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Physical and virtual water transfers and the impacts on regional ecosystem quality and resources

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Abstract: The environmental impacts analysis for water transfers are lacking. In this study, the impacts on ecosystem equality and resources due to physical and virtual water transfers were evaluated for the Hetao irrigation district, China. Results indicate: about 4.50×10^9 m^3 of water transferred from the Yellow River to the Hetao irrigation district during 2001-2010 and 2.92×10^9 m^3 water was flowed out from this district virtually simultaneously. The impacts of physical, virtual and net water inflow on ecosystem quality were 1.33×10^9 $m^2\cdot yr$ (positive), 867.60×10^6 $m^2\cdot yr$ (negative) and 465.70×10^6 $m^2\cdot yr$ (positive). The impacts on resources were 28.16×10^9 MJ (positive) for physical water, 18.26×10^9 MJ (negative) for virtual water and 9.89×10^9 MJ (positive) for net water transfer. The environmental influences were more significant for middle areas. The flows of physical and virtual water have increased water stress in some already water scare regions. The increase of physical water flow-in in this district would be difficult due to high financial cost, while the increase of virtual water flow-in could be possible measures to relieve environmental influences. However, others factors such as the social or economic factors should also be considered

1 Introduction

The temporal and spatial mismatches between water availability and water demand have become one of the largest problems to sustainable development for many parts of the world under the impacts of climate changes and human activities [1-7]. Based on the latest projection, an increase of 55% for global water demand would be achieved during the 2000-2050 period which is mainly due to the increase of population and globalization of economy [8]. To relieve the severe water scarcity, a large number of inter-basin physical water transfer projects including the Snowy Mountains Hydro-electric scheme in Australia, South-North Water Transfer Project in China, Great Lakes Basin diversions in Canada, National River-Linking Project in India, Central Valley Project in the United States and others have been developed [9]. In the early 1990s, the concept of virtual water has been promoted which means the water embedded in the traded products. Virtual water transfer means another kind of water resources for the regions that import products and it has been used as a new way to alleviate regional water scarcity [10-12]. Most of the researches are focus on physical or virtual water transfer only, while only a comprehensive analysis by integrating these two kinds of water resources could provide a completed picture for regional water management. Ye et al. have developed a multi-objective optimization model to allocate the water resources for Beijing, China considering the physical water and virtual water at the same time, while the virtual water flows were only focus on agricultural sector [13].

To evaluate the resources consumption impacts, environmental impacts analysis is one of most important parts. Many different methods such as the life cycle assessment methodology have been used to evaluate the environmental impacts associated with resources consumption while the environmental impacts analysis for water transfers are lacking [14-15]. In this study, both the physical water transfer and virtual water transfer due to different kinds of products trades were considered to analyze: 1) the water transfers at the irrigation district scale, 2) the impacts of water transfers on regional ecosystem quality, and 3) the impacts of water transfers on regional resources. In China, more than 3/4 of the grain was produced at the irrigation districts, thus the Hetao irrigation district (the largest gravity-fed irrigation district) was used for a case study. This study was helpful in providing a completed analysis for regional water transfers and could be useful in forming better regional water management practices.

2 Material and methods

2.1 Study area

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Hetao irrigation district, the largest gravity-fed irrigation district of Asia, is located in western Inner Mongolia of China (40°13′–42°28′ N, 105°12′–109°53′E) and five counties (Qianqi, Wuyuan, Linhe, Hanghou and Dengkou) are included. A continental monsoon climate could be found in this district. Rainfall is about 130–215 mm/year while evaporation is more than 10 times of the rainfall. The needs of different sectors could not be met by local water resources and the main water diversions are from the Yellow River. For Hetao irrigation district, the areas occupied by crops accounted for one-third of its land [16]. Consequently, large volume of water transferred in virtual form between Hetao irrigation district and its trade patterns due to the trade of crops and other kinds of products.

2.2 Methods

2.2.1 Virtual water transfer

The volume of virtual water transfer was calculated according to product categories. For the Hetao irrigation district, three different kinds of products were studied: crops, other agricultural products, and industrial products, and only blue water resources were considered which was mainly due to the lack of data. The value of virtual water flows related to crops trade could be obtained by multiplying the virtual water content by trade volume, and the virtual water content was calculated as follows [17-18]:

$$VWC_i = \frac{IWU \cdot \alpha_{irr} \cdot \delta_i}{P_i} \quad (1)$$

where VWC_i is virtual water content for crop i (m^3/kg), IWU is irrigation water use (m^3/year), α_{irr} is irrigation water consumption ratio, δ_i is the ratio of irrigation water consumption for crop i to irrigation water consumption in the district, P_i is the production for crop i (kg).

δ_i was calculated as follows [17-18]:

$$\delta_i = \begin{cases} \dfrac{(ET_{c\,i} - P_{e\,i}) \cdot S_i}{\sum_{i=1}^{n} \left((ET_{c\,i} - P_{e\,i}) \cdot S_i \right)} & (ET_{c\,i} \geq P_{e\,i}) \\ 0 & (ET_{c\,i} < P_{e\,i}) \end{cases} \quad (2)$$

where $ET_{c\,i}$ is water evapotranspiration for crop i during growth period (mm), $P_{e\,i}$ is effective precipitation for crop i (mm), which was calculated using the method proposed by the Soil Conservation Service of the United States Department of Agriculture, S_i is sown area for crop i (ha), and n is kinds of crops.

The value of virtual water flows related to other agricultural products or that due to the trade of industrial products was the difference between water footprint of production and water footprint of consumption. The values of water footprint of production were the product of water withdrawal and the related consumption ratio [19-20]. And the values of water footprint of consumption for other agricultural products and industrial products in the Hetao irrigation district during the 2001–2010 year period were derived from the previous work [16].

2.2.2 Impacts of water transfer on ecosystem quality

Water flow-in to an area means more water availability, and it has a positive influence on regional biodiversity which contributes significantly to the overall ecosystem quality within a region. On the other hand, water flow-out from an area means less water availability, and negative influences on biodiversity and ecosystem quality could be obtained. In this study, the positive influences were shown in the color of green while the negative ones are shown in red.

The impacts of physical or virtual water transfer on regional ecosystem quality (ΔEQ (m2 · year)) are assessed using the following method [15]:

$$\Delta EQ = CF_{EQ} \cdot WT \quad (3)$$

Where CF_{EQ} is the ecosystem quality influencing factor (m^2·year/m^3), the value of it was based on the study of Pfister et al. [15], WT is the volume of physical or virtual water transfer (m^3).

2.2.3 Impacts of water transfer on resources

As mentioned above, water flow-in to an area means more water availability and a positive influence could be obtained for local water resources, while water flow-out from an area means more water consumption and a negative influence on water resources could happen. In this study, the positive influences were shown in green while the negative ones are shown in red.

In this study, the backup-technology concept which was shown in surplus energy to make resource available in the future is used for assessing the impacts of water transfer on freshwater resources (ΔR (MJ)). And the desalination of seawater was used as the backup technology in the Hetao irrigation district [15]. Thus the impacts of water transfers on resources could be calculated as follows:

$$\Delta R = E_{des} \cdot F_{dep} \cdot WT \quad (4)$$

Where E_{des} is energy required for seawater desalination (MJ/m^3) and we set it to 11 MJ/m^3 which was based on state-of-the-art energy demand, F_{dep} is the characterization factor for freshwater depletion and it was calculated as follows:

$$F_{dep} = \begin{cases} 1 - \dfrac{WA}{WU} & (WU > WA) \\ 0 & (WU \leq WA) \end{cases} \quad (5)$$

Where WU is water withdrawals for different sectors (m^3) and WA is local freshwater availability (m^3). Water depletion could emerge when local available water could not meet the needs, otherwise this phenomenon would not emerge because of precipitation compensation.

2.3 Data sources

Monthly meteorological data was from the China Meteorological Data Sharing Service System. Agricultural data (crop yield and area sown), social and economic data (population, product consumption) were from the Statistical Yearbook for Bayan Nur and Inner Mongolia). Data on water withdrawals, water availability and water diversions from the Yellow River were from the Bayan Nur Water Resources Bulletin.

3 Results

3.1 Physical and virtual water transfers

The temporal and spatial variations for water transfers in the Hetao irrigation district are shown in Figure 1 and 2 respectively. In 2001, about 4.18×10^9 m^3 of blue water resources were extracted from the Yellow River to this district and the volume of physical water flow presented a slight increasing trend until reaching 4.61×10^9 m^3 in 2010, with an average changing rate of 56.22×10^6 m^3 per year (Figure 1). Due to the trades of different kinds of products, the virtual water flows were mainly from the Hetao irrigation district to its trade patterns and the largest and smallest volumes of virtual water transfer were 3.29×10^9 m^3 in 2009 and 2.55×10^9 m^3 in 2003 respectively.

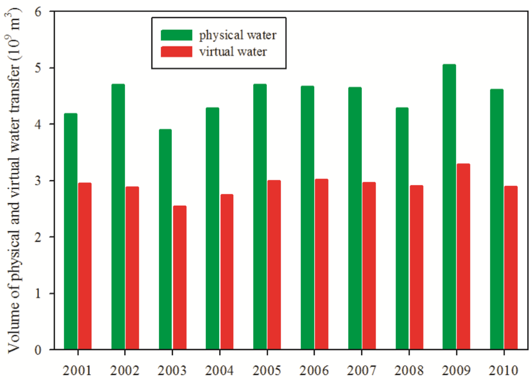


Figure 1 Temporal variations in physical and virtual water transfers

Among the five counties of the Hetao irrigation district, Linhe (1.18×10^9 m^3) and Wuyuan (1.13×10^9 m^3) were the counties whose physical water inflow were more than 1.00×109 m^3 while Qianqi had the smallest physical water inflow (586.50×10^6 m^3) and it was only about half of that in Linhe or Wuyuan (Figure 2). Compared with physical water transfer, the volumes of virtual water flows were smaller. The largest and smaller virtual water flows could be seen in Wuyuan (908.55×10^6 m^3) and Dengkou (355.52×10^6 m^3) respectively and the former was about 2.56 times of the latter.

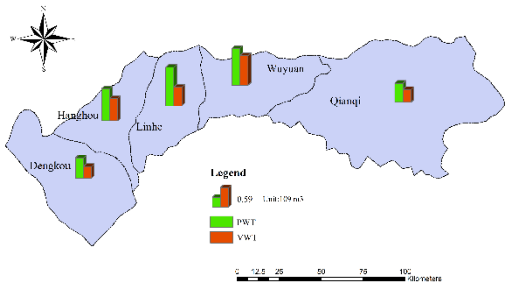


Figure 2 Spatial variations in physical and virtual water transfers

Note: PWT and VWT mean physical water transfer and virtual water transfer respectively.

3.2 Impacts of water transfer on ecosystem quality

The impact of physical water inflow on the ecosystem quality in the Hetao irrigation district was positive and the value of it ranged from 1.16×10^9 $m^2\cdot yr$ to 1.50×10^9 $m^2\cdot yr$ with an average value of 1.33×10^9 $m^2\cdot yr$ during the 2001-2010 year period (Figure 3). For the virtual water outflow from the Hetao irrigation district, the influences of it on the regional ecosystem quality was negative and the largest and smallest values of it during the study period were 977.82×10^6 $m^2\cdot yr$ in 2009 and 759.69×10^6 $m^2\cdot yr$ in 2003 respectively. Under the combined influences of physical and virtual water transfers, a positive impact on regional ecosystem quality could be observed. The value of it was 358.02×10^6 $m^2\cdot yr$ in 2001 and it presented a slight increasing trend until reached 510.63×10^6 $m^2\cdot yr$ in 2010.

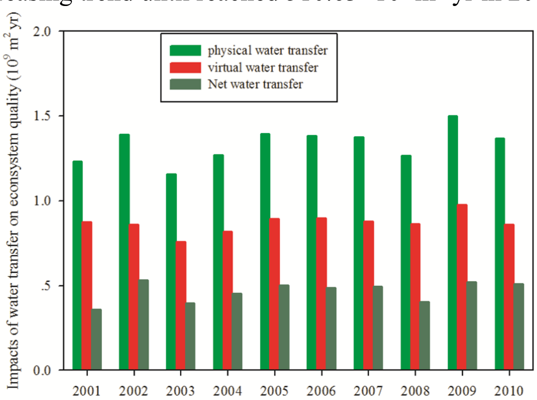
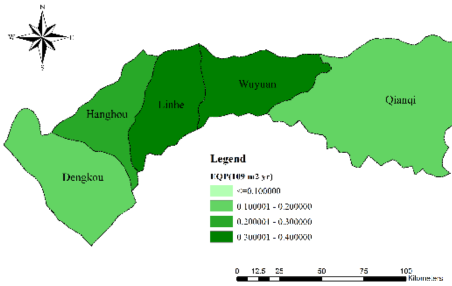
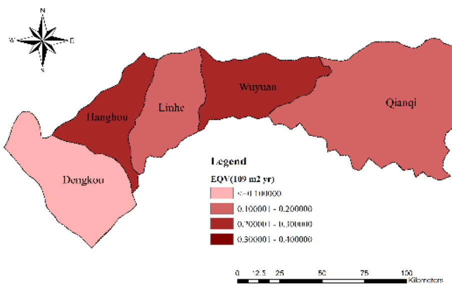


Figure 3 Temporal variations in impacts of physical and virtual water transfers on ecosystem quality

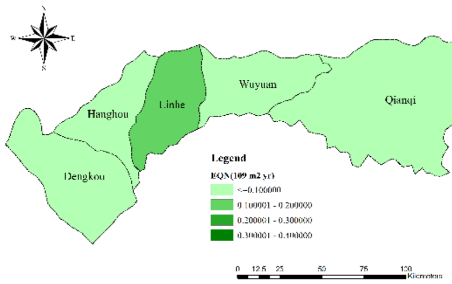
As can be seen from Figure 4(a), the impacts of physical water inflow on ecosystem quality in the counties of Linhe (360.33×10^6 $m^2\cdot yr$) and Wuyuan (343.52×10^6 $m^2\cdot yr$) were larger than other areas during the 2001-2010 year period and the value in Dengkou was the smallest which was about 40% of that in Linhe. For the virtual water outflow from the Hetao irrigation district, the negative influences of it on ecosystem equality in the Wuyuan (276.65×10^6 $m^2\cdot yr$) and Hanghou (208.07×10^6 $m^2\cdot yr$) were much larger than those in other three areas and the smallest influence was still occur in Dengkou and it was 86.60×10^6 $m^2\cdot yr$ (Figure 4(b)). Among the five counties of the Hetao irrigation district, Linhe was the one whose ecosystem quality was influenced most significantly by the net water transfer (184.62×10^6 m^2·yr), and the value of it was about double of that in Hanghou and about triple of those in Wuyuan, Dengkou and Qianqi (Figure 4(c)).



(a)



(b)



(c)

Figure 4 Spatial variations for impacts of physical (a), virtual (b) and net water transfers (c) on ecosystem quality

Note: EQP, EQV and EQN mean the impacts of physical water transfer, virtual water transfer and net water transfer on ecosystem quality respectively.

3.3 Impacts of water transfer on resources

During the 2001-2010 year period, a positive influence of physical water transfer on resources in the Hetao irrigation district could be seen and the average value was 28.16×10^9 MJ (Figure 5). The largest and smallest influences of physical water transfer on resources were in 2009 (32.61×10^9 MJ) and 2003 (23.06×10^9 MJ) respectively. The negative influence on regional resources caused by the virtual water flows between the Hetao irrigation district and its trade parterners changed from 19.83×10^9 MJ in 2001 to 17.61×10^9 MJ in 2010 with an average value of 18.26×10^9 MJ during the study period. Under the combined influences of physical and virtual water transfers, a positive impact on regional resources could be observed and the value of it increased from 8.26×10^9 MJ in 2001 to 10.51×10^9 MJ in 2010 with a mean changing rate of 168.21×10^6 MJ per year.

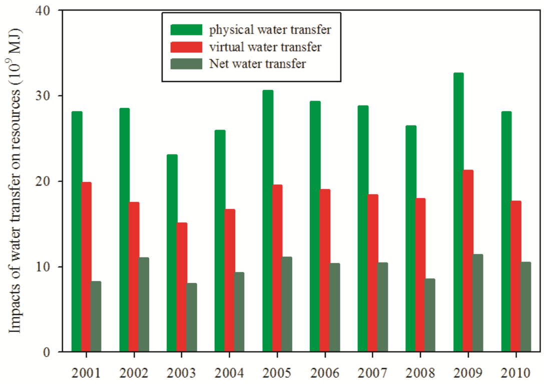
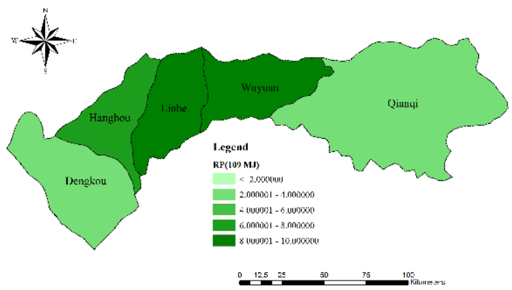
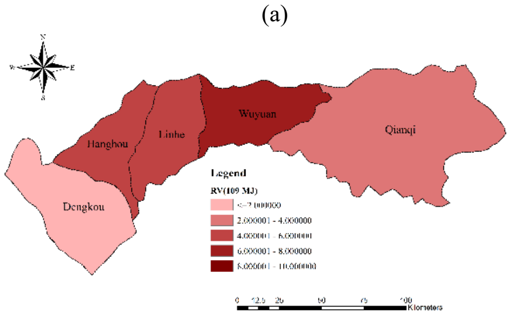


Figure 5 Temporal variations in impacts of physical and virtual water transfers on resources

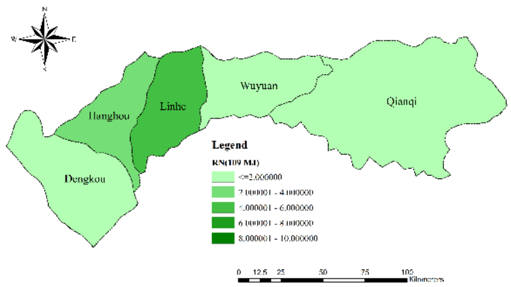
As can be seen from Figure 6(a), the impacts of physical water transfer on resources in the middle areas (Linhe, Wuyuan and Hanghou) were much significant than other areas and the largest value (8.34×10^9 MJ in Linhe) was about 3.83 times of the smallest value (2.18×10^9 MJ in Dengkou). For the virtual water outflow from the Hetao irrigation district, the negative influences of it on regional resources in Wuyuan was the largest (6.55×10^9 MJ), those in Hanghou and Linhe were between 4×10^9 MJ and 5×10^9 MJ and the influence in Dengkou was the smallest whose value was 1.25×10^9 MJ (Figure 6(b)). As can be observed from the Figure 6(c), Linhe (4.27×10^9 MJ) and Hanghou (2.09×10^9 MJ) were the counties whose ecosystem quality were influenced greatly by the net water transfer, and the influence of net water transfer on resources in Dengkou was the smallest whose value was 928.07×10^6 MJ .



(a)



(b)



(c)

Figure 6 Spatial variations for impacts of physical (a), virtual (b) and net water transfers (c) on resources

Note: RP, RV and RN mean the impacts of physical water transfer, virtual water transfer and net water transfer on resources respectively.

4 Discussions

Besides local water resources, as much as 4.50×10^9 m^3 of blue water were transferred from the Yellow River to meet the needs of the Hetao irrigation district during 2001-2010 and about 2.92×10^9 m^3 water resources were flowed out from this district virtually due to products trades simultaneously (Figure 1). Considering the launched inter-basin physical water transfer projects worldwide, the phenomenon that both physical and virtual water transfers could be seen at a same region exists in many parts of the word besides China [9]. Most of the physical water flow-in areas were important agricultural producing areas and large volume of water resources were flowed out due to the trade of agricultural products. The global international virtual water flows related to products trades was 2320 Gm^3 per year in the period of 1996–2005 and the largest share (76%) is related to international trade in crops and the derived crop products [19]. The United States, Pakistan, India, Australia, Uzbekistan, China, and Turkey are the largest blue virtual water exporters, accounting for 49% of the global blue virtual water export. In the Hetao irrigation district, the volume of virtual water flows related to agricultural products trades was 2.90×10^9 m^3 during 2001-2010, accounted for nearly 2/3 of the physical water flow-in. Regions such as the Hetao irrigation district are often facing water scarcity due to the unbalance between water supply and water demand. The value of blue water scarcity for the Hetao irrigation district increased from 0.242 (medium to high water stress level) to 0.491 (high water stress level) under the influence of physical and virtual water transfer [16]. Furthermore, the research of Zhao et al. shows that both physical and virtual water flows do not play a major role in mitigating water stress in the water-receiving regions but exacerbate water stress for the water-exporting regions of China [7]. Besides, the facts that virtual water flows have increased the water stress in some already water scare regions have been shown by Feng et al. [21]. Thus the adjustment of regional water transfer pattern including both physical and virtual water should be included in the regional future water management.

The impacts of physical, virtual and net water inflow on the ecosystem quality in the Hetao irrigation district were 1.33×10^9 $m^2\cdot yr$ (positive), 867.60×10^6 $m^2\cdot yr$ (negative) and 465.70×10^6 $m^2\cdot yr$ (positive) respectively during the 2001-2010 year period and the middle areas (Hanghou, Linhe and Wuyuan) were influenced more significantly than other areas (Dengkou and Qianqi) (Figure 3 and 4). Compared with ecosystem damage factor, the value of impact of water transfer was mainly influenced by water transfer (volume and direction), thus a similar trend could be found between water transfer and the impact of it on ecosystem quality. Studies have shown that products trades contributed to biodiversity threats, especially in the developing nations where specific commodities were produced for export to more developed countries those without a suitable climate to produce these commodities [14, 22]. According to our study, the impacts of water transfers on the resources in the Hetao during 2001-2010 were 28.16×10^9 MJ (positive) for physical water, 18.26×10^9 MJ (negative) for virtual water and 9.89×10^9 MJ (positive) for net water transfer and the middle areas (Hanghou, Linhe and Wuyuan) were influenced more significantly when analyzing the spatial distribution (Figure 5 and 6). Besides the value of water transfer, the ratio of water withdrawals and local water availability was also an important factor influencing the value of the impacts on resources. For the five counties of this district, the ratios of water withdrawals and local water availability in the Dengkou (1.47) and Qianqi (1.93) were much smaller than those in Hanghou (2.71), Linhe (2.78) and Wuyuan (2.91). Combined with the fact that most of the water transfers were occurred in the middle areas (Figure 2), higher influences of water transfer on resources in the middle areas could be observed. Pfister et al. has evaluated the resources influencing factor with a spatial resolution of 0.5°×0.5° and they found that nearly half of the areas were with a value larger than 10 MJ/m^3 [15]. Based on method used in this study, the increase of physical water flow-in or the decrease of virtual water flow-out could be helpful for the optimization of influences of water transfer on regional ecosystem equality or regional resources. The increase of physical water flow-in in the Hetao irrigation district would be difficult due to the high financial cost and the corresponding environmental and social impacts, while the increase of virtual water flow-in could be possible measures that this district could take in the near future due to the loosening on the self-sufficiency in food supply of Chinese government [23].

In this study, only two influencing factors were included to evaluate the environmental influences of regional water transfer which was mainly due to the lack of data. Besides the environmental factors, others factors such as the social or economic factors should also be considered in future study to optimize the regional water management [24-25].

5 Conclusions

This study proposed two indicators (the impacts of water transfers on ecosystem quality and the impacts of water transfers on resources) to evaluate the environmental influences for both physical and virtual water transfers at the Hetao irrigation district during 2001-2010. The conclusions could be listed as follows:

Most of the physical water flow-in areas were important agricultural producing areas and large volume of water resources were flowed out due to the trade of agricultural products. For the Hetao irrigation district, the volumes of physical water flow-in and virtual water flow-out were 4.50×10^9 and 2.92×10^9 m^3 respectively and the latter accounted for nearly 2/3 of the former. The flows of physical and virtual water have increased the water stress in some already water scare regions, thus the adjustment of regional water transfer pattern should be included in the regional future water management.

The value of impact of water transfer was mainly influenced by water transfer (volume and direction), thus a similar trend could be found between water transfer and the impact of it on ecosystem quality. The impacts of physical and virtual water transfers on the ecosystem quality in the Hetao irrigation district were 1.33×10^9 $m^2\cdot yr$ (positive) and 867.60×10^6 $m^2\cdot yr$ (negative) respectively and the middle areas (Hanghou, Linhe and Wuyuan) were influenced more significantly than other areas (Dengkou and Qianqi).

Besides the value of water transfer, the ratio of water withdrawals and local water availability was also an important factor influencing the value of the impacts on resources. The impacts of water transfers on the resources were 28.16×10^9 MJ (positive) for physical water and 18.26×10^9 MJ (negative) for virtual water transfers and the middle areas were influenced more significantly.

The increase of physical water flow-in in the Hetao irrigation district would be difficult due to the high financial cost and the corresponding environmental and social impacts, while the increase of virtual water flow-in could be possible measures that this district could take in the near future due to the loosening on the self-sufficiency in food supply of Chinese government.

Acknowledgments

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