16	-2.27%
Total Out	-11.02	-11.50	-12.09	-13.65	11.02%
In- Out	0.00	0.01	-1.44	-1.49	

A third calibration target was to obtain a reasonable match between water budgets from our calculation and previous studies (Table 2.5). The water budgets produced by prior models (Zhang et al. 2004) yielded similar results to this study. Furthermore, the water budget calculated by transient model for 2010 is very close to the result of a groundwater model developed by Wang et al. (2011).

5.Results and Discussion

5.1. Groundwater Flow Dynamics

The model was able to reproduce the pattern of hydraulic head fluctuations in observation wells and match the observed heads for the 11-year simulation period. The simulated water level varies gradually from 50-300m in depth in the piedmont area of Qilian Mountain to 0-10m in depth in the flood plain. Hydraulic gradients are up to 1% in the eastern part of Zhangye Basin and relatively flat at 0.1% in the central and western part of the basin. Groundwater in the basin generally flows from the piedmont area towards the center of the basin and discharges at the edge of the alluvial fan in the middle and north parts of this basin by upward seepage and springs. Increasing groundwater withdrawals caused decline of groundwater levels in most of the study area (Figure 2.7).



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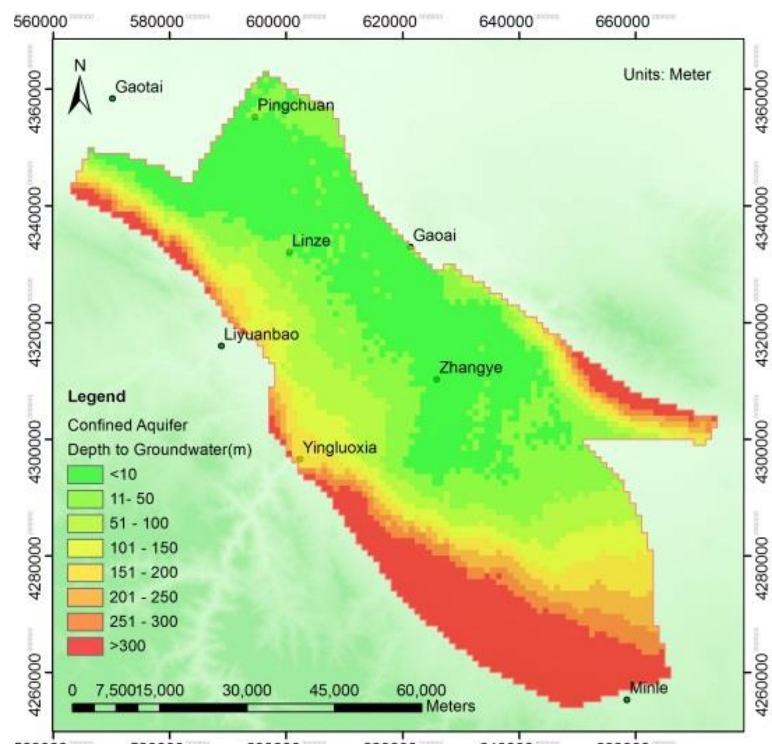

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Figure 2.7. (a) Simulated depth to groundwater for unconfined aquifer by2010, (b) Simulated depth to groundwater for confined aquifer by 2010.

Model results show that by 2010, over 93% of the whole basin has been facing ground water declining. However, in northwestern of the Zhangye urban area, the groundwater level has increased by 0.5 to 5m (Figure 2.8).

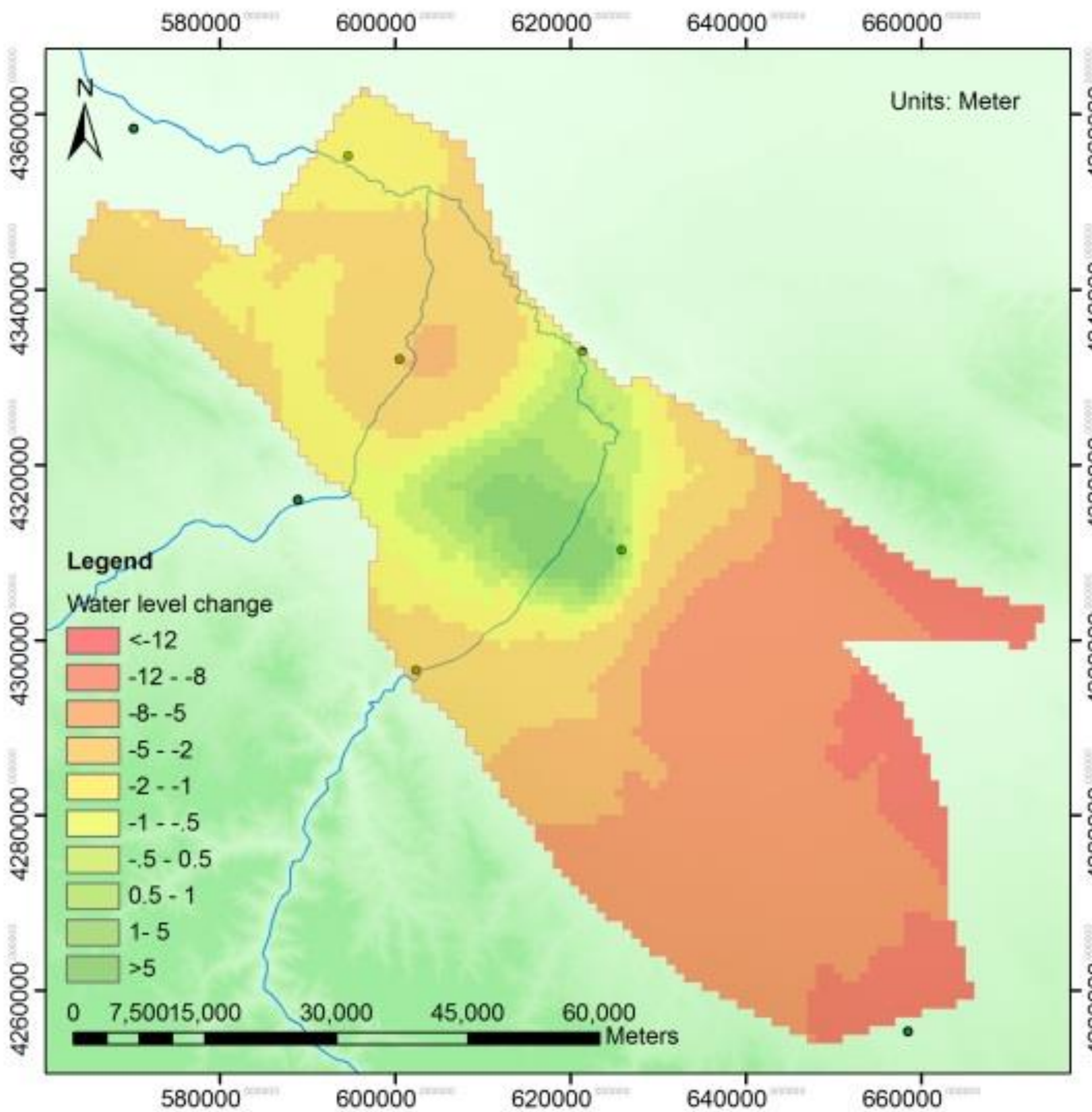

Figure 2.8. Simulated water level change in unconfined aquifer layers by 2010 after 10 years implementation of the HWDP project.

5.2. Water Budget

Water budget summaries for the steady-state simulation of 1999 and for transient simulation are provided in Table 2.6. The water budget information is useful for understanding how the aquifer storage volume, spring and river discharge respond to varying recharge inflow and well-pumping demands.

As indicated in Table 2.5, though recharge inflow increased 5.02% and ET decreased 15.4% in 2010, comparing to 1999, the total in an out still has a gap of -1.47 billion m^3/a. This is because the well pumping rate increased 70.1%, which causes continuous decrease of spring discharge and groundwater storage depletion (Figure 2.9).

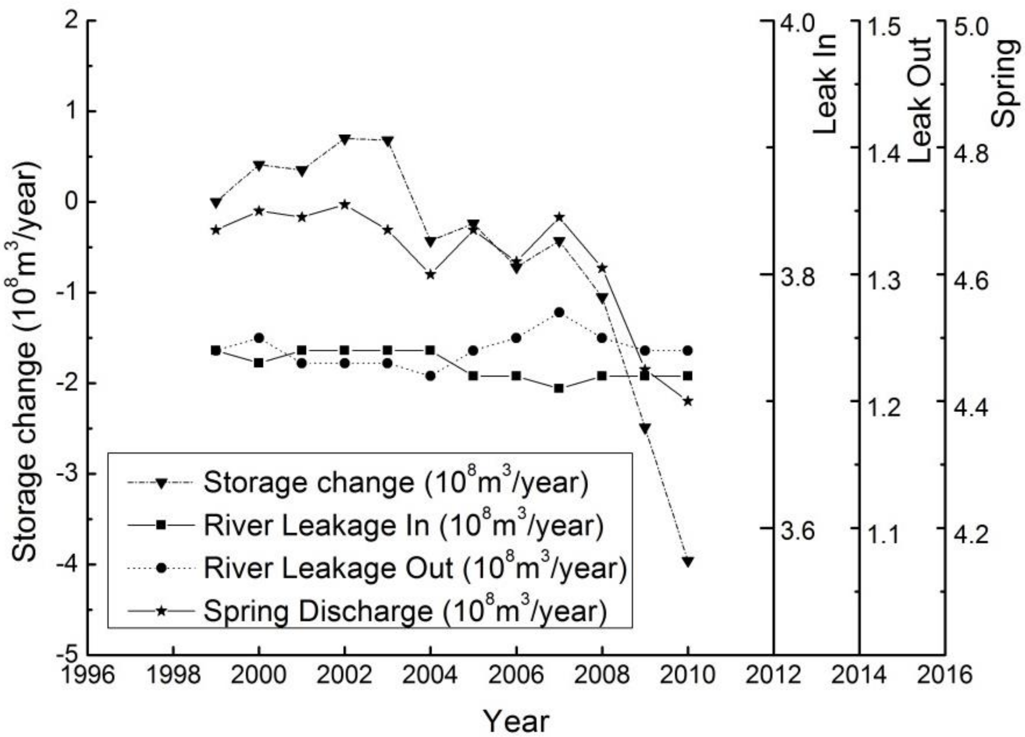

Figure 2.9. Model simulated groundwater storage depletion in relation with river leakage and spring discharge.

Table 2.6. Simulated water budget and storage change for the Zhangye Basin for steady state (pre-HWDP) and transient simulations. Units: 10^8 m^3/ year.

	Steady state	**End of stress periods**										
	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Inflow												
Lateral Seepage	3.43	3.35	3.30	3.25	3.20	3.17	3.14	3.11	3.08	3.05	3.02	3.00
Recharge	3.86	4.47	4.28	4.92	4.69	3.76	4.83	4.30	5.26	4.66	3.90	4.05
River Leakage In	3.74	3.73	3.74	3.74	3.74	3.74	3.72	3.72	3.71	3.72	3.72	3.72
Total Inflow	11.02	11.56	11.32	11.90	11.63	10.68	11.70	11.13	12.05	11.43	10.64	10.77
Outflow												
River Leakage Out	-1.24	-1.25	-1.23	-1.23	-1.23	-1.22	-1.24	-1.25	-1.27	-1.25	-1.24	-1.24
ET	-2.48	-2.43	-2.56	-2.55	-2.55	-2.60	-2.05	-2.03	-1.90	-2.11	-2.11	-2.10
Spring Discharge	-4.67	-4.70	-4.69	-4.71	-4.67	-4.60	-4.67	-4.62	-4.69	-4.61	-4.45	-4.40
Pumping	-2.64	-2.77	-2.91	-3.05	-3.21	-3.37	-3.54	-3.71	-3.90	-4.08	-4.28	-4.50
Total Outflow	-11.02	-11.15	-11.38	-11.55	-11.65	-11.78	-11.51	-11.61	-11.76	-12.05	-12.09	-12.24
Storage change	0.00	0.41	-0.06	0.36	-0.03	-1.11	0.19	-0.48	0.29	-0.62	-1.44	-1.47

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5.3. Groundwater-surface Water Interactions

Figure 2.9 shows plotted values of simulated groundwater storage depletion in relation with river leakage and spring discharge. There was a larger difference between inflow and outflow of river leakage during 2006-2009, while, in general the total amount of river leakage had not changed much.

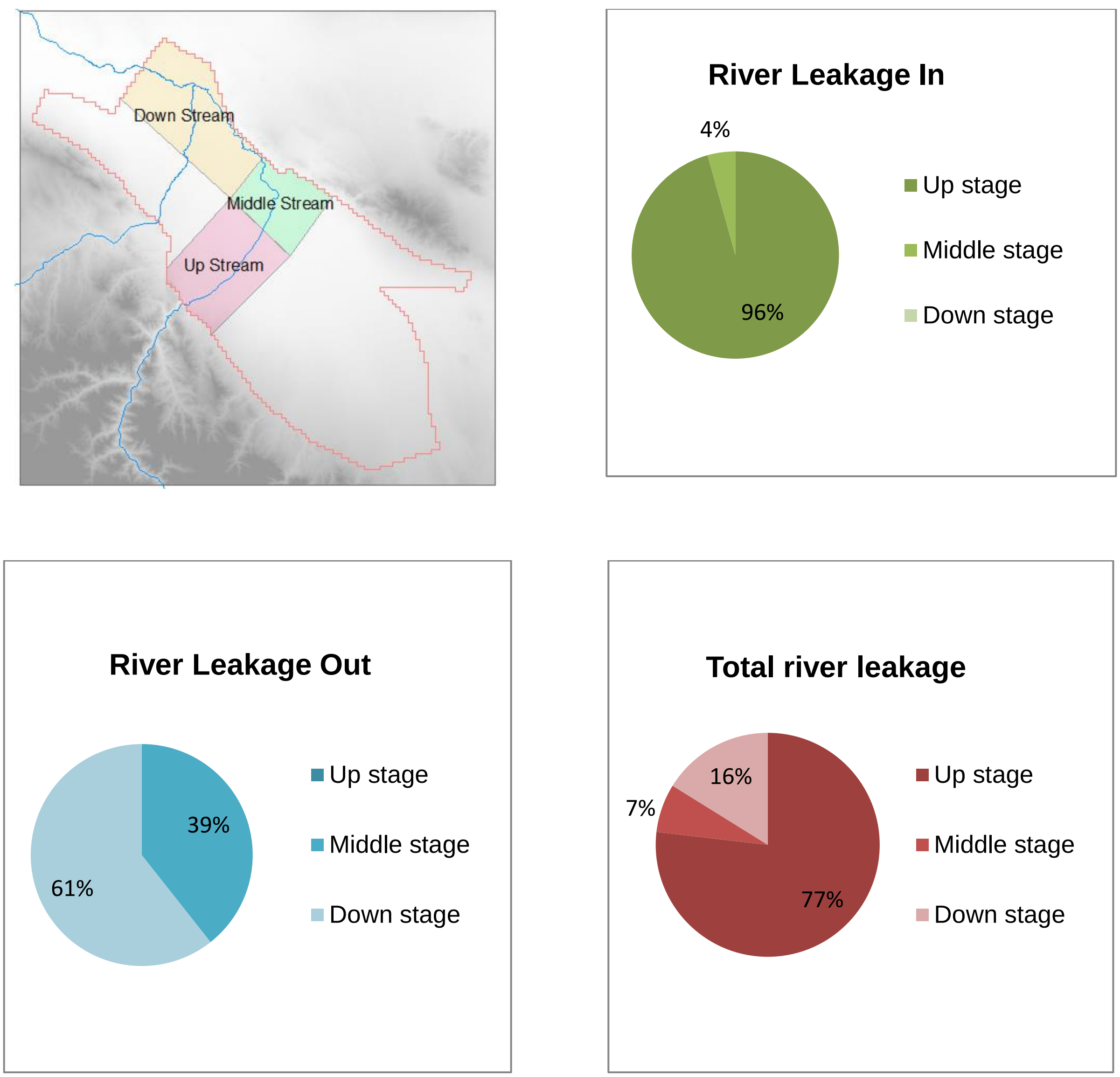

Figure 2.10. River leakages in different zones.

The Zone Budget (Harbaugh 1990) tool has been used to calculate river leakages and spring discharge rates in 3 zones along the Heihe River. Each zone covers the area whiten 5km distances away from the Heihe river divided by Zhangye and Gaoai.

Figure 2.10 shows the zonation and simulated fluxes in the 3 zones respectively. In the upstream, river discharges to groundwater, total discharge rate is 0.35 billion m^3/year, which is 95.6% of the total inflow of river leakage in the Zhangye Basin. In middle stream, groundwater and river interactions are relatively intensive, with a river leakage inflow rate of $0.16\times10^8 m^3/a$ and an outflow rate of $0.49\times10^8 m^3/a$. In the downstream, Groundwater discharge dominated the flow direction. The sum of river leakage outflow rate in the middle stream and downstream is 87% of the total for the entire basin.

A field investigation using Distributed Temperature Sensing (DTS) was conducted in June 2010 to evaluate the groundwater-surface water interaction of a 550m reach along the Heihe River near Pingchuan (Huang et al. 2012). The result matches with the simulation result, which indicates zone 3 is the groundwater discharge zone. A roughly calculated discharge rate of groundwater based on measured river flux agrees with the model's results.

6.Conclusions

The three-dimensional groundwater flow model have been developed for the Zhangye Basin including a steady state model simulating the flow regime in 1999 as a representative flow system pre- HWDP and a transient model simulating the flow field from 2000 to 2010. The model has been reasonably calibrated using multiple sources of field data. Such a sophisticated model regional groundwater model provides reliable information of flow dynamics, produces water budget data which facilitate the regional water resource management. It defines the intensive groundwater-surface water interaction zones, and reveals the increasing flux exchanging to both climate change and human activities. The study enhances our understanding of watershed hydrology and provides the scientific basis for sustainable water resources management in arid inland river basins. In addition, the development of a robust numerical groundwater flow model, describing groundwater flow conditions in a basin, makes it possible to integrate all the available data to evaluate the impact of climate change and water resources exploration on groundwater-surface water interactions in the Zhangye Basin. It can also be used for further research of integrated hydrological, ecological and economical models in the arid basin.

However, the model does not precisely match well responses in all areas of the model domain. Because the well responses to recharge events are quite sensitive to their distributions and values, the assumption of uniform pumping values and even distribution of drilling wells in irrigation units limits the ability to consistently match observed head responses in all areas of the model.

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CHAPTER 3 INTEGRATED MODELING OF GROUNDWATER-SURFACE WATER INTERACTIONS IN THE ZHANGYE BASIN

Abstract

The Zhangye Basin is located in the arid region in northwest China. Like other inland river basins in arid and semi-arid northwest China, the Zhangye Basin faces severe problems of water scarcity and ecological deterioration. Additionally, global climate change and the implementation of the Heihe Water Diversion Project (HWDP) results in a more complicated situation for the hydrogeological system in the basin. Understanding interactions between groundwater and surface water is critical to effectively address the water problems. An integrated 3D groundwater-surface water model was built for the Zhangye Basin using GSFLOW for both pre-HWDP (1999) and during the implementation of HWDP (2000-2010). The model calibration was done by first running PRMS and MODFLOW-2005 models separately, and then followed by the calibration of the integrated GSFLOW model. The output of the integrated model illustrates the temporal and special variation pattern of groundwater table, provides estimates of water budget and flow dynamics data of the Zhangye basin. The model shows a detailed water storage change tendencies and their relationship with each inflow and outflow. More importantly, this study demonstrated the applicability of integrated models of a basin-scale in characterizing the GWSW interaction, reproducing the flow system, and supporting sustainable water resources management, accounting for the effects of climate change in arid inland river basins.

1.Introduction

Groundwater-surface water interaction is defined as interactions of groundwater with all types of surface water, such as streams, lakes, and wetlands (Winter T.C. 1998). Interactions take places in three basic ways: surface water gains water from the inflow of groundwater, it loses water to groundwater, or it does both. Since the 1960s, the studies of GWSW interaction have been gaining widespread attention among hydrogeological professionals because of concerns related to eutrophication and acid rain (Arnold et al. 1993, Winter 1995). The interactions between groundwater and surface water play an important role in hydrological systems, especially in arid and semi-arid regions. GWSW interactions in arid regions are also important in the context of water management to meet water demands of both ecological systems and human society.

However, it is very difficult to quantify the interactions of GWSW (Kalbus et al. 2006a, b) and to identify the distribution of groundwater recharge/discharge areas due to the complexity of GWSW interactions (Gardner et al. 2011). Methods used for measuring interactions include direct measurements of water flux (Lee 1977), heat tracers (Anderson 2005, Constantz 2008), mass balance approaches, and methods based on Darcy's law to identify the hydraulic gradient, hydraulic conductivity, groundwater velocities, etc. (Kalbus et al. 2006a). Nevertheless, there is no method currently available to directly identify distributions of recharge/discharge areas. Thus, integrated GWSW modeling has been considered a powerful tool to solve the issue (Markstrom et al. 2008).

Surface water and groundwater have long been studied as separate entities; thus, hydrogeological models traditionally have been developed with a focus on either the surface water or groundwater resource. Commonly used models, such as PRMS (Leavesley et al. 1995) and SWAT (Arnold et al. 1996), mainly simulate the surface runoff and oversimplify the groundwater process. In contrast, the widely used MODFLOW (Harbaugh 2005) and FEFLOW (Diersch 1998) are powerful models that simulate groundwater flow, but they only have simplistic functions to represent the impact of surface flow to groundwater systems. In recent years, integrated hydrogeological models, such as GSFLOW (Markstrom et al. 2008) and HydroGeoSphere (Brunner and Simmons 2012), have been developed to support multi-component hydrogeological studies (Huntington et al. 2009, Sudicky et al. 2005). Both integrated models are useful for analyzing complex water resources problems because they can account for feedback processes affect the timing and rates of surface runoff, soil zone flow and groundwater interactions. HydroGeoSphere, as a fully integrated approach, uses the three-dimensional form of Richards' equation to simulate unsaturated and saturated flow (Brunner and Simmons 2012, Freeze 1971, Panday and Huyakorn 2004) and requires much finer spatial grids and smaller time steps than typically are used to simulate saturated flow, which limits the model's application for simulating regional flow systems. Thus, GSFLOW as an integrated model, which does not use the three-dimensional form of Richards' equation, is better suited for simulating flow through regional hydrologic systems (Markstrom et al. 2008).

The Zhangye Basin is located in the arid region in northwest China, which refers to one of the most important agricultural bases for the country. Like other inland river basins in arid and semi-arid northwest China, the Zhangye Basin faces severe problems of water scarcity and ecological deterioration (Cheng et al. 2006). This has involved the drying up of rivers and lakes, decline of water tables, deterioration of water quality, land salinization, desertification and other eco-hydrological problems (Cheng 2002, Wang and Cheng 1998, Wang and Cheng 1999b, Xiao and Cheng 2006). As the dominant surface water resource in the Zhangye Basin (Zhang et al. 2004a), the Heihe River used to be the major source of water for agriculture and industry. Increased demand and implementation of HWDP has driven the intensive development of groundwater use in the Zhangye Basin. The above mentioned problems bring a pressing need to understand these GWSW interactions in relation to hydrogeological conditions, climate changes and human activities in the basin (Zhang et al. 2004b).

Traditional approaches such as isotopic traces have been used to identify GWSW interactions in the Zhangye Basin (Nie et al. 2011, Qian et al. 2005, Zhang et al. 2005). Qian et al. using ^{222}Rn as a tracer found that the Zhangye Basin can be divided in two zones by the Heihe Bridge (Qian et al. 2005). Surface water recharges to groundwater in the zone upstream of the Heihe Bridge, and groundwater discharges to surface water in the other zone. Nie et al. reach similar results with Qian using geochemical methods (Nie et al. 2005). Zhang et al. indicated that the recharge of groundwater to surface water has increased because of irrigation by using ^{18}O (Zhang et al. 2005). Several numerical models have been built to evaluate flow dynamics (Su 2005, Wang et al. 2011, Wen et al. 2007, Zhang et al. 2004a, Zhou et al. 1990). However, these models are developed with a focus on groundwater resources. Some models were developed to simulate the leakage of river to groundwater (Wang et al. 2010b), or the interaction of surface water and groundwater (Li et al. 2008). However, the surface water system has been oversimplified.

A further limitation of most existing models is that the temporal and spatial variations of climate change in terms of temperature fluctuations have been insufficiently applied in simulations. To better understand GWSW interactions in relation to climate change, hydrogeological conditions and human activities, an integrated GWSW model has been developed using GSFLOW for both pre-HWDP (1999) and during the implementation of HWDP (2000-2010).

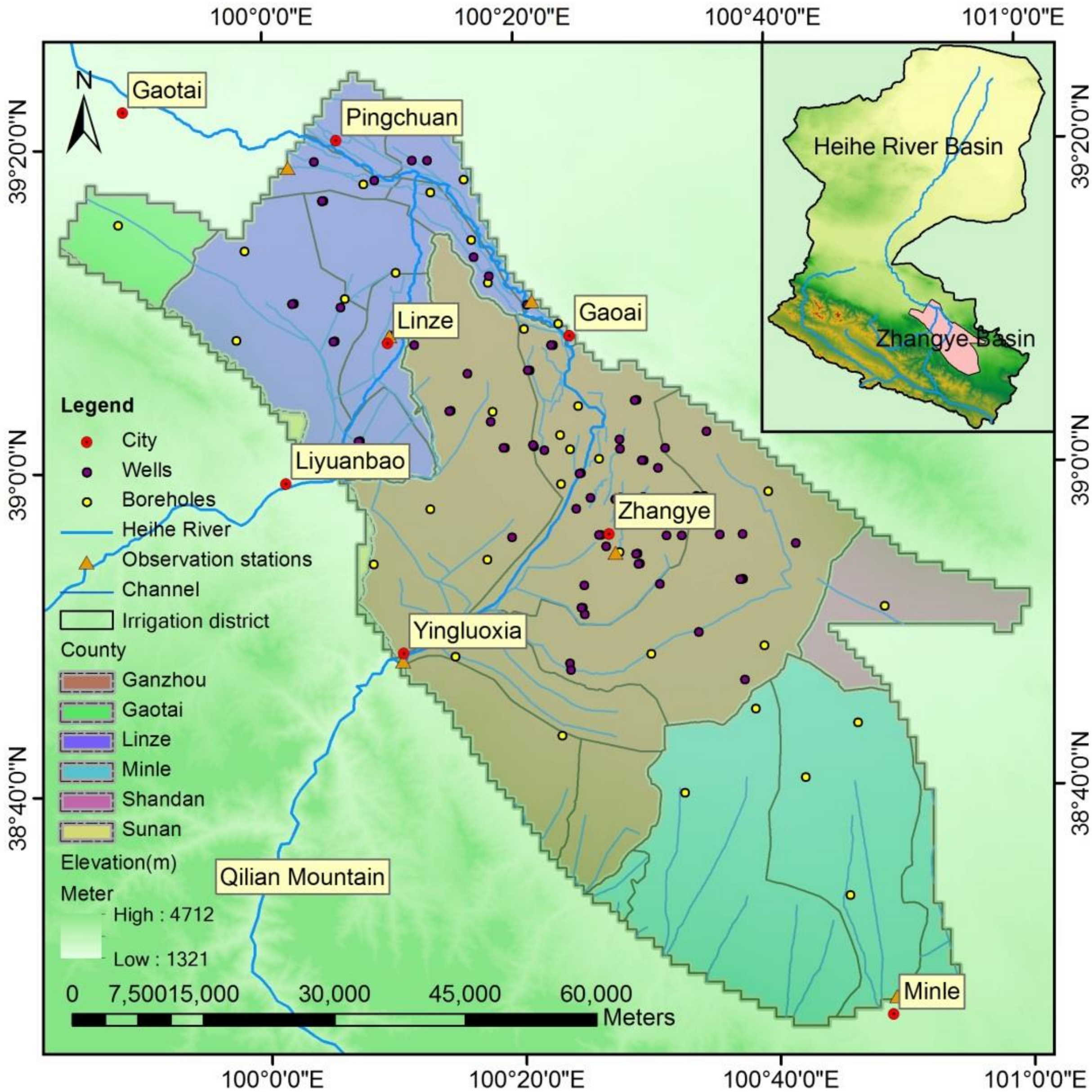


Figure 3.1. Location and DEM of the Zhangye Basin. (1) Boreholes used in 3D hydrostratigraphy model construction; (2) Locations of hydrogeologic monitoring stations, meteorological stations and observation wells used in model construction and calibration; (3) Irrigation districts of the Zhangye Basin.

2.Site Description

The Zhangye Basin as defined in this study ranges the Qilian Mountains in the south, the Beishan Mountains in the north, the Mingle Basin in the east and the Jiuquan Basin in the west (Figure 3.1). The total area of the Zhangye Basin is ~5000 km^2. The Zhangye Basin is located in the middle reach of the Heihe River in the northwestern China. The north-south trending basin was caused by the uplift of Qilian Mountains. It is divided in to three discrete geomorphologic units: the alluvial fan, floodplain, and desert.

The model of the Zhangye Basin relies on precipitation, evaporation and air temperature data that were collected from 3 meteorological stations within the study area (Figure 3.1). Three of these stations are provided by the Cold and Arid Regions Environment and Engineering Research Institute of the Chinese Academy of Sciences (CAREERI). The basin has a typical temperate continental semiarid climate, with temperatures ranges from -16.2℃ to 29.3℃. Precipitation in the Zhangye Basin is highly variable in intensity and generally increases with altitude. The annual precipitation ranges from ~50 to ~280mm from southeast to northwest, with ~ 80% of precipitation falls from June to September. Evaporation in the Zhangye Basin is highly related to the cover type and generally high in the bare soil area. The potential evaporation rate ranges from ~800 to ~2400mm from northwest to southeast (Wang et al. 2011, Wen et al. 2007).

As the dominant surface runoff in the Zhangye Basin, the Heihe River Originated in the Qilian Mountains, it merges with the Liyuanhe River, in the Zhangye wetland and enters the desert through Zhengyixia gorge. Daily runoff values were obtained for the basin at the Gaoai hydrological station near the outlet. Mean daily stream flow was ~31.7m^3/s for 1999-2010. The maximum daily mean stream flow on record was ~457m^3/s on July 11, 2002. Maximum flows usually occur in July-September when irrigation is low and precipitation is high. As an agriculture base, the temporal and spatial variations of irrigation have a major influence on surface water (Zhang et al. 2006).

3.Model Preparation

In the study, an integrated GWSW model was built using GSFLOW. GSFLOW was developed based on the integration of the U.S. Geological Survey Precipitation-Runoff Modeling System (PRMS) (Leavesley et al. 1995) and the U.S. Geological Survey Modular Ground-Water Flow Model (MODFLOW) (Harbaugh 2005).

GSFLOW simulates flow within and among three regions: soil zone, streams and lakes, and subsurface zone. PRMS is used to simulate hydrologic responses in the first region and MODFLOW-2005 is used to simulate hydrologic processes in the second and third regions.

Storage and all inflows and outflow in the soil zone for each PRMS Hydrologic Response Unit (HRU) are calculated using Soil-Zone Module (soilzone_gsflow).

Flow in the unsaturated zone is governed by one dimensional approximation to Richards' equation (Markstrom et al. 2008):

$$\frac{\partial \theta}{\partial t} + \frac{\partial K(\theta)}{\partial z} + i = 0 \qquad 3.1$$

$where\ \theta$ is the volumetric water content; z is the altitude; $K(\theta)$ is the vertical hydraulic conductivity in unsaturated zone; i is the evapotranspiration rate under the soil-zone base.

Flow in the saturated zone is simulated by a 3D groundwater flow differential equation (Harbaugh 2005):

$$\frac{\partial}{\partial x}\left(K_x \frac{dh}{dx}\right) + \frac{\partial}{\partial y}\left(K_y \frac{dh}{dy}\right) + \frac{\partial}{\partial z}\left(K_z \frac{dh}{dz}\right) + q_{ss} = S_s \frac{dh}{dt} \qquad 3.2$$

$where\ K_x, K_y$ and K_z are the hydraulic conductivities aligned with the x, y, and z coordinate directions; h is the potentiometric head; q_{ss} represents the sources and(or) sinks of water; S_s is the specific storage of the aquifer.

To prepare the inputs of the GSFLOW model, a number of hydrological, meteorological, geological, hydrogeological and ecological data related to the study were collected. The collected data includes DEM; maps of land use type and soil type; daily mean values of temperature, precipitation, evaporation and stream flow rate; borehole and monitoring well logs; and pumping rates.

3.1. PRMS Input

A PRMS data file was assembled for the PRMS model for 1999 through December 31, 2010. The PRMS data file includes daily stream flow at the Gaoai hydrological station and climate data from Linze, Zhangye and Mingle meteorological stations.

Using GIS, the Zhangye Basin was delineated into 17 HRUs (Figure 3.2), determined by a combination of hydrological and ecological conditions. The generation of HRUs included a series of watershed analyses in GIS. This resulted in 4722 gravity reservoirs when the HRUs were intersected with active cells in the top layer of the MODFLOW grid. The PRMS-only model has 17 groundwater reservoirs, one corresponding to each HRU.

3.1.1. Digital Elevation Model

The DEM with a resolution of 30m by 30m covering the whole Zhangye Basin was obtained from the Cold and Arid Regions Environment and Engineering Research Institute of the Chinese Academy of Sciences. The original DEM was preprocessed by GIS before using it for further analyses.

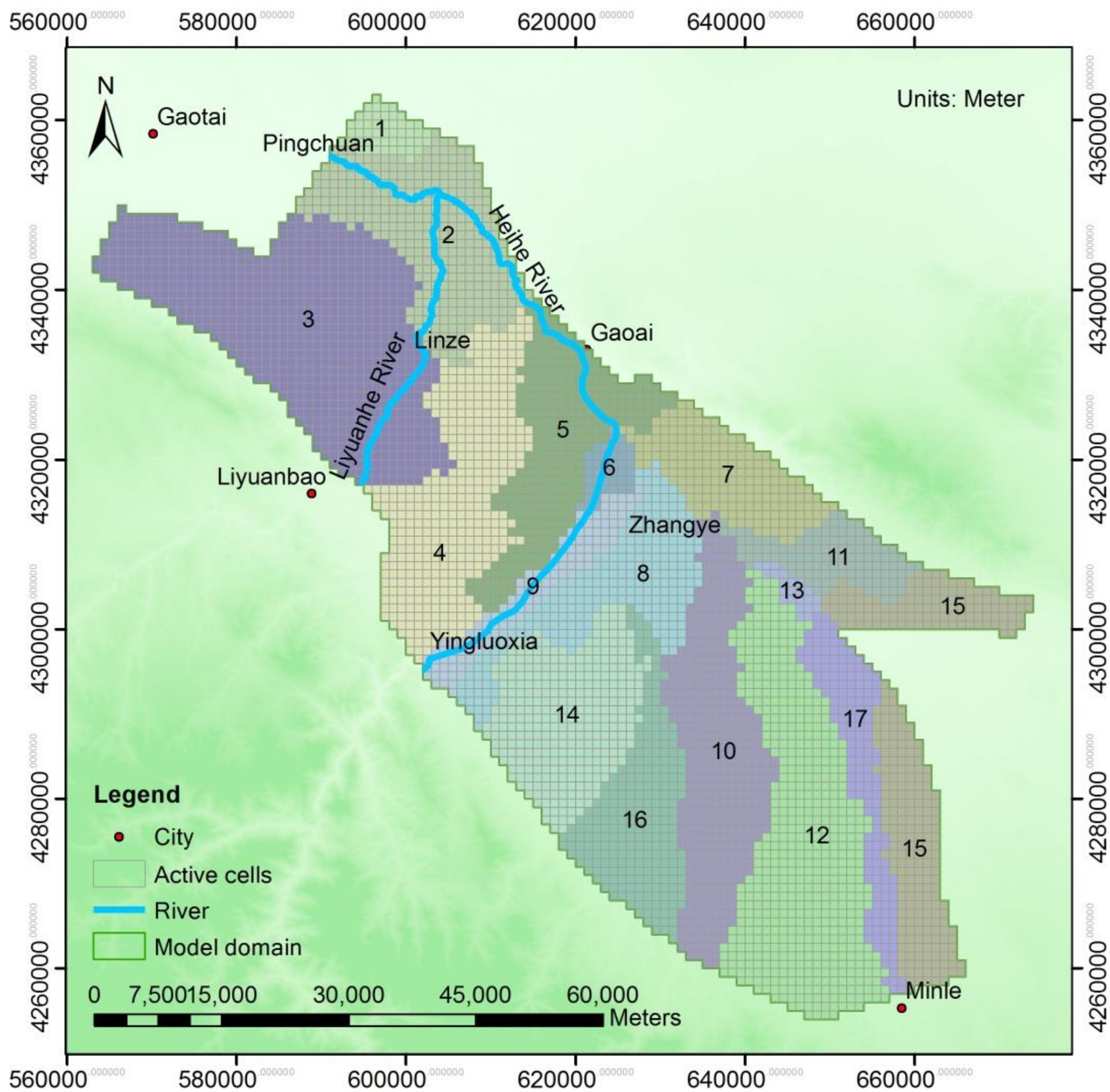


Figure 3.2. Finite-difference cells in relation to 17 hydrologic response units (HRUs) discretized for the Zhangye Basin, northwest China.

3.1.2. Land-use Data

The land-use map for the whole Zhangye Basin was obtained from LUCC2000. This land-use map had to be reclassified into 4 classes to be used in GSFLOW. The 4 land-use classes in GSFLOW are: 0= bare, 1= grass, 2= shrubs and 3= trees. As shown in Figure 3.3, the majority of land-use types are bare and grass.

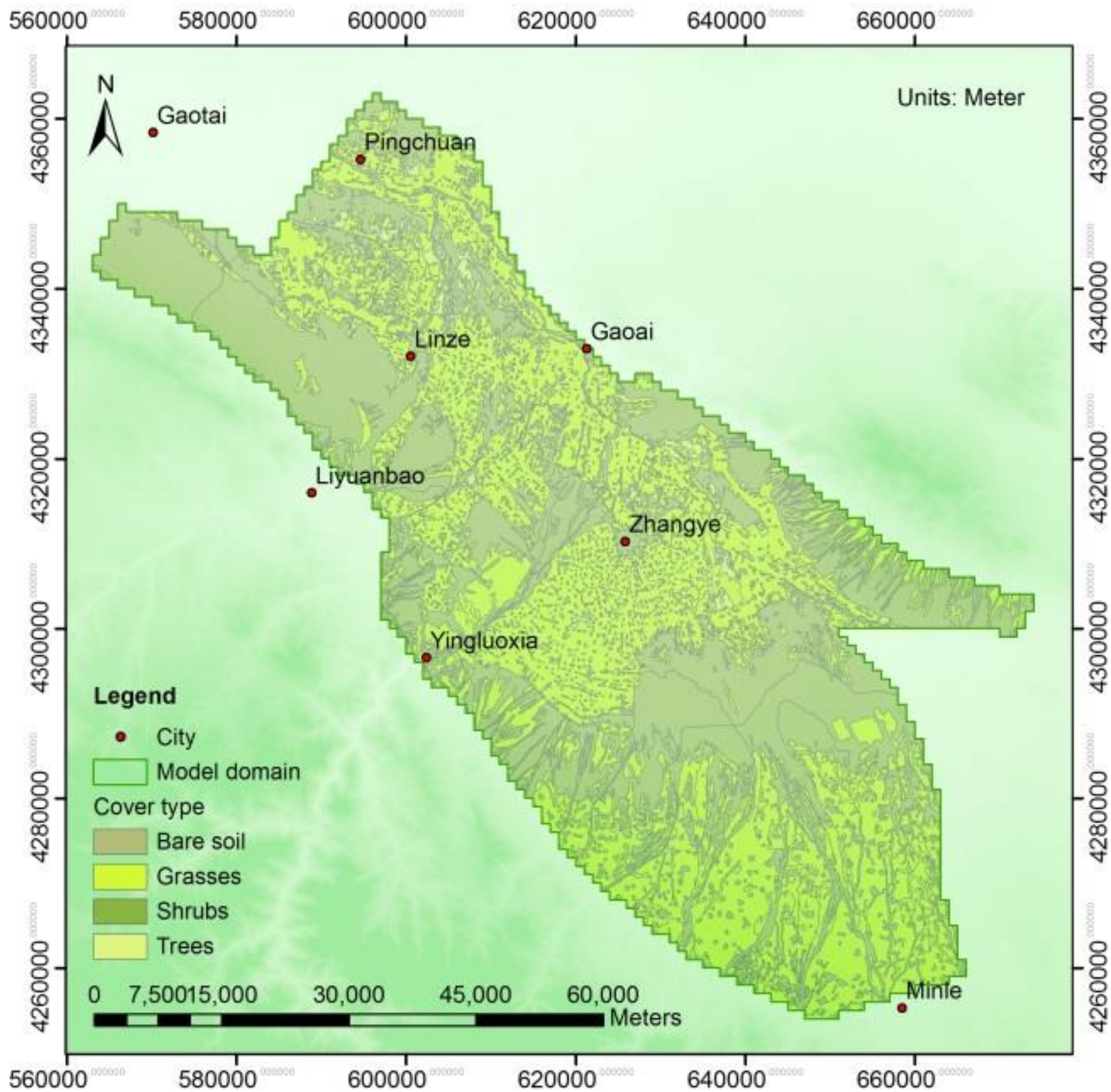


Figure 3.3. Land-use map of the Zhangye Basin, northwest China.

3.1.3. Soil Data

The soil map was obtained from the Harmonized World Soil Database (2009). To make this soil map usable for GSFLOW, it was first converted and reclassified into three soil classes: sand, loam and clay. The soil map was based on the topsoil texture, which refers to the simplified texture for 0–30cm used in the Soil Map of the World (FAO/Unesco, 1970-1980).

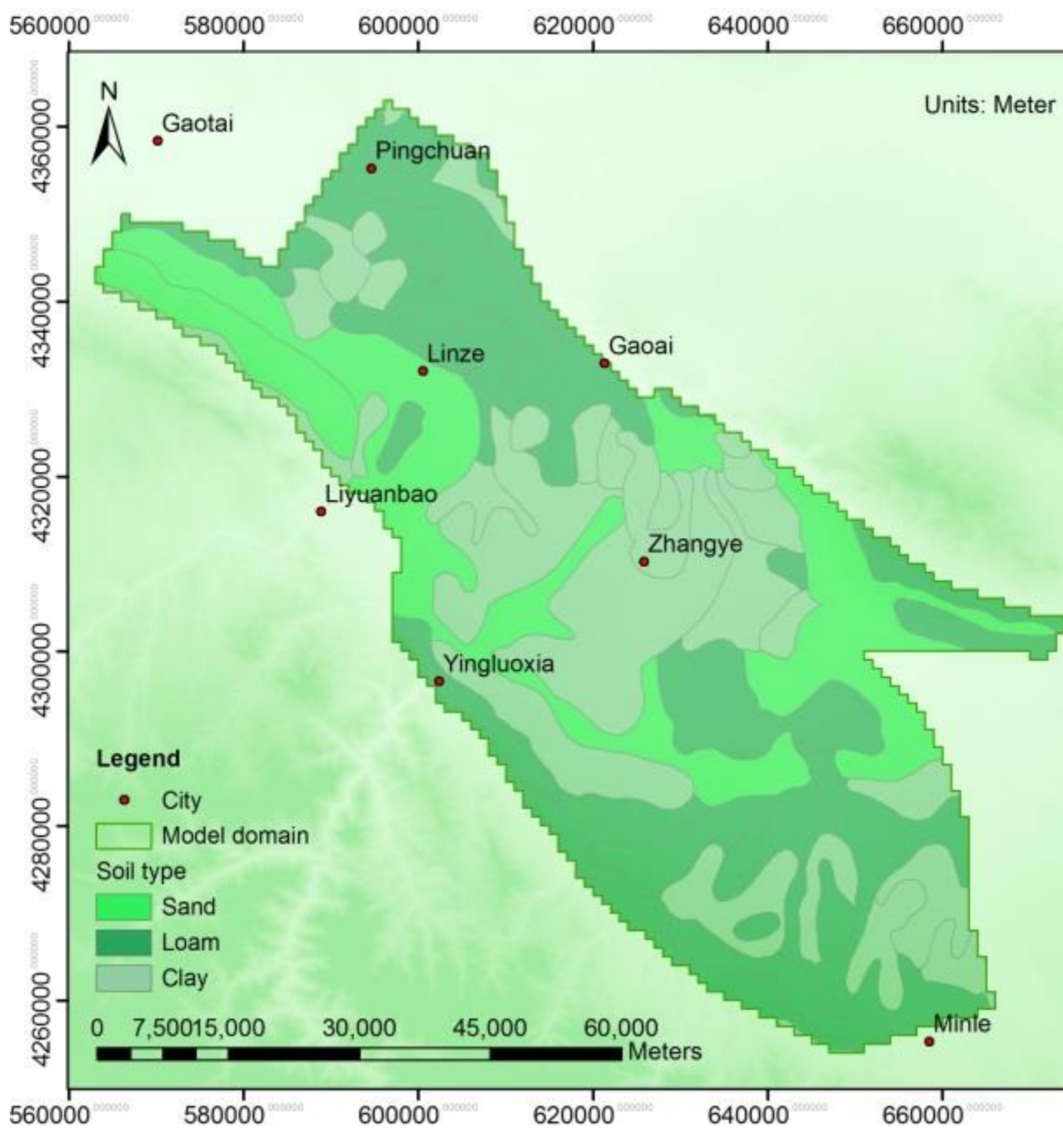


Figure 3.4. Soil map of the Zhangye Basin, northwest China.

The reclassification is based on the percentage of sand, silt and clay. If the percentage of sand is greater than 50%, then the soil type is sand; if the percentage of clay is greater than 40%, then it is clay; otherwise, it is loam. Figure 3.4 shows the soil map of the study area used for GSFLOW.

3.1.4. Temperature Distribution

In this study the module temp_laps_prms was used. It comprised data from at least two stations at different altitudes, which were used to estimate the air temperature of each HRU. These HRUs were assigned air temperature on the basis of computed lapse rates from a pair of stations. The stations associated with each HRU are specified by hru_tsta and hru_tlaps. Maximum and minimum daily HRU temperatures are calculated according to (Markstrom et al. 2008) :

$$T_{HRU}^{m} = T_{base}^{m} + \left(T_{lapse}^{m} - T_{base}^{m}\right)\left(\frac{Z_{HRU} - Z_{base}}{Z_{lapse} - Z_{base}}\right) - taf_{HRU} \qquad 3.3$$

$where\ T_{HRU}^{m}$ is the maximum (or minimum) daily temperature at each HRU for time step m; T_{base}^{m} is the maximum (or minimum) daily temperature at the base station that is most representative of the temperature at the HRU; taf_{HRU} is the maximum (or minimum) daily HRU temperature adjustment factor; $T_{lapse}^{m}$is the measured temperature at the lapse station; Z_{HRU} is the mean land surface altitude of each HRU; and Z_{lapse} and Z_{base} are altitudes of the two stations.

3.1.5. Precipitation Distribution

The module precip_laps_prms was used in this study. In this module, a monthly correction factor, which accounts for elevation, topography and other factors, is used to estimate the daily precipitation at the HRU according to (Markstrom et al. 2008):

$$P_{HRU}^{m} = P_{base}^{m} CF_{HRU} \quad 3.4$$

$where\ P_{HRU}^{m}$ is the precipitation at the HRU during time step m; $P_{base}^{m}$is the precipitation at the base station that is most representative of the precipitation at the HRU; CF_{HRU} is the monthly correction factor used to adjust rain at the HRU. It can be calculated as:

$$CF_{HRU} = 1.0 + psf_{base} \left[\frac{\left(\frac{\bar{P}_{lapse} - \bar{P}_{base}}{Z_{lapse} - Z_{base}} \right) \left(Z_{HRU} - Z_{base} \right)}{\bar{P}_{base}} \right] \quad 3.5$$

$where\ psf_{base}$ is the mean monthly factor used to adjust the rain lapse rate (usually 1.0); $\bar{P}_{base}$ and $\bar{P}_{lapse}$ are mean precipitations at the base station and the lapse station, respectively. The two stations associated with each HRU are specified by hru_psta and hru_plaps.

3.1.6. Solar Radiation and Potential Evapotranspiration

In the study the module ddsolrad_hru_prms was used, since the Zhangye Basin is located in an arid region where predominantly clear skies prevail on days without precipitation. The module potet_pan_prms was used to compute potential evapotranspiration for each HRU, and pan evaporation data was obtained from three meteorological stations.

3.2. MODFLOW Input

The MODFLOW-2005 model of the Zhangye Basin consisted of six layers, with each layer comprising 120 rows and 120 columns. All cells in each layer had a constant width and length of 1,000m. The top altitudes of finite-difference cells were set equal to land-surface altitudes for each cell and ranged from 1,362 to 2,518m. Thicknesses of 6 layers ranged from ~30m to ~400m. The vertical hydraulic gradient ranged from 0.001 to 0.01, and the horizontal hydraulic conductivity generally ranged from 1-40 m/d for gravel; 0.2-10 m/d for sand; and 0.1-0.001m/d for loam and sandy loam. Specific yields ranged from 2%-5% in loam to 10%- 20% in sand. Storage coefficients in confined aquifers decreased from 0.001-0.005 in the alluvial plain to 0.00005-0.0005 in the flood plain.

Packages used in the simulation are listed in Table 3.1. The Heihe River and the Liyuanhe River were represented by 17 stream segments that were made up of 170 reaches using the Streamflow-Routing Package, which also included the simulation of unsaturated flow beneath streams. The unsaturated-zone had a saturated water content of 0.3, and its vertical conductivity was set equal to intersecting saturated layers.

Table 3.1. MODFLOW-2005 Packages and files used for MODFLOW run in stand-alone mode by using GSFLOW.

MODFLOW-2005 Packages and Files	
Basic Package	.BAS
Time-Variant Specified-Head Package	.CHD
Discretization file	.DIS
Layer-property Flow Package	.LPF
Preconditioned Conjugate-Gradient Solver Package	.PCG
Time-Variant Specified-Head Package	.CHD
Well Package	.WEL
Gage Package	.GAG
Streamflow-Routing Package (SFR2)	.SFR
Unsaturated-Zone Flow Package	.UZF
Gage Package	.GAG

4.Model Calibration

The GSFLOW model of the Zhangye Basin was calibrated using a stepwise procedure: First, the independent PRMS and MODFLOW-2005 models were calibrated by running these models separately (that is, PRMS-only and MODFLOW-only simulations). Then, the integrated GSFLOW model was calibrated.

4.1. PRMS Calibration

The initial calibration of the PRMS was done by running a PRMS-only simulation. The calibration procedure consisted of adjusting parameters that affected the average streamflow.

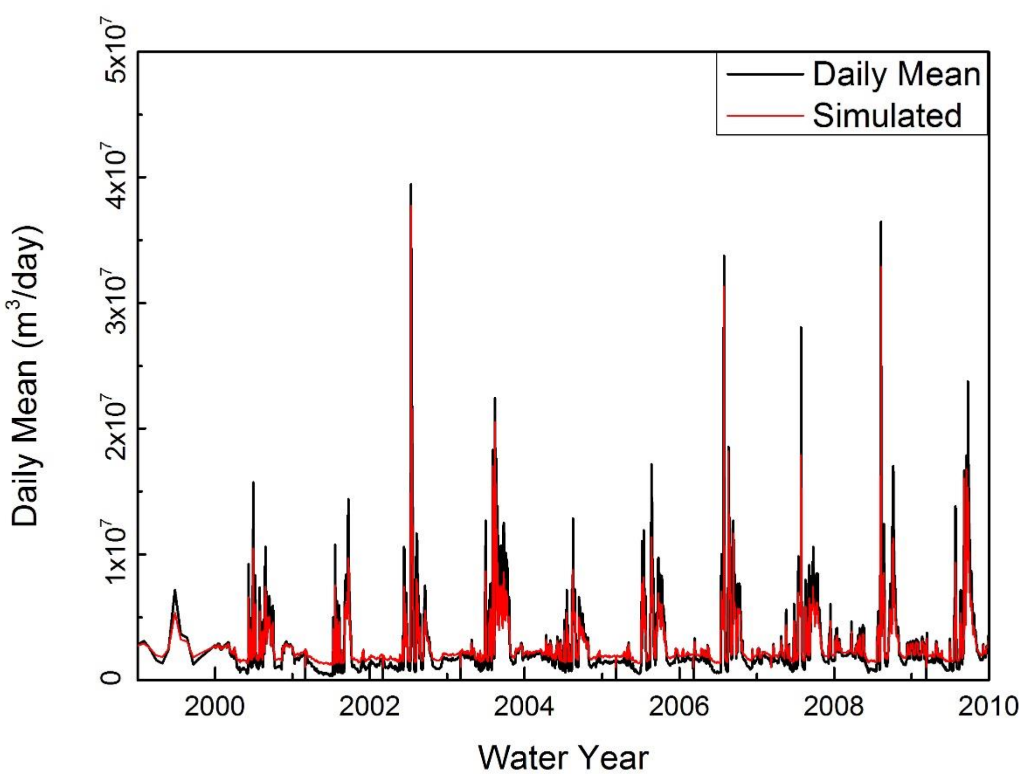


Figure 3.5. Measured and PRMS simulated daily-mean streamflow at the Gaoai hydrological station for calibration period 1999-2010.

All adjusted parameters were kept within a reasonable range to provide a close match of simulated and measured daily streamflow. The measured and calibrated fluxes from 1999-2010 are shown in Figure 3.5.

The Nash-Sutcliffe efficiency coefficient (Nash and Sutcliffe 1970) was used to assess the fit between the simulated and measured hydrographs. The Nash-Sutcliffe efficiency coefficient ($E_{N\&F}$) is defined as:

$$E_{N\&F} = 1 - \frac{\sum_{t=1}^{n} \left(Q_c - Q_o\right)^2}{\sum_{t=1}^{n} \left(Q_o - \bar{Q}\right)^2} \qquad 3.6$$

$where\ Q_c$ and Q_o are simulated and measured values of streamflow, $\overline{\mathrm{Q}}$ is the mean of the measured value of streamflow. The $E_{N\&F}$ can range from $-\infty\ to\ 1$, and an efficiency of 1 indicates a perfect match (Markstrom et al. 2008). The $E_{N\&F}$ of the calibrated model of the Zhangye Basin was 0.86.

Visual inspections of fluxes in Figure 3.5 indicate that the PRMS-only model performs very well. The temporal variation of the streamflow has been reproduced by the model. However, there are some differences during the low-flux periods, where measured low streamflow are slightly lower than simulated values. There are also some differences during the summer months, where measured peak streamflows are slightly higher than simulated values.

4.2. MODFLOW Calibration

The initial calibration of MODFLOW-2005 was done by running a MODFLOW-only simulation. The calibration was done using a trail-and-error approach, followed by PEST (Doherty et al. 1994) to further adjust parameters. The distribution of horizontal hydraulic conductivity (Kx) was initially created on the basis of hydrogeological maps. During the calibration, Kx and the infiltration rate for the unsaturated zone were adjusted within a reasonable range. The water table for1999 and head observations from 75 wells from 1999-2007 were used as calibration targets. The ratio between vertical and horizontal hydraulic conductivity (Kv/Kz) was also adjusted in calibration and estimated to be 4-8 for all layers.

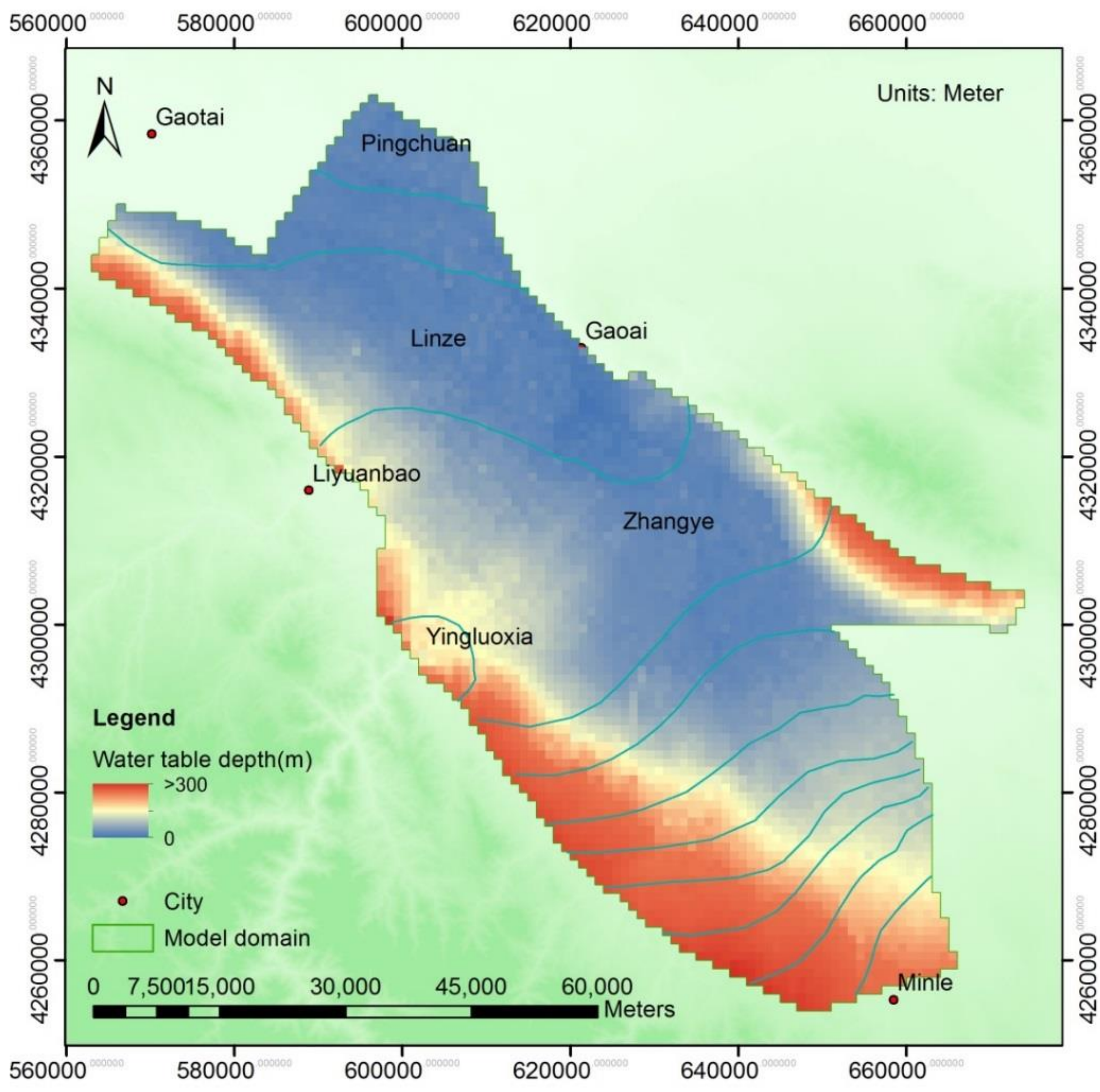


Figure 3.6. Simulated steady state water table depth below land surface in the Zhangye Basin, northwest China.

Simulated depths to the water table were more than 300m beneath the land-surface in areas near the southwest boundary, where the upper alluvial fan lies. The water-table depths in the north part of the flood plain were generally 3-5m beneath the land-surface (Figure 3.6).

4.3. GSFLOW Calibration

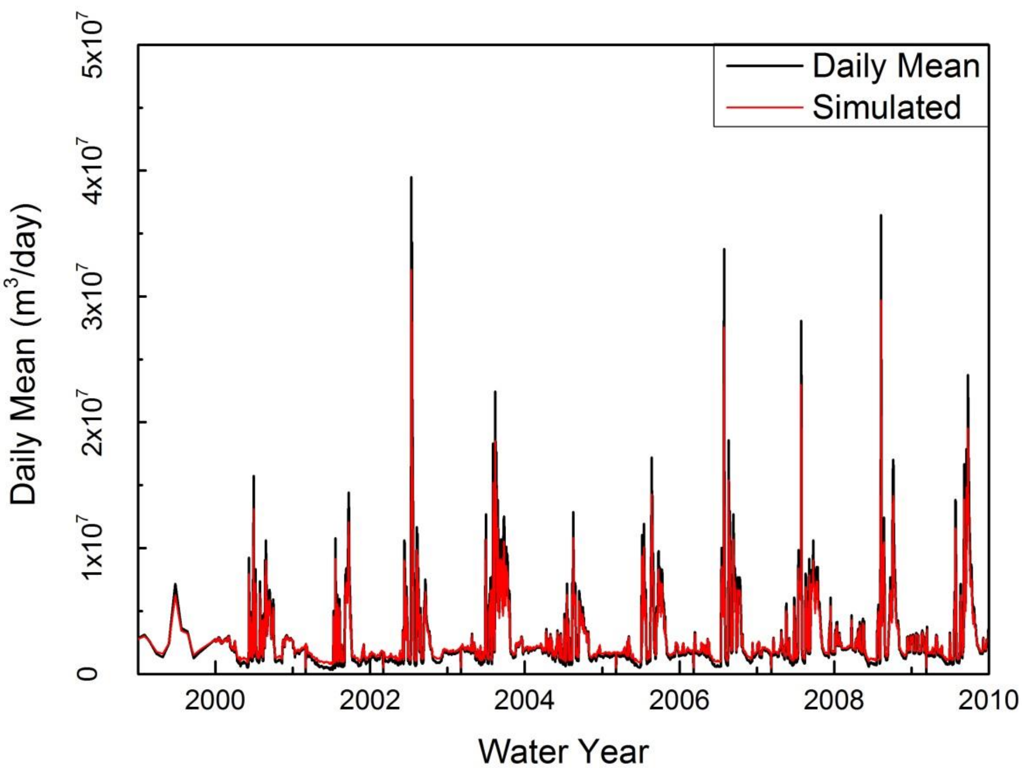


Figure 3.7. Measured and GSFLOW simulated daily-mean streamflow at the Gaoai hydrological station for calibration period 1999-2010.

Parameter sets from the PRMS-only and MODFLOW-only models of the Zhangye Basin were initially used as input parameters for the GSFLOW model (Markstrom et al. 2008). Most of the parameters remained unchanged during the calibration of the GSFLOW model; only a few of the parameters that influenced the flows between the PRMS and MODFLOW-2005 were adjusted.

Generally, the GSFLOW model was calibrated to find a close match to the streamflow measured between1999 and 2010 in the Gaoai hydrological station. The $E_{N\&F}$ of the calibrated GSFLOW model of the Zhangye Basin was equal to 0.82. The observed and simulated streamflow is shown in Figure 3.7.

5.Model Results and Discussion

5.1. Storages and Fluxes

Total inflow in the Zhangye basin included precipitation and river inflow from the Yingluoxia Gorge. Total outflow included ET, pumping, river outflow at the outlet of the basin, and a diversion flow from the river. The different of total inflow and outflow was reflected as storage change in the basin. Storage was divided into four major compartments in the GSFLOW model of the Zhangye Basin. These are surface storage, soil-zone storage, unsaturated-zone storage and saturated-zone storage. In the study area, the surface storage had less change. Unsaturated-zone storage and soil zone generally peaked when precipitation peaked. Saturated-zone storage change had the same tendency with the pumping rate (Table 3.2).

The main fluxes of water across land surface for the Zhangye Basin included precipitation and evapotranspiration (ET). Compare to a groundwater model, which normally roughly distributes ET calculated based water table, this integrated model provides a way to compute daily evapotranspiration based on pen evaporation data to obtain more accurate simulation.

Table 3.2. Computed water budget for the GSFLOW model simulation.
Units: $10^8 m^3$/year.

Water year	In: Stream flow	In: Precipitation	Out: Evapotranspiration	Out: Stream flow	Out: Pumping	Out: Boundary flow	In-Out
1999	16.21	5.60	5.43	10.31	2.64	3.43	0.00
2000	14.63	8.04	5.91	9.37	2.77	3.35	1.27
2001	13.05	7.32	7.17	6.55	2.91	3.30	0.44
2002	16.18	9.45	7.60	9.41	3.05	3.25	2.31
2003	19.01	8.15	8.09	12.74	3.21	3.20	-0.08
2004	15.10	5.19	9.31	8.39	3.37	3.17	-3.95
2005	18.18	10.54	8.93	9.74	3.54	3.14	3.37
2006	18.14	7.74	8.99	10.27	3.71	3.11	-0.20
2007	20.92	13.79	8.75	11.20	3.90	3.08	7.78
2008	19.44	9.79	10.45	11.25	4.08	3.05	0.39
2009	20.93	10.54	10.83	11.77	4.28	3.02	1.56
2010	17.26	7.74	12.51	9.11	4.50	3.00	-4.12

Water year	Storage change: Surface	Storage change: Soil zone	Storage change: Unsaturated	Storage change: Saturated	Storage change: Total	Percent discrepancy
1999	0.00	0.00	0.00	0.00	0.00	0.00
2000	-0.01	0.00	0.87	0.41	1.27	-0.01
2001	-0.01	0.18	-0.07	0.35	0.44	-0.01
2002	-0.01	0.92	0.69	0.70	2.31	-0.01
2003	-0.01	-0.04	-0.71	0.68	-0.08	-0.01
2004	0.00	-2.37	-1.15	-0.43	-3.95	0.00
2005	0.00	0.34	3.28	-0.24	3.37	0.00
2006	-0.01	-0.08	0.61	-0.72	-0.20	-0.01
2007	0.01	1.56	6.64	-0.43	7.78	0.01
2008	-0.01	0.12	1.33	-1.05	0.39	-0.01
2009	0.00	0.16	3.89	-2.49	1.56	0.00
2010	-0.01	-0.82	0.67	-3.96	-4.12	-0.01

Precipitation, mainly as rain, peaks in July to September. Evapotranspiration is the total evaporation and evapotranspiration from plant and soil zone. Peak evapotranspiration generally occurred in the summer period as irrigation was high and plants reached their highest transpiration rates (Figure 3.8). Three major fluxes of water in the basin added streamflow to the Heihe River. These were surface runoff, interflow and groundwater discharge directly to stream. Since runoff and recharge to groundwater in the Zhangye Basin were dominated by precipitation and streamflow from the Yingluoxia Gorge. Surface runoff and interflow showed seasonal variations.

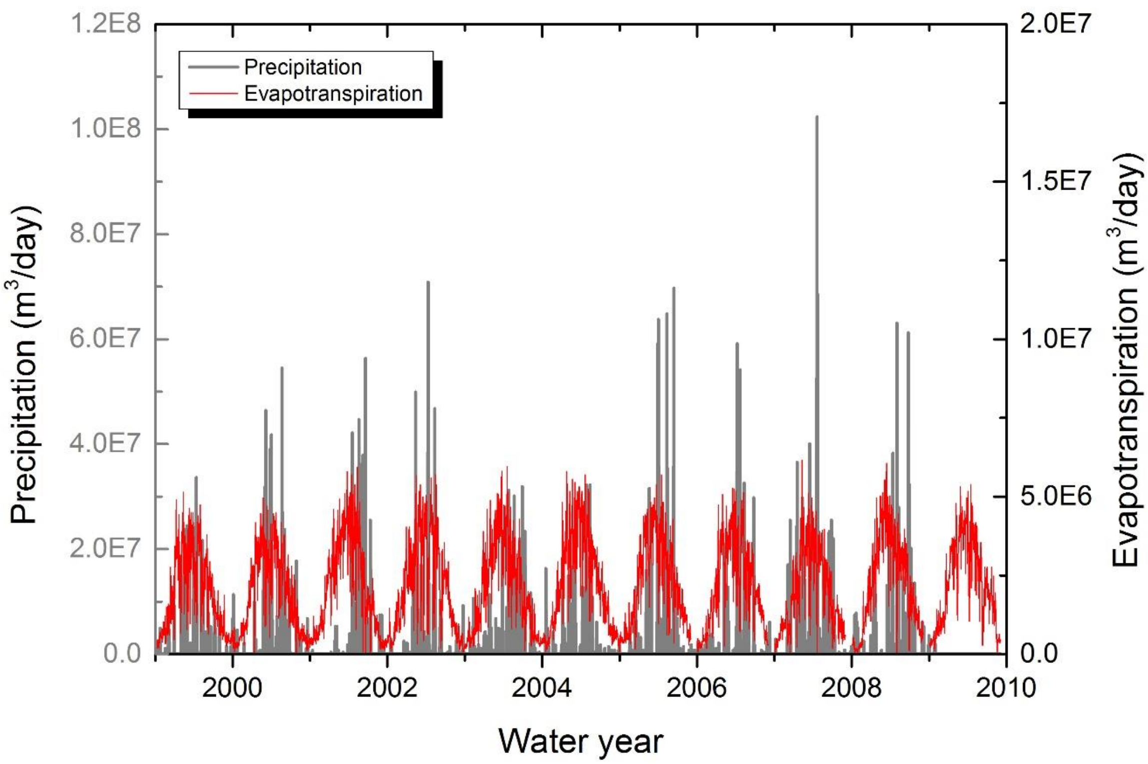


Figure 3.8. Major fluxes across land-surface during 1999-2010 include precipitation, evapotranspiration.

5.2. Groundwater and Stream Interactions

Streams are simulated by Streamflow Routing Package, which accumulates surface runoff and interflow generated in related HRUs, directly calculates the base flow generated by groundwater recharge, and provides insights understanding temporal variation of stream flux components.

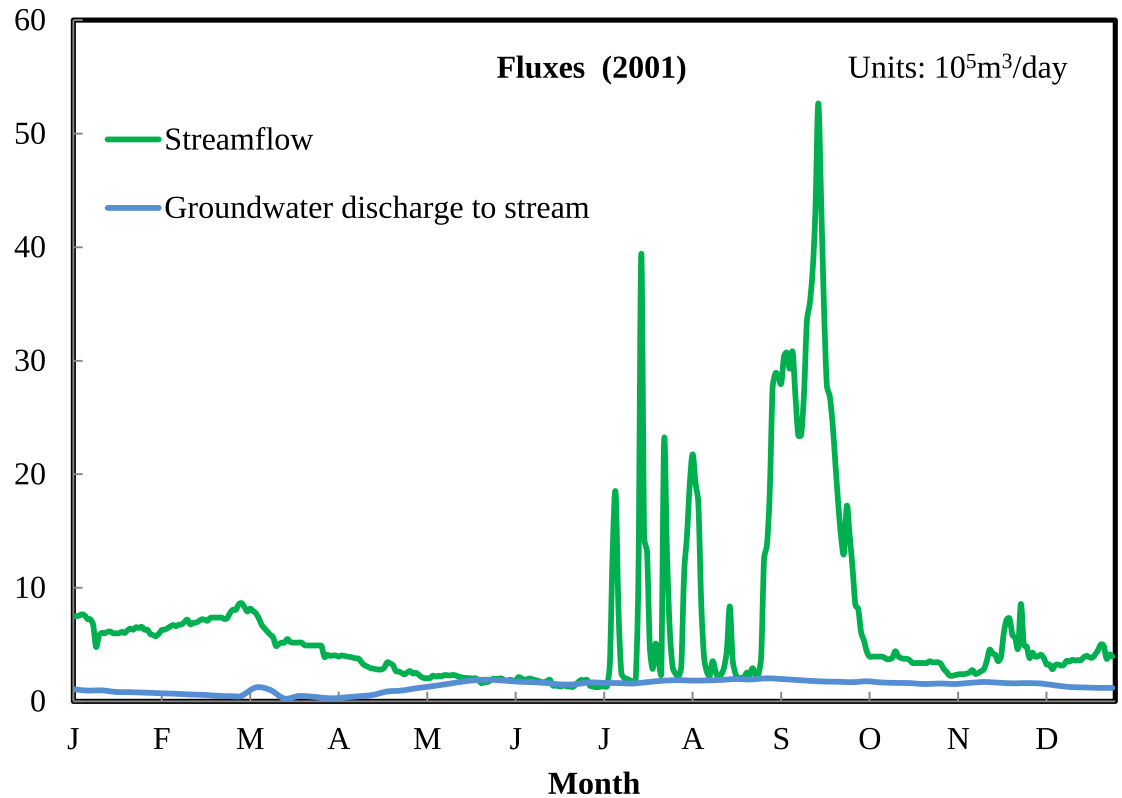


Figure 3.9. Major fluxes in stream in 2001. Streamflow and groundwater discharge to streams.

Besides demonstrating the overall pattern that the Heihe River generally discharged to groundwater in upstream, gained water from groundwater in downstream and intensively exchanged water with groundwater in the middle, the model indicated groundwater discharge rates to stream peaked in the summer time, flux data can also extract from the model result to support specified research interest. (Figure 3.9 and Figure 3.10).

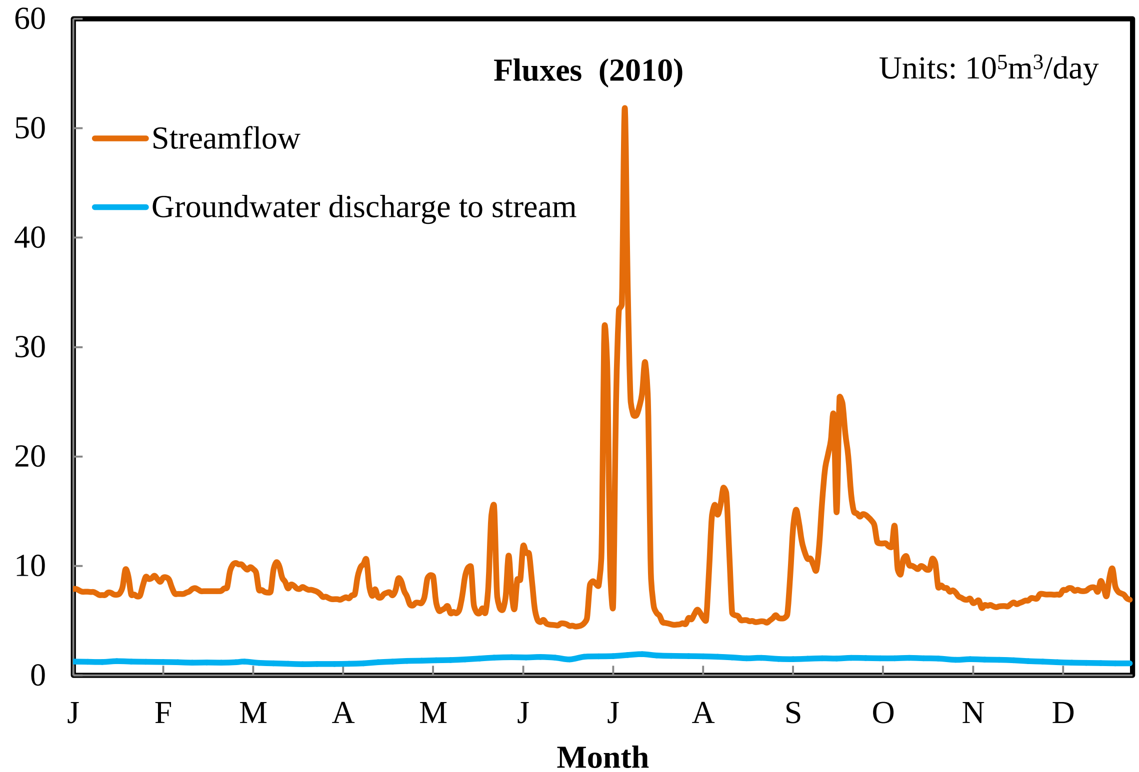
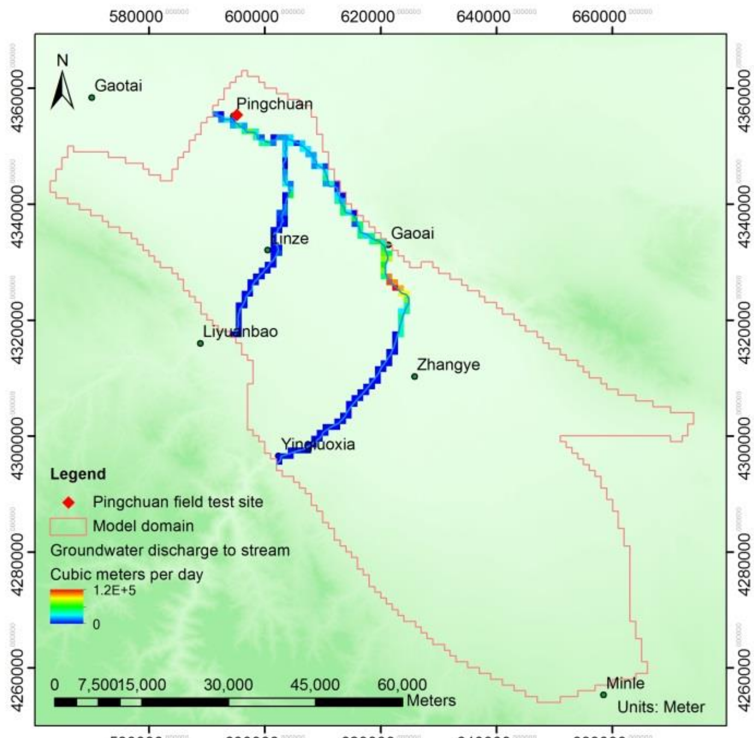
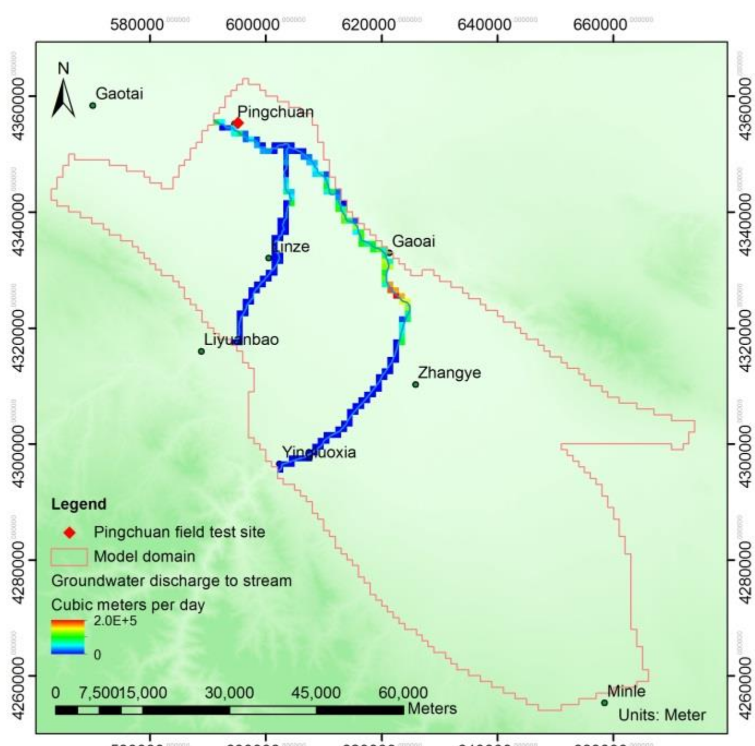


Figure 3.10. Major fluxes in stream in 2010. Streamflow and groundwater discharge to streams.

In the study, two strings of base flow and stream flux has been illustrated to show us the comparison of the stream components of years 2001(beginning of HWDP) and 2010(10 years implication of HWDP). In June, groundwater discharge used to contribute most of the streamflow of the Heihe River (Figure 3.9). After the implication of HWDP, most streamflow from Yingluoxia Gorge were hold to deliver to downstream, thus, groundwater discharge contributed a relative small portion of the total streamflow in the Heihe River (Figure 3.10).



a,



b,

Figure 3.11. Simulated groundwater-stream interactions in the Zhangye Basin, northwest China. (a) steady- state; (b) June 16, 2010.

The special distribution of groundwater discharge rates were computed by the GSFLOW model. The maximum groundwater discharge zones were located at the reaches between Gaoai and Pingchuan. Figure 3.11 illustrated differences of groundwater discharge to stream in the steady state and in June 16, 2010 (low precipitation, low stream inflow). The average maximum discharge rates were about ~$1.2\times10^5 m^3$/day in the steady state and ~$2.0\times10^5 m^3$/day in the summer period (Figure 3.11).

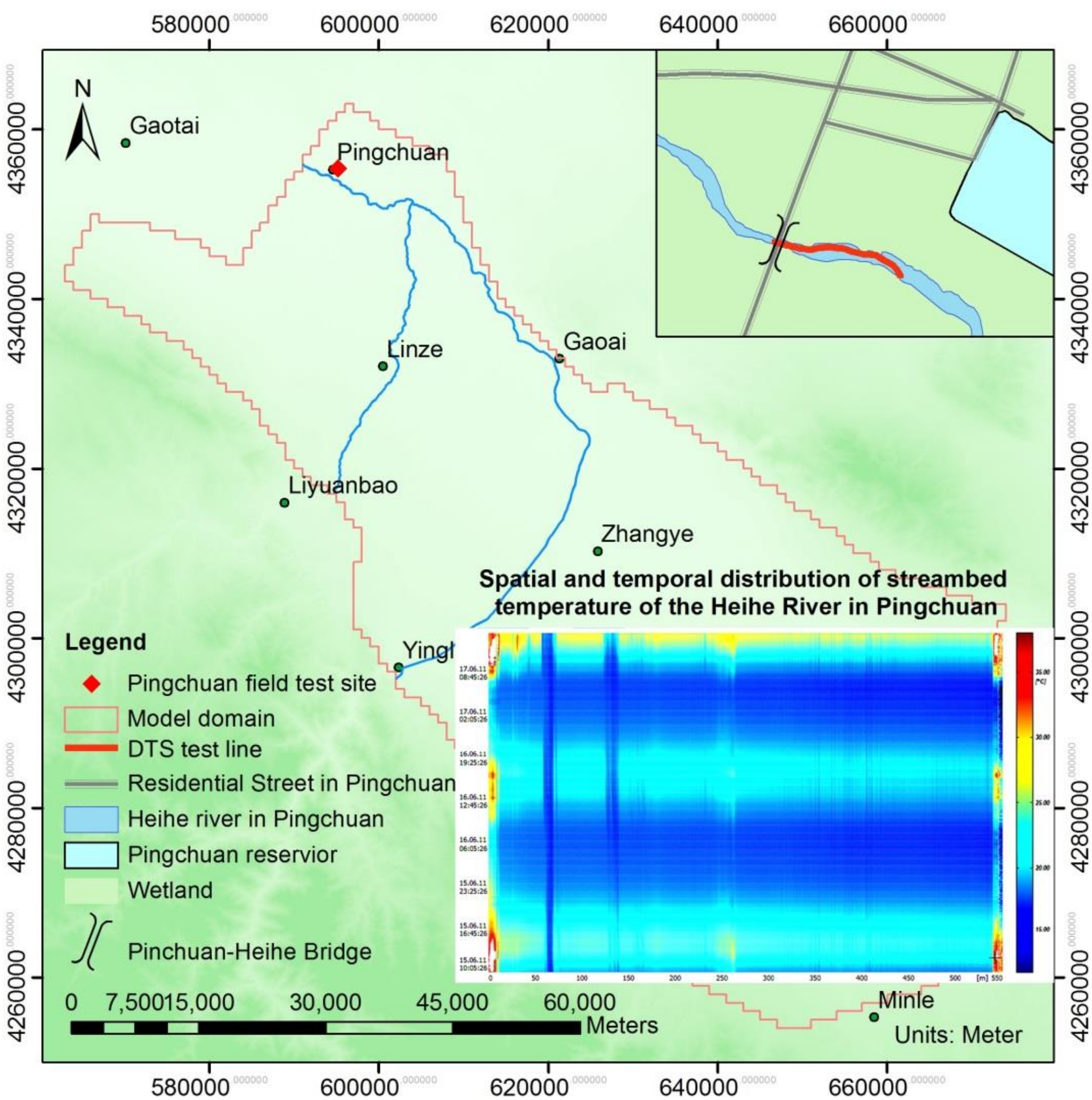


Figure 3.12. Location of the Pingchuan field investigation and DTS results.

Distributed temperature sensor (DTS) was a powerful tool to identify discrete zones of groundwater discharge in a steam on the basis of variations in streambed surface temperature (Anderson 2005, Constantz 2008, Tyler et al. 2009), especially it was an efficient and cost effective tool to investigate groundwater-surface water on basin scale. A DTS was used in the Zhangye Basin to study groundwater-surface water interactions (Huang et al. 2012). By continuously monitoring the streambed and stream surface temperatures along the river channel through a fiber-optic cable, the 550m long river segment was identified as a groundwater discharge zone (Figure 3.12). Based on the comparison of observed temperature variations in the atmosphere, streambed and stream surface, the distribution and variation pattern of temperature anomalies were easily identified, thus providing a sound support for simulation results of groundwater-surface water interactions.

5.3. Analysis of Irrigation Water Management Schemes

The main water used in the Zhangye Basin is by irrigation, which account for ~71% in 1999 (Chen et al. 2005) and increased by 2% per year. With further economic development and population growth, the water shortage was expected to become more serious. In order to mitigate conflicts between water supply and demand, irrigation water allocation, efficiency improvement and water saving strategies should be considered in agricultural water management.

The water authority of the Zhangye Basin is decentralized into multi-level sections to coordinated management of water resources. Generally, water management scheme are applied at three levels: the county level, the irrigation district level and the field level (Ge et al. 2013). At the county level, water commonly was allocated to counties on the basis of water rights ratio. At the district level and the field level, the water allocation was more complicated, since crop water consumption, domestic and industrial water use, water use efficiency should be taken into account.

Table 3.3. The actual irrigation water allocation at 20 irrigation districts.

ID	Irrigation District	Area (Km^2)	Water allocation volume ($10^8 m^3$)	Irrigation Rate (mm/year)
1	Suyoukou	24.90	0.03	120
2	Nijiaying	80.32	0.06	77
3	Xiaotun	123.17	0.07	53
4	Liaoquan	59.78	0.08	134
5	Tongziba	70.36	0.08	120
6	Yanuan	66.53	0.08	127
7	Shahe	108.18	0.08	73
8	Pingchuan	74.21	0.08	111
9	Banqiao	94.97	0.11	114
10	Anyang	133.98	0.16	120
11	Luotuocheng	144.24	0.16	110
12	Huazhaizi	186.09	0.22	120
13	Mayinghe	203.37	0.24	120
14	Shangsan	172.98	0.31	180
15	Xinhua	380.09	0.39	103
16	Yimin	478.69	0.57	120
17	Daduma	565.49	0.68	120
18	Yingke	494.64	0.66	133
19	Daman	654.93	0.63	94
20	Xijun	605.08	0.87	144

Table 3.4. Present situation and scenario alternatives for different water-saving practices.

ID	Irrigation District	Current water use efficiency	Current ratio of grain and cash crops	Current groundwater abstraction (10^8m3)	Alternative 1	Alternative 2	Alternative 3
					water use efficiency	**The ratio of grain and cash crops**	**% of farmland reduced**
1	Suyoukou	0.65	60:40	0	0.7	55:45	5
2	Nijiaying	0.7	60:40	0.01	0.75	55:45	0
3	Xiaotun	0.7	60:40	0.015	0.75	55:45	0
4	Liaoquan	0.7	60:40	0.0059	0.75	55:45	0
5	Tongziba	0.67	60:40	0	0.72	55:45	5
6	Yanuan	0.66	60:40	0.03	0.71	55:45	0
7	Shahe	0.74	60:40	0.024	0.79	55:45	0
8	Pingchuan	0.71	60:40	0.02	0.76	55:45	0
9	Banqiao	0.64	60:40	0	0.69	55:45	0
10	Anyang	0.65	60:40	0	0.7	55:45	5
11	Luotuocheng	0.68	60:40	0.0049	0.73	55:45	5
12	Huazhaizi	0.65	60:40	0	0.7	55:45	5
13	Mayinghe	0.61	60:40	0.343	0.66	55:45	5
14	Shangsan	0.65	60:40	0	0.7	55:45	0
15	Xinhua	0.7	60:40	0.021	0.75	55:45	5
16	Yimin	0.7	60:40	0	0.75	55:45	5
17	Daduma	0.67	60:40	0	0.72	55:45	5
18	Yingke	0.68	60:40	0.63	0.73	55:45	0
19	Daman	0.62	60:40	0.63	0.67	55:45	5
20	Xijun	0.69	60:40	0.17	0.74	55:45	5

In this study, due to lacks of accurate spatial distribution of the crop structure, our assumption was made at the irrigation district level. Water management schemes were assessed using Recharge Package in MODFLOW by adjusting the recharge rate to the groundwater flow system. The irrigation rates of 20 irrigation district are listed in Table 3.3. Values are calculated on the basis of the sum of irrigation water use from groundwater, rivers and channels (irrigation infiltration coefficient of ~ 0.3). Maximum irrigation applied to Shangsan and Xijun irrigation districts ranging from 140-180mm/year (Table 3.3). Actual precipitation are generated from data obtained 5 meteorological stations ranging from 75-480mm year. Precipitation is highest in the piedmont area in Minle and Yingluoxia and decreased to 75-150mm/year in flood plain in Linze and Gaoai. The recharge rate was input based on the total of precipitation and estimated irrigation return flow.

The model simulated the flow system during the application of the actual irrigation water allocation and the optimized irrigation water management scheme generated when following management approaches implemented: Improving the irrigation (water use) efficiency by 5%, reducing the farmland in regions that are far from the surface water sources by 5%, adjusting crop structures (substitute the high water consumption crops for the water saving and high value crops, in the optimized scheme, a current ratio of grain and cash crops of 60:40 was changed in to 55:45 (Table 3.4).

Figure 3.13 showed the spatial distribution of groundwater table depths for different alternatives. In present situation, most area with groundwater depth less than 1.0 m was in the northwest of Zhangye city. Most area at the flood plain had depth to groundwater close to or less than 5 m. Application of those water alternatives increased the area with depths to groundwater less than 5 m from 16.8% to 22.7%, 19.7% and 18.9%, which means the alternatives led to a reduction of groundwater use. Application of alternative 2 and 3 resulted in decrease of the area with depths less than 1.0 m. This implied the alternatives could reduce groundwater evaporation and thus were helpful to salinity control.

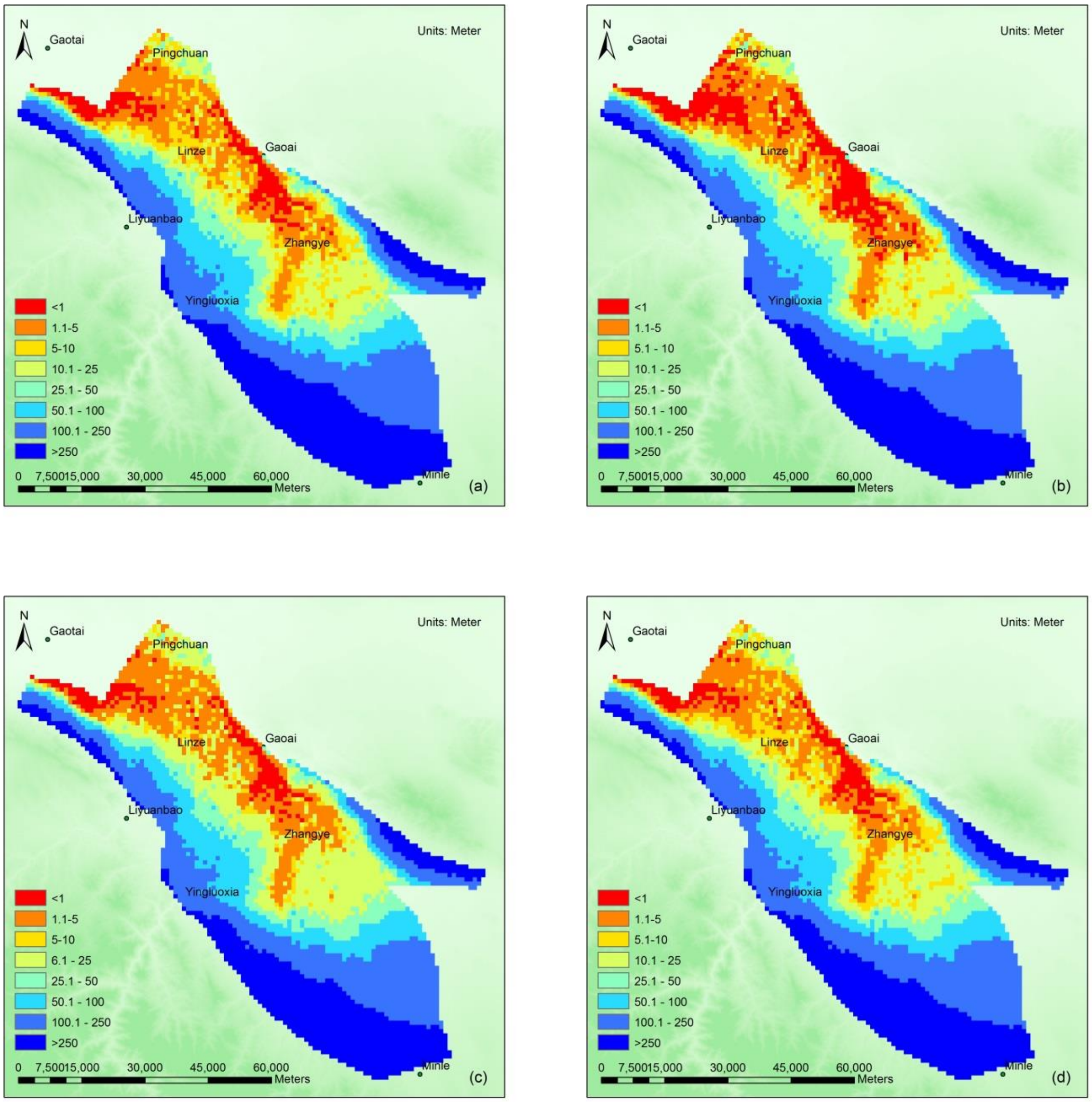


Figure 3.13. Simulated depth to groundwater for unconfined aquifer, where (a), (b), (c) and (d) are corresponding to the simulation of actual, alternative 1, 2 and 3, respectively. (Units: m)

6.Conclusions

In this study, an integrated three-dimensional groundwater-surface water model using GSFLOW have been developed for the Zhangye Basin including a steady state model simulating the flow regime in 1999 as a representative flow system pre-HWDP and a transient model simulating the flow field from 2000 to 2010. The model has been reasonably calibrated by first running PRMS and MODFLOW-2005 models separately, and then followed by the calibration of the integrated GSFLOW model. Model performance is very good, its results are consistent with observed data.

The output of the integrated model illustrates the temporal and special variation pattern of groundwater table, provides estimates of water budget and flow dynamics data of the Zhangye basin. The model shows a detailed water storage change tendencies and their relationship with each inflow and outflow. Cell by cell flow data could be used to analyze fluxes between the soil zone and the unsaturated and saturated zones. More importantly, this study demonstrated the applicability of integrated models of a basin-scale in characterizing the GWSW interaction, reproducing the flow system, and supporting sustainable water resources management, accounting for the effects of climate change (e.g., precipitation and temperature fluctuation) and human activities (e.g., Heihe Water Diversion Project) in arid inland river basins. The model has been further developed to evaluate the implementation of HWDP and analyze the irrigation management schemes.

Although this study only brought up certain scenarios into the system to pursue its capability of solving actual water issues, the approach is applicable to assess other water problems and management options. With additional data, (e.g. crop type, farm-channels, farm-wells, crop structure and distribution etc.) Models at the field level like Farm Process (FMP)

(Mir and Quadri 2009, Schmid and Hanson 2009) could be used to dynamically estimate supply-and-demand components of irrigation water in future. Simulation results improved our understanding of the hydrological cycle even the model was built on limited data, thus, it is recommended that follow-up work be carried out to collect additional data to support the modeling.

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CHAPTER 4 DECISION SUPPORT WITH BAYESIAN NETWORK AND INTEGRATED GROUNDWATER-SURFACE WATER FLOW MODELING

Abstract

Like other inland river basins in arid and semi-arid northwest China, the Zhangye Basin, as one of the most important agricultural bases of China, faces severe problems of water scarcity and ecological deterioration. Decision makers need management plans to address climate changes and rising water conflicts, in the face of substantial uncertainty. Advances in hydrological process models and computational statistics have made the Bayesian network (BN) coupled with an integrated groundwater-surface water model a valuable tool for this purpose. The chapter presents an efficient decision making tool, taking into consideration all the relevant complexities and interactions in different water resource components, to improve the water resources management solutions for the Zhangye basin. On the basis of data collection and data mining, incorporated with integrated hydrological conceptual models and numerical models, and accounting for the effects of climate change and human activities, a BN has been developed and calibrated by K-fold cross validation based on the observed data and outputs of the integrated groundwater-surface water flow model. The BN trained captures the important hydrological cycle characteristics and uncertainty of related factors to produce optimal management solutions. The concepts and approaches of this study are applicable to inform decision making in both Zhangye and elsewhere.

1.Introduction

Water is essential to human substance and ecological system. Because of global climate change and the increasing intensity of human activity, water scarcity becomes an urgent issue globally, especially in arid and semi-arid regions (Grafton et al. 2012, Konikow and Kendy 2005). There is an increasing need for water management advice that covers various policies and environment uncertainties (Comas and Poch 2010). Decision Support Systems (DDS) and process model are two main approaches for forecasting with uncertainty (Molina et al. 2013).

In the study, we described DSS as "interactive Computer-based systems that help decision makers to solve unstructured problems using data and models" (Sprague Jr and Carlson 1982). A Decision Support System (DSS) is considered to be an efficient tool for handling water crisis and facilitating the decision making processes. (Mir and Quadri 2009). The DSS was first built in the 1960s in studies of computer sciences (Keen and Morton 1978). It was defined and used in various ways depending upon the author's point of view (Power 2002) , including model-driven, communication-drive, data-driven, document-driven and knowledge-driven systems (Liao 2005, Mir and Quadri 2009).

The DSSs have proven to be a useful tool for integrated water resources management (Comas and Poch 2010, Fassio et al. 2005, Froukh 2001, Guariso et al. 1985, Makropoulos et al. 2008, Recio et al. 2005, Simon et al. 2004, Sophocleous and Ma 1998, Watkins and McKinney 1995, Zhang et al. 2011a) ranging from environmental crisis (Monte 2011, Sophocleous and Ma 1998, Uricchio et al. 2004), water resources planning (Andreu et al. 1996, Jamieson and Fedra 1996), water policies (Bazzani 2005, Fassio et al. 2005, Recio et al. 2005), economic and ecological impacts (Zwarts et al. 2006) and sustainable management (Giupponi et al. 2004).

The development of integrating Expert Systems (ESs) and Geographic Information Systems (GISs) together with simulation models (SM) in a decision support systems (DSS) framework to solve complex environmental problems is facilitated by the new advancements of computer technologies (Lukasheh et al. 2001).

Process models, on the other hand, have the ability to incorporate exhaustive natural system details(Devia et al. 2015, Kour et al. 2016). Fully distributed hydrogeological process models, such as GSFLOW (Markstrom et al. 2008), MIKESHE (Graham and Butts 2005), Hydrogeosphere (Brunner and Simmons 2012)are widely used to help understanding the water cycle.

In our case, the integrated groundwater-surface water model represent all the important aspects of the hydrological process. However, Process models are often difficult to develop, computationally expensive (Wu et al. 2015). They suffer from uncertainty of input parameters and nonconvergency problems. A DDS with sound support of process model, but visualized, simple and fast, easier to manipulate for decision makers is needed. This paper, therefore, introduced the use of a Bayesian network (BN) to emulate the original process model, propagating the uncertainties of input variables, including hydrological parameters and decision factors.

The Zhangye Basin is located in the arid region in northwest China, which refers to one of the most important agricultural bases for the country. Like other inland river basins in arid and semi-arid northwest China, the Zhangye Basin faces severe problems of water scarcity and ecological deterioration (Cheng et al. 2006). Therefore, an integrated water management is necessary to consider all the aspects related to water resources in their complexity and interaction. Many efforts have been made recently to study the local water management. Chen et al. investigated the water supply and demand situation in the Heihe River Basin and oriented water management approach in the irrigated aspect (Chen et al. 2005). Cheng et.al researched issues of water, ecology and environment on hydrological aspects in the Heihe River Basin (Xiao and Cheng 2006), and brought up the idea of water-saving eco-agriculture and integrated water resources management, which was supported by their eco-hydrological observational experiments and integrated eco-water management research at the watershed scale (Xiao et al. 2008). However, a sound DSS system is needed for further studies.

This study developed a BN model to bridging the integrated flow model for decision support of water resources management in the Zhangye Basin. On the basis of data collection and data mining, training with the extracted samples from observations and integrated hydrological model, the BN has been developed and validated. The trained BN model provides an integrated forecasting tool considering important hydrological cycle characteristics under uncertainty.

2.Study Area

The Zhangye Basin occupies an area of 5000 km^2 in northwest China. It is bordered on the north by Beishan Mountains, on the south by Qilian Mountains, on the east by the Mingye Basin and on the west by the Jiuquan Basin (Figure 4.1). The Zhangye Basin is one of the agriculture base in China. Farmlands and desert are dominated landscape in the basin. The average annual precipitation in the Zhangye Basin is about 170mm, mainly in June to September. The average annual potential evaporation rate is 1600mm (Wang et al. 2011, Wen et al. 2007).

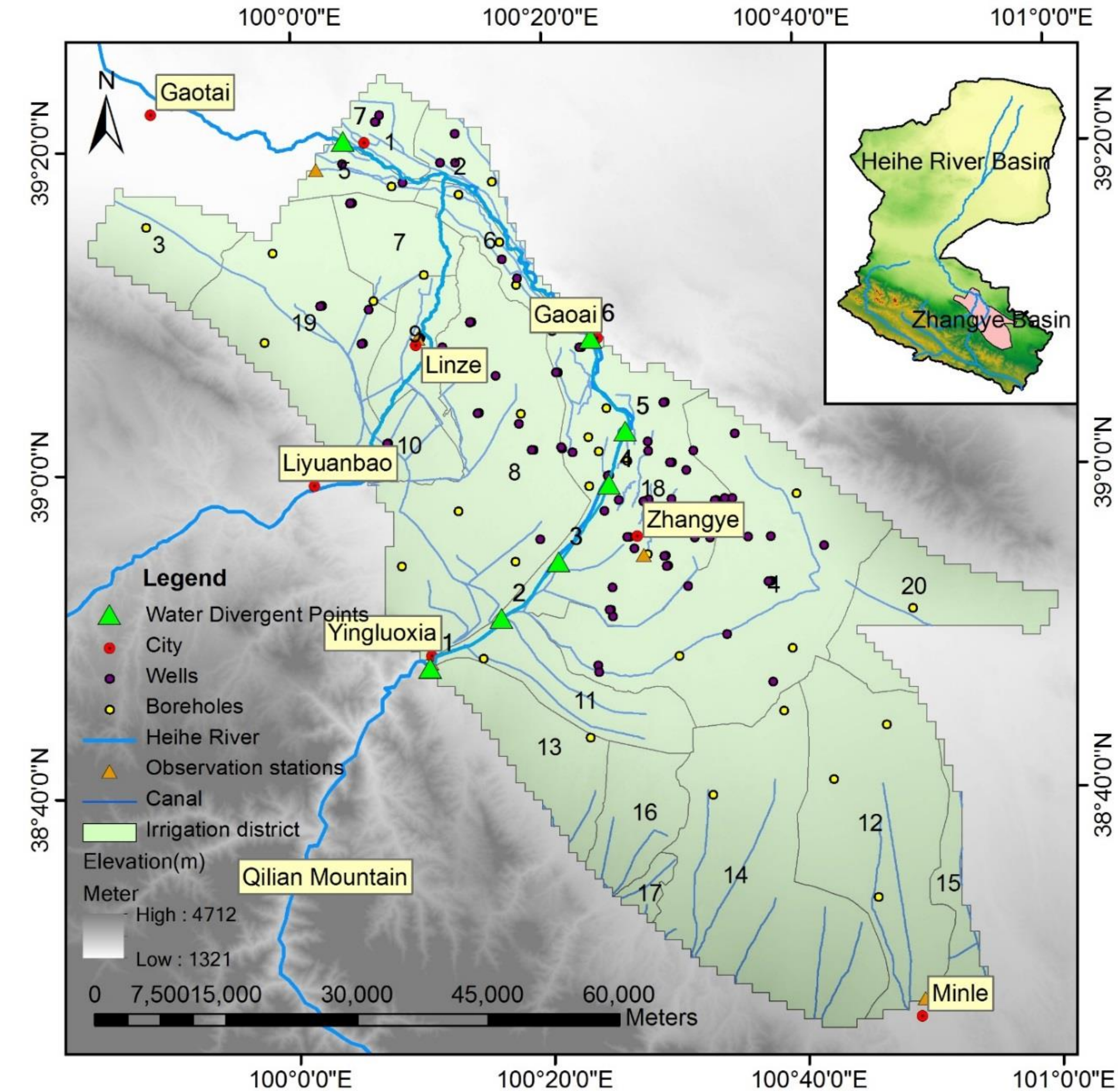

Figure 4.1. Site location and modeling domain, depicting irrigation districts and water divergent points in the Zhangye Basin.

Agriculture is the dominant activity in the Zhangye Basin. About 71% of the total available water resource volume is consumed by irrigation (Chen et al. 2005). The agricultural water consumption has gradually increased due to population growth and local economic development, which consequently leaded to the groundwater overexploitation. Thus, the management of agriculture water is important in water resources management. The basin was divided into 20 irrigation districts (Figure 4.1). Additionally, global climate change and the implementation of the Heihe Water Diversion Project (HWDP) results in a more complicated situation for the hydrogeological system in the basin.

3.Integrated Groundwater-surface Water Flow Model

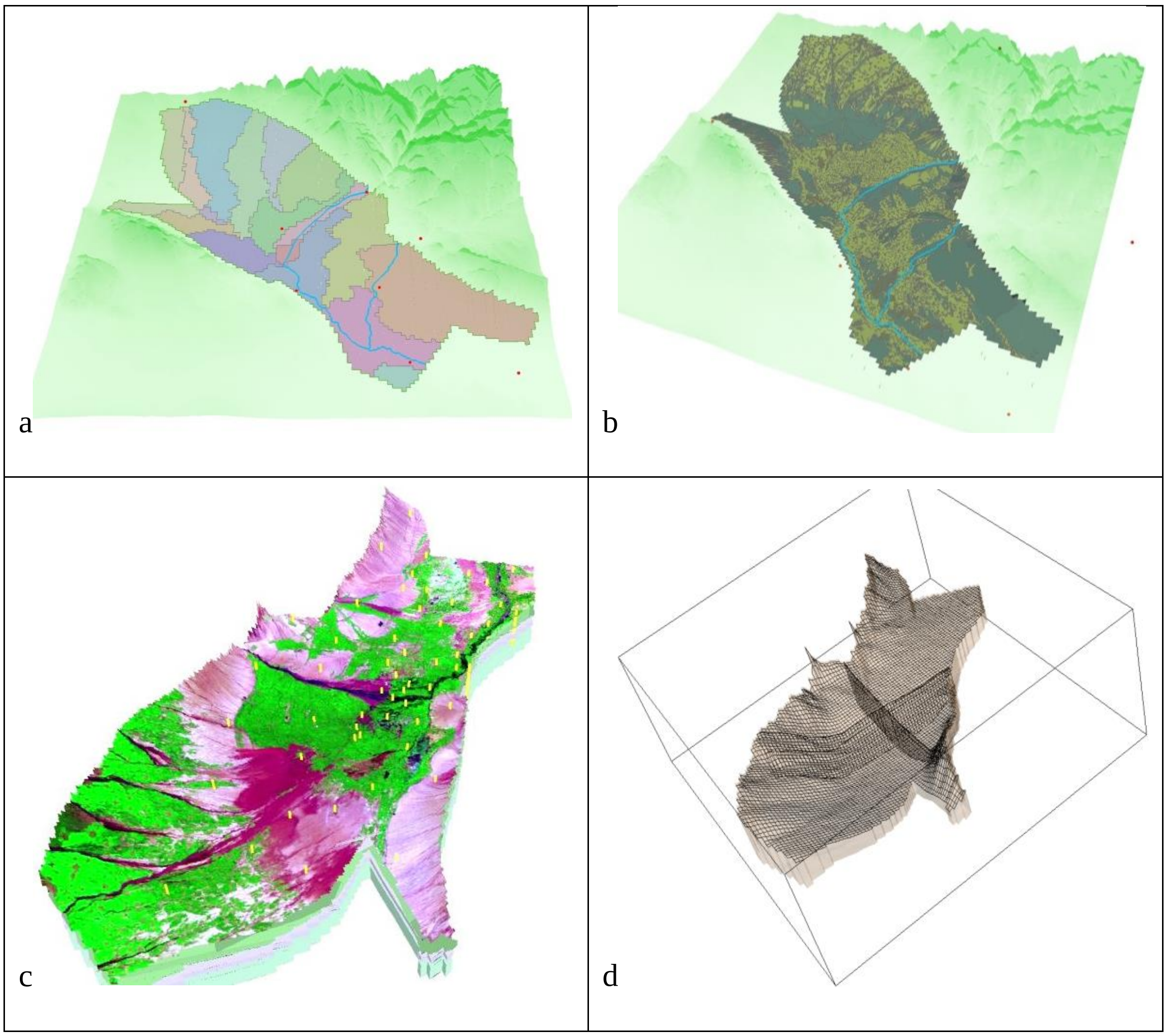

Figure 4.2. Construction of integrated Groundwater-surface water modeling (GSFLOW). (a) DEM reconditioning and generation of HRUs for PRMS, (b) generation of HRU Parameters (c) 3D hydrostratigraphy model, (d) MODFLOW grids.

In previous chapters, an integrated 3D groundwater-surface water model was built for the Zhangye Basin using GSFLOW for both pre-HWDP (1999) and during the implementation of HWDP (2000-2010), as showing in (Figure 4.2), to evaluate the hydrological response to climate change and water diversion. The model was constructed by using geologic and hydrological data to repent the actual physical processes.

The model calibration was done by first running PRMS and MODFLOW-2005 models separately, and then followed by the calibration of the integrated GSFLOW model. It was well calibrated to observations of daily streamflow and groundwater levels data. The output of the integrated model illustrates the temporal and special variation pattern of groundwater table, provides estimates of water budget and flow dynamics data of the Zhangye basin. The model also shows a detailed water storage change tendencies and their relationship with each inflow and outflow. More details about the integrated model setup, calibration, and results can be found in previous chapters.

4.Bayesian Network Model

4.1 Introduction to BN

A Bayesian network (BN) is an annotated probabilistic directed acyclic graphical(DAG) model, consists of nodes and edges (arcs or links) (Korb and Nicholson 2010). Nodes represent states of parameters or variables, edges connect pairs of nodes, represent the conditional dependencies between nodes. We consider n random variables X_1, X_2, …, X_n, and X_j ($1\leq j\leq n$) of the graph is associated to the X_j variables. Then the BN graph represents the joint probability distribution of the set of variables, if:

$$P(X_1, X_2, \dots, X_n) = \prod_{j=1}^{n} P\left(X_j \middle| parents(X_j)\right) \tag{4.1}$$

where: Parents(X_j)donates the set of all variables X_i (1≤ i≤n), such that there is an arc from node i to node j in the DAG. Once the DAG is specified, then condition probability table (CPT) can be used to quantify the relationships between connected nodes. The BN can be used to perform diagnostic reasoning, predictive reasoning, and intercausal reasoning (Andrieu et al. 2003). BN has been widely used in interactive decision support fields on groundwater systems (Fienen et al. 2013, Henriksen et al. 2012, Molina et al. 2013), but its applications incorporated with integrated GWSW have not been reported.

4.2 Frame Work

Establishing a BN model requires the identification of the water problems, configuration of different scenarios and their ultimate impact on human activities and the environment. Figure 4.3 is a flowchart shows how to build a BN model.

1. Define the object, split the object into practical elements, and identify a number of aspects or attributes (variables) that characterize the object.
2. Run the GSFLOW model, derive a collection of training data from observations and integrated model outputs.
3. Build the graphical structure of BN model through manually constructing based on expert knowledge and machine learning from prepared datasets, determine the prior probabilities.
4. Run the BN model, calculated probabilities and the likelihood. The model can be validated with extra data and if it does not suit well, then return to step one and adjust variable and re-exam their connections, and retrain the model.

5. Explain the validated model, use BN inferencing to perform prediction under difference probability conditions to provide and insight of decisions.

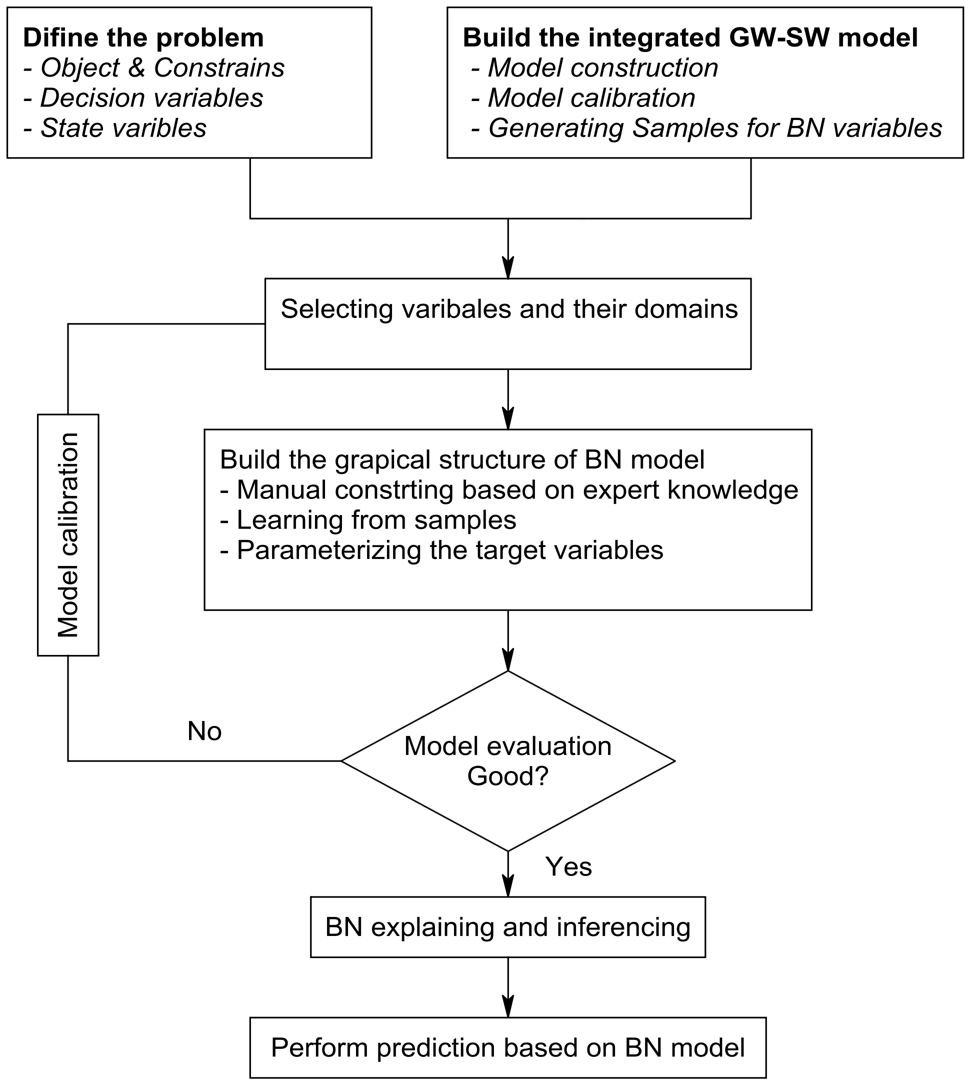

Figure 4.3. Framework of bridging flow model and decision support with the Bayesian network.

4.3 Generation of the Bayesian Network

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987).

Originally, sustainability in the context of water resources management simple meant meeting human demands by nature supplies. While as the demand for human consumption, agriculture and industry grew, the water resources became insufficient. For this reason, to balance supply and demand, to allocate resources and maintain storage became the main content of sustainable development. The objectives of this study were to design a BN model that could be used to assess the effects of climate change and human activities on water balance and dynamic system, consequently, to support the decision making for sustainable water resources management. In the BN, climate change and human activities are considered as state variables and control variables in form of precipitation, evapotranspiration (ET), streamflow rate, canal discharge and pumping rate.

The water cycle for the study area then can be expressed as follows:

$$\Delta \mathrm{S} = \mathrm{Precipitation} - \mathrm{ET} + \sum \mathrm{SW} + \sum \mathrm{GW} \tag{4.2}$$

where ΔS is the total storage change, $\sum SW$and $\sum GW$ represent the sum of boundary flow of surface water and groundwater. To be more specific,

$$\sum \mathrm{SW} = \mathrm{Stream\ inflow} - \mathrm{Stream\ outflow} - \mathrm{Canal\ discharge} \tag{4.3}$$

$$\sum \mathrm{GW} = \mathrm{Groundwater\ inflow} - \mathrm{Groundwater\ outflow} - \mathrm{Pumping} \tag{4.4}$$

where the stream and groundwater inflow represent the surface water and groundwater inputs from the upper Heihe River Basin, stream outflow contains the output of the Heihe River to its lower reach, the groundwater outflow to the lower reach of the Heihe River Basin is 0, the canal discharge and pumping add up to the total water use of the study area, its 80% is irrigation (Chen et al. 2005). In the other world, according to the characteristics of the local hydrological cycle, our object of sustainable development can be expressed as to maintain storage (minimize ΔS) when the other variables in equation 4.2 change. The variables can be classified into three categories: state variables as precipitation and stream inflow; controlled variables as canal discharge and pumping; and target variables as storage change and stream outflow. The rest of variables are implicitly given as the above are determined from the flow model.

4.4 Bayesian Network Structure

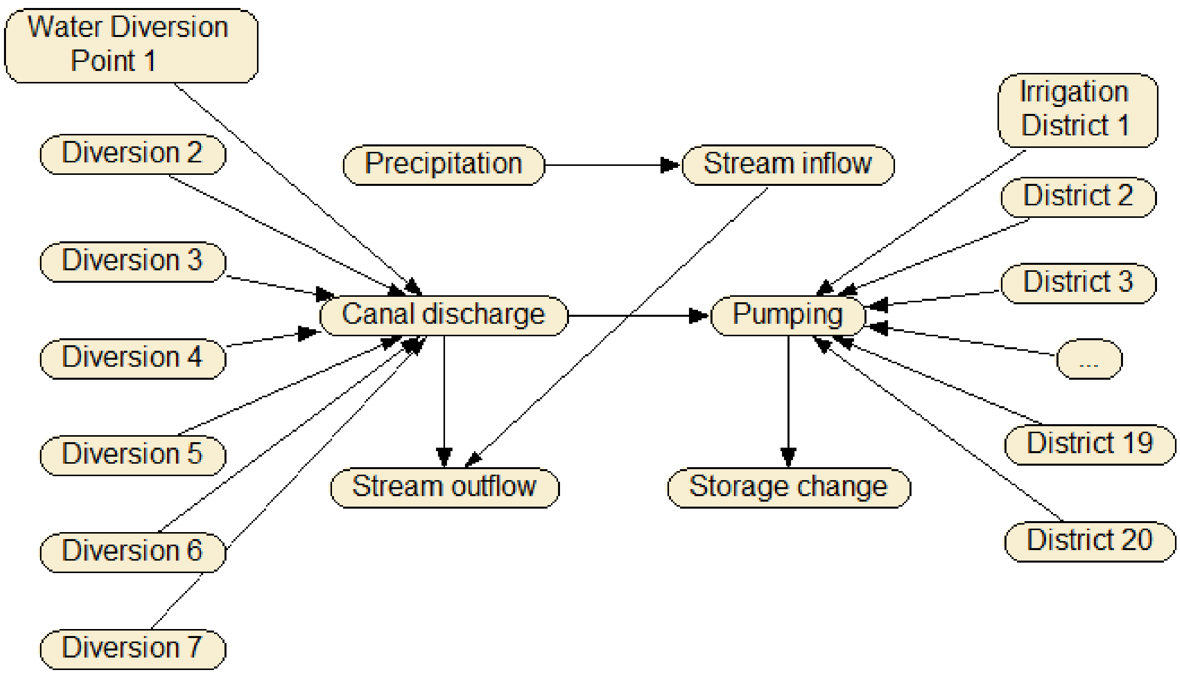

Figure 4.4. Layout of the Zhangye Basin Bayesian network. Nodes (boxes) indicate variables, edges (arrows) indicate general causal dependencies.

The structure of the BN model was built based on understanding of the local hydrological cycle. All the variable in equation 4.2 are either directly connected or indirectly dependent. They can be fully connected and requires as CPT entries, this kind of BN offers no computational or representational advantage. A compact BN model is more tractable. The model we developed can represent independencies and causal dependencies of variables explicitly. The elicitation of the structure are determined by the objectives with the idea of conditional independencies. D-separation can be applied to help finalize the BN structure. Figure 4.4 shows the layout of the dependencies among those variables.

Assembling the observation data and outcomes of the integrated flow model associated to our elicited variables results in our samples to build conditional probability tables (CPTs). Probabilistic equations are developed through statistical analyses. The CPTs are calculated by essentially using Bayes' Theorem,

$$P(O_i|X_i) = \frac{P(O_i)P(X_i|O_i)}{P(X_i)} \tag{4.5}$$

Where X_i represents the variables and $O_i$represents the outcomes. In plain English the above equation 4.5 means that,

$$\text{Posterior} = \frac{Prior \times likelihood}{evidence} \tag{4.6}$$

The precipitation comes from observed data, the canal discharge, pumping rate, storage change and stream outflow refer to outcomes of the calibrated flow model. The BN model was then trained by prepared CPTs (Figure 4.5). The full joint probability of the graph was updated by considering the entire schemes (Figure 4.6). It now represent the posterior probability. To our knowledge, the precipitation is an important independent inputs.

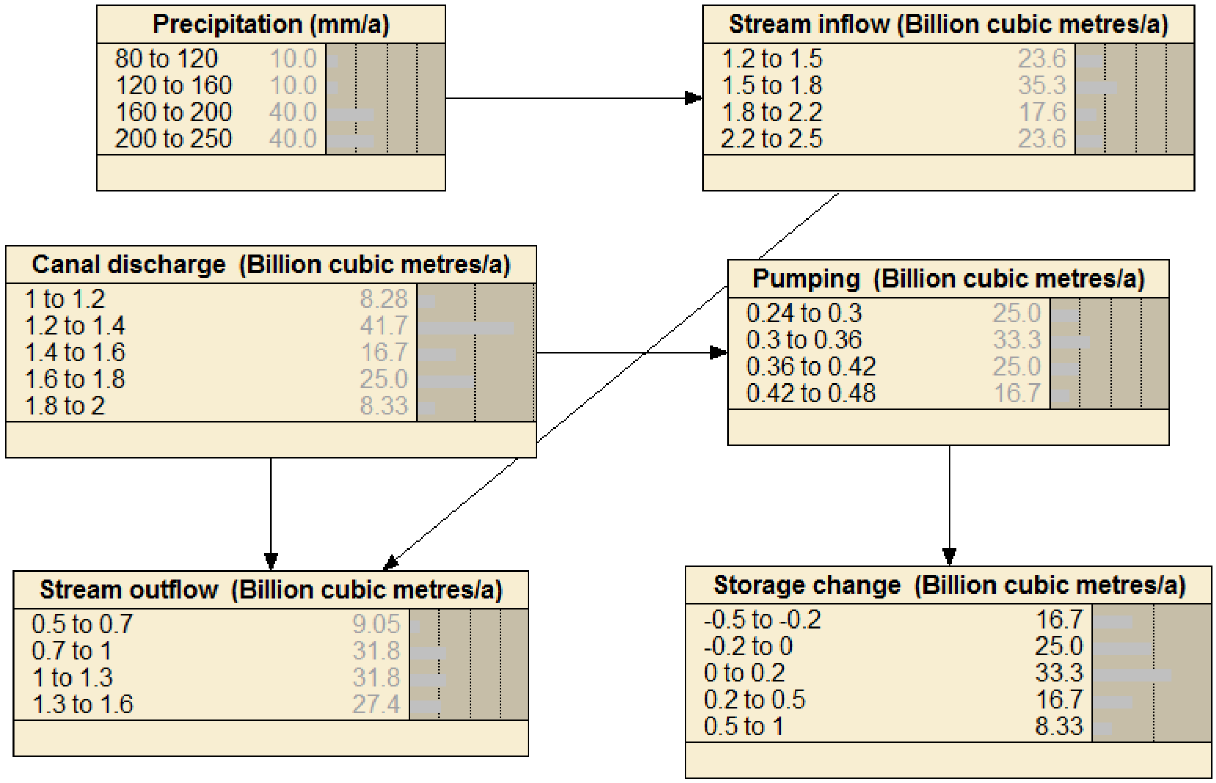

Figure 4.5. Prior probabilities for the Zhangye Basin Bayesian network. Stream outflow and storage change are response variables to the other bins corresponding to inputs. Numbers on the left of boxes indicates bin boundaries, numbers on the right show prior probabilities, and the horizontal black bars graphically show probabilities.

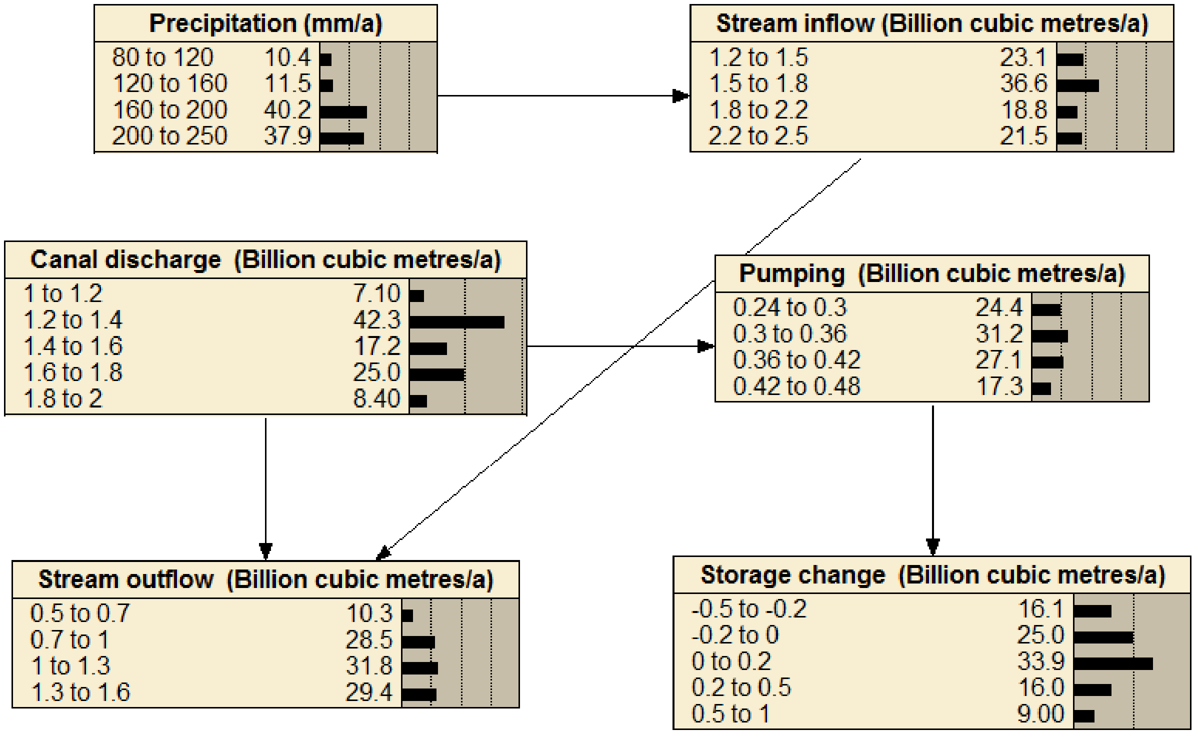

Figure 4.6. Updated probabilities for the Zhangye Basin Bayesian network. All probabilities in the BN are updated by using Bayes' theorem to bins of all variables, including the target variables. After the updates, the probabilities in the BN reflect the combinations of parameters that are most closely associated with the inputs.

4.5 Model Calibration and Validation

The relationship between the value of precipitation and stream inflow was statistically calibrated using regression analyses of observation data. The relationship of those two nodes and the others are calibrated against subsets of data generated from the outcomes of integrated flow model. The objective of calibration and validation is that the BN model well characterizes the existing data, and not overfits. In another word, the model was calibrated through maximizing the likelihood and the predictive strength. As the probability is extremely small, the log-likelihood is preferred.

$X_1, X_2, \dots, X_n$ have joint density denoted:

$$\int_{\theta} (x_1, x_2, \dots, x_n) = \int (x_1, x_2, \dots, x_n | \theta) \tag{4.7}$$

Given observed values (in this study observed values refer to sample data obtained both from observation and the flow model outputs)$X_1 = x_1, X_2 = x_2, \dots, X_n = x_n$, and the distribution is discrete, the log-likelihood will thus be:

$$l(\theta) = \sum_{i=1}^{n} log\big(P(x_i|\theta)\big) \tag{4.8}$$

K-cross validation has been chosen since it is efficient both with data and computational time for our validation purpose. It randomly divides the data set in to K subsets, and returns the average error over the K subsets. The subsets are partitioned into retained subsets and left-out subsets. The BN model is trained on the data in retained subsets and is tested on the data in left-out subsets. In this study, The BN network reached 84.9% accuracy using tenfold-cross validation (Table 4.1).

Table 4.1. Summary of the log-likelihood evaluation and K-fold cross validation test of the Zhangye Bayesian network.

Variables	**Train sample size**	**Test sample size**	**Log-likelihood**	**Accuracy (%)**
Precipitation	3288	365	319	90.5
Steam inflow	3288	365	286	89.4
Canal discharge	3942	438	465	91.7
Pumping	3942	438	137	85.1
Stream outflow	3942	438	892	94.2
Storage change	3942	438	93	84.9

5.Results and Discussion

The Zhangye BN model is well suited to complex hydrological problems involving large numbers of interrelated uncertain variables. Unlike the flow model, the variables in a BN model are cognitively meaningful and directly interpretable. The Zhangye BN model employs logically coherent methods for managing uncertainties of inputs and updating conclusions to reflect new evidence or updating the evidences for hypotheses of interest. In other words, it combines inputs from all sources to produce better knowledge of unknowns.

5.1 Results and Comparison with the Flow Model

The method described in calibration and validation section provide a tool to evaluate the model performance. Table 4.1 shows the size of training data and testing data we used to evaluate the model. Both summed log-likelihood and accuracy of variables have been calculated to emphasis the fitness of the model.

Figure 4.7 shows a comparison of the BN simulated and observed values. The 45-degree solid line indicates one-to-one correspondence between observed stream flux and the BN modeled results. All dots (summarized stream flux) are close to the solid line. It means that the BN model well captures and reproduces the hydrological issues in the Zhangye Basin.

The prior probabilities show us the exactly input values and probabilities of all variables. The summed annual precipitation rate are most in the range of 160-250 mm. Annual stream inflow has a probability 76.5% to be larger than 1.5 billion m^3. Meanwhile, the annual canal discharge and pumping represent the water consumption of the Zhangye Basin, which are mostly in the range of 1.2-1.8 billion m^3, and 0.3-0.42 billion m^3.

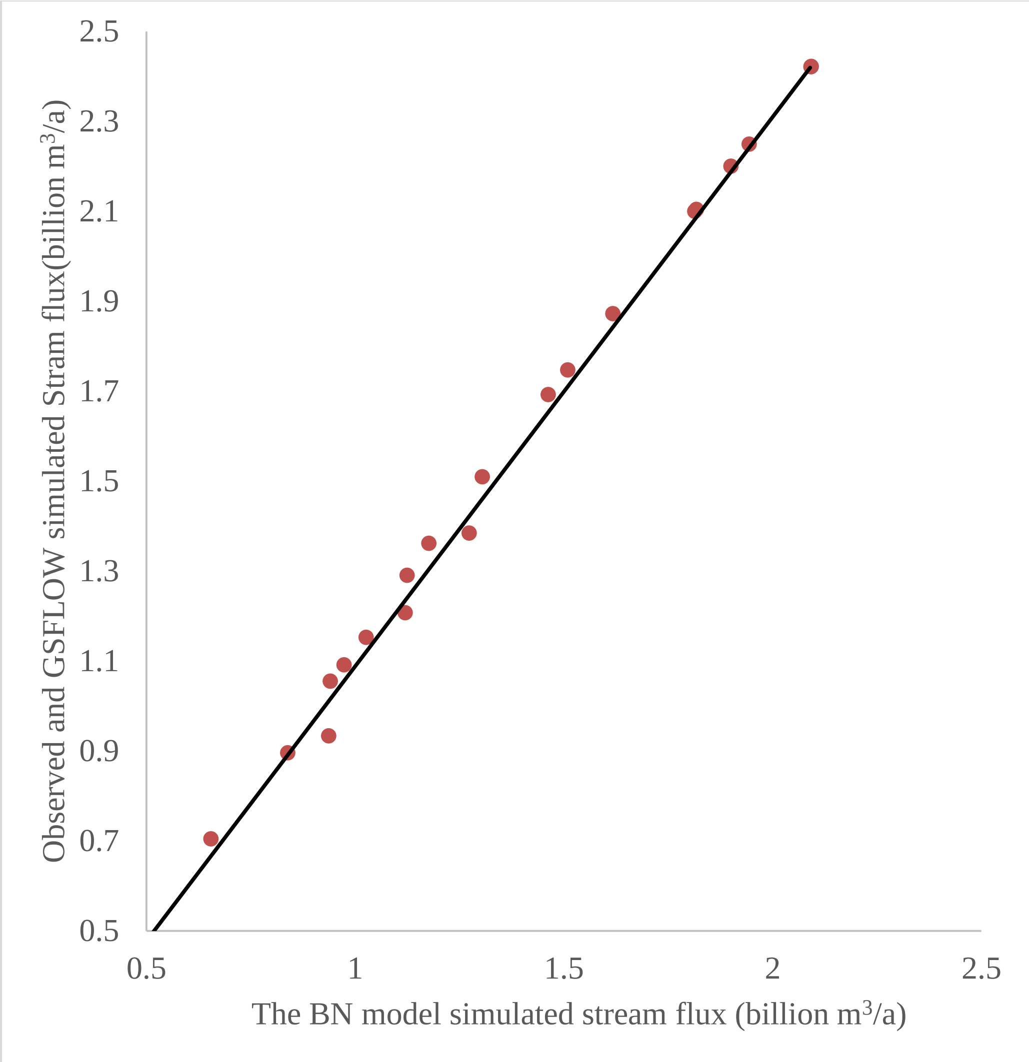

Figure 4.7. Comparison of the BN model simulated stream flux against observed inflow and the GSFLOW model simulated outflow (Summarized annual data).

It is worth pointing out that, unlike the integrate flow model or a fully connected BN model, the model in our study has explicitly express conditional independencies in probability distributions of all variables. The precipitation has a direct influences on the stream inflow. Despite the influence of precipitation and stream inflow on it, the canal discharge is under directly control of water demand of irrigation and urban consumptions. One of our major interests is the annual storage change. The BN model shows pumping affects storage change directly, because pumping is a control variable as well as canal discharge. That means, the model does not only consider the hydrological process, in which storage change is affected by surface water recharge and groundwater discharge, but also take human action with uncertainties as a major factor.

5.2 Responses to Extreme Events

Once the BN model is calibrated and validated, it can be used in both active and proactive ways. In reactive way, the BN model can handle the external uncertainties of policy making through control variables, such as canal discharge and pumping, and it can process uncertainties of climate challenges through state variables, such as precipitation and stream inflow. The model processed those uncertainties as specific configuration of inputs and present the outcomes. We applied 2 extreme events generated based on the historical distribution to the BN model, it updated and provided us an estimated of associated uncertainties.

Here we consider the climate extreme event as following: a), the greatest precipitation and b) the greatest precipitation with the greatest stream inflow. Figure 4.8a and Figure 4.8b represent results of those two extreme events. Compare to original model (E0), Figure 4.8a show that, in the study area, increased precipitation leads to higher stream inflow, stream outflow, and storage, also causes lower canal discharge and slightly higher pumping, which can be explained as increased precipitation would increase river stage, leads to higher stream inflow and enhance the stream discharge to groundwater. Therefore, the stream outflow and storage both increase. However, according to the model, the precipitation has little to canal discharge and pumping.

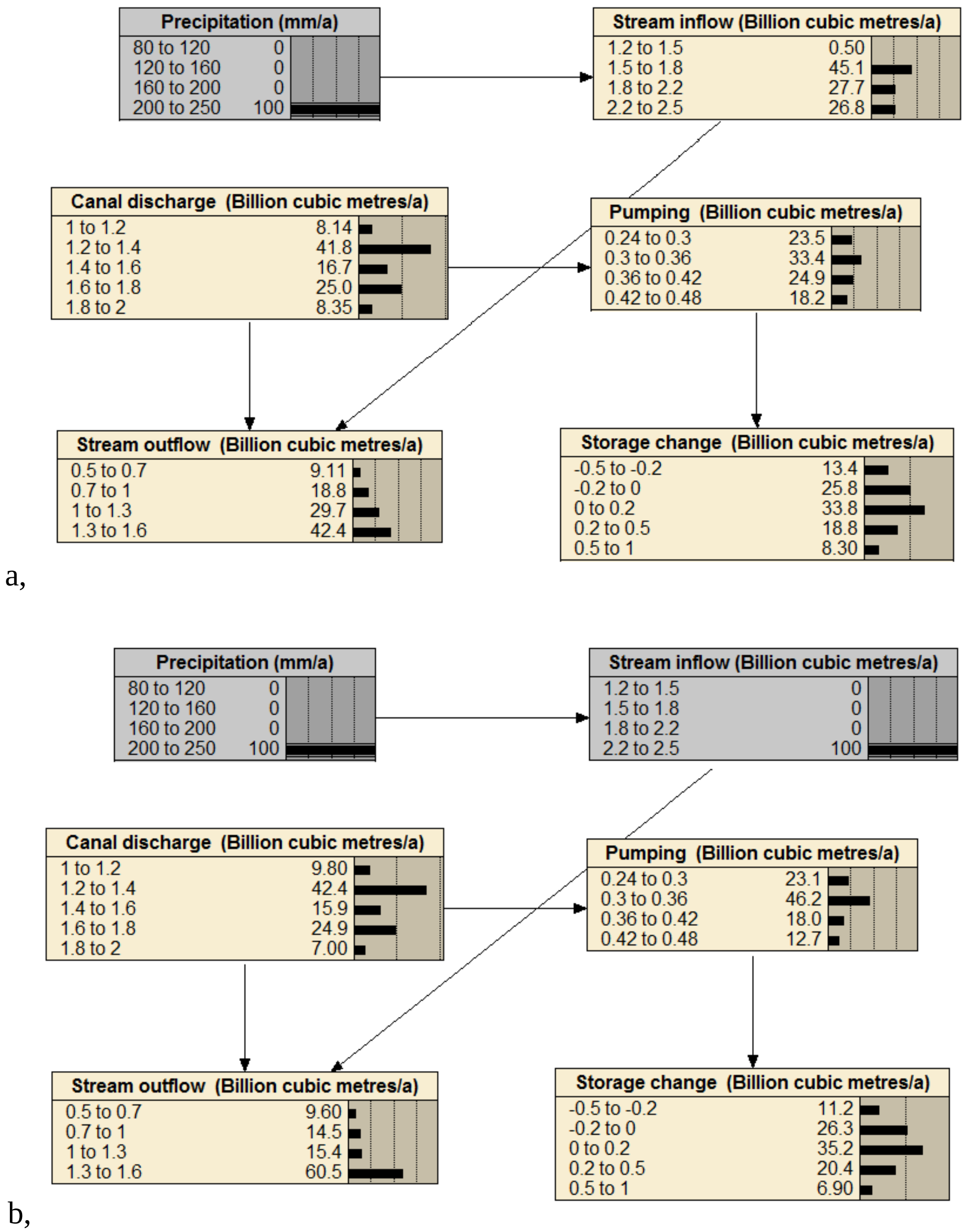

Figure 4.8. Example extreme climate events (E1 and E2) evaluation using the Zhangye Basin Bayesian network: (a) the response to E1, the greatest precipitation is evaluated and (b) the response to E2, this condition is accomplished by also selecting the greatest stream inflow.

Figure 4.8b implies that, if the increase of precipitation in the Zhangye Basin is further accompanied by the increase of stream inflow from the upper Heihe River basin, the combined impact on the stream inflow and stream outflow will be significant. However, they will partially recharge to the groundwater and thus increase the volume of the storage. It is worth mention that, without human interventions, the effects of precipitation and stream inflow on the canal discharge and pumping is fully determined by the hydrological process, and it is slightly decreased the demand of canal discharge and pumping. Figure 4.9 provides more details on the summed changes of all variables.

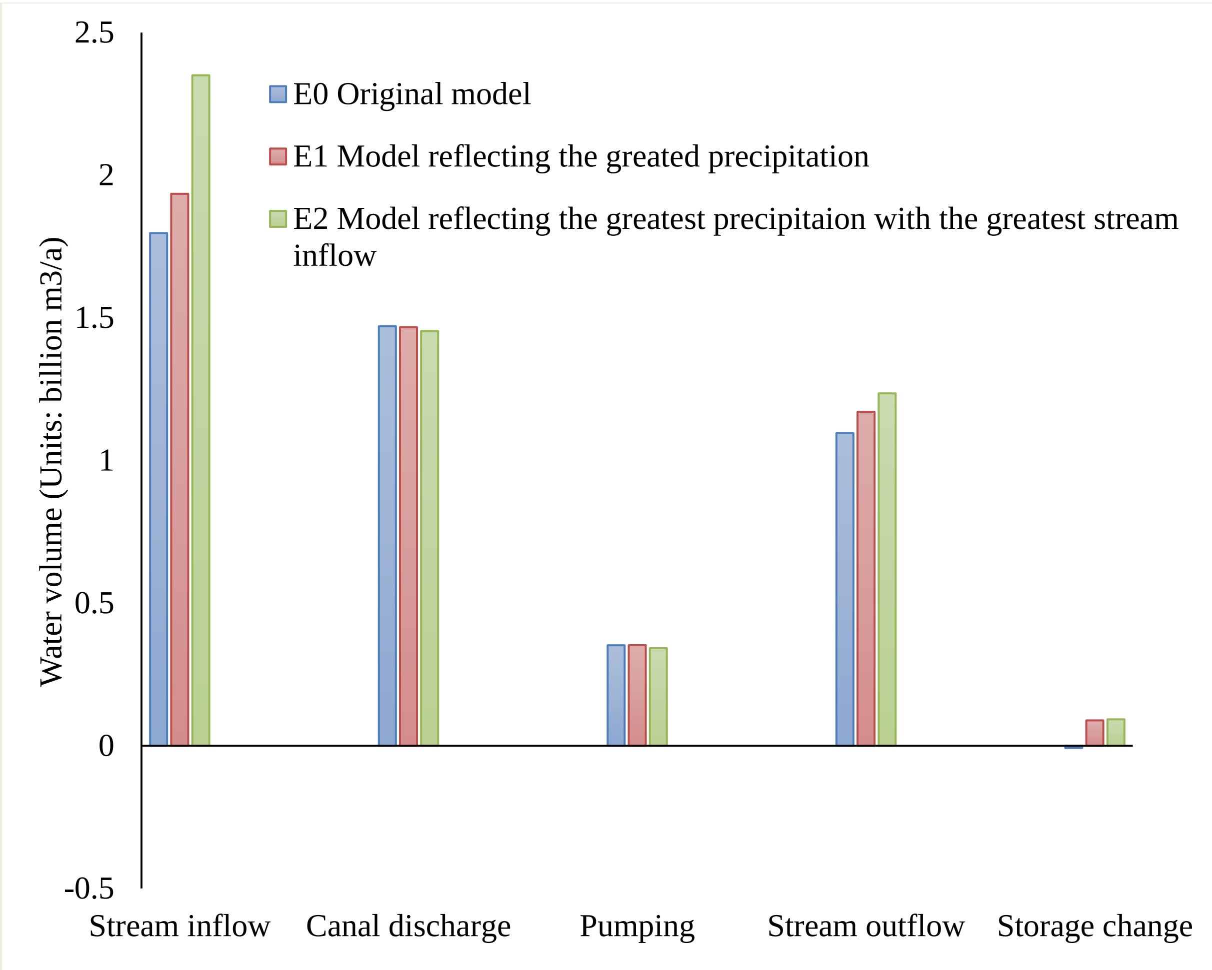

Figure 4.9. Comparison of the BN simulated results in response to climate extreme events.

Generally speaking, even under extreme climate conditions, when both precipitation and stream inflow largely increase in a reasonable range, the change of stream outflow and storage are not going to reach the highest value of their threshold. In other words, it will take a long time for the hydrological system to recover from the previous over drafting of water resources without human interventions.

5.3 Optimal Water Allocation

The Heihe Water Diversion Project (HWDP) stipulated that the middle reach deliver at least 0.95 billion cubic meters of surface water to the downstream annually when the inflow from Yingluoxia is not less than 1.58 billion m^3/a (Chang 2003) (Figure 4.10). The HWDP clearly have positive impacts on ecosystem in the lower reaches. However, the long term impacts of HWDP on water system of the Zhangye Basin in the middle reach of Heihe River had received continuous attentions from the police makers and local water authorities. Thus, the BN model was used to reveal joint effects of the HWDP, and to support the further implementation of HWDP.

Figure 4.10 shows that, during 2000-2010, when the stream inflows are low, the actual stream outflows were always lower than the HWDP requirements, and when the stream inflows are higher than 1.8 billion m^3/a, the actual outflow were greater than the HWDP requirements. To balance the HWDP requirements and its implementation, an optimal water allocation equation has been developed and used to retrain the BN model.

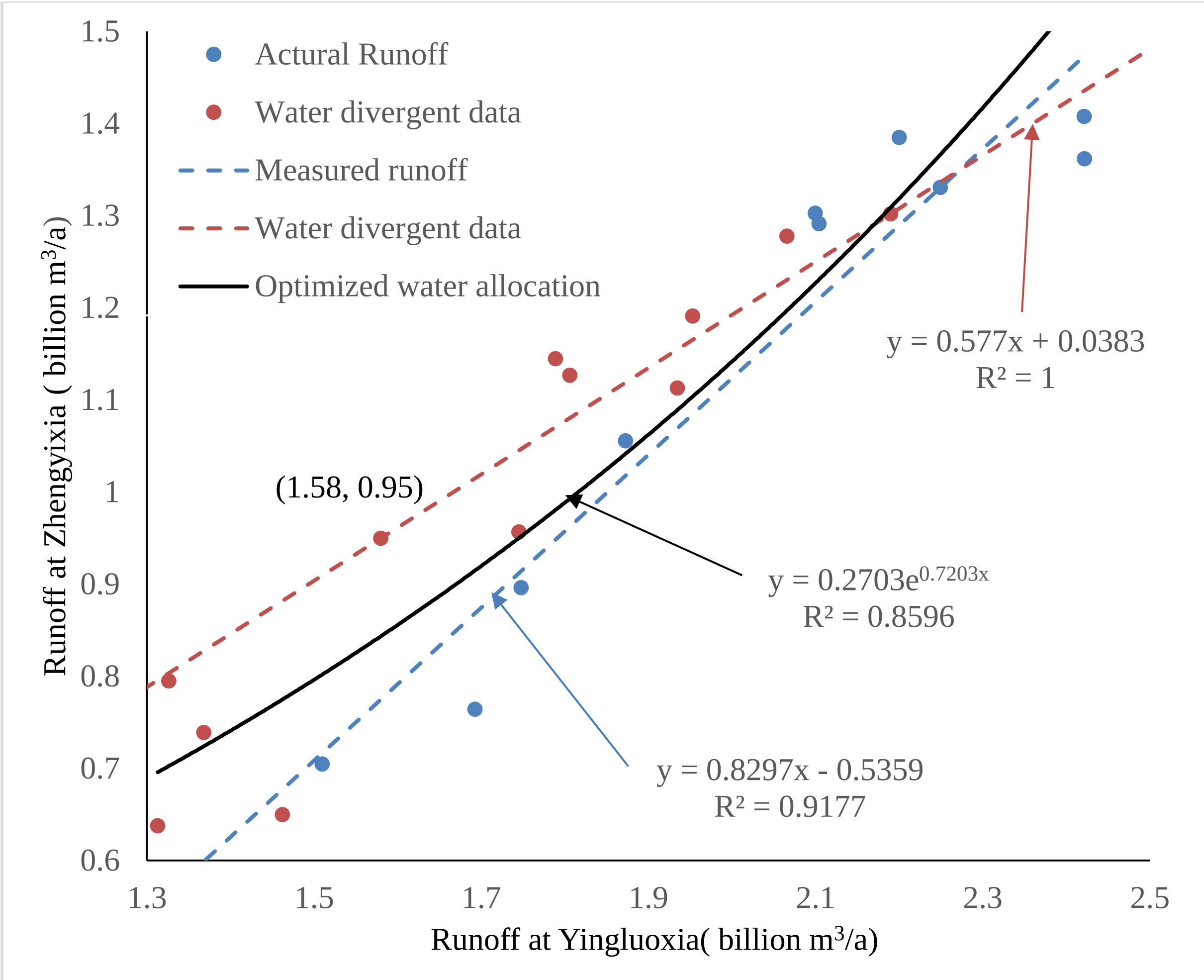

Figure 4.10. Optimized water allocation plan in the Zhangye Basin.

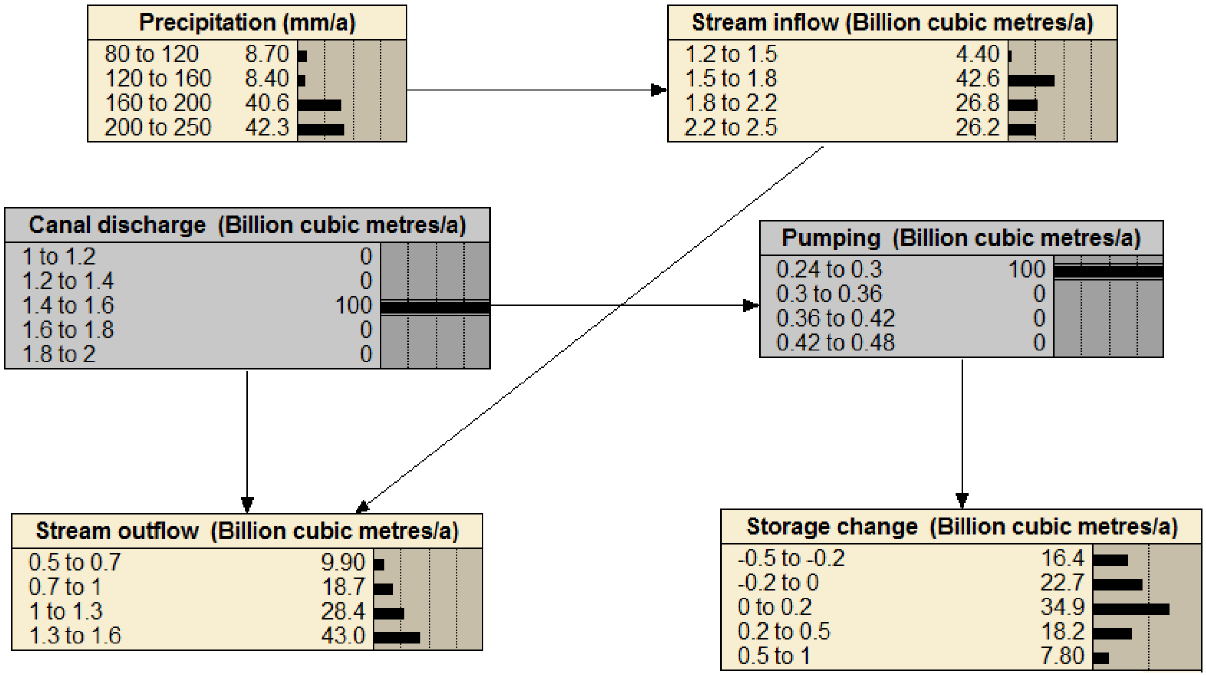

Figure 4.11. Presentation of the BN results of an optimized water allocation plan.

In the updated BN model, we set the canal discharge and pumping to be annual average values. Figure 4.11 demonstrates the predicted stream outflow and storage change with the application of optimal water allocation plan. Compare to Figure 4.6, the available outflow and storage are both greater.

6. Conclusions

A compact BN model was developed to support sustainable water resources management in the Zhangye Basin, which faces severe problems of water scarcity and ecological deterioration. The BN model has been proven to be a valuable tool in exploring and representing hydrological issues. The ability of the BN model to visually display and rapidly manipulate variables is a very useful property. The BN model represents independencies and causal dependencies of variables explicitly. It emphasizes interrelations of precipitation, canal discharge, pumping rate and stream outflow to the lower reach of the Heihe River basin.

This study demonstrates an early effort to develop a BN model (probabilistic directed graphical model) to bridging the integrated groundwater-surface water model for decision support of water resources management. The integrated process model (groundwater-surface water model) simulated the comprehensive natural hydrological processes and provided valuable data for the BN model that are unavailable from observation or via measurement. The BN model, on the other hand, can provide great flexibility in capturing the uncertainties in decision making and nature processes. It can manage uncertainty and update solutions to reflect new data, hence allowing us to get the prospective of future water allocation associated with certain scenarios. Nevertheless, this study has some limitations and deserves further future work. First, the BN model is unable to cross spatial/temporal scales in the same model. Second, BN algorithms are of non-polynomial complexity, especially when dealing with temporal reasoning.

Overall, decision support for sustainable water resources management is one of the most critical research topics. An efficiently BN model is not only a powerful tool to find an optimal solution, but also a mechanism to make the decision process more open and transparent.

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CHAPTER 5 CONCLUDING REMARKS

The immediate objective of this study was to develop a decision support system that could be used to address issues of sustainable management of water resources in the Zhangye Basin. An effective decision support tool is not only a powerful tool to find an optimal solution, but also a mechanism to make the decision process more open and transparent. This study has not only addressed this problem, but also explored a systematic approach to support decision making under uncertainty in general.

The numerical models developed in the first two papers are hydrological process models. The outcomes of these models supported progressive understanding of the hydrological cycle. The groundwater flow model presented in the first paper should be helpful in reproducing groundwater levels, examining water budgets, and providing reliable information of flow dynamics. It is necessary for the model of a regional scale hydrological study to capture the long-term characteristics, fundamental behaviors without overfitting with data. The integrated groundwater-surface water model in the second paper can be used to improve our knowledge of the hydrologic system. Its temporal and spatial accuracy in representing the field conditions can be improved beyond that based on the groundwater flow model alone. In this study, the integrated model has been developed to characterize the groundwater-surface water interaction, evaluate the implementation of the Heihe Water Diversion Project (HWDP), and analyze the irrigation schemes.

The Bayesian network (BN) model documented in the third paper can be used to manage uncertainties both in nature processes and in decision making by linking the integrated process model with statistical tools. The trained BN model represents independencies and causal dependencies of linked variables explicitly. It evaluates the hydrological responses to climate extreme events, and reveals the joint effects of the HWDP and climate uncertainties.

Our study shows that, by 2012, over 93% of the whole basin has been facing groundwater declining. The basin has continuous decrease of spring discharge and depletion of groundwater storage. The simulation shows that increases in precipitation and stream inflow have slowed down the depletion, even though under extreme climate conditions, it would take a long time for the hydrological system to recover from the previous over drafting of water resources without human interventions. More importantly, the groundwater-surface water interaction has been intensified, with could not only cause flow issues, but raise the possibilities of water quality issues in the future. Optimal water allocation plans have been developed to mitigate adverse circumstances.

This dissertation project was constrained by limited data availability. Some model parameters were based on empirical analyses and model calibration. Missing values of certain periods were filled by statistical tools. As more data become available, models should be updated in an effort to improve the calibration. It is recommended that follow-up work be carried out to collect additional data to support the modeling and improve decision support tools.