Mitigating Climate Change Impacts for Optimizing Water Productivity

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Abstract

In ecologically fragile areas with arid climate, such as the Heihe River Basin in Northwest China, sustainable social and economic development depends largely on the availability and sustainable uses of water resource. However, under the influence of the rapidly changing climate and human activities, the Heihe River Basin undergoes serious water shortage and water productivity decline. In this chapter we adopted a semi-distributed conceptual hydrological model (SWAT – Soil Water Assessment Tool) coupled with a glacier melting algorithm to investigate the sensitivity of streamflow to climatic and glacial changes in the upstream of the Heihe River Basin. The glacier mass balance was calculated at daily time-step using a distributed temperature-index melting and accumulation algorithm embedded in the SWAT model. Specifically, the model was calibrated and validated using daily streamflow data measured at Yingluoxia Hydrological Station and decadal ice volume changes derived from survey maps and remote sensing images between 1960 and 2010. This study highlights the effects of glacier melting on streamflow and their future changes in the mountainous watersheds. Further, we used improved CGE model to analyze the difference and change between different industries in middle stream of the Heihe River Basin. Simulation results indicate that industrial transformation and development of water-saving industries will also improve water productivity. Lastly, we put forward some strategies on how to mitigate climate change impacts for optimizing water productivity from three perspectives: (1) scientific research needed by scientists, (2) management and institution formulation needed by governments, and (3) water resource optimal allocation by the manager at all administrative levels.

Keywords

Water productivity · Climate change · Water yield · Sustainable development · Streamflow simulation · Water balance · Glacier melting · Snowmelt · SWAT · CGE model · Heihe River Basin

Introduction

Climate Change in Heihe River Basin

Water resource is the foremost element for production, living, and ecosystem (Fang et al. 2007); however, the rapidly changing climate coupled with population growth has aggravated water shortage at a global scale. The percentage of the world population that suffered from water shortage increased from 2% in the early 1900s to 35% in 2005 (Kummu et al. 2010). China, one of the countries in the world with the most serious water shortage, has only 2185 m^3 per capita, which is below the average level of the world (Martin-Carrasco et al. 2013). Therefore, water resource is becoming a restricted production factor of sustainable development (Yu et al. 2008). In particular, Water resource is vital connection between the economy and ecosystem for arid and semiarid areas (Rijsberman 2006). The North and Northwest China have less than 20% of available water although the total area of these places account for almost half of the whole China (Zhou et al. 2012). Therefore, the problem of water shortage is getting more and more attention worldwide (Bakker 2012). There are lots of elements affecting the water resource, and climate change, one of the main factors, has begun to have a serious effect on water availability, which will be to greater extent in the future (Bates et al. 2008; Vörösmarty et al. 2000). During the research about stress of water demand growth in agriculture, industry and urbanization, the Intergovernmental Panel on Climate Change (IPCC) (Change 2007) found that the sensitivity of semiarid and arid regions to climate change is relatively high. Hence, researchers increasingly pay close attention to the effect of climate change on water issues, including surface water and groundwater (Kim et al. 2013). It is a common sense that human activity will cause climate change and then affect water resource. The amount of usage of municipal water has increased from 200×10^8 m^3 to 4400×10^8 m^3 during the last century (Bao and Fang 2007). Climate change will increasingly be more uncertain with population increase and the intensified human activities, and consequently more serious water issues.

Heihe River Basin (HRB), the second largest inland river in China, which is located in arid region of Northwest China, has characteristics of higher rate of evaporation and smaller amount of precipitation as with other arid areas (Fig. 1). Due to the comparatively simple natural process and socioeconomic activities, HRB is an ideal experimental region, and many research works about water management, policies, environmental protection, and ecosystem service have been carried out (Cheng et al. 2014; Guo et al. 2009; Qi and Luo 2005). The typical trait of HRB is that the source of water is from the snow melt in the upper stream, major water usage and consumption of socioeconomic activities are concentrated on middle stream, and in the end the water flows into downstream for ecosystem service. Unfortunately, the irrational usage of water caused serious environmental deterioration and ecological degeneration since the 1950s (Cheng et al. 2014). However, limited water resource is not able to meet the demand of rapid increase for agricultural irrigation and manufacturing production, such as the expansion of irrigated area and the development of manufacture. As a result, large amount of water consumption in middle stream caused water shortage and severe decrease of groundwater level in the downstream in HRB (Cheng et al. 2014; Xi et al. 2010). A number of studies analyzed the hydrological process and the water problems of the HRB (Cheng et al. 2014; Ding et al. 2009; Xi et al. 2010). These research works have put forward some approaches and schemes for water management. However, some knowledge gaps on the spatial variability of water and water efficiency in the HRB ought to be stressed.

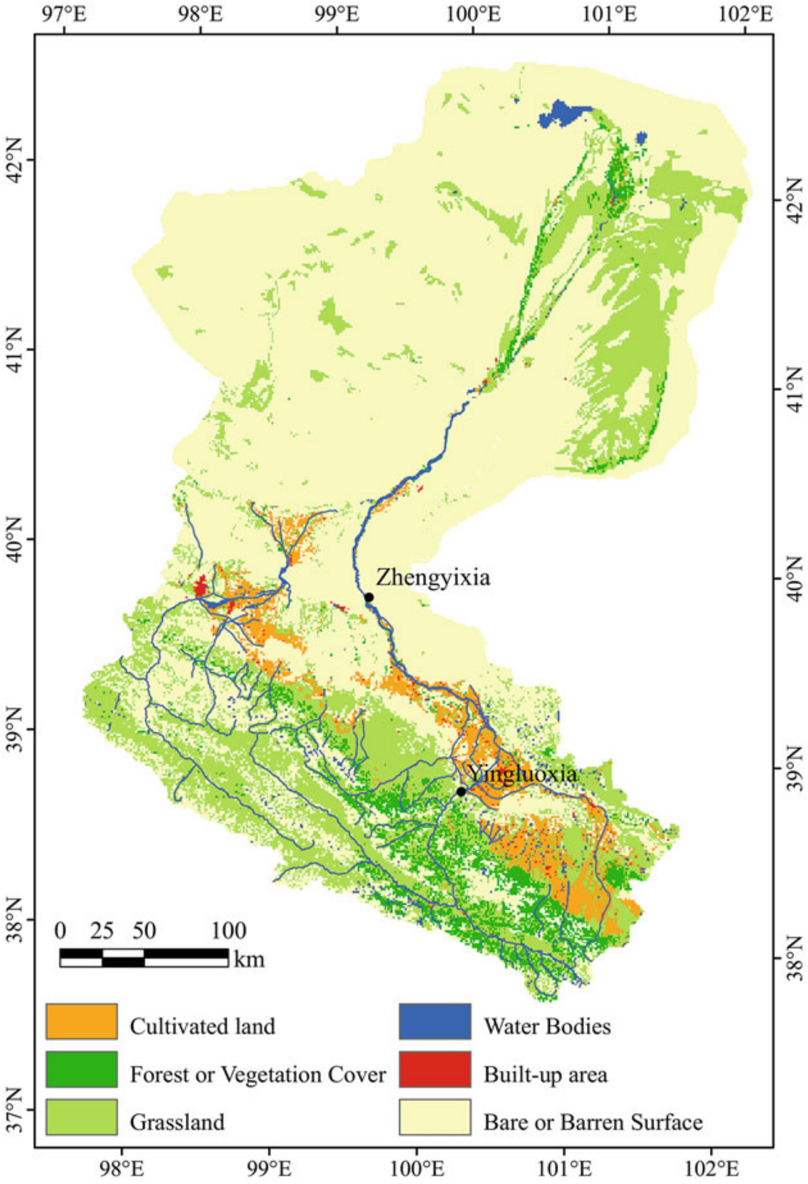

Fig. 1 Location of the Heihe River Basin

Water Productivity in Heihe River

With more and more water issues, the value of water is drawing more and more close attention, and water is changing from public goods to decisive production factor. Water productivity, the output per cubic meter water, is a proper measurement for water value. The output can be physical output, and also economic value of output. Climate change will cause water resource change, and then change water productivity. Therefore, migrating climate change impacts for optimizing water productivity is critical problem in HRB, and is necessary for water resource management.

The most direct influence on water in HRB is the streamflow variation due to climate change. Climate change will affect hydrological processes seriously; however, the degree of influence is still uncertain (Immerzeel et al. 2014). Meanwhile, snow and glacier melting, primary water resource in HRB, contributes about 30–50% of water discharge in arid areas (Viviroli and Weingartner 2004; Yin et al. 2014). It is necessary to analyze the response of glacier variation to climate change and estimate and predict streamflow variation due to glacier variation. Generally speaking, water resources will decrease because of climate change in glacier-fed region and will influence socioeconomic development throughout the entire basin (Hagg et al. 2007; Luo et al. 2013). The most common method for estimating the influence of climate change on water resource is large-scale simulation of hydrology (Fontaine et al. 2002). The ideal simulation is the long-term impacts of glacier melting, and usually the greatest challenge is complex hydrological process and low quality climate data in many of the river basins (Hock 2003; Howells et al. 2013).

Streamflow trait will be altered by climate change substantially, and even worse melting or complete wastage of glacier will be caused by climate change during next decades (Thorsteinsson et al. 2013). From the perspective of precipitation which will influence the amount of runoff and especially the largest accumulation of snow, changes will usually happen between the late winter and the early melting season, but from the view of temperature, alteration mainly affect runoff time. It is an effective way to analyze the contribution of climate change to the variation of runoff using model simulation (Luo et al. 2013).

Methodology and Data

SWAT Model

The Soil and Water Assessment Tool (SWAT) simulation model has been widely applied in some watersheds where streamflow concentrated on rainfall events (Castillo et al. 2014; Zheng et al. 2012). Some scholars are trying to improve the snow melting algorithm for streamflow simulation related to the effect of climate change (Zheng et al. 2012). Nevertheless, long-term impact on glacier and snow melting about hydrological process is still underexplored. Therefore, reliable model on glacier melting in SWAT still require accurate parameterization. SWAT, a semi-distributed hydrological model using geography data, is good at dealing with hydrological process at watershed scale. Besides the elementary unit of SWAT is Hydrological Response Units (HRUs) which are the sub-watershed linked with river network subdivided by entire watershed. Every HRUis on behalf of a combination of land use, slope and soil, and hypothesis on HRUs is nonspatially distributed without dependency or interaction. SWAT has been applied to deal with so many water issues relating to quality and quantity (Pradhanang et al. 2011). The core components of model are hydrology, soil temperature and properties, land management, pesticide, plant nutrients and growth, bacteria and weather. The variables about meteorology in SWAT include relative humidity in daily or sub-daily time steps, wind speed, precipitation, temperature, and solar radiation. In addition to these, hydrological routine in SWAT also contains evapotranspiration, discharge and snow melting. In the research, hydrological process connected with glacier melting at watersheds, and then runoff from snow melting feed water resource in the spring, Thus the SWAT model added a glacier melting and a snowmelt process module using some equations to describe the relationship between temperature and glacier melting in this study.

1. Simulation of glacier mass balance

Ice volume is the first priority in the long-term simulation of streamflow in glacier-fed watersheds. There are several steps we followed to calculate glacier runoff. Firstly, typical mass balance gradients for alpine glaciers are assumed to be $-0.009\mathrm{a}^{-1}$ for the ablation and $-0.005\mathrm{a}^{-1}$ for the accumulation area (Huss et al. 2008a), thereafter, we used Digital Elevation Model (DEM) to acquire mass balance distribution. We also set the area-averaged mass balance of the glacier surface to zero. Secondly, we define a balance ice flux as the total amount of the ice volume gain and loss during a year at intervals of 300 m. Thirdly, an ice flow law in an integrated form (Glen 1955) was solved for the ice thickness h on the central flow-line.

$$h = \sqrt[5]{\frac{q}{\frac{2}{5} hA\left(S_f \rho g \sin \bar{a}\right)}} \tag{1}$$

Where q (m^2/s) is ice flux normalized with glacier width; g is the acceleration of gravity; A is the rate factor of the ice flow law (Glen 1955); S_f is used to account for the valley shape (Nye 1965); ρ is the ice density; and ā is the slope of the glacier surface. A is calibrated to optimize agreement with the radio-echo sounding profiles. We assumed $A = 6 \times 10^{-15}\ \mathrm{s}^{-1}\ \mathrm{kPa}^{-3}$ which is consistent with a previous study (Huss et al. 2008b). $S_f = 0.6$ is cited from a literature (Nye 1965), and $\overline{a}$ is equal to the mean slope along the flow-line. Finally, the spatially distributed values of h were connected by accounting for the local surface slope at every grid cell and by assuming $h\sim (\sin\ \overline{a})^{3/5}$. This proportionality presents the redistribution of ice along the cross-flow section. The selected proportionality factor guarantees that the previous total ice volume is unchanged. Surface melt rate M_{gla} is computed as follows:

$$M_{\mathrm{gla}} = \begin{cases} \left(F_M + r_{\mathrm{ice/snow}} I\right) T_B : T_B > 0^{\circ} C \\ 0 \qquad\qquad\qquad\quad : T_B \le 0^{\circ} C \end{cases} \tag{2}$$

where F_M is a melt factor; $r_{\mathrm{ice/snow}}$ is radiation factor between ice and snow; I is the clear-sky direct radiation; and T_B is the band-averaged temperature (°C). The site-specific parameters F_M and $r_{\mathrm{ice/snow}}$ are further calibrated by direct observations.

$$\frac{dh}{dt} = -(1-f)M_{gla} - S + F \tag{3}$$

where f is ratio for melt water refreezing; M_{gla} is melt rate of glacier in given day (mm H_2O); S is sublimation rate of glacier in given day (mm H_2O); F is glacier accumulation rate in given day (mm H_2O), and t is the time step in day. Therefore, the depth of water equivalent of glacier mass is expressed as:

$$V_{gla} = \frac{h \times A_{gla}}{\rho_i} \tag{4}$$

where ρ_i is the bulk density of ice, usually, 0.9 kg m^{-3}. To capture the seasonal and gradual pattern of the accumulation, we develop an algorithm to account for the accumulation of glacier mass. Turnover of snow to ice is assumed as a ration of water equivalent of snow over ice given as below:

$$F = \beta \times SNO_i \tag{5}$$

where SNO is the water content of snowpack over ice on day i (mm H_2O); β is an accumulation coefficient which is assumed to be changing seasonally and given as follows (Luo et al. 2013):

$$\beta = \beta_0 \left\{ 1 + \sin\left[\frac{2\pi}{365}(t-81)\right]\right\} \tag{6}$$

where β_0 is a basal accumulation coefficient.

2. Snowmelt routing algorithm

As above mentioned, snowfall appears usually as the form of snowpack or snow cover in ground storage. We set a threshold of snow-melt temperature to calculate snow accumulation. If mean air temperature in a day is below this threshold, the form of precipitation is regarded as snow within an HRU, on the other hand, the precipitation will be treated as rainfall. When snowfall happens, the equivalent water will be added to the snowpack. In the model, the snowpack is intensified as snowfall proceeds, and is weakened as the snow melts. The mass balance of snowpack is computed as follows (Neitsch et al. 2005):

$$SNO_i = SNO_{i-1} + R_{\mathrm{day}} - E_{\mathrm{sub}} - SNO_{\mathrm{mlt}} - SNO_{\mathrm{gla}} \tag{7}$$

where SNO_i is the water content of snowpack on day i (mm H_2O); SNO_{i-1} is that on day $i-1$ (mm H_2O); R_{day} is the precipitation amount on a given day (added only if the average daily temperature T_{ave} is $<T_{s-r}$) (mm H_2O); and E_{sub} is the amount of sublimation on a given day (mm H_2O). SNO_{mlt} is the amount of snowmelt on a given day (mm H_2O), and SNO_{gla} is the amount of glacier converted from snow on a given day (mm H_2O). Further information on the equations used in SWAT to calculate snow sublimation has been described in the SWAT Theoretical Documentation (Neitsch et al. 2005).

3. Snowpack temperature

Because of spatial heterogeneity and various factors, snowpack distribution cannot be uniform throughout the entire given area. The situation is that some areas are free of snow; however, some other areas are covered by thick snow. When the simulation of streamflow is carried out, in order to calculate snowmelt accurately, these regions will be handled specially. In this study, a depletion curve expresses the seasonal growth and decay of snowpack as a function of the amount of present snow in the basin. This curve is based on natural logarithm (Neitsch et al. 2005). The snowpack temperature on the current day is calculated as follows:

$$T_{\mathrm{snow}}(i) = T_{\mathrm{snow}}(i-1) \times (1 - l_{\mathrm{snow}}) + \overline{Tav} \times l_{\mathrm{snow}} \tag{8}$$

where $T_{\mathrm{snow}}i$) is the snowpack temperature on a given day (°C); $T_{\mathrm{snow}}(i-1)$ is that on the previous day (°C); l_{snow} is the snow temperature lag factor; and $\overline{Tav}$ is the mean air temperature on the current day (°C). As l_{snow} approaches 1.0, the mean air temperature on the current day will increasingly influence the snowpack temperature when the snowpack temperature from the previous day exerts increasingly less influence.

4. Snowmelt process

The common method for researching snowmelt process is to use temperature index with elevation band approach (Hock 2003). There are many factors affecting snowmelt, such as melting rate, temperatures of snowpack and atmosphere, and area coverage of snow. Melted snow is calculated as the form of runoff and percolation in SWAT model. The rainfall energy produced by the fraction of snowmelt is regarded as 0 while calculating snowmelt, which is assumed that the rate of melt is uniform for 24 h in a day.

Two other r major variables related to spatial meteorological parameters, including snow volume and temperature. One of the advantages of SWAT is that it is able to a watershed into a maximum of ten elevation bands, and then simulate snow cover or snowmelt at each elevation band (Fontaine et al. 2002). The temperature and precipitation at each band were adjusted accordingly:

$$\begin{aligned} T_B &= T + (Z_B - Z) \times \mathrm{d}T/\mathrm{d}Z \\ P_B &= P + (Z_B - Z) \times \mathrm{d}P/\mathrm{d}Z \end{aligned} \tag{9}$$

where T_B is the band-averaged temperature (°C); T, Z, and P are temperature (°C), elevation (m), and precipitation (mm), respectively, which are measured at the weather stations; Z_B is the midpoint of band elevation (m); $\mathrm{d}T/\mathrm{d}Z$ is the temperature lapse rate (°C/m); P_B is the band-averaged precipitation (mm), and $\mathrm{d}P/\mathrm{d}Z$ is the precipitation lapse rate (mm/m). Ten elevation bands were set up for the snow-glacier-dominated watershed with vertically equal distance from the mean elevation of the centroid of the sub-watershed. $\mathrm{d}P/\mathrm{d}Z$ and $\mathrm{d}T/\mathrm{d}Z$ were set to be 0.5 (mm/km) and −0.5 (°C/km) following local lapse rate calculation. Therefore, the snowpack temperature (T_{snow}) and mean daily temperatures were used along with a melt coefficient to calculate the potential volume of melt water. We coupled the glacier melting algorithm to snowmelt process as:

$$M = \alpha((T_{\mathrm{SNOW}} + T_B)/2 - T_m) + M_{\mathrm{gla}} \tag{10}$$

where T_m is the snowmelt base temperature, which is the mean air temperature at which snowmelt occurred. The appropriate melt coefficient approximately ranged between 2 and 6 mm/deg. The snowmelt coefficient was calculated as:

$$\alpha = (\alpha_{\max} + \alpha_{\min})/2 + \sin([(\text{day of year})\pi/366])((\alpha_{\max} - \alpha_{\min}))/2 \tag{11}$$

where $\alpha_{\max}$ is the maximum snowmelt rate during a year. $A_{\min}$ is the minimum snowmelt rate during a year.

5. Model performance evaluation

Following a standard hydrological model performance criterion, we used E_{ns} and R^2 as model evaluation indices in this study. Model performance was high when $E_{ns} > 0.5$ and $R^2 > 0.8$. Here, E_{ns} is the relationship strength between observed value $Q_{o,i}$ and simulated value $Q_{m,i}$ at time t. E_{ns} lies between $-\infty$ and +1, which indicates that the model performance is higher when the E_{ns} is closer to +1. The square of Pearson's product moment correlation, R^2, presents the proportions of total variance of measured data that can be explained by simulated data, which indicates that the model performance is higher when R^2 is closer to 1.

$$E_{ns} = 1 - \frac{\sum_{i=1}^{n} \left(Q_{o,i} - Q_{m,i}\right)^2}{\sum_{i=1}^{n} \left(Q_{o,i} - \overline{Q}_o\right)^2} \tag{12}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n} \left(Q_{o,i} - \overline{Q}_o\right)\left(Q_{m,i} - \overline{Q}_m\right)\right]^2}{\sum_{i=1}^{n} \left(Q_{o,i} - \overline{Q}_o\right)^2 \sum_{i=1}^{n} \left(Q_{m,i} - \overline{Q}_m\right)^2} \tag{13}$$

where E_{ns} is the Nash–Sutcliffe coefficient; $Q_{o,i}$ is the observed runoff in i years; $Q_{m,i}$ is the simulated runoff in i years; and n is the length of the time series. E_{ns} and R^2 closer to 1 indicate that the model predicts more accurately.

CGE Model

Computable General Equilibrium (CGE) model, is an ideal form of expression for simplified economic system, and there are three assumptions for general CGE model. First, zero profit condition, which means that total revenue equals to total cost, because the original hypothesis is constant return to scale and perfect competition, and all revenues of all enterprises are used to purchase intermediate input or production factors. Second, market clearing condition, gross value of output of enterprises equals to intermediate gross purchasing value, which means that supply equals to demand at each market, including factor market. Third, making both ends need, in order to make maximum profits, household income from rent of production factors all purchase commodities in the market. We can easily infer three major characteristics through the name of CGE model, the first one is computable, CGE model is not theoretical economic model, instead, it is a computable model based input output table or social accounting matrix to describe the subject behavior within economic system. Thus the most important part is to make accurate data, which is closely related to the quality of simulation. The second is general, the whole economic system is as an entirety and uses the view of universal relation to study interaction of all market, rather than chooses a sole market as the study object.

Ordinary CGE model includes several basic modules as follows; of course, we can add some modules based on the need of our study. The first and the most import module is production process; production functions are the basic model to describe the behavior of enterprises, and are the core of neoclassic economy. In addition, production functions describe the pattern of combination of input of production factors and the transformation process from resource and input to commodities and services. The second is income distribution modules, the distribution in the module includes transfer payment between income of factors and household, between government and foreign remittance, besides the module also consists of intermediate sectors which distribute operating surplus. The third is final demand module; it contains household demand, government expenditure, personal and public investment, inventory and export. The fourth is trade module, which includes import demand, export supply, and export demand. The fifth is commodity market, in the model, import and export meet the assumption of “small country,” which means that export and import will be satisfied and the price will not be affected, and export demand assumes is infinite. The sixth is factor market equilibrium, the supply and demand of factor must be equal. The seventh is macro closure, we need to set exogenous variables to make the number of variables equal to the number of equations, which can get the unique solve.

In the research we improved the ORANI-G, a single-country CGE model, through adding the water as the production factor into the model (Fig. 2).

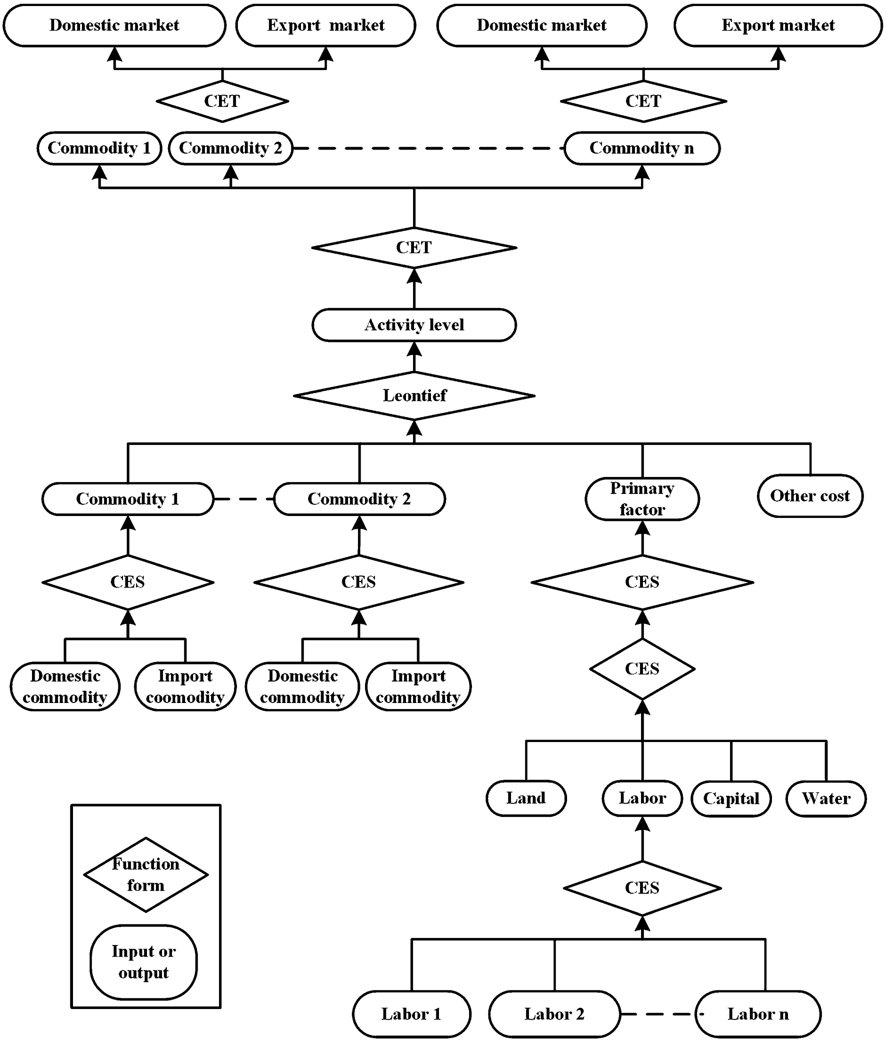

Fig. 2 A nested CES production function in the ORANI-G model (Reprinted from Zhan et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

$$LND_i = slnd_i \cdot \left[\frac{POPRM_i}{PLND_i}\right]^{\sigma oprm_i} \tag{14}$$

$$LAB_i = slab_i \cdot \left[\frac{POPRM_i}{PLAB_i}\right]^{\sigma oprm_i} \tag{15}$$

$$CAP_i = scap_i \cdot \left[\frac{POPRM_i}{PCAP_i}\right]^{\sigma oprm_i} \tag{16}$$

$$POPRM_i = \left[slnd_i \cdot PLND_i^{1-\sigma oprm_i} + slab_i \cdot PLAB_i^{1-\sigma oprm_i} + scap_i \cdot PCAP^{1-\sigma oprm_i}\right]^{\frac{1}{1-\sigma oprm_i}} \tag{17}$$

$$WTR_i = swtr_i \cdot \left[\frac{PPRIM_i}{PWTR_i}\right]^{\sigma prim_i} \tag{18}$$

$$OPRM_i = soprm_i \cdot \left[\frac{PPRIM_i}{POPRM_i}\right]^{\sigma prim_i} \tag{19}$$

$$PPRIM_i = \left[swtr_i \cdot PWTR_i^{1-\sigma prim_i} + soprm_i \cdot POPRM_i^{1-\sigma prim_i}\right]^{\frac{1}{1-\sigma prim_i}} \tag{20}$$

where LND_i is land input in the ith commodity; LAB_i is labor input in the ith commodity; CAP_i is capital input in the ith commodity; WTR_i is water input in the ith commodity; $PWTR_i$ is water price; $PLND_i$ is land price; $PLAB_i$ is labor price; $PCAP_i$ is capital price; $LABO_o{,}i$ is j type of labor input in the ith commodity; $PLABO_o{,}i$ is j type of labor price in the ith commodity; $slnd_i$ is the share of land input in the ith commodity; $slab_i$ is the share of labor input in the ith commodity; $scap_i$ is the share of capital input in the ith commodity; $soprm_i$ is the share of intermediate input; $\sigma prim_i$ is CES of land–labor–capital; and $\sigma oprm_i$ is CES of water-CES (water–land–capital).

Scenarios

Simulation with multiple scenarios was carried out to analyze the impacts of water supply change on GDP and calculate the water productivity. We set four scenarios that changing rate of water supply in all sectors, agricultural sector, industrial sector, and urban construction, under which the change rate of water supply was set to be −10%, −5%, −4%, −3%, −2%, −1%, 1%, 2%, 3%, 4%, 5%, and 10% respectively. The scenario without change in the water supply was used as the baseline scenario, and the results under other scenarios were compared with the result under the baseline scenario. In order to analyze the influence of water supply decrease on the economic development in Gansu Province, this study simulated the change rate of the output of various goods when the water supply decreases by 1%, according to which the response of the output of different sectors to the water supply change was analyzed.

Results of Climate Change on Water Productivity

The process of hydrology in the upper stream will affect water use of entire basin, so the more accurate in upper stream, the better for the water management of entire basin. Calibration and validation, the guarantee for the simulation, employed daily data of observation in 2009 and 2010 from Yingluoxia Hydrological Station which is the demarcation point between upper stream and middle stream. E_{ns} and R^2, standing for the accurateness of model, are very good in this paper (the values of E_{ns} are 0.88 and 0.87 separately in 2009 and 2010; the values of R^2 are 0.87 and 0.89 in 2009 and 2010, respectively). Further, comparing the simulation results with observed data from Yingluoxia Hydrological Station, we failed to reject the significance of parameters of the SWAT model, and hence, the model is appropriate for simulation in the upper stream. We identified and listed the most sensitive parameters. The temperature lapses rate (TLAPS) is the most sensitive parameter since it is directly related to the melting process of snow and glacier. Snow melting occurs mostly from March to June in a sub-watershed. The snow melting factor on June 21st was parameterized to be SMFMX, which is the maximum melt rate; any increase of SMFMX drives snow melting. The snow temperature lag factor TIMP is also linked with SMFMX because it is based on the previous situation. Along with TIMP surface water lag time, SURLAG plays an important role in the model performance as a melted snow routing process is related to the geology of the watershed, where the melted water mainly flows to the surface runoff covering the impervious rock formations. SMTMP is sensitive since it indicates the starting and ending of melting and considers the availability of snow melting on a specific day, and the model-simulated streamflow, especially the peak values, is significantly influenced by the variation of SMTMP. Both calibration of the model the validation of the simulation results show that the model performed well in simulating the runoff variation due to glacier melting and climate change in upstream Heihe River Basin.

Changes of Glaciers

Changes of temperature and precipitation were both different seasonally in mountains from 1960 to 2010. The result found that annual precipitation gradually increased, though precipitation decreased in autumn and spring, and increased in summer and winter. On the other hand, annual average temperature increased slowly, while temperature increased mostly in winter and slightly in autumn, but it is relatively constant in summer and decreased a little in spring. The annual growth rate of precipitation is 1.2%, and at the speed of 14.84 mm per decade in summer, nevertheless, the rate is much lower in winter. Although there was obvious variation between seasons of temperature and precipitation in Qilian Mountains in past 50 years, the trend of two critical variables increased as a whole.

The change in temperature and precipitation would cause glacier changes inevitably, whose accumulation will be affected by these two variables seriously. The precipitation would increase with elevation below 4700 through the observation data in study area. Such as, the annual precipitation increases by 16.9 mm/100 m and the precipitation increases by 10.9 mm/100 m in summer along with elevation (Fig. 3). Nonetheless, once the elevation surpassed the 4700 m, the precipitation would decrease, so precipitation increase ought to attribute to the

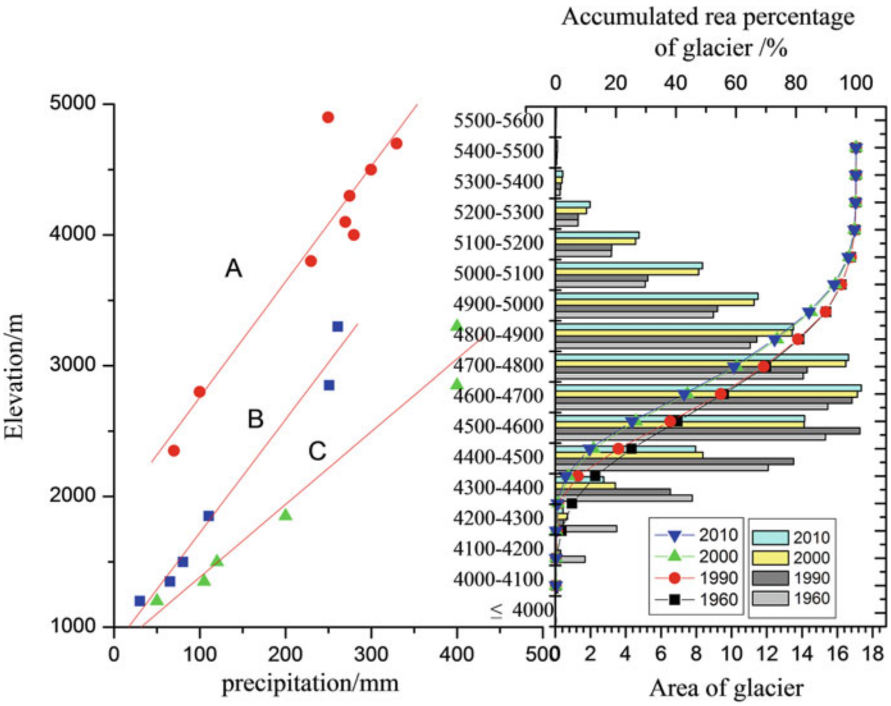

Fig. 3 The distribution of glaciers by precipitation at different elevations (Reprinted from Wu et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

glacier accumulation. In fact, temperature increase would cause rainfall rather than snowfall, which brings about shrinkage of glaciers, increases snowmelt, and upsets water balance. The situation is worse in winter due to glacier accumulation would not compensate the loss in summer. Thus the glacier is speeding up melt.

The Effect of Glacier on Streamflow

Watersheds in mountain have the majority of geographical features, which includes frozen soils, accumulative snows and mountain glaciers. These are particular sensitive to the climate change. Precipitation is the most crucial factor influencing streamflow based on the models about streamflow response to climate change in HRB. Comparing the results of the SWAT model and the SWAT model coupled with the glacier melting algorithm, we found that the glacier contributed 8.9% to streamflow in 2010. In particular, the highest rate of streamflow increase is 2.7×10^7 m^3 in spring, which equals to 0.96% of total streamflow per year. The significant increase of streamflow in spring was likely connected with increasing glacier melting (Fig. 4). In general, the streamflow increased along with precipitation

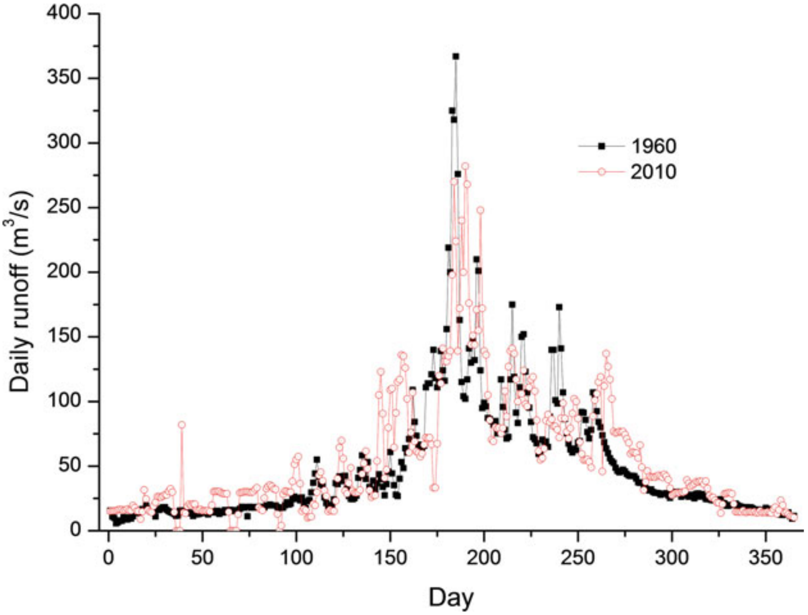

Fig. 4 Comparison of the simulated daily runoff between SWAT and SWAT coupled a glacier melting algorithm in 2010 (Reprinted from Wu et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

growth and decreased with rise of temperature. Nonetheless, stable precipitation attributed to the 1.6% increase of streamflow because snowmelt and glacier melting increased by 1 °C, and the same percentage will decrease if the temperature decreases by 1 °C. The runoff depth would increase by 12.3 mm if the temperature is kept stable and precipitation is increased by 10% when ignoring the effects of glacier melting on streamflow. Besides, runoff depth would decrease by 2.32 mm if the temperature increased by 3°C and the precipitation stayed stable (Fig. 5). Thus, the increasing temperature in spring and summer contributed to streamflow positively because the growth of glacier melting, snowmelt, and annual precipitation. With the gradual increase of precipitation and temperature, the streamflow in HRB is increasing marginally after a counterbalance of evapotranspiration and infiltration loss (Fig. 6).

Water Balance Component

Water balance about spatial distribution in SWAT model contains glacier melting, rainfall and streamflow from sub-watersheds. Simulated water-yield by SWAT model includes three parts, lateral flow, surface runoff and shallow groundwater runoff. Lateral flow attributed to most of mountainous runoff, about 54.5%. Streamflow is more intensive and more glaciers in the east than that in the west of

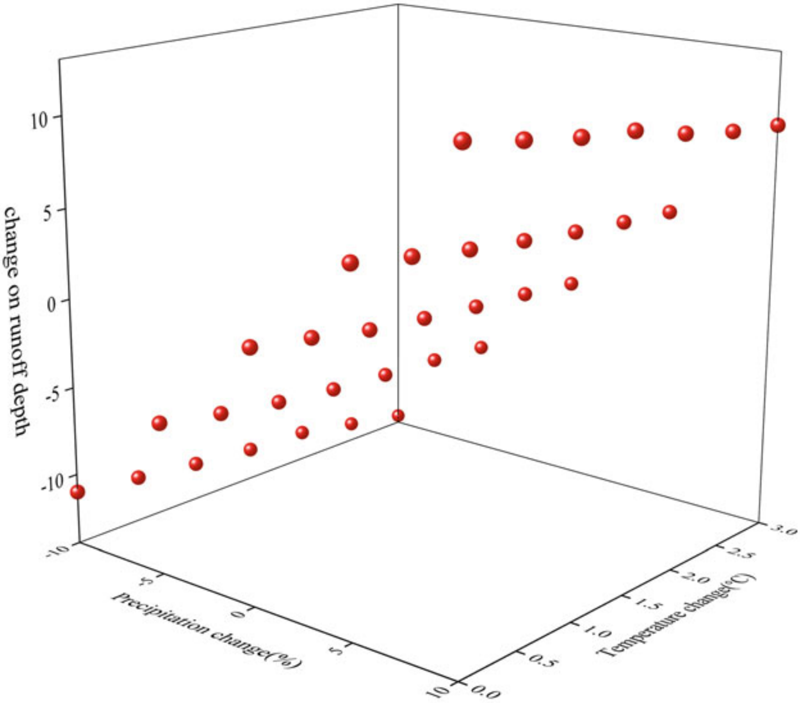

Fig. 5 Simulated relevant changes on the runoff depth with regard to climate changes (mm)

HRB. The simulated result about water balance in 2010 is shown in Fig. 5, and the range of precipitation in sub-watersheds in upper stream is from 240 to 760 mm, however, the potential evapotranspiration which is higher in east than west, was about two times than that of precipitation, and on the other hand, the actual evapotranspiration is a little lower than the precipitation, from 150 to 300 mm. Besides, simulated results of glacier melting were still higher in east than the west and demonstrated that the range of precipitation was from 200 to 500 mm. Eliminating the evapotranspiration, infiltration and tributary streamflow, and the increase of streamflow, from 0.5 to 4 mm, is attributed to glacier melting.

Water Productivity

The climate change affected water balance in upper stream in HRB seriously, which will influence water use in entire basin. The major socioeconomic activities concentrated on the middle stream, water productivity is an appropriate indicator to measure the value of water, and therefore it is important to analyze water productivity in middle stream in HRB (Table 1).

From the result of the improved ORANI-G model and the definition of water productivity, the average water productivity for all industries is 0.47 USD/m^3.

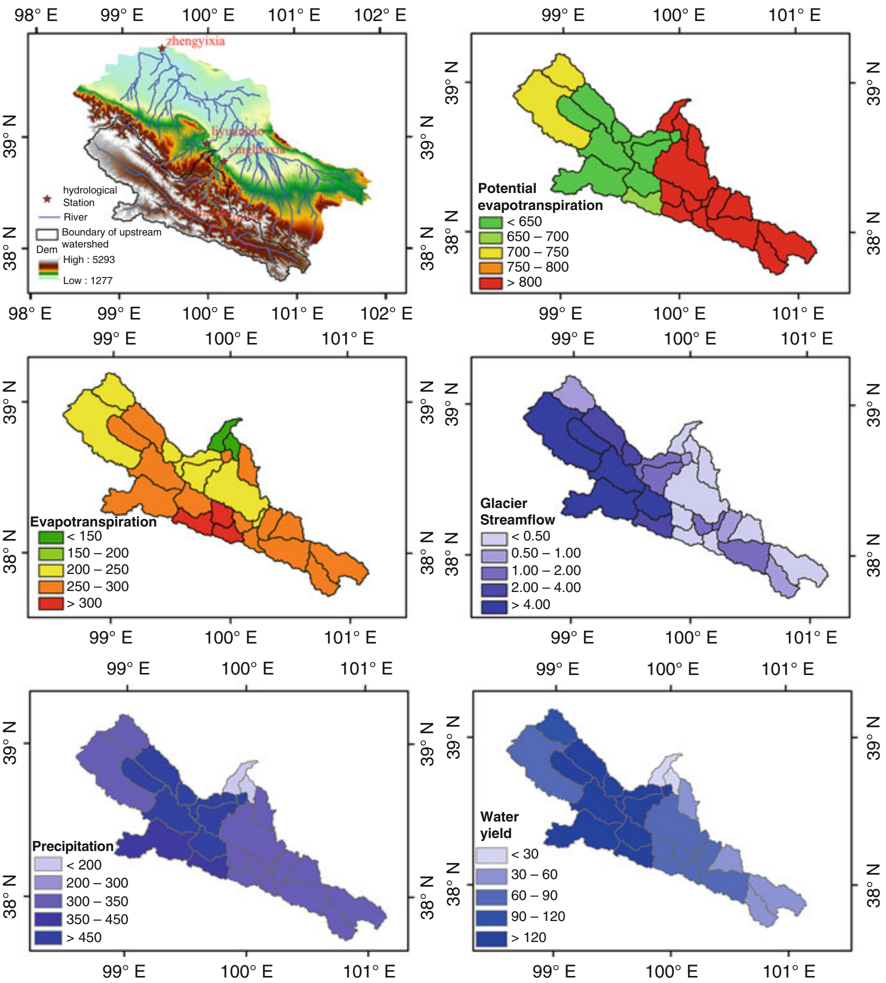

Fig. 6 Distribution of water balance component in the upstream Heihe River Basin in 2010 (Reprinted from Wu et al. (2015) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

Based on the Tables 2, 3, and 4, we found that values of water productivity are different from industries, and are 0.16, 2.23, 4.21 USD/m^3 for agricultural sectors, manufacture sectors, and service sectors, respectively. Comparing with the marketed prices of water in agricultural sectors, manufacture sectors, and service sectors, which are 0.013 USD/m^3, 0.33 USD/m^3, and 0.4 USD/m^3, water productivity is higher than market price. Particularly, underestimated water price indicated severer water scarcity than real expression in economic system. In other words, water productivity can be improved through optimizing water allocation etc. Water productivity in agriculture is 0.16 USD/m^3, which is approximate

Table 1 Water productivity in Gansu (Unit: %)

Water supply change	Water input changes	GDP changes	Water productivity in GDP
−10	−11.374	−5.293	0.465
−5	−5.687	−2.646	0.465
−4	−4.55	−2.117	0.465
−3	−3.412	−1.588	0.465
−2	−2.275	−1.059	0.465
−1	−1.137	−0.529	0.465
0	0	0.000	0.465
1	1.137	0.529	0.465
2	2.275	1.059	0.465
3	3.412	1.588	0.465
4	4.55	2.117	0.465
5	5.687	2.646	0.465
10	11.374	5.293	0.465

Table 2 Water productivity of agriculture industry in Gansu (Unit: %)

Water supply change	Water input change	Agricultural production change	Water productivity in agricultural production
−10	−9.312	−1.508	0.162
−5	−4.656	−0.754	0.162
−4	−3.725	−0.603	0.162
−3	−2.794	−0.452	0.162
−2	−1.862	−0.302	0.162
−1	−0.931	−0.151	0.162
0	0	0.000	0.162
1	0.9312	0.151	0.162
2	1.8624	0.302	0.162
3	2.7937	0.452	0.162
4	3.7249	0.603	0.162
5	4.6561	0.754	0.162
10	9.3122	1.508	0.162

to the value simulated by Wang (Wang et al. 2008) that is 0.11 USD/m^3, and water productivity is much lower in agriculture than that of manufacture and service sectors. Therefore, industrial transformation will improve water productivity.

The inputs including labor, capital, water, and land would cause change of economic production directly or indirectly, and these changes will be simulated by improved ORANI-G model we adopted while water use changes. When the CES elasticity between water and other input factors is 0.05, and water use decreases by 1%, the change of economic production in model will vary in different sectors (Table 5). From the perspective of percentage change in different sectors, the most obvious change was in agriculture, which decreased by 0.381%; however the least

Table 3 Water productivity of industrial industry in Gansu (Unit: %)

Water supply change	Water input change	Industrial production change	Water productivity in industrial production
−10	−0.723	−1.605	2.219
−5	−0.361	−0.802	2.223
−4	−0.289	−0.642	2.221
−3	−0.217	−0.481	2.219
−2	−0.145	−0.321	2.213
−1	−0.072	−0.160	2.229
0	0	0.000	2.221
1	0.072	0.160	2.229
2	0.145	0.321	2.213
3	0.217	0.481	2.219
4	0.289	0.642	2.221
5	0.361	0.802	2.223
10	0.723	1.605	2.219

Table 4 Water productivity of urban construction in Gansu (Unit: %)

Water supply change	Water input change	Urban construction change	Water productivity in urban construction
−10	−0.107	−0.454	4.200
−5	−0.054	−0.227	4.200
−4	−0.043	−0.181	4.201
−3	−0.032	−0.136	4.202
−2	−0.021	−0.091	4.198
−1	−0.011	−0.045	4.198
0	0	0.000	4.200
1	0.0107	0.045	4.198
2	0.0215	0.091	4.198
3	0.0322	0.136	4.202
4	0.0429	0.181	4.201
5	0.0537	0.227	4.200
10	0.1073	0.454	4.200

obvious change was in education, which decreased by only 0.019%. Because most water was used for agricultural production, improving water productivity in agriculture will mitigate water scarcity in arid region. In comparison with change in economic production driven by water, service sectors are less sensitive; however, values of water productivity in service sectors are the highest. Therefore, as mentioned above, the water from agriculture production to service sectors would improve water productivity. Water productivity is a crucial indicator for measuring economic value of water, and industrial transformation will optimize water productivity. However, climate change will have an impact on the change, and there are a lot of adaptation measures mitigating climate change impacts for optimizing water productivity.

Table 5 Sectoral economic production changes by water input decrease 1% under CES of water to other factors at 0.05 in Gansu

Sectors	Economic output change (%)
Agriculture	−0.381
Forest	−0.295
Livestock	−0.052
OAgriculture	−0.044
CoalExtWash	−0.187
ExtPetGas	−0.095
ExtMetal	−0.166
ExtNmetal	−0.193
ManuPaper	−0.262
ProFuelFood	−0.135
OPSPEqu	−0.263
OManufacture	−0.230
ManuArtwork	−0.169
RecyWaste	−0.277
ProdSuppEPHP	−0.146
ProdSuppGas	−0.209
ProdSuppWtr	−0.266
Construction	−0.234
TransWare	−0.041
Post	−0.089
Information	−0.016
WholeRetail	−0.018
HotelCater	−0.025
Finance	−0.074
Estate	−0.010
ServBusin	−0.043
Research	−0.080
ServTech	−0.079
EnvManage	−0.086
WtrManage	−0.071
ServResident	−0.030
Education	−0.015
PubManage	−0.019

Mitigating Climate Change Impacts for Optimizing Water Productivity

Considering the water scarcity character of the HRB, it is important to clarify the coupling relationship between water, ecology, and social economy, reveal the driving mechanism of the socioeconomic system on the evolution of water resource, improve the systems and institution designs for water management, and explore innovative approaches on optimal water allocation.

Research Findings on Decision-Making for Water Management

There are significant differences in ecosystem structure among the upper, middle and lower reaches. Industrial and agricultural water demand in the middle reaches and ecological water consumption in the lower reaches form the mechanism of interaction of water supply and demand with the water producing in the upper reaches. Therefore, research works on the HRB should firstly focus on simulation of hydrologic process of the basin with the help of complex systematic modeling technology (Bracken and Oughton 2009). Granted by the "Major Research Plan on the HRB" initiated by the National Natural Science Foundation of China, Chinese scholars have conducted a series of research works, which are focused on the hydrologic process as well as the impacts of human activities on water resource. These research works basically conceptualized the basic laws of eco-hydrological process in the HRB, and revealed mechanisms on water cycling, ecological system evolution as well as the coupling mechanism between them.

The modeling work on the HRB is highlighted by model integration and mainly based on subregional modeling. There have been a lot of research works on hydrological process, groundwater, water resource, land use, land surface process, ecology, and social economy of the HRB based on a series of related models (Cheng et al. 2014). The model integration on the upper reaches of the HRB takes the distributed hydrological model as the core, and realized the model coupling in a series of issues including the characteristics of runoff from mountainous sub-watershed, the unity of atmosphere–vegetation–soil–permafrost–snow cover. As for the model integration in the middle reaches in the HRB, these research works are focused on coupling troubles among the surface water, groundwater, and the ecological models. For example, there was a study coupling SiB2 (land surface model) with aquifer flow, which significantly enhanced the capability of simulate evapotranspiration and surface–groundwater interaction, and achieved systematic simulation for hydrological cycle in the middle reaches of the HRB. More comprehensively, a genuine farmland eco-hydrological model was established by integrating MODFLOW (Groundwater model), Hydrus-1D (soil water model), WOFOST (crops growth model) models, coupling the land surface process module and stomatal–photosynthesis module. In addition, the model has certain capability of prediction and decision support. For instance, if the model is used to optimize irrigation system, it can save 27.27% irrigation water than the existing irrigation system. These studies have proved that the coupling model can be used to analyze ecological system and the interactions of the hydrological cycle, and guide the water-saving practices on agriculture.

Another important consideration in model integration is modeling environment. It is the visual computer software platform that supports the efficient development of integration model, convenient connection among existing models or modules, module management, data pretreatment and parameter calibration. The application of modeling environment in the integrated research of the HRB has mainly two directions: one is to use the existing international mature model to realize the coupling modeling environment to solve the key problems in integration issue. Considering the defects of existing modeling environment in the flexibility, another direction is to develop a new modeling environment. In this aspect, some Chinese scholars established the new modeling environment to explore the hydrology and land surface process. By using highly efficient and flexible module and data transfer mechanism, this environment has realized the flexible extensibility and reusability of the module. Based on this platform, some case studies of the modeling integration of the HRB have been implemented. For instance, the hydrological model TOPMODEL and the evaporation module from Noah (land surface process model) can be coupled together to make TOPMODEL be more reasonable when considers the effect of vegetation on water balance. In addition, with the help of this modeling environment, the question that "who supplies, how much, how to fill" about water on ecological compensation of the upper reaches of the HRB has been answered.

Generally, studies in HRB meanly focused on the eco-hydrological processes, water use mechanism of the typical plants and their characteristics when response to stress. A series of eco-hydrology process model had been introduced, interpreted, or set up (Li et al. 2009), including the Noah for ecological and hydrological processes, MODFLOW models for groundwater process, SWAT model for distributed hydrological processes, and HYDRUS model and the systematic conceptual model of Goulburn Broken Catchment for atmosphere–hydrology–vegetation interaction. At the upper reaches of the HRB, the integration research on eco-hydrology process revealed the interaction mechanism between ecological system and hydrologic system, enhanced the cognition of mechanism on water resource formation and transformation, and laid the foundation for water resource evolution research under climate change. At the middle and lower reaches, the eco-hydrological integration research clarified the relationship between the transformations of different kinds of water resource, illustrated the interaction and coupling mechanism between the water cycle and vegetation structure, rebuilt the spatial–temporal distribution of water resource in the historic periods and forecasted it in the future.

However, the basin is a complete system for cooperative development and evolution of the human society as well as ecology. The HRB is an ideal case for integration study of "Water-Soil-Gas -Biology-Human" (Cheng et al. 2008, 2014). Human activities have become the main driving force for hydrological circulation, and the social–economic water dimension rather than the natural hydrological dimension has become the driving water circulation, but research works on the former is very weak (Li et al. 2010). Model on either single process cannot comprehensively simulate the characterization of the process, behavior and interaction mechanism of the whole system.

Based on the modeling and integration analysis, the Decision Support System (DSS) is vital to achieve the adaptive water management in the HRB. At present, there are two types of DSS: Research-oriented DSS and Application-oriented DSS. Research-oriented DSS for the HRB is a scientific model integrating "Water–Soil–Gas–Biology–Human." It tries to integrate the expert knowledge and experience of the HRB to build a spatially explicit model with scenario analysis method. For the development of the Research-oriented DSS, it has integrated multiple hydrologic models, and coupled many GIS functions to support coupled work of multidisciplinary model. Also, it has made technical breakthroughs on the mismatch of the models at different spatial–temporal scales. Through providing scenario-driven decision-making strategies graphically and multiobjectively, and providing various auxiliary decision tools, it is expected to be a new generation of DSS for river basin integrated management. For the Application-oriented DSS, some water management DSS can analyze the climate and human activities at the middle reaches of the HRB. It is also able to study the planting structure of different crops, spatial–temporal distribution of water requirement with different hydraulic engineering conditions. Finally, it can realize the simulation of water resource allocation process at multilevel (the whole basin, administrational district, and irrigation region) and evaluate the influence of various water resource management strategies.

Taking the arid climate and the unique relationship among the three reaches of the HRB into consideration, there should be an innovative framework and research components for DSS for the HRB based on the existing studies (Fig. 7). Spatially, water consumption of the HRB mainly concentrated in the middle reaches, where industrialization and urbanization are evident. Institutionally, there is a history of water right and water price system and institutions in the HRB, especially in the middle reaches where irrigation agriculture is preformed widely. Naturally, the desertification process exacerbated the deterioration of the ecology and change of oasis area. Also, the future climate change will greatly influence the hydrological process and water supple, that is, the precipitation as well as the solid glacier in the upper reaches. Therefore, as a unit of the whole scientific framework of the DDS, we should firstly comprehensively consider and make multiple scenarios analysis on the impacts of water right system reform, industrialization and urbanization, land use change, change of oasis area and climate change on the HRB. This work can be conducted on basis of existing knowledge, data and regional models. The scenarios analysis results would help to deepen and widen the recognition of the mechanism and linage of a series of factors within the ecology and economy of the arid area.

Secondly, the water resource utilization in the HRB is often confronted with the contradiction between ecological service and social and economic development. Therefore, it is necessary to realize the modeling integration between the social–economic model and eco-hydrological model for the optimization of watershed management. Also, Millennium Ecosystem Assessment put forward the idea

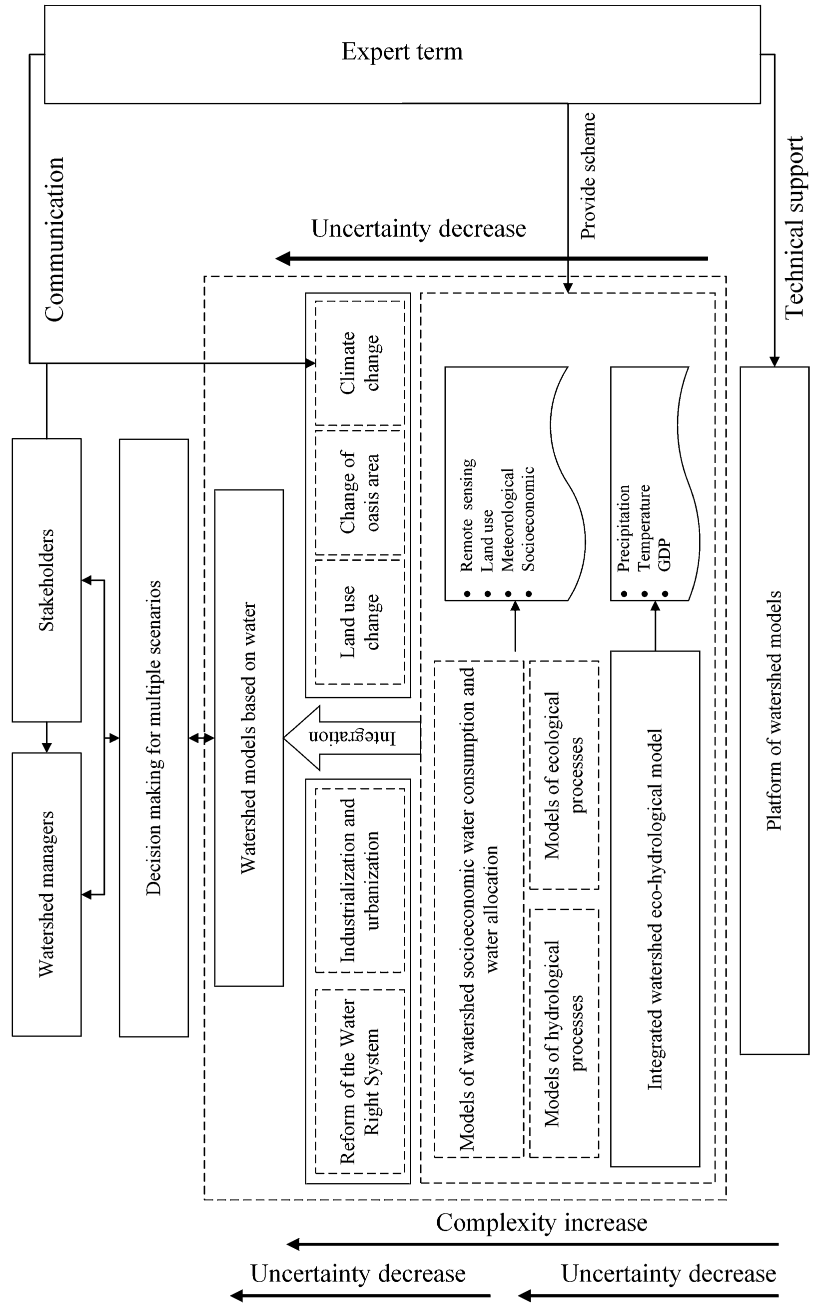

Fig. 7 Framework and components for a DSS for the integrated water management in the Heihe River Basin

that "Regulating water supply service on ecosystem by means of economy and market is the preferred method of management". The balance between the water supply and demand is the core to integrate the social–economic model and eco-hydrological model as separate module. The work on model integration needs to analyze the water supply capacity, water consumption structure, water efficiency and water demand trend at multilevel (whole basin, administrational district, and irrigation region). Specifically, it needs to clarify the interaction mechanism among the water supply in the upper reaches, the industrial water consumption in middle reaches and ecological water consumption in the lower reaches.

Further, the water management system is indispensable for the whole framework of the DDS. In practice, due to the absence of proper water management system, the conflicts among counties often arise because of competition on water use and jurisdictional mandates of the related stakeholders. An integrated watershed water management system should comprehensively consider the ecology, hydrology, and socioeconomy in the basin, in order to provide scientific support for the water security, ecological security, and sustainable development of the inland river basin. Last but not least, water optimal allocation strategies should be involved to explore the regulation measures under different natural and social scenarios. In recent years, a series of studies have been carried out on understanding the impact of human activities (irrigation, livestock activities, and institutional change) on water (Wang et al. 2009). However, compared to the study on the eco-hydrological process and modeling research on the HRB, the mechanism studies water resource allocation is relatively weak. In this sense, both the system and institution design for water management and the optimal water resource allocation would be extended in the follows.

Improving the System and Institution Design for Water Management

In recent years, the integrated management of the HRB has drawn great attention from Chinese government. Yellow River Conservancy Commission (YRCC) of the Ministry of Water Resources has organized a series of tasks such as "Water problems and solutions of the HRB," "Ecological environment problems and solutions of the HRB," as well as "Safeguard measures of water management of HRB" to improve the systems and institution design of water management. Further, Chinese government set up Heihe River Bureau, an institution that belongs to the YRCC, in the year 1999. A major task of this Bureau is to lead the project on uniform water management and water distribution throughout the HRB. Before that, water was used mainly for forest and grassland irrigation, groundwater recharge, and replenishment of the rivers in East Juyan Lake in lower reaches. Unfortunately, there has been no fundamental improvement for the water solutions.

Globally, there is a long-standing and widespread recognition that the river basin is the natural unit for water management (Warner et al. 2008; White 1957). For instance, the USA began to set up institutions to comprehensively manage river basins from 1930s. Created in the year 1933, the Tennessee Valley Authority (TVA) in 1933 is a river basin authority for the unified planning and full development of water resource on a river basin scale in order to achieve comprehensive regional socioeconomic development (Warner et al. 2008; White 1957). Specifically, a far-reaching work was the Universal Soil Loss Equation (USLE), an empirical predictor for soil loss by water erosion (Cardei et al. 2009). It was built based on systematically analysis of observation data from more than 10 thousand runoff regions in 30 states in Eastern America in 30 years.

The last decades witnessed growth in research examining partnerships for integrated water resources management (IWRM) in different global regions. It is now employed globally in various physical, socioeconomic, cultural, and institutional settings. Compared to traditional approaches to water problems, IWRM takes a broader holistic view and examines a more complete range of solutions. It has promoted the water management move into the substantial scientific research period, with good public participation mechanism and considering water, ecology, and social economy in the basin scale (GWP 2004; Alcamo et al. 2007). Water managements of basins in Colorado, Sacramento are based on the IWRM model. IWRM was also applied to water management practices in Murray–Darling Basin in Australia, River Rhine Basin, and The River Thames Basin in Europe and received satisfactory results (Tortajada et al. 2005; Giri et al. 2012; Mitchell 2005). In addition, the Arabia region paid great attention to the groundwater management and wastewater reuse, and considered that IWRM must be considered when building the institutional framework; countries belonging to the Southern African Development Community (SADC) also tried to improve the water efficiency in arid areas with the help of IWRM method to confront the food crisis and poverty.

One representative work on integrated river basin management is reflected in Water Framework Directive (WFD) implemented by EU in the year 2000. Taking over 10 years to develop, the objective of WFD is to build a comprehensive monitor and management system for all water bodies and develop programs and measures to formulate an up-to-date watershed management plan for dynamic water management. The basic requirement is that the watershed management plan must be comprehensively presented, making it clear that how to achieve the targets (ecological conditions, water conditions, chemical conditions, and protected scope) within the required time. In addition, it must carry on the economic analysis to effectively consider the cost and benefit of all the stakeholders as for all the measurement, making itself truly participating in watershed management planning work. Although this command has been implemented for nearly 10 years, the management condition of these cross-border rivers are still in the stage of national independent development and management, and the mechanism of cooperation and negotiation within countries still need to improve. With the rapid globalization and economic development, the development of the basin dynamics will continue to increase, so how to realize the basin management across administrative boundaries is an urgent problem (Table 6).

In particular, there are some similar problems on water management among Murray–Darling River Basin in Australia, the Nile River Basin in Egypt, and the

Table 6 International water management strategies at typical watersheds and its inspirations for the Heihe River Basin

	Management modes and strategies	Inspiration
Mississippi valley in the USA	It has a comprehensive management system operated by multiple sectors and organizations at multiple levels, including the military, institutions composed of representatives from federal government and state government, nongovernmental organizations. The division of labor is clear-cut, avoiding confliction caused by duplication of work. A number of organizations at different levels to coordinate the interests of all parties concerned.	Strengthen the legal system, and establish a series of watershed management regulations to constraint the behaviors from various stakeholders. Manage the whole basin rely on sub-basin as the unit by sharing information and cooperating by various institutions. Relying on the nonengineering measures, instead of engineering technology.
Murray–Darling River Basin in Australia	Developed organization systems, which included three levels: The first level is the Ministerial Council in the national level, which is the highest decision-making body; the second level is the executing agency from the Ministerial Council, including the river basin committee and its office. The third level is the community advisory committee, which is responsible for communication between the council and the community, and emphasizes public participation in watershed management.	Authority for watershed management should be established on consultation mechanism. The full participation in proposal making is the key to implement. An effective organization system can guarantee the implementation of the protocol. Introduce a new theory and method in the water distribution, separate the water right from the land right and provide water for trading to formulate water market. Make the watershed management process more scientific, democratic, transparent and fair.
Rhine River basin in the EU	This river applied international coordination and management mechanism early. Countries along the coastal signed agreements and regulations, as well as built different kinds of organization in the last centuries. The International Commission for the Protection of the Rhine (ICPR) was established in 1950 as the first intergovernmental body for protection against pollution in the Rhine and has made great success. ICPR set up supervision organizations and various professional groups, achieved remarkable success	Give preference to prevention and source controlling, formulate detailed, standardized strict to regulate basin development. Pay emphasis on real-time monitoring and evaluation of the watershed management measures implement for timely adjustment. Increase storage capacity both in cities agriculture area to reduce water loss and soil erosion. Prohibit developing in riverbed. Present new concept of river ecosystem management, and pay attention to the river health function, socioeconomic factors as well as the support from modern science and technology.

HRB. For instance, the responsibilities for water management in response to drought is unclear, water management authorities based on sub-river basin have not paid enough attention compared to government management authority based on administrative regions, and economic and legal measurement still need to be improved. To some extent, the comprehensive water management in Murray–Darling River Basin and the Nile River basin can provide useful experiment and lessons for the water management in the HRB. The successful river management model and experience in Murray–Darling River Basin include water management based on sub-watershed rather than administrative regions, three layers coordination (decision level, execution level, and coordination level), market management strategy such as trade in water rights, as well as regular legal system based on interstate water compact. In addition, as for water management in arid region, Egypt is setting up the Nile River Forecast Center (NFC) for controlling Nile water resource, in order to achieve the Goal “Maximum exploiting of existing water resource, restricting the projects that can pose a threat to water quality and water resource” by the year 2017. The prediction of river flow using the remote sensing, geography information system, and global positioning system (3S) technology can provide the basis for management and decision. Moreover, it emphasizes on the drainage reuse in the agricultural field, and strengthens the utilization of rainfall resources through the implementation of farmland rainwater harvesting project. It reduces the rice planting area through the adjustment of planting structure and promotes drought resistant crops, thus effectively reducing the water consumption on agricultural production.

Reforming Management to Actualize the Optimal Water Allocation

Aside from scientific framework and institutions, the reform of water resource management needs investigations and studies at multiple levels to provide key parameters for DSS based on water demand of production, life and ecology. First and foremost, it is necessary to carry out investigation at the irrigation district level to clarify the water management system in each irrigation district. By this method, we can evaluate the performance of the water management systems, such as “water price” and “water right.” By doing so, we understand the current situation as well as the transformation character of existing water policies, and then clarify the impact mechanism on agricultural department and ecological systems. Secondly, we have to further our research at the administrational level, making clear the WUAs, water-consuming situations, water association system, and other socioeconomic features. The performance evaluation for WUAs can clarify the situation of WUAs (organization, incentive mechanism, and institutional arrangement), the evolution character of the WUAs as well as its impacts on the agricultural production and the water efficiency.

Furthermore, the third level of investigations should focus on the household level to clarify water use of different crops, agricultural activities, and their socioeconomic characteristics. By doing so, we can analyze the impacts of various policy scenarios on water demand. For example, the land use patterns, labor force allocation, crop production and food security, and agricultural input–output benefits can be affected by different land use patterns and economic behavior of farmers in different water resource allocation scenarios. In addition, the income compensation policies, the adjustment on irrigation water price, and the progress on irrigation technologies are also related to various policy scenarios on water demand. Based on the above three levels of investigations, the useful and key parameters for the DSS can be obtained, thus providing suggestions and recommendation for the management, institution, and policies to build a water-saving society.

As for the water efficiency in the HRB, the existing water management strategy should be improved firstly. Establishing water management system based on the theory of "water rights, water market" is an important method to improve the allocation efficiency of water. Although water managers in the middle reaches of the HRB introduces the "water right" for water resources management, the leverage function is failed to play a role because of the deficient water rights trading market. Research shows that market-oriented water management framework is beneficial to allocate water and improve water efficiency (Pigram 1999). How to allocate the water resource among multiple regions and industries efficiently is the vital joint of augmenting the water use efficiency to sustain the balance between ecology and economy, and also within the related economies.

Research on the optimal allocation of water resource in China is to build the input–output model and the Computable General Equilibrium (CGE) model, both including the water resource account (Deng et al. 2014a; Wu et al. 2014; Zhao et al. 2010).The extended input–output model and CGE model can be used at basin and county level to analyze the impacts of water right transformation and industrialization (Deng et al. 2014b). Other partial equilibrium models can be used to allocate the water resource among the irrigated areas according to the crop pattern, irrigation rate and other agricultural attributes, and these are the core of the system to calculate and improve the water efficiency. Some scholars explored the effects of water market regulation strategies such as the reform of water price and the transaction of water rights through building input–output model in the Yellow River Basin.

In addition, with the development of computer modeling technology, CGE model has become an effective tool to explore the effects of policies on water management. For instance, the CGE model had been used in Beijing to evaluate the economic policies on the water price and water allocation (Deng et al. 2014a). A number of indicators of water consumption were established to analyze the structural relationships between economic activities and their physical relationships with the water in Zhangye (Wang et al. 2009). Other relevant studies at different scales includes the impact of water allocation on socioeconomy of different districts in Yellow River basin, the economic impact of South-to-North Water Diversion Project on different Administrative Region (Berrittella et al. 2006; Feng et al. 2007). The social and economic data used in most of these studies are static and on a single period, which are unfavorable for the scientific research applied to water management.

In this sense, it is necessary to build multisector dynamic CGE model for water allocation to comprehensively consider the effects of technological progress, the water rights system, water market on water demand (industrial water, ecological

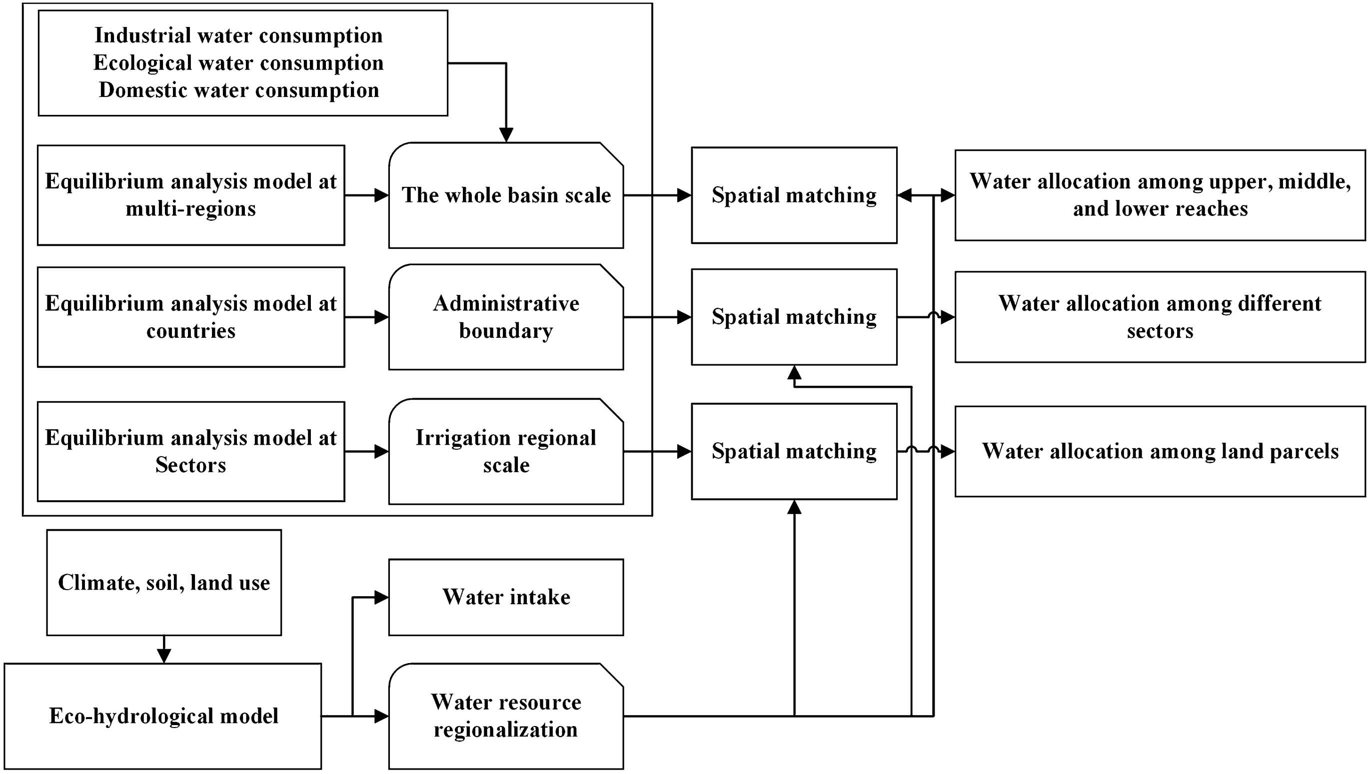

Fig. 8 Multilevel water allocation strategy among irrigated area, counties and sections of basin in the Heihe River Basin

water, and domestic water), and water efficiency (Fig. 8). The framework of CGE model should incorporate the water and land use resource as the production inputs into the production function to characterizes the configuration on the water and land resources in various social and economic sectors under market price adjustment. The rationality of water rights allocation of the river basin is that it can clarify a series of complex relationships, such as the contradiction between water supply and demand; the competition among different sectors; the water coordination among upper, middle, and lower reaches; the investments about different water projects; the benefits of economic and ecological water consumption; as well as the contemporary and future water consumption. Only in this way, can we achieve a relatively fair, acceptable water allocation scheme.

Summary

In this chapter we discuss how to mitigate climate change impacts for optimizing water productivity. Firstly, we present an approach to investigate the contribution of glacier melting and climate change to streamflow by coupling the SWAT model with a glacier melting algorithm. We examine the performance of the improved SWAT model in the upstream Heihe River Basin where topography is complex and the runoff is influenced by snowfall, glacier, and climate change. This is the first attempt for predicting future streamflow in the upstream Heihe River Basin. The approach is proved to be effective in simulating glacier melting to describe streamflow changes influenced by climate changes. Technically, calibration is performed using the automatic SWAT-CUP tool. The simulated streamflow better matches with our observed records. The analysis of water balance shows that the glacier melting influences the marginal changes of streamflow, infiltration, and evapotranspiration. The model performance is statistically improved by using the elevation band approach, and thus this approach is highly recommended to be applied for similar mountainous watersheds. The simulation results indicate that the glacier melting made about 8.9% contribution to streamflow in 2010. However, such an increasing trend of glacier runoff is not sustainable since the glacier recession will sufficiently decrease glacier area and thus reduce the melt-water volume in the long run. Our study reveals that alpine glacier of the upstream area is significantly unbalanced in the regional water resource under the current climatic condition, and the glacier would disappear in upstream Heihe River Basin over the next 40 years, which might further aggravate future water scarcity in the Heihe River Basin. The average snowline will rise by 100 m for each degree of warming, and the glaciers will also retreat. The results also indicate that the streamflow increased with precipitation rise, and decreased with temperature rise, without considering the contribution of glacier. The elevation around 4700 m is the threshold of the glacier change, below which there will be likely less glacier. Meanwhile, the 4700 m elevation is also the tipping point of precipitation change.

Due to the relationship between upper stream and middle stream in Heihe River Basin, we used and improved the ORANI-G model by introducing the water resource into the CES production function. Based on the definition of water productivity, we analyzed water productivity changes caused by change of the water input. The results firstly show that the current water productivity is underestimated. Secondly, agricultural water use accounts for the largest part of water consumption, and therefore enhancing agricultural water productivity can greatly mitigate the water shortage. Thirdly, the water productivity of the agriculture industry is lower than that of the secondary and tertiary industries. This indicates that reformation of the industrial structure and development of water-saving industries can also mitigate the water shortage. Fourthly, the results of sensitivity analysis show that CES changes have relatively small impacts on production in each sector, but a higher CES of water to other production factors can still contribute to sustainable development.

Finally, we came up with some strategies to mitigate climate for optimizing water productivity. With an increasing competition for water across sectors and regions, the river basin has been recognized as the appropriate unit to analyze and confront the challenges of water management. Especially, the HRB is facing competition problems for water uses among domestic, industrial, and agricultural sectors, and between users and ecological needs. Therefore, coupling of the eco-hydrological model and social–economic model is to optimize the necessary premise of integrated river basin management. Generally, conflicts of priorities on water resource coupled to the severe natural conditions make it urgent to build a successful water management system for different stakeholders in the HRB. In this sense, establishing a DSS for water management is an important method to realize the adaptive water management for the sustainable development of the HRB. Contemporarily, there are a series of worldwide research works on water management in river basin. Some counties have presented and improved their own policies and regulation measures based on their own water problems and national conditions. All of these provide some experience for integrated water management of the HRB. Nevertheless, the basin is a dynamic, multivariate unbalanced, open dissipative “unstructured” or “semi-structured” system. Considering driving characters of two dimensions (Nature-Society) for water reallocation, there did not exist modes or systems, which could be copied or applied to the HRB directly.

Throughout studies on the HRB and other inland rivers, it can be identified that promoting water management from water demand management to water consumption management is an important direction for scientific and sustainable development of the HRB. Furthermore, from the institutional perspective, a spatially and dynamically effective water allocation scheme is a strategic need for rational and efficient use of water in the HRB. In view of the abovementioned structure and efficiency of the current water consumption situation, a pressing matter of the moment for reforming the water management systems in the HRB is to improve the water right system based on the water demand in production, human living, and natural ecology.

In summary, it is necessary to establish an integrated water management system based on the water carrying capacity in order to provide support for the strategic decision-making at watershed scale for sustainable development of the HRB. In addition, establishing an integrated model on river basin with a clear physical process, powerful functions, and strong applicability has universal significance. It can also be applied to many inland basins in China, as well as other inland river basins which are distributed over all the continents of the world and accounts for 11.4% of the global land area, and provide significant support for sustainable development of regions with severe water shortage, fragile environment, and rapid development demand.

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