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Assessing the economic impact of North China's water scarcity mitigation strategy: a multi-region, water-extended computable general equilibrium analysis

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This paper describes a multi-region computable general equilibrium model for analyzing the effectiveness of measures and policies for mitigating North China's water scarcity with respect to three different groups of scenarios. The findings suggest that a reduction in groundwater use would negatively affect economic growth and household incomes. A planned water-transfer project would improve economic development and reduce the over-exploitation of local water resources, while water demand management policies would improve water-use efficiency through reallocating water to those sectors having a higher marginal product value. Several important policy implications are drawn from these findings.

Keywords: computable general equilibrium; water scarcity; marginal value of water; water reallocation; economic impact

Introduction

According to recent official statistics, the total amount of water available annually in China is 2812 km^3. However, the per capita annual sustainable freshwater availability amounts to only 2196 m^3, about one-quarter of the world average. Due to China's marked continental monsoon climate, water resources are unevenly distributed, both temporally and spatially. Water resources are relatively abundant in the south, whereas in the north of the country they are generally scarce. Our study area – the metropolises of Beijing, Tianjin and almost all of Hebei Province – is located in the Haihe River basin of North China (see Figure 1), which is facing a severe water crisis. The Haihe River basin has the lowest water availability in the country – in 2007, for example, it was only 189 m^3 per capita, which is about 14% of the national average and less than 2.5% of the world average (Ministry of Water Resources [MWR], 2008).

Water shortages in the Haihe River basin are becoming an increasingly urgent problem as a result of climate change and growing human activity. Decreasing precipitation in the

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Figure 1. Map showing the boundaries of the Haihe River basin.

basin is further reducing the already limited water resources: average annual precipitation declined from 564 mm in the period 1956–1979 to 498 mm in the period 1980–2005. On the other hand, demand for water has increased rapidly in this region due to population growth, industrialization and urbanization. Major rivers are already being exploited to their maximum capacity, leaving little or no water to flow into the sea.

To compensate for the shortage of surface water, agriculture has been relying increasingly on groundwater resources, resulting in a rapid depletion of aquifers and with it a rapid fall in groundwater levels (Shi, 1997). The average over-exploitation of groundwater resources is estimated to be close to 8 km^3 per year (Global Environmental Facility [GEF], 2008).

To achieve and maintain sustainable development of the economy, society and environment, a series of measures and policies to solve the water crisis have been proposed or adopted in the region, including the reduction of excessive exploitation of groundwater resources, the construction of the South–North Water Transfer (SNWT) project, and implementation of demand-side management policies (Han, 2011; Liu, Luo, & Xu, 2011; Qin, Gan, Wang, & Wang, 2013; Yu, 2008; Zhang & Jia, 2003). Effective water management strategies could yield multiple benefits for the economy, society and environment.

Although the general equilibrium approach may not provide a perfectly definitive solution for the problem, it does provide figures that policy makers can work with. They can use this information and link it to appropriate hydrological, biophysical and cost-benefit analyses to assist in decision making aimed at benefiting the economy, society and environment.

Many scholars have used computable general equilibrium (CGE) models to analyze the effectiveness of water management policies and their economic impact (Diao, Dinar, Roe, & Tsur, 2008; Diao & Roe, 2003; Diao, Roe, & Doukkali, 2005; Fang, Roe, & Smith, 2006; Juana, Strzepedk, & Kirsten, 2009; Qin, Bressers, Su, Jia, & Wang, 2011; Xia, Deng, & Sun, 2010), mainly because general equilibrium analysis provides a richer set of economic feedback data and implications for social welfare. Qin, Jia, Su, Bressers, and Wang (2012) analyzed the likely effects of water taxes on the Chinese economy using the GeneRal Equilibrium Analysis sysTem for Water (GREAT-W), which is an economy-wide, static Walrasian CGE model with water as a production factor.

This study extends the GREAT-W model to include multi-regional disaggregation to investigate the role of water in the Chinese economy. Focusing specifically on the Jing-Jin-Ji (Beijing-Tianjin-Hebei) economic zone of North China, the role of water in the regional economy was analyzed with respect to several scenarios by using a multi-region, multi-sector CGE model to help decision makers develop cost-effective policies and measures to achieve a sustainable supply of water and, consequently, a sustainable economy.

Description of model structure

A model has been developed using the Mathematical Program System for General Equilibrium analysis (MPSGE) developed by Rutherford (1998), which is an extension of the General Algebraic Modelling System (GAMS), with the mixed complementarity problem (MCP) GAMS solver. The model has a multi-regional, multi-sectoral structure to help quantify similarities, differences and linkages between regions. Each region is modelled separately as an individual economy. The theoretical structure of the model is typical of most static CGE models; its main equations are as given by Robinson, Yunez-Naude, Hinojosa-Ojeda, Lewis, and Devarajana (1999).

Regional disaggregation

This study focuses on three regions, Beijing, Tianjin and Hebei, which together constitute the core of the Haihe River basin (Figure 1). The model adopts a bottom-up method for regional disaggregation, which has key advantages over simply adding a top-down regional disaggregation module of economy-wide simulation results. Within a bottom-up regional structure, each region is modelled separately as an individual economy, with many variables, including a region subscript in the equations. Regional differences can be captured through region-specific prices, region-specific industries, region-specific consumers, and so on. Economic linkages across regions can be reflected by inter-regional trade, factor flows and transfer payments.

Production technology

The model assumes that each region includes three sectors: agriculture (AGR), industry (IND), and services (SER). Producers are constrained in their choice of inputs by multi-level, nested production technology. A diagrammatic overview of the production structure is shown in Figure 2. At the top level, the technology is specified by a constant elasticity of substitution (CES) function of two broad categories of inputs in each sector: primary

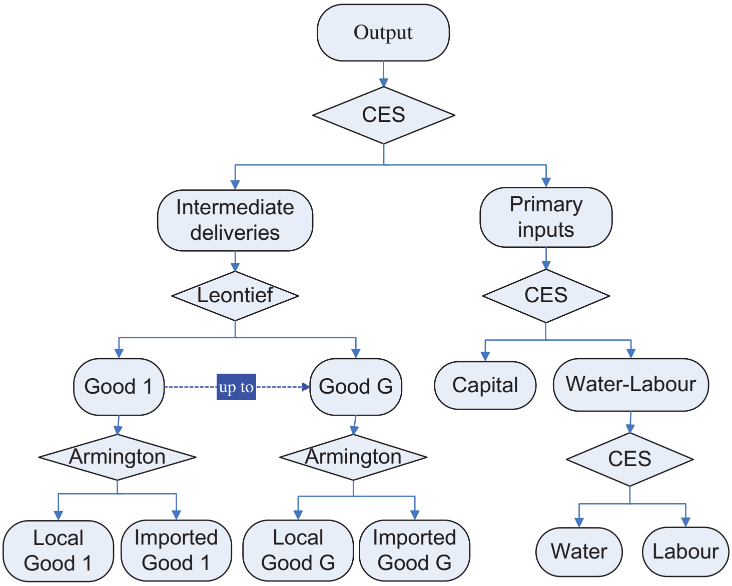

Figure 2. The structure of production technology.

factors and aggregated intermediate inputs. Aggregated intermediate input is determined by a Leontief function of disaggregated intermediate inputs, while value added is itself a nested CES function of primary factors.

In this study, water is introduced into the CGE framework as an explicit factor of production. Water and labour are combined by a CES function at the bottom level, and this water-labour composite is subsequently linked with capital, also by a CES function. Because water is currently allocated to major user groups in China, it is assumed not to be mobile across sectors and regions. Water prices may, therefore, differ in each sector of each region.

Local final demand

In each region there are two types of representative household consumers: those belonging to rural households (RHH) and those belonging to urban households (UHH). Both types of households receive direct and indirect income from factor endowments (labour and water), and transfer payments from other institutions (i.e. enterprises). Households maximize their utility by adjusting consumption choices for different goods subject to a budget constraints. The expenditure is determined by the linear expenditure system. Enterprises do not consume any commodities, and their major source of income is the return on regional capital. After paying direct taxes to government, part of the net profit after tax is transferred to households, while the remainder is retained as enterprise savings. Government income comes mainly from tax revenues, while government expenditure is determined by a Cobb-Douglas consumption function.

Inter-regional, domestic and international trade

In each region, aggregated domestic output is allocated between local sales and exports to other regions in the study area, the rest of China (ROC) and the rest of the world (ROW).

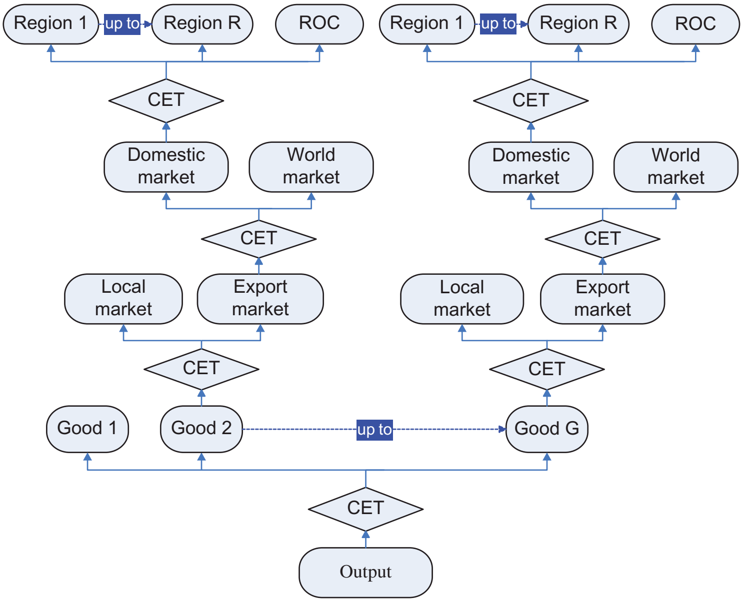

Figure 3. Regional allocation structure of commodities.

A multi-level, nested constant elasticity of transformation (CET) function is used to formalize this concept of imperfect substitution between goods with different destinations. Figure 3 shows the regional output allocation structure.

In each region, local market demand consists of the sum of the intermediate demands from production, rural and urban household consumption, government consumption, investment and intermediate inputs. All local market demands are for a composite commodity made up of local supply and imports from other regions in the study area, the ROC and the ROW.

This study used a multi-level, nested Armington (1969) CES function to determine the composition of demand between local outputs and imported goods of differing origin. The Armington assumption of imperfect substitution between domestic and imported products makes existing trade statistics immediately usable for inter-regional trade models. However, substitution elasticities are exogenous parameters determined outside the model's theoretical structure, and as a consequence the simulation results of the model can be strongly influenced by the value of the substitution elasticities (Zhang, 2006). Figure 4 shows the regional commodity supply structure.

Macro-closure

The model adopts the neoclassical closure rule. For each region, the closure rules for macro-system constraints in this model consist of three parts: government expenditure–receipts balance, savings–investment balance, and trade balance. The government savings rate is exogenous, while government expenditure is endogenous. Regional capital formation is flexible, and the marginal propensity to save (MPS) for all households is fixed. The real exchange rate is exogenous, while foreign savings (equal to imports minus exports) are endogenous. In this study, the MPS for each household of each region is defined as household income minus tax to government, divided by current household savings. The rate of government saving for each region is determined by subtracting government expenditure

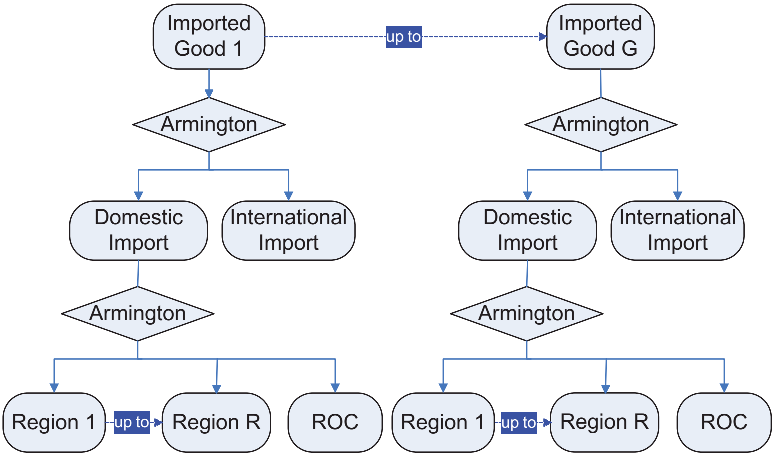

Figure 4. Regional supply structure of imported commodities by origin.

from government revenue and dividing the result by government revenue. The exchange rate is fixed at 1.

Social accounting matrix

For water policy analysis, it is necessary to establish a water-embedded social accounting matrix (WSAM) to provide a consistent macro-economic database for the calibration of the model parameters. Because of the lack of an official social accounting matrix (SAM) published by the government in China, a multi-regional SAM had to be built for Beijing (BJ), Tianjin (TJ) and Hebei (HB) by incorporating data from various sources into a consistent SAM framework.

Owing to the use of different sources of data and various statistical discrepancies, the compiled SAM for China for the base year 2007 was not initially balanced. To fulfil the row-column constraint, the cross-entropy method was adopted to balance the micro-SAM for China under the GAMS software environment (Robinson, Cattaneo, & EI-Said, 1998).

Economic data

The data for activities, commodities, and import and export accounts were based on the input-output table 2007 for Beijing, Tianjin and Hebei (National Bureau of Statistics, 2011). The data for import tariffs were taken from the *Customs Statistics Yearbook 2008* (General Administration of Custom [GAC], 2008), while the revenue for government expenditure accounts came from the *Finance Yearbook of China 2008* (Ministry of Finance [MOF], 2008) and tax data from the *Tax Yearbook of China 2008* (State Administration of Taxation [SAT], 2008). The revenue and expenditure of households and the government were adjusted based on the flow-of-funds accounts of the *China Statistical Yearbook 2008* (National Bureau of Statistics, 2008).

Inter-regional trade

Because domestic trade accounts in Chinese provincial-level input-output tables only provide totals of commodities imported from and exported to the rest of China, inter-regional trade data within the study area cannot be obtained directly. Therefore, the gravity model of trade (Tinbergen, 1962) was adopted to estimate the inter-regional trade flows between Beijing, Tianjin and Hebei. However, one must keep in mind that estimation of inter-regional trade flows might impact on the findings drawn from simulation results. In this study, the following equation (Li, 2010) was used:

$$x_i^{\mathrm{gh}} = e^{\alpha}(x_i^{\mathrm{gO}})^{\beta_1}(x_i^{\mathrm{Oh}})^{\beta_2}\frac{(G^{\mathrm{g}})^{\beta_3}(G^{\mathrm{h}})^{\beta_4}}{(d^{\mathrm{gh}})^{\beta_5}}, \tag{1}$$

where x^{gh} is the volume of product i traded from region g to region h, x_i^{gO} is the volume of product i exported from region g to the rest of China, x_i^{Oh} is the volume of product i imported from the rest of China to region h, G^{g} and G^{h} are the GDP for regions g and h, respectively, d^{gh} is the distance between region g and h, e is a constant and α, β_1, β_2, β_3, β_4 and β_5 are elasticity parameters.

Water equilibrium price

In this study, the marginal value of water (shadow price of water) in the base year was adopted to represent the water equilibrium price. A marginal productivity model was developed for valuing sectoral use of water in each region. In this model, water, like capital and labour, is treated as an input for the Cobb-Douglas production function:

$$Z = AK^{\alpha}L^{\beta}W^{1-\alpha-\beta}, \tag{2}$$

where Z is the value added (in CNY hundreds of millions), L and K are labour and capital, respectively (in CNY hundreds of millions), and W is the quantity of water input (in 10^8 m^3). A is a constant term representing the technical efficiency of the industry, while α, β and $1 - \alpha - \beta$ represent the output elasticity of labour, capital and water, respectively.

Equation 2 can be linearly transformed with the natural logarithm:

$$\ln\left(\frac{Z}{W}\right) = \ln A + \alpha \ln\left(\frac{K}{W}\right) + \beta \ln\left(\frac{L}{W}\right) \tag{3}$$

Using data from the years 1978 to 2009, the values of α and β were estimated through regression analysis using the SPSS software package. Then the output elasticity of water (σ) was obtained for each sector in each region as:

$$\sigma = \frac{\partial \ln Z}{\partial \ln W} = 1 - \alpha - \beta \tag{4}$$

Similarly, the marginal value (ρ) of water can be computed as:

$$\rho = \sigma \times \frac{Z}{W} \tag{5}$$

The computed output elasticity and marginal values of water are presented in Table 1. The agricultural sector has the highest output elasticity for water input, but its water use has a low marginal value. This means that water supply plays an important role in agricultural production, even though the marginal value of water use in this sector is lower than in

Table 1. Computed output elasticity and marginal value of water in 2007.

	Output elasticity of water			Marginal value of water (CNY/m^3)		
Sectors	Beijing	Tianjin	Hebei	Beijing	Tianjin	Hebei
Agriculture	0.420	0.447	0.434	3.42	3.50	5.03
Industry	0.079	0.069	0.088	32.24	45.78	24.32
Service	0.109	0.091	0.087	125.27	163.14	184.57
Weighted average	0.105	0.086	0.133	41.41	23.05	9.86

other sectors. Water used in the service sector has the highest marginal value. For the macro-economy, water use in Beijing has the highest marginal value in the entire economy, because the service sector in Beijing adds value in a greater proportion than it does in Tianjin and Hebei. Because the agricultural sector consumes a large amount of water in Hebei, the marginal value for water use in the Hebei economy is very low.

This estimate for output elasticity of water is credible when compared with other studies, such as those by Shen et al. (2000) and Gong (2007). The estimate of the marginal value of water for agriculture and industry is close to the accounting results of Qin, Gan, Zhang, and Jia (2012). According to Zhang, Qin, Jia, Xie, & Niu (2012), the marginal value of water in the service sector is higher than that of industry. The results of the marginal value of water used in the service sector can, therefore, be accepted as representing a reasonable level.

Water SAM

Using the statistics on water supply and use from the *Water Resources Statistics Bulletins 2007* (MWR, 2008), the marginal value of water was computed to estimate the total return of water in the economy (total economic value of water, TEV):

$$\mathrm{TEV} = \rho \times \mathrm{W} \tag{6}$$

Water is one of the most important natural resources needed for both residential use and production. Water use as a normal consumer good for residential purposes is a derived demand. But water can also be consumed in production processes as an input demand, similar to labour and capital (Gatto & Lanzafame, 2005). Therefore, in this study, water is treated as a primary input to be added into the production function; the water accounts are extracted from the corresponding capital and labour accounts. The households of each region receive the income of water endowments of that region. The final WSAMs for the base year 2007 for Beijing, Tianjin and Hebei are given in the Appendix.

Calibration

In the CGE model, the shared parameters, including consumer and government consumption, average savings rate and average tax rate, can be calibrated by the constructed WSAM. The calibration procedure ensures that the initial data-set can be reproduced in the benchmark tests.

The other type of parameters to be found in the model are elasticity parameters. The values of CES elasticity between primary factors and aggregated intermediate inputs, Armington elasticity, CET elasticity and own-price elasticity were determined from other studies (Dervis, de Melo, & Robinson, 1982; Li & He, 2010; Wang, Xue, & Zhu, 2009; Zheng & Fan, 1999; Zhuang, 1996). Here again one must keep in mind that these exogenous parameters are determined outside the model's theoretical structure, and hence simulation results of the model can be strongly influenced by the choice of parameter values.

In this study, water is introduced into the production function as an explicit factor of production. As such, the elasticity parameters of substitution across production factors are much more critical in determining the results of the alternative water policy simulations. Therefore, their values were estimated for each sector of each region through econometric analysis. In the model framework, water, labour and capital are represented by a two-level CES production function:

$$Y_{\mathrm{WL}} = (aW^{-\rho_1} + (1-a)L^{-\rho_1})^{-\frac{1}{\rho_1}} \tag{7}$$

$$Y = A(bY_{\mathrm{WL}}^{-\rho} + b(1-b)K^{-\rho})^{-\frac{m}{\rho}} \tag{8}$$

where Y_{WL} represents the combination of water and labour; Y is the value added; A represents technical efficiency; m represents the return level to scale; a and b are shared parameters ($0 < a, b < 1$); and ρ_1 and ρ are shift parameters ($\infty > \rho_1, \rho > -1$).

The above equations can be linearly and approximately transformed with the natural logarithm:

$$\ln Y = \ln A + bm \ln Y_{\mathrm{WL}} + (1-b)m \ln K - \tfrac{1}{2}\rho m b(1-b)\left(\ln\left(\frac{Y_{\mathrm{WL}}}{K}\right)\right)^2 \tag{9}$$

$$\ln Y_{\mathrm{WL}} = a \ln W + (1-a)\ln L - \tfrac{1}{2}\rho_1 a(1-a)\left(\ln\left(\frac{W}{L}\right)\right)^2 \tag{10}$$

Substituting Equation (10) into Equation (9) gives:

$$\begin{aligned} \ln Y = {} & \ln A + bma \ln W + bm(1-a)\ln L + (1-b)m \ln K \\ & - \tfrac{1}{2}\, mb\rho_1 a(1-a)\left(\ln\left(\frac{W}{L}\right)\right)^2 - \tfrac{1}{2}\rho\, m\, b(1-b)\left(\ln\left(\frac{W}{K}\right)\right)^2 \end{aligned} \tag{11}$$

The values of a, b, m, ρ_1 and ρ can be computed through regression analysis. This gives the values of the substitution elasticity between water and labour (σ_1) and between capital and the water-labour composite (σ):

$$\sigma_1 = -\frac{1}{\rho_1} \tag{12}$$

$$\sigma = -\frac{1}{\rho} \tag{13}$$

The computed results are shown in Table 2.

Table 2. Estimated elasticity parameters of substitution across factors.

Region	Sector	CES elasticity between water and labour	CES elasticity between capital and water–labour composite
Beijing	Agriculture	0.72	0.13
	Industry	0.29	0.43
	Service	0.73	0.84
Tianjin	Agriculture	0.74	0.26
	Industry	0.34	0.50
	Service	0.52	0.82
Hebei	Agriculture	0.79	0.60
	Industry	0.40	0.67
	Service	0.40	0.87

Defining the scenario groups

After the calibration procedure, three alternative groups of water-strategy scenarios were defined and the CGE model applied to assess their impact on the region.

Scenario Group 1: reducing groundwater use to renewable levels

In the past, economic development has relied on excessive use of both groundwater and surface-water resources, which has resulted in a decline of the water-table and reduction of environmental flows (Shi, 1997; Yang, 2001). For the Haihe River basin, a key task is to reduce the exploitation of groundwater to renewable levels, to achieve sustainable development of available water resources. To assess the economic outcomes of reducing groundwater use, this scenario group was set up to analyze the economy-side impacts of reducing water use. The results of this assessment can also be regarded as the economic losses induced by the water-supply crisis if groundwater is exhausted.

Based on the research report in GEF (2008), the average over-exploitation of groundwater is estimated at close to 8 km^3 annually, which is equivalent to about 20% of the total volume of water use in the Haihe River basin. This study assumes that water users in Beijing, Tianjin, Hebei and other regions in China are proportionately assigned the task of reducing groundwater use. For Scenario Group 1 the following three scenarios were chosen:

S1a: A 5% reduction in water supplied, with respect to the 2007 water-use level for the production sector in Beijing, Tianjin and Hebei.
S1b: A 10% reduction.
S1c: A 20% reduction. This degree of reduction would enable the water-table to return to renewable levels.

Scenario Group 2: receiving water transferred by the SNWT project

Availability of water is the greatest constraint for the economic development in the study area. With this in mind and, in addition, to protect scarce water resources and satisfy environmental water requirements, the Chinese government is adopting effective measures to control the total volume of water used. This will inevitably reduce water supply and have negative impacts on economic growth. To improve water supply in the Haihe River basin, several large-scale projects have been proposed, some of which have already been launched. The eastern and middle routes of the SNWT will play key roles in supplying freshwater to the region. In order to assess the economic gains of improving water supply, this scenario group was used to simulate the economy-side impacts of constructing the SNWT. The results may also be considered by policy makers who wish to assess the economic feasibility of the project.

Taking into account the construction stages of the project, two scenarios were developed within this scenario group. According to project plans, the transferred water is to be supplied mainly for industrial, service and domestic use. However, agriculture would receive a greater proportion of local water resources after the construction of the SNWT. Therefore, in this scenario group two assumptions were made: local water supply is reduced to 80% of the base-year level; and transferred water is proportionately allocated across water users in each region. The scenarios in the group are:

S2a: Local water supply is reduced to 80% of the base-year level, and transferred water is supplied to each region according to the water transfer capacity of the project in 2020 (the first stage of the project).

S2b: Local water supply is reduced to 80% of the base-year level, and transferred water is supplied to each region according to the water transfer capacity of the project in 2030 (the second stage of the project).

Scenario Group 3: reallocation of water from agriculture to industry and the service sectors

Owing to complex technical, economic, social and environmental issues, solutions to meet increasing demand for water via supply-side mechanisms are gradually becoming less viable as a result of resource constraints and the increasing marginal costs of such engineering-based solutions. Alternative management options, such as demand-side management, must receive more attention in developing water policies (Ashton & Seetal, 2002). As the economy grows, especially in the Jing-Jin-Ji economic zone, demand for water from non-agricultural sectors will continue to increase (Han, 2011; Yu, 2008).

In accordance with previous estimates, water for agricultural use has a lower marginal value than that for non-agricultural uses. If more water is supplied to high-value sectors, water-use efficiency should improve. The main purpose of this scenario group is, therefore, to investigate whether water reallocation from agriculture to non-agricultural sectors will indeed promote water-use efficiency.

To simplify the setting of a benchmark scenario and to make results more comparable, this scenario group does not take into account water transfer from the SNWT; rather it simply considers transferring some of agriculture's water to the industrial and service sectors on the basis of current water supply. The simulation results can be used to analyze the economy-wide impacts of different water-reallocation shares. The three water-reallocation scenarios in this group are:

S3a: 5% of the water used in the agriculture sector of each region is transferred, and allocated proportionately between the industry and service sectors of the same region according to the estimated marginal value of water for each sector.

S3b: 10% is transferred and allocated.

S3c: 20% is transferred and allocated.

Results and discussion

Simulation results of Scenario Group 1: reducing groundwater use

The results of changes in the main economic variables under Scenario Group 1 are shown in Table 3. Reduction in groundwater use affects the output of the production sector, resulting in changes in product prices, which are closely related to consumer consumption, imports and exports in the trade sector, and gross domestic product (GDP). As the CGE model shows, water inputs decline due to a reduction in groundwater exploitation.

Table 3 shows that output and GDP of all regions decline in a similar way. With decreasing water supply, the macro-economic losses become increasingly severe. When groundwater exploitation is reduced to renewable levels, the output and GDP of the whole study area decline by 2.76% and 2.66%, respectively.

As shown in Table 3, household and government incomes also decline due to the declines in output and GDP. This is especially severe for rural households. If groundwater exploitation is reduced to renewable levels, the income of rural households declines by 13.76%. A decline in households' income reduces their purchasing power and welfare. In this study, Hicksian equivalent variation (EV) was used to analyze the impact on household welfare of readjusting water strategies. Table 3 also shows that a reduction in water supply results in welfare losses of increasing severity for both rural and urban households in all regions of the study area.

At the sector level, the output of the sectors in each region declines due to a decline in water inputs. Agricultural production suffers the most in each region. If groundwater exploitation is reduced to renewable levels, then agricultural production for the whole study area would decrease by approximately 9%. This is because agriculture has the highest output elasticity for water input and water plays a very important role in the production of agricultural goods, even though agricultural water use has a low marginal value.

Declines in output and consumption lead to declines in exports and imports. Only the export of service goods increases slightly; this may be because local demand declines due to a reduction in purchasing power, and more service goods need to be sold in the world and domestic (Chinese) markets outside the study regions. A decrease in local demand and consumption can also have an impact on imports.

Currently, economic benefits in North China are to some extent being achieved through the over-depletion of groundwater aquifers. Although the experimental results of the scenario group for reducing groundwater exploitation (Scenario Group 1) show that a reduction in water supply has a severe negative impact on the economy and household welfare, continuing over-depletion of water resources would severely threaten the environment and ultimately result in an uncontrollable downward economic spiral. If this situation is not reversed and the security of water supply guaranteed, sustainable development of the economy, society and the environment will be severely threatened. If groundwater resources were exhausted, the subsequent water-supply crisis would result in huge GDP, welfare and environmental losses. The Chinese government should, therefore, adopt measures to effectively reduce groundwater use to renewable levels and allow the aquifer to recharge.

Simulation results for Scenario Group 2: water transfer through the SNWT project

The results of changes in the main economic variables under Scenario Group 2, for water transfer under the SNWT, are given in Table 4. Output of the study area increases once

Table 3. Changes (in %) of main economic variables under Scenario Group 1: reducing groundwater use.

	S1a: Reducing water supply 5%				S1b: Reducing water supply 10%				S1c: Reducing water supply 20%			
Economic variable	Beijing	Tianjin	Hebei	Total	Beijing	Tianjin	Hebei	Total	Beijing	Tianjin	Hebei	Total
GDP	−0.56	−0.43	−0.65	−0.58	−1.17	−0.91	−1.35	−1.21	−2.56	−2.04	−2.97	−2.66
Total output	−0.70	−0.44	−0.54	−0.58	−1.48	−0.94	−1.15	−1.23	−3.30	−2.17	−2.58	−2.76
Agricultural output	−3.77	−2.02	−1.80	−2.12	−7.66	−4.15	−3.65	−4.31	−15.82	−8.73	−7.58	−8.94
Industrial output	−0.83	−0.40	−0.42	−0.52	−1.80	−0.87	−0.89	−1.11	−4.19	−2.06	−2.00	−2.54
Service output	−0.53	−0.42	−0.59	−0.53	−1.09	−0.89	−1.27	−1.12	−2.35	−1.97	−2.97	−2.51
All household EV	−0.85	−1.07	−1.93	−1.41	−1.76	−2.24	−4.01	−2.93	−3.84	−5.00	−8.70	−6.39
Rural household EV	−0.75	−3.88	−3.56	−3.22	−1.63	−8.15	−7.34	−6.67	−3.84	−18.14	−15.66	−14.33
Urban household EV	−0.86	−0.72	−1.10	−0.93	−1.77	−1.51	−2.31	−1.94	−3.84	−3.37	−5.13	−4.28
All household income	−0.76	−1.01	−1.87	−1.32	−1.58	−2.12	−3.87	−2.75	−3.44	−4.73	−8.39	−5.98
Rural household income	−0.64	−3.61	−3.50	−3.10	−1.39	−7.59	−7.20	−6.40	−3.29	−16.89	−15.36	−13.76
Urban household income	−0.77	−0.68	−1.05	−0.86	−1.59	−1.43	−2.20	−1.80	−3.45	−3.19	−4.89	−3.97
Government income	−1.27	−1.28	−0.95	−1.14	−2.65	−2.73	−2.04	−2.42	−5.81	−6.32	−4.75	−5.46
Total export to ROC & ROW	−0.54	−0.43	−0.56	−0.53	−1.15	−0.92	−1.18	−1.12	−2.59	−2.13	−2.58	−2.49
Agricultural export	−9.46	−4.64	−3.36	−3.52	−18.53	−9.24	−6.71	−7.02	−35.41	−18.29	−13.38	−13.96
Industrial export	−1.24	−0.49	−0.37	−0.57	−2.70	−1.07	−0.79	−1.24	−6.39	−2.60	−1.86	−2.94
Service export	0.03	0.04	0.36	0.12	0.11	0.15	0.66	0.27	0.48	0.62	1.09	0.67
Total import from ROC & ROW	−0.56	−0.46	−0.59	−0.55	−1.19	−0.99	−1.23	−1.17	−2.66	−2.29	−2.71	−2.61
Agricultural import	0.60	0.00	−0.60	−0.30	1.19	−0.10	−1.29	−0.66	2.22	−0.71	−2.98	−1.69
Industrial import	−0.49	−0.34	−0.46	−0.45	−1.03	−0.73	−0.96	−0.94	−2.30	−1.67	−2.11	−2.08
Service import	−0.95	−0.74	−1.26	−1.00	−2.01	−1.59	−2.63	−2.10	−4.48	−3.70	−5.76	−4.70

the SNWT has been completed. GDP also increases in accordance with increases in output levels. Only in Hebei Province do output and GDP decline before the completion of the second stage of the project. However, all scenarios in this scenario group have been chosen on the basis of reducing groundwater use to renewable levels. Water volumes allocated to Hebei by the first stage of the project are smaller than the volume of groundwater reduction in the region.

Comparing the results in Table 4 with the results of Scenario S1c (20% reduction in groundwater use) in Table 3 shows that the construction of the SNWT has a positive impact on the economy of all regions in the study area. According to the Development Research Center of the Ministry of Water Resources (DRCMWR, 2003) and Qin, Pei, and Zhang (2010), these benefits should cover the costs of constructing the project. Table 4 also shows that household and government income increase due to the construction of the SNWT. Increasing household income raises the purchasing power of households and improves their welfare. Therefore, based on the experimental results of this scenario group, we conclude that the construction of the SNWT leads to positive economic, social and environmental effects for the regions in the study area.

At the sector level, Table 4 shows that agricultural production increases greatly after completion of the SNWT; this increase is much higher than the increase in the output of the industrial and service sectors. Because agriculture comprises only a small proportion of the whole economy, economic gains achieved through the construction of the SNWT are lower than might be expected, as shown in Table 4. Once the project is completed,

Table 4. Changes (in %) of main economic variables under Scenario Group 2: transferring water under the SNWT.

	S2a: Project Stage 1				S2b: Project Stage 2			
Economic variable	Beijing	Tianjin	Hebei	Total	Beijing	Tianjin	Hebei	Total
GDP	0.96	1.66	−0.44	0.41	1.96	2.99	1.52	1.93
Total output	1.20	1.77	−0.44	0.50	2.29	2.86	1.17	1.84
Agricultural output	7.36	10.38	−1.50	0.94	14.63	19.87	4.34	7.34
Industrial output	1.34	1.47	−0.38	0.39	2.40	2.12	0.89	1.49
Service output	0.95	1.85	−0.39	0.61	1.89	3.33	1.21	1.85
All household EV	1.43	3.96	−1.30	0.51	3.02	7.31	4.62	4.49
Rural household EV	1.22	15.63	−2.72	−0.65	2.19	28.01	8.48	9.32
Urban household EV	1.45	2.51	−0.57	0.82	3.09	4.74	2.64	3.21
All household income	1.28	3.75	−1.25	0.48	2.70	6.92	4.46	4.20
Rural household income	1.04	14.55	−2.67	−0.63	1.84	26.08	8.32	8.95
Urban household income	1.30	2.38	−0.55	0.77	2.78	4.49	2.52	2.98
Government income	2.18	4.36	−0.33	1.51	4.35	7.18	2.14	3.90
Total export to ROC & ROW	0.98	1.74	−0.51	0.40	1.74	2.67	1.25	1.69
Agricultural export	19.03	26.54	−2.72	−1.17	42.88	57.54	8.76	11.31
Industrial export	1.89	1.62	−0.35	0.58	3.30	2.04	0.70	1.55
Service export	0.18	0.88	0.20	0.28	0.33	2.24	−1.14	0.18
Total import from ROC & ROW	0.95	1.62	−0.43	0.41	1.84	2.61	1.35	1.77
Agricultural import	−0.76	−1.00	−0.45	−0.57	−2.41	−2.99	1.26	0.07
Industrial import	0.83	1.30	−0.36	0.30	1.61	2.13	1.04	1.41
Service import	1.55	2.44	−0.75	0.99	3.12	3.94	3.00	3.34

total output and GDP each increase by less than 2%. This is because transferred water is allocated proportionately across sectors in this scenario group, and agriculture receives a greater amount of water; however, the marginal value of water is low. Limited water availability in the study area should be transferred from low-value use to high-value use. (In the next scenario group, the economic impact of the water reallocation strategy is studied by redistributing water from agriculture to other sectors.)

Simulation results of Scenario Group 3: water reallocation across sectors

The results of the changes in the main economic variables under Scenario Group 3, i.e. reallocating water from agriculture to other production sectors, are given in Table 5. Reallocating between 5% and 20% of the water from agriculture to the industrial and service sectors could result in similar growth in output and GDP of all regions. If 20% of the water is transferred from agriculture to the industrial and service sectors, output and GDP of the whole study area increase by 3.26% and 2.05%, respectively. As most water in the basin is already controlled by infrastructural measures (reservoirs, channels, etc.), the cost of water reallocation would be low. Indeed, reallocating water from a low-value sector to high-value sectors could create positive macro-economic effects. In the past, some large manufacturing and service industries could not be constructed in this area due to water constraints. Enough water will encourage these industries to invest here, further improving the development level of the area.

As Table 5 shows, levels of household and government income also increase as a result of reallocating water from agriculture to other sectors. If 20% of the water used for agriculture is transferred to the industrial and service sectors, income of households and the government in the whole study area increases by 3.1% and 8.1%, respectively. Growth of households' income improves their purchasing power and welfare. Indeed, as Table 5 shows, if 20% of the water used for agriculture is transferred to the industrial and service sectors, welfare increases by 4.16% and 3.08% for rural and urban households, respectively. This is because rural households currently receive income from the other sectors by supplying them with labour. Nevertheless, it should be borne in mind that a water reallocation policy will inevitably lead to welfare losses in those rural households that receive the majority of their income from the sale of agricultural products.

At the sector level, Table 5 shows that agricultural production suffers substantial losses when part of the water used for agriculture is transferred to other production sectors. If 20% of the water used for agriculture is reallocated to the industrial and service sectors, agricultural output for the whole study area will decline by more than 10%. On the one hand, reallocating water from a low-value sector to a high-value sector could promote economic restructuring from a low-water-efficiency sector to relatively high-water-efficiency sectors. On the other hand, the region produces a substantial amount of good-quality agricultural products, especially wheat and corn. Agricultural water plays an important role in the food security of the country. To maintain the stability of agricultural production and the standard of living of fragile agricultural households, the government could provide subsidies for farmers to invest in water-saving technologies; but if solely dependent on government investment, this is a very expensive option. Another policy option would be to set up a water market and allow those who use water inefficiently (i.e. in agriculture) to sell it to users in other sectors (e.g. service industries) where there is a demand for it. In this way the efficiency of water use would improve in both sectors. Farmers who lose access to water could leave the sector and migrate to the cities, where their increased earnings and government programs can provide them with better services and/or work-skills training.

Table 5. Changes (in %) of main economic variables under Scenario Group 3: water reallocation from agriculture to other sectors.

	S3a: Reallocate 5% of agricultural water				S3b: Reallocate 10% of agricultural water				S3c: Reallocate 20% of agricultural water			
Economic variable	Beijing	Tianjin	Hebei	Total	Beijing	Tianjin	Hebei	Total	Beijing	Tianjin	Hebei	Total
GDP	0.48	0.71	1.22	0.87	0.89	1.25	1.89	1.43	1.54	1.99	2.44	2.05
Total output	0.49	0.77	2.08	1.31	0.93	1.34	3.37	2.18	1.66	2.07	4.81	3.26
Agricultural output	−3.33	−1.97	−2.49	−2.57	−6.91	−4.12	−4.92	−5.14	−14.66	−8.87	−9.73	−10.39
Industrial output	0.59	0.77	2.01	1.43	1.09	1.30	3.29	2.38	1.87	1.92	4.80	3.53
Service output	0.53	0.95	3.18	1.49	1.03	1.75	5.26	2.57	1.96	3.07	7.84	4.12
All household EV	0.84	1.75	2.11	1.60	1.53	3.07	3.05	2.52	2.63	4.92	3.27	3.31
Rural household EV	1.87	6.29	2.09	2.42	3.57	11.12	2.88	3.67	6.64	17.94	2.26	4.16
Urban household EV	0.75	1.18	2.12	1.39	1.36	2.07	3.15	2.21	2.30	3.30	3.78	3.08
All household income	0.75	1.66	2.03	1.50	1.37	2.91	2.95	2.36	2.36	4.66	3.15	3.10
Rural household income	1.66	5.84	2.02	2.30	3.18	10.32	2.77	3.49	5.94	16.65	2.13	3.95
Urban household income	0.67	1.12	2.04	1.29	1.21	1.97	3.03	2.07	2.05	3.14	3.66	2.88
Government income	1.31	2.48	5.14	3.01	2.47	4.35	8.51	5.16	4.45	6.91	12.66	8.10
Total export to ROC & ROW	0.43	0.83	1.60	1.09	0.85	1.43	2.58	1.82	1.61	2.21	3.62	2.73
Agricultural export	−12.43	−9.87	−10.86	−10.84	−23.70	−18.47	−19.22	−19.27	−43.43	−33.28	−32.46	−32.69
Industrial export	0.93	1.04	2.93	2.06	1.68	1.74	4.86	3.45	2.72	2.50	7.27	5.18
Service export	0.13	0.53	3.69	1.19	0.36	1.25	6.39	2.18	1.03	2.97	10.49	3.97
Total import from ROC & ROW	0.54	0.84	1.63	1.14	1.02	1.44	2.64	1.91	1.85	2.22	3.73	2.85
Agricultural import	3.31	4.27	4.38	4.15	6.56	8.07	7.63	7.46	13.26	14.99	12.59	12.98
Industrial import	0.34	0.58	1.28	0.87	0.66	0.99	2.05	1.44	1.21	1.52	2.85	2.12
Service import	0.95	1.23	2.67	1.68	1.73	2.08	4.23	2.76	2.94	3.06	5.65	3.98

Thanks to increases of output and consumption, international trade also increases. When 20% of the water used in agriculture is reallocated to the industrial and service sectors, total exports and total imports grow by 2.73% and 2.85%, respectively. However, the decline in agricultural production leads to a substantial reduction in agricultural output. If 20% of the water is reallocated from agriculture to other sectors, agricultural exports decline substantially, by more than 32%. To satisfy local demand for agricultural products, agricultural imports under this approach increase to 13%. Based on the Heckscher-Ohlin theorem for trade (Heckscher, 1919; Ohlin, 1933), the comparative advantage of different regions is dependent on the endowment of their relative factors. The modelling results in Table 5 indicate that reallocating water from a low-value sector to a high-value sector changes the relative comparative advantage of those sectors. Sectors with low water-use efficiency increase their imports to satisfy local demand, while the competitive advantage of sectors with relatively high water-use efficiency increases, and they export more products to other regions. In terms of "virtual water" theory (Allan, 1998), this is equivalent to reducing local water demand and improving water-use efficiency.

Conclusions and policy implications

As described in this paper, water was introduced into the CGE model framework as an explicit factor of production, and the marginal value of water was adopted to represent its equilibrium price; an econometric model was used to estimate the marginal value of water. According to this econometric analysis, a multi-regional, multi-sectoral, water-extended computable general equilibrium model was developed, and applied to analyze the effectiveness of measures and policies for mitigating North China's water scarcity under three different groups of scenarios. Several important policy implications can be drawn from the simulation results.

First, it is necessary to establish a water permit system and set a total groundwater withdrawal target to gradually reduce the over-exploitation of groundwater. Over-exploitation of water resources in the region can lead to severe ecological degradation, although economic benefits may be achieved in the short term. Our research findings suggest that once groundwater supplies become exhausted, the subsequent crisis in water supply will result in huge GDP, welfare and environmental losses. Licensing of water use and total water-use control are not new on the Chinese water-policy agenda, but in the study area there is an urgent need to reduce total groundwater use through a strict water-permit system to ensure that the water supply remains at a sustainable level.

Second, engineering measures to improve water supply can make a significant contribution to mitigating North China's water scarcity. Research findings suggest that construction of the South–North Water Transfer project will have a positive impact on economic development, household welfare and environmental sustainability. The benefits can be expected to cover the financial investment of building the project (DRCMWR, 2003; Qin et al., 2010). Once construction of the project has been completed, not only can exploitation of groundwater be reduced to renewable levels, but the water-supply capacity for productive use can also be improved.

Third, market mechanisms should be used to allocate water among the production sectors (after meeting domestic and environmental requirements). Our research findings suggest that marginal values of water vary both for regions and for sectors. Modelling results also indicate that transferring water from low-value sectors to high-value sectors can have a positive impact on the macro-economy and household welfare, and can promote economic restructuring from low-water-efficiency sectors to relatively high-water-efficiency sectors. We therefore suggest that reallocation of water be based on its marginal value. On the grounds of equity and efficiency, a reasonable policy would be to set up a water market to allow those who use water inefficiently (i.e. in agriculture) to sell water to users in industries (e.g. services) where there is a strong demand for it. Market mechanisms should play an active role in this process.

This analysis needs to be extended in several ways to remove a number of limitations. The CGE model used in our study is comparative-static in its nature, which does not allow for the consideration of cumulative effects. Moreover, many measures and policies cannot be realized overnight. It is necessary, therefore, to develop a dynamic CGE model to investigate long-term effects and capture the accumulated impact of these measures and policies. In addition, the modelling framework in the study does not include regions that donate water; it is recommended that the model be extended to cover the donation provinces in order to analyze the future impacts of the SNWT on water-donating regions.

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Appendix: Water social accounting matrices

This appendix shows the water social accounting matrices developed for Beijing, Tianjin and Hebei for the base year 2007.

Table A1. WSAM 2007 for Beijing (in 10^8 CNY).

		Activity			Commodity			Factor		Water			Household		Institution		S-I	Trade				TOT
		AGR	IND	SER	AGR	IND	SER	CAP	LAB	AGR	IND	SER	RHH	UHH	ENT	GOV	INV	TJ	HB	ROC	ROW	Total
ACT	AGR				273																	273
	IND					11,391																11,391
	SER						15,650															15,650
COM	AGR	94	173	101									16	123		8	14	0	0	0	33	562
	IND	45	7,213	3,732									76	1,102		0	3,134	372	498	2,089	2,304	20,565
	SER	32	1,443	4,618									130	1,425		2,206	1,411	460	445	3,792	2,022	17,984
FAC	CAP	18	1,082	2,766																		3,866
	LAB	39	847	3,109																		3,995
WAT	AGR	42																				42
	IND		166																			166
	SER			721																		721
HHD	RHH								296	42	5	22			55							420
	UHH								3,700		161	699			690							5,250
INS	ENT							3,866														3,866
	GOV	2	467	603	2	47	21						34	305	2,026							3,507
S-I	SAV												164	2,295	1,095	1,294		−2	314	164	−765	4,558
TRA	TJ				5	742	83															830
	HB				66	1,007	183															1,257
	ROC				106	4,972	967															6,045
	ROW				109	2,405	1,079															3,594
TOT	Total	273	11,391	15,650	562	20,565	17,984	3,866	3,995	42	166	721	420	5,250	3,866	3,507	4,558	830	1,257	6,045	3,594	

Table A2. WSAM 2007 for Tianjin (in 10^8 CNY).

		Activity			Commodity			Factor		Water			Household		Institution		S-I	Trade				TOT
		AGR	IND	SER	AGR	IND	SER	CAP	LAB	AGR	IND	SER	RHH	UHH	ENT	GOV	INV	BJ	HB	ROC	ROW	Total
ACT	AGR				241																	241
	IND					11,664																11,664
	SER						3,891															3,891
COM	AGR	30	100	15									8	75		58	−5	5	13	58	18	375
	IND	74	6,484	843									57	525		0	2,370	742	488	3,834	1,771	17,187
	SER	26	2,188	986									80	564		697	557	83	111	943	451	6,687
FAC	CAP	2	1,425	940																		2,367
	LAB	59	707	656																		1,422
WAT	AGR	49																				49
	IND		159																			159
	SER			159																		159
HHD	RHH								279	49	11	11			265							617
	UHH								1,143		148	148			1,085							2,524
INS	ENT							2,367														2,367
	GOV	0	601	293	0	24	7						11	62	336							1,335
S-I	SAV												461	1,297	680	580		2	−62	589	−625	2,922
TRA	BJ				0	372	460															832
	HB				21	402	127															551
	ROC				93	3,498	1,833															5,424
	ROW				20	1227	368															1,615
TOT	Total	241	11,664	3,891	375	17,187	6,687	2,367	1,422	49	159	159	617	2,524	2,367	1,335	2,922	832	551	5,424	1,615	

Table A3. WSAM 2007 for Hebei (in 10^8 CNY).

		Activity			Commodity			Factor		Water			Household		Institution		S-I	Trade				TOT
		AGR	IND	SER	AGR	IND	SER	CAP	LAB	AGR	IND	SER	RHH	UHH	ENT	GOV	INV	BJ	TJ	ROC	ROW	Total
ACT	AGR				3076																	3,076
	IND					28,067																28,067
	SER						8,955															8,955
COM	AGR	475	1,190	156									112	283		6	−275	66	21	1,772	21	3,827
	IND	668	17,040	2,119									575	1,132		0	6,659	1,007	402	11,141	1,243	41,987
	SER	128	2,526	2,017									653	1,196		1,958	377	183	127	2,706	124	11,997
FAC	CAP	32	3,947	1,953																		5,933
	LAB	1,017	1,507	1,652																		4,176
WAT	AGR	804																				804
	IND		524																			524
	SER			342																		342
HHD	RHH								1,432	804	24	16			376							2,652
	UHH								2,744		500	326			1,511							5,081
INS	ENT							5,933														5,933
	GOV	−49	1,333	715	1	11	2						29	116	393							2,551
S-I	SAV												1,283	2,354	3,653	587		−314	62	−196	−668	6,761
TRA	BJ				0	498	445															942
	TJ				13	488	111															613
	ROC				664	12,355	2,405															15,423
	ROW				74	567	79															720
TOT	Total	3,076	28,067	8,955	3,827	41,987	11,997	5,933	4176	804	524	342	2,652	5,081	5,933	2,551	6,761	942	613	15,423	720	