Science of the Total Environment 741 (2020) 140387

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Alleviating water scarcity and poverty in drylands through telecouplings: Vegetable trade and tourism in northwest China

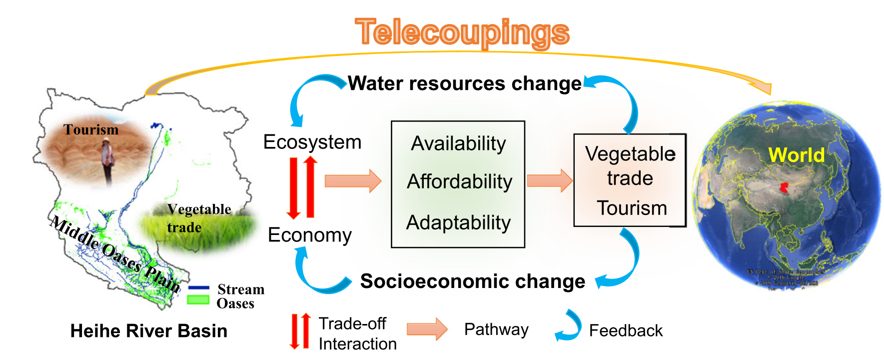
Yingying Yao [a,*], Jing Sun [b], Yong Tian [c], Chunmiao Zheng [c], Jianguo Liu [d]

[a] Department of Earth and Environmental Science, School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi, China
[b] Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing, China
[c] School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, Guangdong, China
[d] Center for Systems Integration and Sustainability, Michigan State University, East Lansing, USA

HIGHLIGHTS

- Telecoupling effects of vegetable trade and tourism on water saving and poverty alleviation are evaluated.
- A quantification framework integrating the hydrological and socioeconomic systems is built.
- Water sustainability is determined by climate and social attributes.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 17 April 2020
Received in revised form 28 May 2020
Accepted 19 June 2020
Available online 20 June 2020

Editor: Deyi Hou

Keywords:
Drought
Poverty alleviation
Tourism
Vegetable trade
Water scarcity

ABSTRACT

Water scarcity and poverty are among the most significant global challenges, especially in the world's arid regions. Many countries have been trying to address these challenges. Facilitated by the construction of infrastructure (e.g., high-speed rails) and development of services industries (e.g., hotels and resorts), telecouplings (human-nature interactions over distances, e.g., vegetable trade and tourism industry) are expected to alleviate both water scarcity and poverty, and have been much supported by the central government of China. However, the extent to which these telecouplings can save water and reduce poverty remains unclear and requires quantification. Employing the simulated results from an integrated hydrological model, crop growth model, and multiple socioeconomic data from a large arid region of northwest China, the Heihe River Basin, we evaluated water scarcity using a composite index that considered both water resources and poverty between 2000 and 2012, and assessed the effects of the vegetable trade and tourism on water scarcity and income. Our results show that the vegetable trade contributed 30% of the total water saving and brought an extra 33% of income to rural residents. The tourism industry's contribution of saving water increased from 1% of its total water use in 2000 to 22% in 2012 through its ongoing expanding market. Our results also implicate that future water sustainability is determined by climate factors and by social factors, such as population, economy, policy, and technological developments. Our study provides insights into northwest China and can be used to develop arid regions around the world to better manage natural resources and reduce poverty.

* Corresponding author at: Xi'an Jiaotong University, China.
E-mail address: yaoyy27@xjtu.edu.cn (Y. Yao).

https://doi.org/10.1016/j.scitotenv.2020.140387

1. Introduction

Water resources are critical for food security, economic development, and ecosystem services (Oki and Kanae, 2006). Poverty and water scarcity are global biggest challenges and among the United Nations Sustainable Development Goals, which are particularly serious for arid developing regions around the world (Reynolds et al., 2007; Sietz et al., 2011; Xu et al., 2020). Recent efforts to save water and reduce poverty through social-ecological approach have been highlighted in the drylands (Adhikari, 2013; Li et al., 2016). China has a vast area of dryland which covers almost half of its territory (4,446,000 km^2) and includes extremely arid drylands (1,127,000 km^2), arid drylands (1,341,000 km^2), and semi-arid drylands (1,978,000 km^2) (LADA Project Team, 2010). To meet population growth, the excessive abstraction of water resources for irrigating water-intensive grain food has become an increasing crisis in arid regions of northwest China (Dalin et al., 2014), and has largely restricted economic development and worsened poverty (Westmore, 2018). To bolster the economy and save water, both the central and local governments in northwest China seek potential solutions to develop water-efficient, and local-adapted industries such as the food trade and the tourism industry.

Improved transportation systems and logistics provide opportunities for the development of telecouplings (human-nature interactions over distances) (Kapsar et al., 2019; Liu et al., 2013), such as the food trade and tourism between northwest China and other places, both in its domestic provinces and other countries. The non-grain food trade (e.g., fruit, vegetables, and processed food) and tourism have been encouraged and supported in northwest China as both industries are regarded as being water and energy-efficient, and they generate a high gross domestic product (GDP) with low water resources consumption (Cai and Wang, 2010; Chao, 2014). However, to what extent can the vegetable trade and tourism save water and alleviate poverty for rural populations in arid regions of northwest China? This is not known and needs to be quantified.

Quantifying the impact of the vegetable trade and tourism on water-saving and poverty reduction at a regional scale is challenging, because both water-saving and poverty reduction are composite outcomes resulting from multiple factors of socioeconomic and environmental systems (Ferraro and Hanauer, 2014; Hedström and Ylikoski, 2010). To address such challenges, we focus on two primary tasks: (*i*) to analyze the causal mechanism and separate the contribution of new industry developments from confounding processes (e.g., climate change and other human activities), and (*ii*) to understand the dynamic effect of the transformation of industries (e.g., the non-steady state), as policy implications based on the steady state assumption may be misleading.

Our case study uses the Heihe River Basin (HRB), the second largest endorheic river basin in China. The HRB is chosen for three reasons. First, it is an arid and underdeveloped region located in northwest China, where over 75% of its population depend on agriculture and have an average income that is far below the national average. Driven by the increased demand for agricultural water use (mainly from the middle stream of the HRB), the environment in the lower HRB's stream has deteriorated, intensifying water conflict and economic development. Second, to address the water crisis and reduce poverty, both the central and local governments along the HRB have actively encouraged the vegetable trade and tourism since 2002. The middle stream of the HRB is one of the major "vegetable baskets" of China, and tourism has become one of the dominant industries. Third, the economic gain from vegetable exports has been clearly recorded in the statistical yearbook.

2. Methods

2.1. Study area

This study focused on the prefecture-level city of Zhangye in the middle stream oasis of the HRB, where the main vegetable trade and tourism industry is centered (see Fig. 1). The total area of Zhangye is 4×10^4 km^2, and its arable land area is 2.8×10^3 km^2 (approximately 7% of Zhangye). According to the statistical data of 2010, the grain

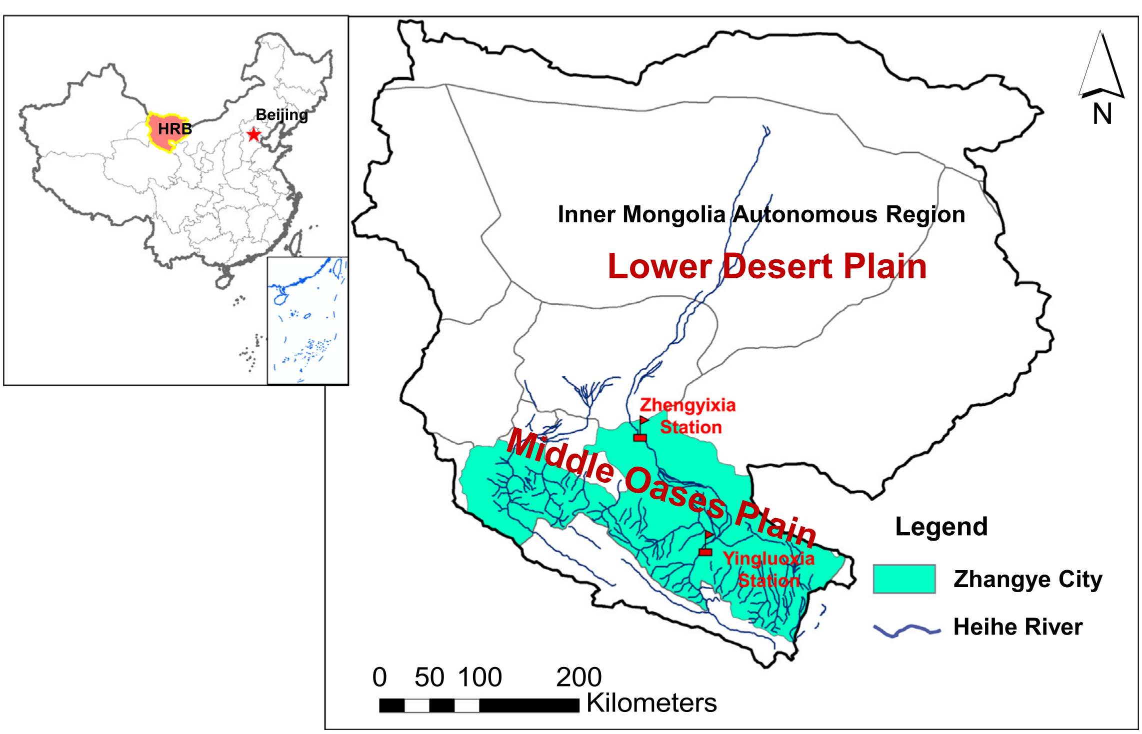


Fig. 1. Study area: the middle oases of Heihe River Basin.

farming area in Zhangye was about 1.8×10^3 km^2, accounting for 65% of the total arable lands; vegetable farming areas was about 286 km^2, accounting for 10.2% of the total arable land. The total population of Zhangye is 1.3 million; approximately 67% of whom are full-time farmers. Zhangye is well known for its high yields in vegetable production among arid regions across Central Asia (Mavlyanova et al., 2014), and has become a significant source of income for local farmers (for example, the vegetable production increased sevenfold between 2000 and 2012) (GDYEB, 2000-2012). Irrigated water depends on the Heihe River, and the gauging stations of Yingluoxia (YLX) and Zhengyixia (ZYX) record the streamflow consumed by Zhangye.

Zhangye is one of the most famous tourist resorts along the Silk Road, and is famous for its splendid cultural heritage and magnificent natural landscapes. There are nine national 4A-level tourist attractions (where 4A refers to top standard in products, services, and environments), and four 3A-level tourist attractions alongside other various natural reserves and parks. The total area of these tourist attractions is approximately 560 km^2 (GFSP, 2014), which is the equivalent of a two-fold in vegetable farming areas in Zhangye. The annual income from the tourism industry increased ten-fold from 2000 to 2012, contributing approximately 45% toward the local economy (GDYEB, 2000-2012).

2.2. Water scarcity index (WSI)

We adopted a composite index—a water scarcity index (WSI)—to evaluate the vegetable trade and tourism on both water-saving and poverty alleviation. The WSI evaluates the availability of natural water resources (e.g., precipitation, surface water, and groundwater), the adaptability toward social water (i.e., water allocation among sectors and people), and the affordability of structural water (i.e., the capacity of people or sectors to obtain water) (Komnenic et al., 2009; Molle and Mollinga, 2003; Sullivan, 2002). The changes of affordability caused by industry transformation can be used to evaluate the poverty alleviation.

The availability, affordability and adaptability are indicators used for quantifying water scarcity. Thus, the WSI here is a composite index based on three indicators:

$$WSI = \frac{\sum_{i=1}^{N} w_i X_i}{\sum_{i=1}^{N} w_i} \tag{1}$$

where X_i represents the indicator of availability, affordability, and adaptability, and w_i is the weight applied to that indicator. The published literature and reports on water issues of Heihe River Basin addressed the significance of availability, affordability and adaptability, however, the weight of these three factors have not been identified (Cheng et al., 2014; Guo et al., 2009; Li et al., 2018a, 2018b; Wang et al., 2018). Thus, it is assigned as 1 for the three indicators in this study on the assumption that the availability, affordability and the adaptability are equally weighted in Zhangye.

In this study, the indicator of availability (R) can be represented as:

$$R = Q - WU \tag{2}$$

where Q represents the maximum total water supply without causing adverse effects on the environment, and the Q includes surface water and groundwater, WU is the actual total water use for the middle HRB.

Since 67% of the population depends on agriculture for a living in Zhangye, the indicator of affordability (P) is represented as the annual per capita income for farmers:

$$P = per\ capita\ income\ (yuan/year) \tag{3}$$

Since the agricultural sector has consumed over 90% of the water supply in the study area (Wang et al., 2009), the indicator of adaptability (S) can be represented as the share (percentage) of total water use (*WU*) for other industry and service sectors:

$$S = 1 - \frac{WU_{Agriculture}}{WU} \tag{4}$$

where, $WU_{Agriculture}$ is the water consumption in the agricultural sector.

As the three indicators have different units, each indicator was transformed to use standardized scores for easier comparison (Joint Research Centre-European Commission JRCEC, 2008):

$$Score_{X_i} = \frac{X_i - \min(X)}{\max(X) - \min(X)} \tag{5}$$

where X_i is value of indicator in year of i, and $\min(X)$ and $\max(X)$ are the maximum and minimum values of all time series of indicator $X_i$during the study period of 2000 and 2012, respectively.

2.3. Quantification framework for WSI

To evaluate the effects of the vegetable trade and tourism on the WSI, we treated them as an experimental factor to quantify the WSI differences between the condition of developing the vegetable trade and tourism (i.e., their real-world historical condition), and the condition of not developing the vegetable trade and tourism (i.e., a scenario used for comparison purposes only). The evaluation process included three parts: (*i*) quantifying the real-world WSI based on collected historical data and modeling results which were used as the baseline reference; (*ii*) quantifying the amounts from the domestic and international vegetable trade and the number of domestic and international tourists and their incomes; and (*iii*) calculating the WSI of designed scenarios, comparisons with the baseline, and evaluating the effects of the vegetable trade and tourism on the WSI (see Fig. 2).

2.4. Water consumption estimation

2.4.1. Water resources estimation

We evaluated water resources using surface streamflow and groundwater based on a well-calibrated integrated model (Tian et al., 2015a; Yao et al., 2018) which incorporated five fundamental hydrological components: atmosphere, soil zone, streams and lakes, unsaturated zones, and groundwater systems. This integrated model was calibrated based on streamflow records of 12 gauging stations and 47 monitoring wells, and the independent remote sensing data of Evaporation (ET) and Leaf Area Index (LAI) were used to compare with the simulated ET and LAI (Tian et al., 2015a). The flux among the five hydrological components and the available water resources were simulated based on this well-calibrated model. The groundwater recharge was derived from the simulated results of this model and acted as the groundwater resources available in this study.

2.4.2. Estimation of water consumption by the vegetable trade

We collected data on Zhangye's total annual city-level agricultural production and export income from published Statistical Bulletin (GDYEB, 2000-2012). Specifically, we collected data on arable areas and on the production of major crops per ha (e.g., grain, vegetable, rapeseed), the amount of export commodities by category from the Statistical Yearbook of Gansu Province (GDYEB, 2000-2012), and data on the provincial-level annual price of agricultural products from the China Yearbook of Agricultural Price Survey (NBSC, 2000-2012). Moreover, we used the price and the total income of international trade to estimate the flow of the vegetable trade in HRB internationally, estimated the domestic trade volumes by calculating the total vegetable production as subtracted from local consumption and the export amount, and collected the annual city-level number of tourist and their income data from Departure and Entry Office in Gansu Province.

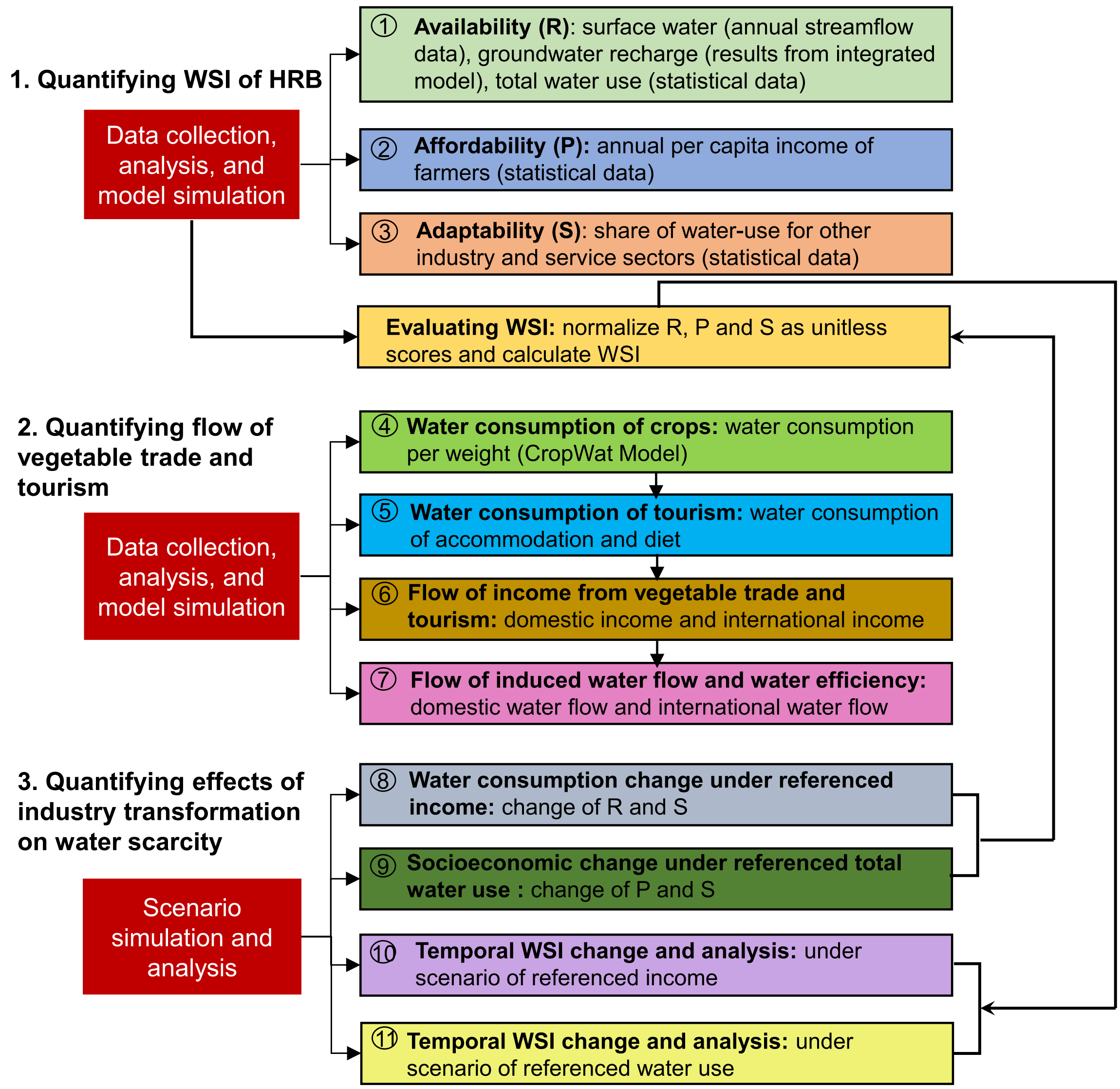


Fig. 2. Schematic summary of quantification framework.

The total water consumption from agricultural products included the water requirements for the growth of crops and the irrigation loss (Eq. (6)). We used the CropWat model (Smith, 1991) to calculate the water requirement per unit area for five agricultural crops of grain, rapeseed, beetroot, vegetables and fruit (Eq. (7)), where the effective irrigation coefficient was set as 0.7 (Xu and Xie, 2004). We then estimated the virtual water use for agriculture based on the calculated virtual water per weight and the estimated export amounts:

$$WR_{Agriculture} = WR_{Crop} + WR_{Irrigation\_loss} \quad (6)$$

where WR_{Crop} is the water requirements for crop growth (m^3/kg), and $WR_{Irrigation\_loss}$ is the loss from irrigation (m^3/kg). Further, the WR_{Crop} was estimated as Eq. (7):

$$WR_{Crop} = \frac{a(ET_0 \times K_c - P_e)}{Y} \quad (7)$$

where, a is the unit conversion factor [unitless], ET_0 is reference evapotranspiration [mm/time] as calculated by the Penman-Monteith equation, K_c is the crop coefficient, P_e is the effective rainfall calculated by the empirical formula based on the analysis of local climatic records and the type of plant [mm/time], and Y is the yield per unit area [kg hm^{-2} time^{-1}]. The monthly climatic data was used to calculate the ET_0 and effective rainfall between 2000 and 2012.

2.4.3. Estimation of water consumption from tourism

The water consumption for tourism mainly included the tourists' daily accommodation and diet (Hadjikakou et al., 2013), referring to the Eq. (4). Water used for accommodation includes the shower, toilet, drinking, and cooking: all of which are consumed directly. We assumed the averaged water used per day per tourist was the same as the averaged water used per day for local urban people (Chung et al., 2018). Moreover, we assumed the averaged staying time of tourists was two days, based on the report from Gansu Tourism Bureau (GFSP, 2014). Therefore, we used the tap water use per capita of local urban areas and the number of tourists to calculate the water consumption within tourists' accommodation (Eq. (9)). The water use for diet covers all water consumed when producing food in an indirect way. We assumed the amount of food that tourists purchased per day was the same as the average amount for local urban people(Chung et al., 2018). The virtual water for producing grain and vegetables was referred from results calculated using the CropWat model. The virtual water for producing livestock products was from published results (Chapagain and Hoekstra, 2003; Chapagain and Hoekstra, 2008; Hoekstra and Chapagain, 2007). Therefore, we used Eq. (6) to calculate the virtual water that tourists consumed as part of their diets in the middle and lower HRB, respectively.

$$TW_{Tourism} = DW_{Accom\ modation} + VW_{Diet} \tag{8}$$

where $DW_{Accommodation}$ is the amount of water directly consumed for accommodation [m^3], and VW_{Diet} is the amount of virtual water consumed for producing diets [m^3], as follows:

$$DW_{accom\ modation} = WU_{local\_urban} \times N_{tourists} \times D_{stay\_time} \tag{9}$$

where WU_{local_urban} is the tap water use per capita in local urban areas [m^3/day], $N_{tourists}$ is the number of tourists, and D_{stay_time} is the stay time.

$$VW_{diet} = N_{tourists} \times D_{stay\_time} \times \sum \left(W_{food(i)} \times VW_{food(i)}\right) \tag{10}$$

where, $W_{food(i)}$ is the weight of the $food(i)$ that the tourists' purchase per day [kg/day], and $VW_{food(i)}$ is the virtual water consumed for producing $food(i)$ [m^3/k].

2.5. Scenario-based experiments design

We constructed scenario-based experiments under the condition that vegetable trade and tourism were not developing, and these experiments were used as an untreated group to compare the realistic situation to evaluate the effects of the vegetable trade and tourism on water scarcity (see Fig. 3). Eight scenario-based experiments were categorized into four classes. The realistic condition was used as the baseline that is the naturally occurring result under the development of both the vegetable trade and tourism. We defined the experiments in class I as the income from the vegetable trade, which changed its planting scheme from vegetables to grain (S1) and rapeseed (S2), to evaluate how much water was saved. We assumed the share of total income from the vegetable trade within the total agricultural GDP remained as the year 2000. We then defined class II as the water consumption of the vegetable trade from its change in planting scheme from vegetables to grain (S3) and rapeseed (S4) to evaluate the increased rural income. We assumed the share of the total water consumption of the vegetable trade in the total agricultural water use remained as the year 2000 in the class II. We defined S5 in the class III as the income from tourism, which changed from developing its strategy from tourism industry to the vegetable trade, to evaluate saving water volumes as caused by tourism, and the effects on rural per capita income. We assumed the share of total income from tourism in the total local GDP remained as the year 2000 in the S5. S6 in class III was the income from the vegetable trade, which changed its developing strategy to tourism. We assumed that the share of the total income from the vegetable trade in the total agricultural GDP remained as the year 2000 in the S6. In class IV, S7 was the total water consumption from tourism, which changed its developing strategy from tourism to the vegetable trade. We assumed that the share of the total income from tourism in GDP remained as the year 2000, replaced water from tourism to plant vegetables, and evaluated the change of water allocation and rural per capita income in the S7.

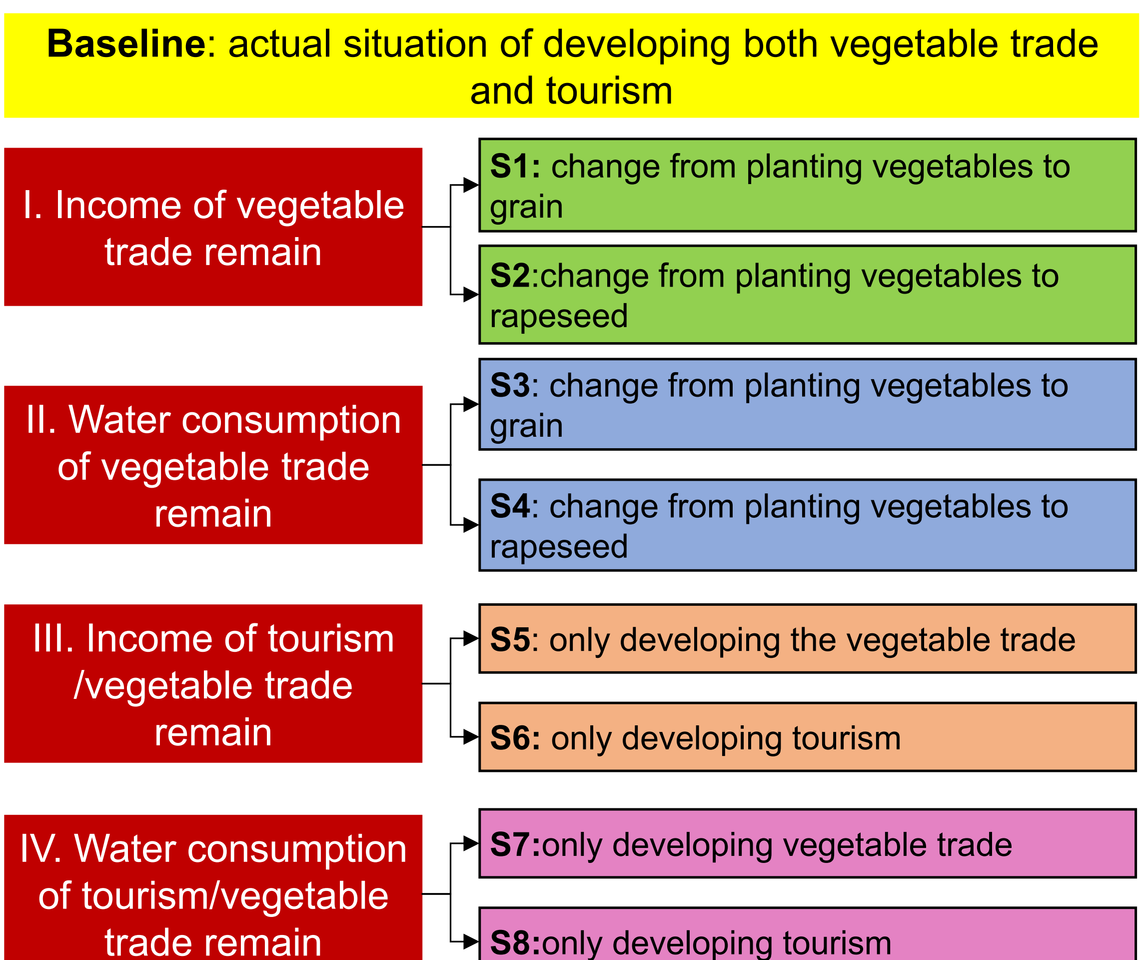


Fig. 3. Schematic summary of scenario design.

In class IV, S8 was the total water consumption from the vegetable trade, which changed its developing strategy from vegetable trade to tourism. We assumed that the share of the total income from the vegetable trade in agricultural GDP remained as the year 2000 in the S8. We then used the replaced water to develop tourism, and evaluated the change of water allocation and rural per capita income.

3. Results

3.1. WSI for baseline condition

Fig. 4 shows the trend of water resources and water use in Zhangye. The rainfall and surface runoff in the gauge stations of YLX and ZYX were observed from records, whereas the groundwater recharge was the simulated results by the integrated hydrological model (Tian et al., 2015b; Yao et al., 2018). All water resources experienced a rising trend, and thus the total available water resources increased between 2000 and 2012. Meanwhile, agricultural water-use experienced a declining trend, and the percentage of agricultural water-use in the total water use decreased from 96% in 2000 to 94% in 2012. Water use for other sectors (hereafter regarded as non-agricultural sectors) increased slightly. The water use in non-agriculture sectors experienced an increasing trend with a “hump” in the profile between 2004 and 2005 (which resulted from the increase in total water supply, but the saving in agricultural water-use). The annual rural income per capita in the study area (indicating the level of poverty and affordability of water resources) increased from RMB 3000 in 2004 to RMB 7000 in 2006 (USD 1 = RMB7.808 in 2006).

Based on the evaluation of the water supply, water-use, and affordability as shown in Fig. 4, the practical WSI was evaluated to show the overall performance of water scarcity of the HRB between 2000 and 2012 (i.e., the baseline condition: see Fig. 5). The higher scores of WSI are indicative of lower level of water scarcity. The increase of WSI indicated that water scarcity was relieved, and vice versa. The increasing WSI (from 0.06 in 2000 to 0.662 in 2012) showed that the water scarcity had been relieved, and that water resource availability was the main contributor (45% on average), followed by adaptability (36% on average). Affordability contributed less than 20% of the WSI. The results indicate that the increased water resources associated with the climate warming trend (i.e., the increase in rainfall and surface runoff) greatly help relieve the water crisis in the HRB, although its uncertainty would fluctuate the WSI. The raised percentage of water-use for non-agricultural sectors (S) indicated the change of water allocation with the industry's transformation.

3.2. Water consumption evaluation for the vegetable trade and tourism

As the local government of Zhangye along the middle HRB has supported the industries being water-efficient since 2002 under the double pressure of water stress and the developing economy, the vegetable trade and tourism have both experienced great improvement. During 2000 and 2012, the vegetable trade experienced a fivefold increase in its volumes and income, where its domestic part kept stable growth while its international part experienced a spike between 2007 and 2010 (see Fig. 6). There was a dramatic decline from 2010 to 2012, mainly because of the change in export tax rebate policy in 2012 (i.e., the taxation rate for dehydrated vegetables declined from 17% to 13%, while the refund duty declined from 15% to 5%). Between 2009 and 2013, domestic tourism increased significantly by both the tourist number and income, and the international tourism also stably increased.

Water consumption for agriculture experienced a rise in its trend from 60×10^6 m^3 to 105×10^6 m^3 from 2000 to 2012 (see Fig. 7, where water consumption in volume per income is the ratio between total water consumption and total income, which indicates the water efficiency for a given sector). For the period of 2004–2012, water efficiency for the vegetable trade decreased by 66%, where the sudden rise in volumes of water consumption in 2004 was mainly caused by the increase in production and trade, yet at a lower price than in 2003. Water consumption volumes for tourism gradually increased by 92% between 2001 and 2009, but experienced a dramatic increase by 475% between 2009 and 2012. Meanwhile, water efficiency for tourism declined by 53% from 2001 to 2009, and continued declining by 35% between 2009 and 2012. Such decline indicates that the growth rate of travel expense was more than that of the number of tourists between 2001 and 2009, yet it became the opposite between 2009 and 2012.

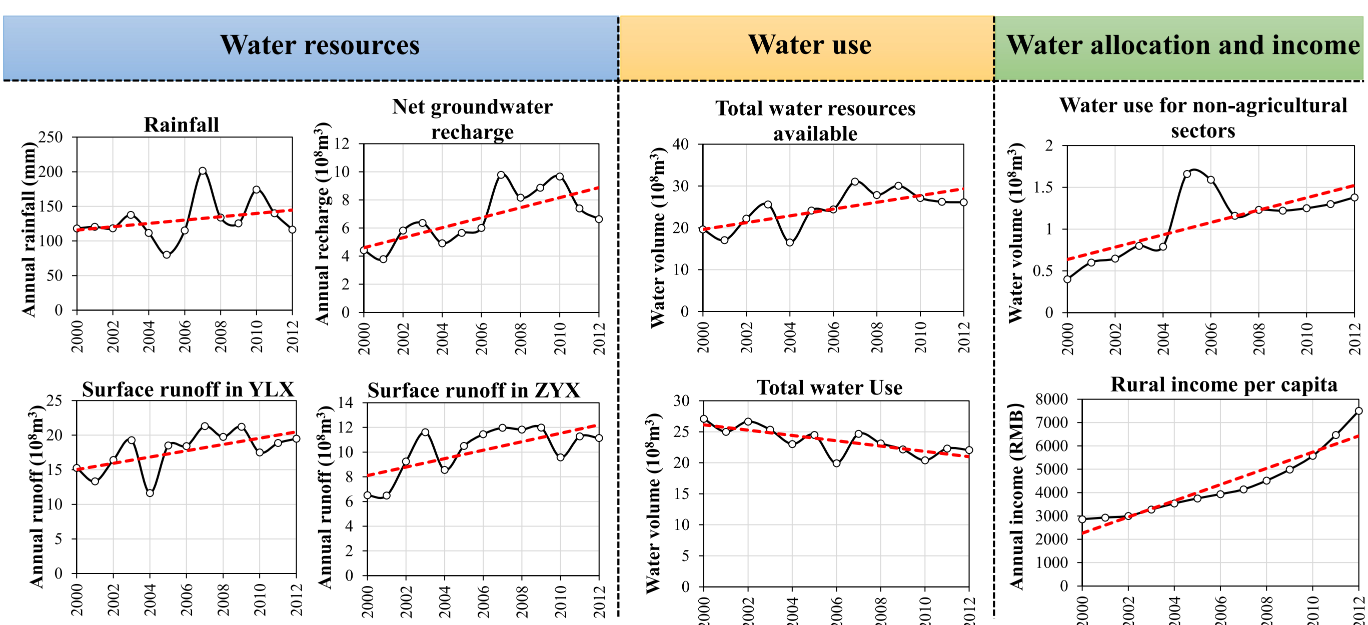


Fig. 4. The trend of water resources, water use, water allocation, and rural income between 2000 and 2012. The graphs with the blue shaded color represent the natural water resources affected by climate change, including rainfall and surface runoff from gauge stations in YLX; the graphs with yellow shaded color represents the water resources associated by climate condition and human activities. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

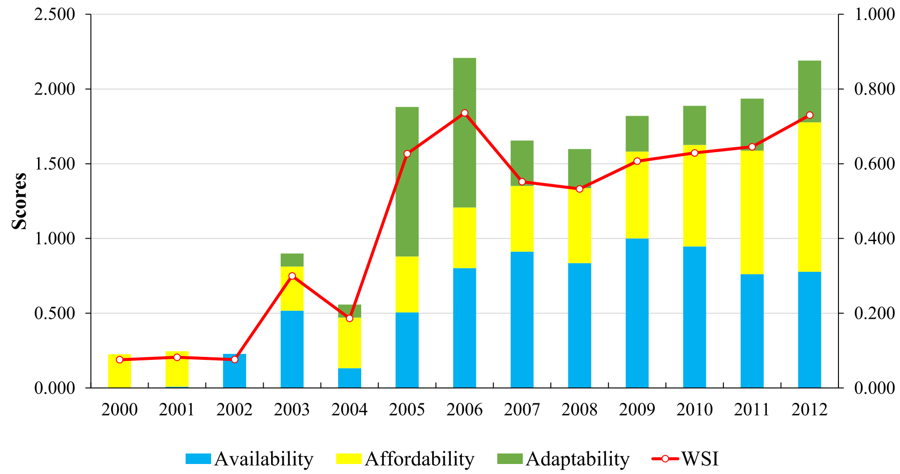


Fig. 5. Evaluated availability (available water resources, referred to as R), affordability (capita income for farmers, referred to as P), adaptability (percentage of water use for non-agricultural sectors, referred to as S), and water scarcity index (WSI) for the HRB between 2000 and 2012.

3.3. Effects of the vegetable trade and tourism on water and income

Based on the evaluated WSI for the real world's historical conditions of water consumption for the vegetable trade and tourism, the scenarios in the quantification framework separate the effects of vegetable trade and tourism on water consumption and rural income, as shown on Fig. 8. The WSI of S1 (if planting grain rather than vegetables) and S2 (if planting rapeseed rather than vegetables) represent the vegetable trade as contributing 8% and 17%, respectively, of the improved WSI in 2012. The positive score ΔR (i.e., more water resources available) and ΔS (i.e., bigger proportion of water use for other non-agricultural sectors) in comparison between the baseline and both S1 and S2 indicate that saved water through selling was reallocated to other sectors. The results of the comparison between the baseline and both S3 and S4 represent that the vegetable trade helps to increase 10% of its rural income under water use constraints. S5 shows that developing the vegetable trade without tourism can increase rural income at the cost of impeding water-saving and the development of the non-agricultural sector. S6 shows that developing tourism without the vegetable trade can help to save water and benefit other sectors, but can cause income losses for farmers. S7 shows that developing the vegetable trade without tourism under water use constraints reduces the total income for

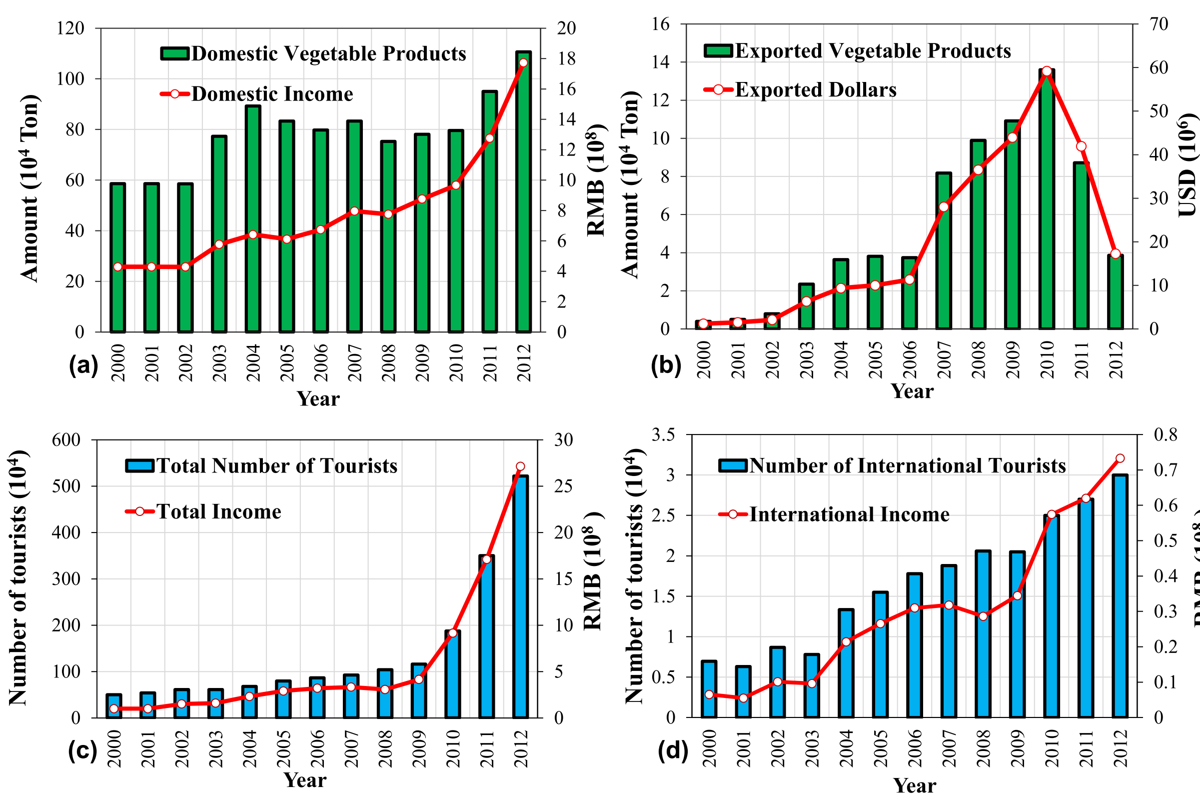


Fig. 6. Evaluated availability (available water resources, referred to as R), affordability (capita income for farmers, referred to as P), adaptability (percentage of water use for non-agricultural sectors, referred to as S), and water scarcity index (WSI) for the HRB between 2000 and 2012.

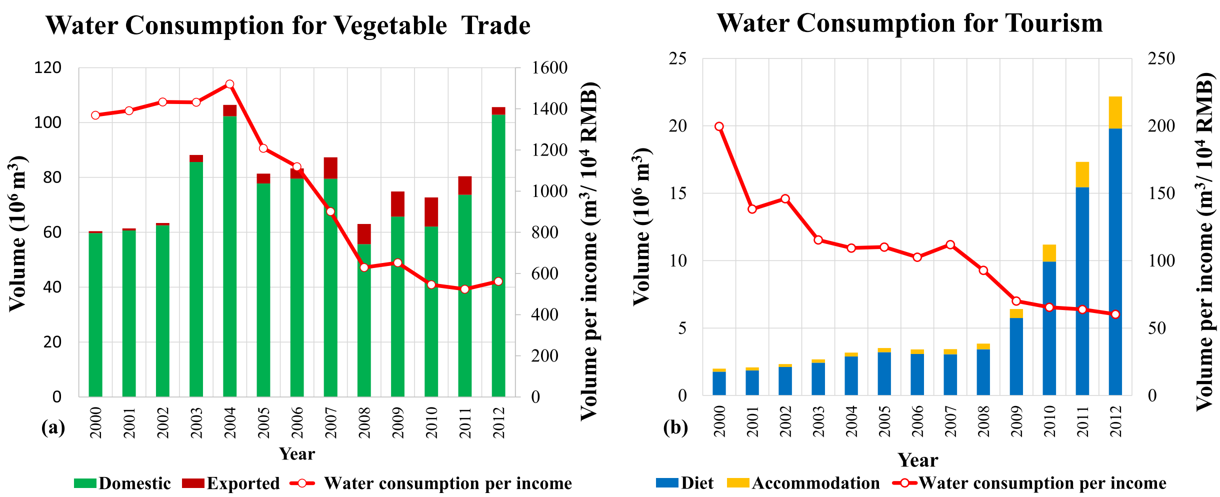


Fig. 7. Estimation of water consumption and water efficiency for the vegetable trade (a) and tourism (b) effect of the vegetable trend tourism on water and income.

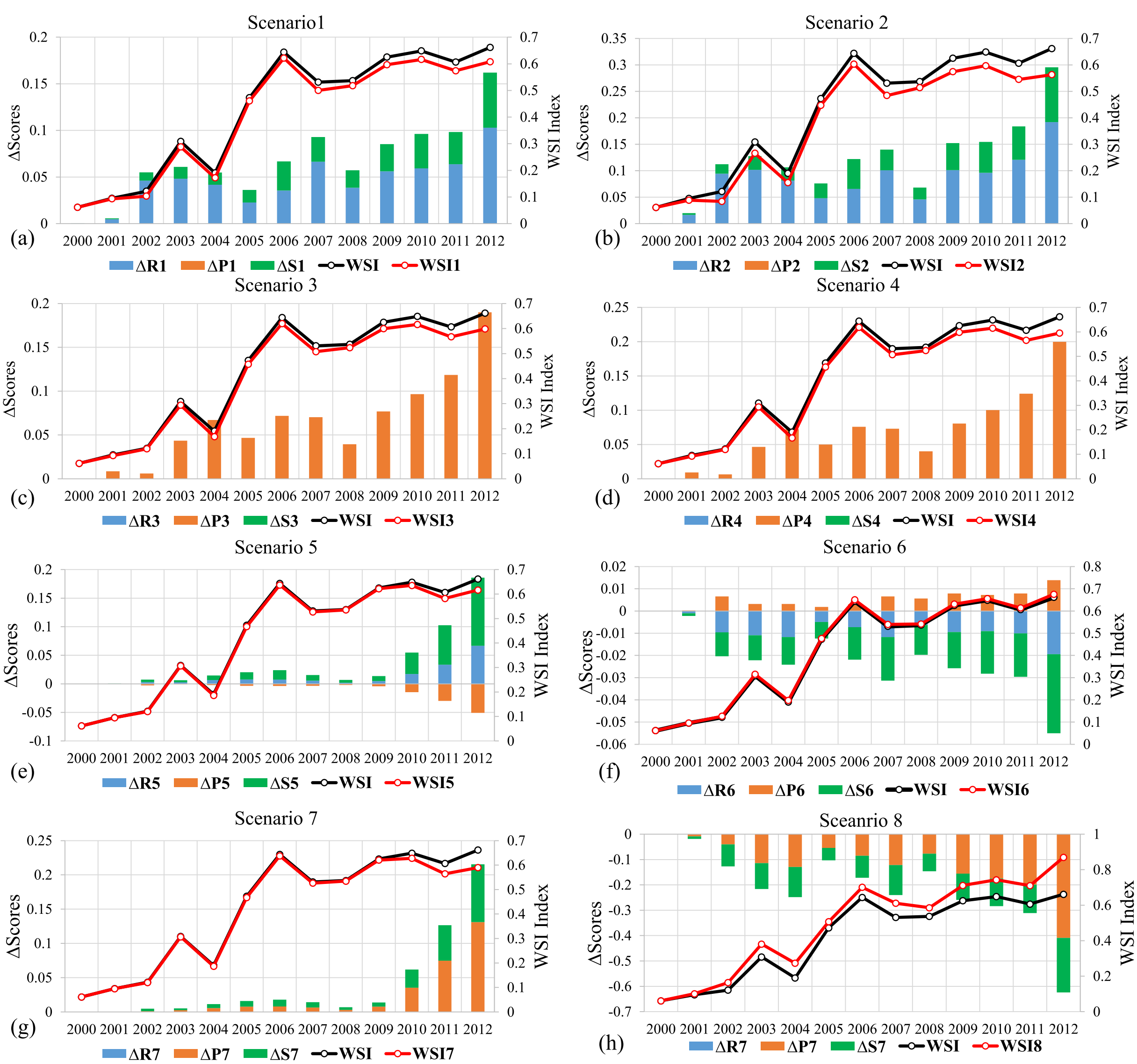


Fig. 8. Simulated WSI for eight scenarios. The WSI (black line) represents the baseline condition and the WSI (red line) represents the simulated scenario. The bar chart represents the contribution of R, P, and S. ΔScores represent the difference between the baseline and scenarios, and ΔR, ΔP, and ΔS represent the contribution of each factor. The positive Δscores represent the strategy of the baseline as better than the scenario, and the negative is the reverse case. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

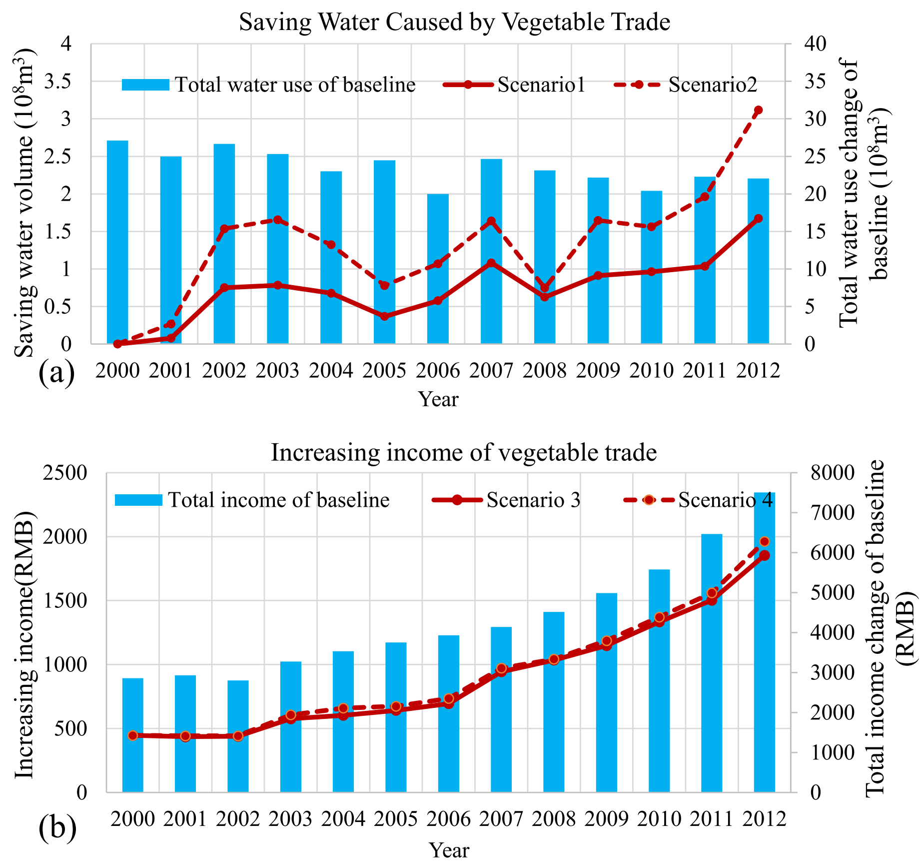


Fig. 9. Effects of the vegetable trade on water-saving and increased income. The red lines in the scenarios represent the saved water volumes (a) and increased income (b) as caused by the vegetable trade, while the blue bars represent the change in total water use (a) and total rural income per capita of the baseline (b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

both rural and urban residents. S8 shows that developing tourism without developing the vegetable trade under water use constraints can contribute 30% of the improved WSI in 2012, indicating that a transformation of the industry can alleviate water scarcity.

The absolute value of saving water and increasing income from the vegetable trade was evaluated by S1 and S1 as shown on Fig. 9. The total water use of the study area represents a decreasing trend from 27.1×10^8 m^3 in 2000 to 22×10^8 m^3 in 2012. Compared with planting grain as shown in S1, the vegetable trade helps to save water by 1.6×10^8 m^3, accounting for 31% of the total water saved in 2012. Compared with planting rapeseed as shown in S2, the vegetable trade helps to save water by 3.1×10^8 m^3, accounting for 60% of the total water saved water in 2012. In Fig. 7(b), the total annual rural income per capita increased from RMB2860 in 2000 to RMB7500 in 2012, while the increasing income from vegetable trade was from RMB500 in 2000 to RMB1900 in 2012, accounting for 41% of the total increased income in 2012. Moreover, the contribution of the vegetable trade on rural income was stable.

The effects of developing both the vegetable trade and tourism were evaluated under the income from the replaced industries (see Fig. 10). The effects of tourism on saving water can also be seen in S5 in this Figure. The tourism industry can help reduce 1– 1.2×10^8 m^3 of water before 2009, but this saving volume was reduced to less than 0.2×10^8 m^3 after 2009. In terms of income, developing the vegetable trade without tourism failed to increase rural income, and the rural per capita income would have reduced by RMB500–600 per year before 2009, because of the decline in the total income level. However, by enlarging the vegetable market, the loss of income from tourism would be offset. If only tourism developed, an extra 0.3×10^8 m^3 of water would have been saved for 2012, and incomes would have increased by about RMB140 per year for farmers.

The effects of only developing the vegetable trade and tourism under water use constraints on annual rural per capita income were evaluated in Fig. 11. The annual rural income would have increased by a maximum of RMB1347 in 2012 if only developing the vegetable trade, while the annual rural income would have declined by RMB4200 in 2012 if only developing tourism. This indicates that developing a non-agricultural industry under water use constraints would greatly hurt local rural incomes.

4. Discussion and conclusions

4.1. Effects of the vegetable trade and tourism on water saving and poverty

The vegetable trade and tourism industry, which are considered as being able to save water and reduce poverty, have been supported by both the central and local governments for arid regions in northwestern China. However, the extent to which these schemes can relieve the water crisis and increase income is rarely quantified. This systemic quantification not only evaluates the state of water scarcity, but also separates the causal effects of developing the vegetable trade and tourism from the composite results. Due to climate change, the increased rainfall and surface river runoff provide more water resources. According to the scenarios of the planting schemes, the vegetable trade contributes at least 30% of water-saving volumes under the condition of no loss of rural income; whereas it supports at least 33% of increased rural income under the water use constraints. Although the tourism industry failed to save water before 2009, its contribution toward water-saving has been ongoing, and has increased from 1% to 22% by its expanding market.

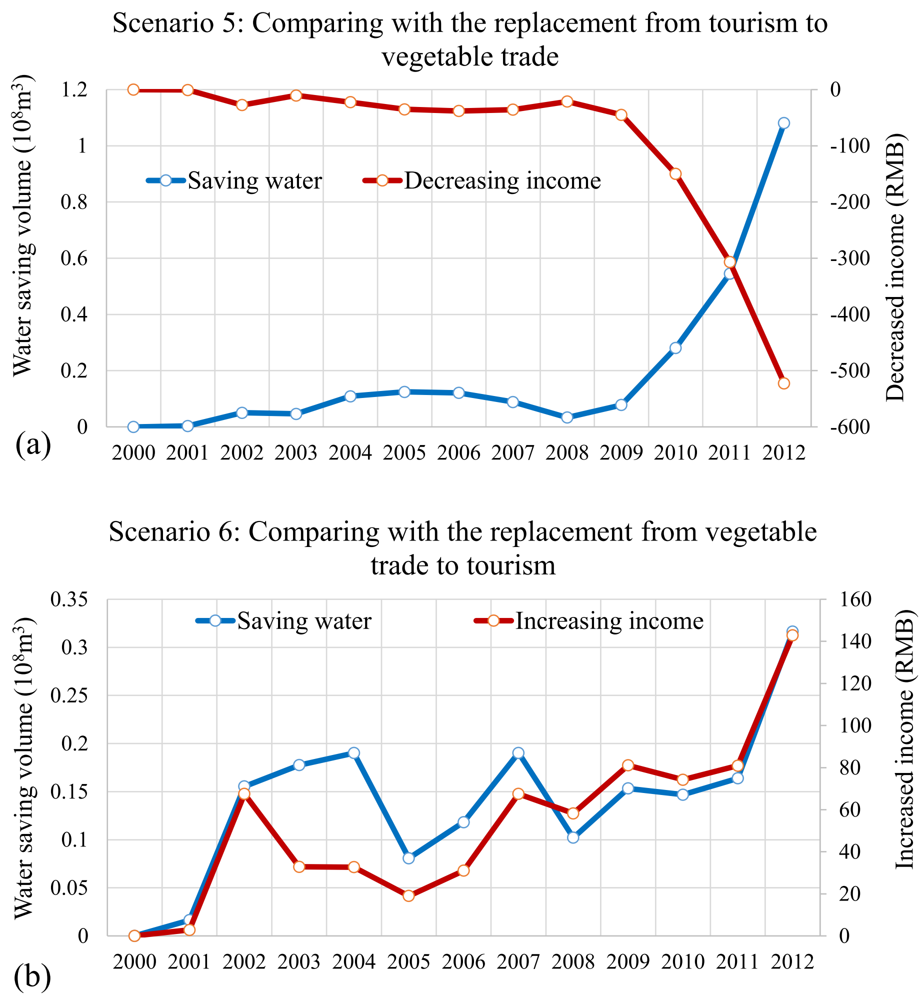


Fig. 10. The effects of developing either the vegetable trade or tourism on water-saving, and the annual rural income per capita.

4.2. Multiple sectors coordinated development

Our quantification further indicates that only developing the vegetable trade and only developing tourism can positively affect local income and can contribute toward water allocation changes. The vegetable trade is the direct source of rural income, whereas tourism improves the local GDP and is beneficial for the per capita income for both urban and rural residents with more effective water use. However,

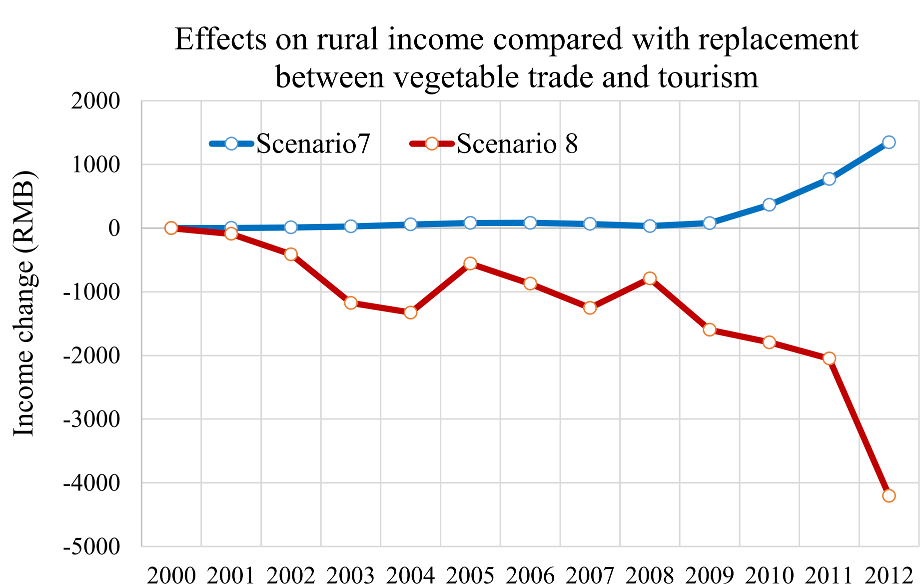


Fig. 11. The effects of only developing the vegetable trade (Scenario 7) or only developing the tourism industry (Scenario 8) on annual rural income per capita under water constraints.

developing tourism without the vegetable trade would greatly hurt rural income on an assumption that the fraction of the rural population in the total local population is unchanged (i.e., the rural population accounts for 67% of the local total population). It implicates that the fast upgrading-industry would instead affect the income of laborers dependent on the traditional industry with low technique-levels if the corresponding labor structure of the socio-economic system remains unchanged. Improved traditional agriculture and expanding tourism industry should be integrated to constitute a synergized development mode. The tourism industry could share the risk of depleting water resources and arable land with the vegetable trade, while the vegetable trade could ensure the direct income of the farmers. Therefore, our analysis calls for water scarcity issues to be discussed in multiple dimensions using local natural-human systems. Relieving water scarcity is not just related to water-use and natural resources, but to the composite results being enacted by the economy, policy, technological developments, and local social structures. Social attributes that influence the water allocation structure determine the fate of water-saving in the future.

4.3. Policy implications

Research on trade-induced water emphasizes the threat of exporting water-intensive products (e.g., particularly by exporting grain) on water scarcity (Dalin et al., 2012; Dalin et al., 2017; Kumar and Singh, 2005). However, understanding how the non-grain trade and tourism is beneficial to water sustainability for export regions and the extent to which it could help save water and improve rural income is even more important. In facing the water scarcity issues in the HRB, policy makers should both consider improving agricultural water-use efficiency in the current condition and adjust the reconfiguration among sectors, for example, by encouraging and guiding farmers to improve their working skills in the industrial or services sectors. Saving water while alleviating poverty is the biggest challenge for drylands around the world. Local water issues are influenced by global mechanisms from climate change that dominates natural water availability, and by the world's economy which drives water-use patterns (Cumming and von Cramon-Taubadel, 2018; Vorosmarty et al., 2015). These should be considered and incorporated in local water management. Our study offers great potential for arid and undeveloped areas to save natural resources and avoid poverty through a reasonable upgrade of the industry.

This study provides a comprehensive study on water scarcity and reducing poverty for northwest China's developing drylands. First, the variations of natural resources and water use were evaluated, and the water allocation and poverty level were addressed accordingly. Second, a composite index considering the factors of availability of water resources, affordability for the rural population, and adaptability for water allocation via a WSI, was used to evaluate the historical water scarcity. Finally, the effects of the booming vegetable trade and tourism industry were analyzed and accessed by a comparison between scenarios and real historical conditions. Our major findings are as follows:

1. Water scarcity has been relieved in the study area. From 2000 to 2012, the increased rainfall and surface runoff upstream as a result of climate change strengthened the availability of the total water resources, and contributed toward 45% of relief for water scarcity. Water use in the agricultural sector decreased, thus promoting water use for other non-agricultural sectors, and increased adaptability, which contributed toward 36% of relief for water scarcity. Increased rural income strengthened affordability, which contributed toward 20% of water scarcity.
2. The evaluated domestic vegetable traded increase about ten-fold from 2000 to 2012, and the international vegetable trade also increased but was easily affected by international policies. The total evaluated number of tourists and their incomes also increased ten-fold. The water consumption for both the vegetable trade and tourism were increasing but their water efficiency was improving with an increase in income.
3. The vegetable trade contributed at least 30% of water in volume under the condition of no loss in rural incomes, while it supported at least 33% of increased rural income under the condition of water use constraints. Although the tourism industry failed to save water before 2009, its contribution to water-saving has continuously increased from 1% to 22% with its expanding market.

Our study offers a new understanding and evidence for examining water scarcity issues in drylands. This provides great implications for policymakers and practitioners to design effective policies and water management schemes to achieve water sustainability.

CRediT authorship contribution statement

Yingying Yao: Methodology, Investigation, Formal analysis, Writing - original draft. **Jing Sun:** Validation, Writing - review & editing. **Yong Tian:** Methodology. **Chunmiao Zheng:** Supervision, Writing - review & editing. **Jianguo Liu:** Conceptualization, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank Editor Deyi Hou and two anonymous reviewers. This work is supported by the National Natural Science Foundation of China (NSFC) (Grants Nos. 41901023 and 91747204). All data reported in this paper can be accessed in the cited references.

References

Adhikari, B., 2013. Poverty reduction through promoting alternative livelihoods: implications for marginal drylands. J. Int. Dev. 25, 947–967.
Cai, M., Wang, Y.-M., 2010. Low-carbon tourism: a new mode of tourism development. Tourism Tribune 1, 13–17.
Chao, L., 2014. Study on the effects of freshwater aquaculture products agglomeration on the adjustment of agricultural structure in Jiangsu Province. J. Anhui Agric. Sci. 36, 117.
Chapagain, A.K., Hoekstra, A., 2003. Virtual Water Flows Between Nations in Relation to Trade in Livestock and Livestock Products. UNESCO-IHE, Delft, The Netherlands.
Chapagain, A.K., Hoekstra, A.Y., 2008. The global component of freshwater demand and supply: an assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. Water Int. 33, 19–32.
Cheng, G., Li, X., Zhao, W., Xu, Z., Feng, Q., Xiao, S., et al., 2014. Integrated study of the water-ecosystem-economy in the Heihe River Basin. Natl. Sci. Rev. 1, 413–428.
Chung, M.G., Pan, T., Zou, X., Liu, J., 2018. Complex interrelationships between ecosystem services supply and tourism demand: general framework and evidence from the origin of three Asian rivers. Sustainability 10, 4576.
Cumming, G.S., von Cramon-Taubadel, S., 2018. Linking economic growth pathways and environmental sustainability by understanding development as alternate social-ecological regimes. Proc. Natl. Acad. Sci. U. S. A. 115, 9533–9538.
Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A., Rodriguez-Iturbe, I., 2012. Evolution of the global virtual water trade network. Proc. Natl. Acad. Sci. 109, 5989–5994.
Dalin, C., Hanasaki, N., Qiu, H., Mauzerall, D.L., Rodriguez-Iturbe, I., 2014. Water resources transfers through Chinese interprovincial and foreign food trade. Proc. Natl. Acad. Sci. 111, 9774–9779.
Dalin, C., Wada, Y., Kastner, T., Puma, M.J., 2017. Groundwater depletion embedded in international food trade. Nature 543, 700–704.
Ferraro, P.J., Hanauer, M.M., 2014. Quantifying causal mechanisms to determine how protected areas affect poverty through changes in ecosystem services and infrastructure. Proc. Natl. Acad. Sci. 111, 4332–4337.
Gansu Development Yearbook Editorial Board (GDYEB), 2000-2012. Stistical Yearbook of Gansu Province (in Chinese). China Statistical Publishing House, Beijing.
Gansu Forestry Survey and Planning Institute (GFSP), 2014. Planning Outline of Tourism Development in "Silk Road" of Gansu Province (in Chinese).
Guo, Q., Feng, Q., Li, J., 2009. Environmental changes after ecological water conveyance in the lower reaches of Heihe River, northwest China. Environ. Geol. 58, 1387–1396.
Hadjikakou, M., Chenoweth, J., Miller, G., 2013. Estimating the direct and indirect water use of tourism in the eastern Mediterranean. J. Environ. Manag. 114, 548–556.

Hedström, P., Ylikoski, P., 2010. Causal mechanisms in the social sciences. Annu. Rev. Sociol. 36.

Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations: water use by people as a function of their consumption pattern. Water Resour. Manag. 21, 35–48.

Joint Research Centre-European Commission (JRCEC), 2008. Handbook on Constructing Composite Indicators: Methodology and User Guide. OECD publishing.

Kapsar, K.E., Hovis, C.L., Bicudo da Silva, R.F., Buchholtz, E.K., Carlson, A.K., Dou, Y., et al., 2019. Telecoupling research: the first five years. Sustainability 11, 1033.

Komnenic, V., Ahlers, R., Van Der Zaag, P., 2009. Assessing the usefulness of the water poverty index by applying it to a special case: can one be water poor with high levels of access? Physics and Chemistry of the Earth, Parts A/B/C 34, 219–224.

Kumar, M.D., Singh, O.P., 2005. Virtual water in global food and water policy making: is there a need for rethinking? Water Resour. Manag. 19, 759–789.

LADA Project Team PRC, 2010. China National Level Report of Land Degradation Assessment in Drylands (LADA).

Li, J., Liu, Z., He, C., Tu, W., Sun, Z., 2016. Are the drylands in northern China sustainable? A perspective from ecological footprint dynamics from 1990 to 2010. Sci. Total Environ. 553, 223–231.

Li, X., Cheng, G., Ge, Y., Li, H., Han, F., Hu, X., et al., 2018a. Hydrological cycle in the Heihe River Basin and its implication for water resource management in endorheic basins. J. Geophys. Res. Atmos. 123, 890–914.

Li, X., Cheng, G., Lin, H., Cai, X., Fang, M., Ge, Y., et al., 2018b. Watershed system model: the essentials to model complex human-nature system at the river basin scale. J. Geophys. Res. Atmos. 123 (6), 3019–3034.

Liu, J., Hull, V., Batistella, M., DeFries, R., Dietz, T., Fu, F., et al., 2013. Framing sustainability in a telecoupled world. Ecol. Soc. 18.

Mavlyanova, R., Mecozzi, M., Ebgmuratov, A., 2014. AVRDC's Partnership for Vegetable Systems Research and Development in Central Asia and the Caucasus. 52 p, Tashkent, Uzbekistan. .

Molle, F., Mollinga, P., 2003. Water poverty indicators: conceptual problems and policy issues. Water Policy 5, 529–544.

National Bureau of Statistics of the People''s Republic of China (NBSC), 2000-2012. China Yearbook of Agricultural Price Survey. National Statistics Press, Beijing, China.

Oki, T., Kanae, S., 2006. Global hydrological cycles and world water resources. Science 313, 1068–1072.

Reynolds, J.F., Smith, D.M.S., Lambin, E.F., Turner, B., Mortimore, M., Batterbury, S.P., et al., 2007. Global desertification: building a science for dryland development. science 316, 847–851.

Sietz, D., Lüdeke, M.K., Walther, C., 2011. Categorisation of typical vulnerability patterns in global drylands. Glob. Environ. Chang. 21, 431–440.

Smith, M., 1991. CROPWAT: Manual and Guidelines. FAO of UN, Rome, Italy.

Sullivan, C., 2002. Calculating a water poverty index. World Dev. 30, 1195–1210.

Tian, Y., Zheng, Y., Wu, B., Wu, X., Liu, J., Zheng, C., 2015a. Modeling surface water-groundwater interaction in arid and semi-arid regions with intensive agriculture. Environ. Model. Softw. 63, 170–184.

Tian, Y., Zheng, Y., Zheng, C., Xiao, H., Fan, W., Zou, S., et al., 2015b. Exploring scale-dependent ecohydrological responses in a large endorheic river basin through integrated surface water-groundwater modeling. Water Resour. Res. 51 (6), 4065–4085.

Vorosmarty, C., Hoekstra, A., Bunn, S., Conway, D., Gupta, J., 2015. Fresh water goes global. Science 349, 478–479.

Wang, Y., Xiao, H.-L., Wang, R.-F., 2009. Water scarcity and water use in economic systems in Zhangye City, Northwestern China. Water Resour. Manag. 23, 2655–2668.

Wang, G., Lin, N., Zhou, X., Li, Z., Deng, X., 2018. Three-stage data envelopment analysis of agricultural water use efficiency: a case study of the Heihe River Basin. Sustainability 10, 568.

Westmore, B., 2018. Do government transfers reduce poverty in China? Micro evidence from five regions. China Econ. Rev. 51, 59–69.

Xu, D., Xie, C.-B., 2004. Key technologies and integration mode for water savings in agriculture during the development of water-saving society in Zhangye Municipality. Journal of China Institute of Water 4.

Xu, Z., Chau, S.N., Chen, X., Zhang, J., Li, Y., Dietz, T., et al., 2020. Assessing progress towards sustainable development over space and time. Nature 577, 74–78.

Yao, Y., Tian, Y., Andrews, C., Li, X., Zheng, Y., Zheng, C., 2018. Role of groundwater in the dryland ecohydrological system: a case study of the Heihe River Basin. J. Geophys. Res. Atmos. 123, 6760–6776.