TEMPORAL AND SPATIAL VARIABILITY OF WATER SUPPLY STRESS IN THE HAIHE RIVER BASIN, NORTHERN CHINA¹

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ABSTRACT: Water resources are becoming increasingly stressed under the influence of climate change and population growth in the Haihe River Basin, Northern China. Assessing the temporal and spatial variability of water supply stress is urgently needed to mitigate water crisis caused by water resource reallocation. Water supply and use data were compiled for the time period of 1998-2003 in this synthesis study. The Water Supply Stress Index (WSSI) as defined as Water Demand/Water Supply was used to quantitate whether water supply could meet the demand of human activities across the study region. We found a large spatial gradient of water supply stress in the study region, being much higher in the eastern subbasins (ranging from 2.56 to 4.31) than the west subbasins (ranging from 0.56 to 1.92). The eastern plain region not only suffered more serious water supply stress but also had a much higher interannual variability than the western hilly region. The uneven spatial distribution of water supply stress might result from the distribution of land use, population, and climate. Future climate change and rapid economic development are likely to aggravate the existing water crisis in the study region.

(KEY TERMS: water crisis; water shortage; river basin; water supply; water demand.)

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INTRODUCTION

Due to population growth and climate change, serious water shortage is becoming increasingly common in many regions around the world (Saeijs and Van Berkel, 1995). The Middle East region faced serious water shortage, which poses serious threat to local economic development (Black *et al.*, 2010). In the arid western United States (U.S.), the hydrologic changes in the last 50 years have resulted in an intense competition for water supplies in some areas (Bishop *et al.*, 2010). Australia suffered a significant rainfall decline

from 1997 to 2006, resulting in a severe water shortage (Murphy and Timbal, 2008). South Africa also suffered a serious water supply crisis as water demand increased (Binns *et al.*, 2001).

Northern China has been facing increasingly severe water scarcity, and the Haihe River Basin is an example (Jiang, 2009). The total volume of annual renewable freshwater in the Haihe River Basin was estimated to be about $370 \times 10^8 \text{ m}^3$, and the average available water supply was only 276 m^3 per capita in 2005 (Zhu *et al.*, 2007), which was far below the international water-shortage criterion ($1,000 \text{ m}^3$ per capita) (Xia *et al.*, 2006). However, the total volume

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of water demand in the Haihe River Basin was about $383 \times 10^8 \text{ m}^3$ in 2005 (Zheng and Li, 2009). The water demand exceeded the annual renewable water supply in recent years, resulting in serious water supply crises in the Haihe River Basin.

In responding to the water crisis, the central government established a special commission—"Haihe River Water Resources Commission"—for effective management of the water resources in the Haihe River Basin in 1979 (Shen *et al.*, 2004). Many water conservancies were built to work toward sustainable use of water resources. So far, more than 1,900 reservoirs have been built with a total water supply capacity of $265 \times 10^8 \text{ m}^3$ (Cao, 2004). However, these water conservancies did not prevent water resources from overuse and exhaustion due to climatic change and human's demand for water.

Several indices have been developed for quantitative evaluation of water shortage or water scarcity (Brown and Matlock, 2011). Examples include the Falkenmark Indicator, Water Scarcity Index (Gleick, 1996), and the Social Water Stress Index (Ohlsson, 2000). The Falkenmark Indicator is also called "water stress index," which is defined as the average available water per capita per year, and 1,700 and 1,000 m^3 per capita per year are used as the thresholds between water stressed and scarce areas, respectively. However, the simple thresholds did not reflect important variations in demand due to lifestyle, climate, etc. Gleick (1996) developed a water scarcity index as a measurement of the ability to meet all water requirements for basic human needs: drinking water for survival, water for human hygiene, water for sanitation services, and modest household needs for preparing food. Ohlsson used the United Nations Development Programme's Human Development Index to weight the Falkenmark's indicator, and called it a "Social Water Stress Index" (Rijsberman, 2006). However, these water scarcity indices have not incorporated renewable water supply and annual actual demand for water (Brown and Matlock, 2011). The Water Resources Vulnerability Index takes the renewable water supply into account, since the index was defined as the ratio of total annual withdrawals to available water resources. A country is considered to be water scarce if annual withdrawals are between 20 and 40% of annual supply, and severely water scarce if withdrawals exceed 40% (Raskin *et al.*, 1997). These indices are generally expressed mostly on a national scale. Therefore, the water scarcity information at smaller scales tends to be lost because these indices were quantified based on the average water scarcity at a large scale.

Sun *et al.* (2008) proposed a Water Supply Stress Index (WSSI) to quantitatively assess relative magnitude in water supply and demand at watershed level. WSSI was defined as the ratio between water

demand and water supply. Water supply was the total potential water available for withdraw from a basin, including: surface water supply (precipitation minus evapotranspiration ($P-ET'$)), total groundwater supply (e.g., historical groundwater withdrawal records), and the return flow from seven water users (commercial, domestic, industrial, irrigation, livestock, mining, and thermoelectric sectors). Water demand was the sum of seven sectors plus public use and losses. This approach is best used when detailed watershed water balances (such as evapotranspiration) at the monthly or annual scale are available.

Water supply and demand issues in the Haihe River Basin have been well studied (Ying and Huang, 1997; Wang *et al.*, 2009), but little attention was paid to its temporal-spatial variability at the regional scale. However, regional basin-scale analysis that examines spatial and temporal water stress dynamics is important to mitigate water crisis through science-based water allocation management. This article focuses on the temporal-spatial variability of water supply crises, and the extent and severity of water supply crises. We evaluated the water crisis in the Haihe River Basin based on WSSI, as defined in Sun *et al.* (2008). The objectives in this article are to identify the water stress "hot spot" by studying the temporal and the spatial distribution characteristics of water supply stress, so that useful information for reallocation of the limited water resources can be derived.

STUDY AREA

The study area is the Haihe River Basin, which is a natural river basin in Northern China, with a total area of $31.8 \times 10^4 \text{ km}^2$. Its latitude ranges 35° - 43°N longitude 112° - 120°E . The terrains are mainly composed of plateau, mountain, and plain. The rivers flow through plateau, mountain, and plain from west to east, then flow into the Bohai Sea (Figure 1). There are $16 \times 10^4 \text{ km}^2$ of crop lands, $5.9 \times 10^4 \text{ km}^2$ of grass lands, $7.3 \times 10^4 \text{ km}^2$ of forestry lands, and $1.7 \times 10^4 \text{ km}^2$ of build lands. Most of crop lands are found on the eastern plain (Figure 2).

The Haihe River Basin has a continental monsoon climate of semi-humid and semiarid. The monsoon climate brings an extreme precipitation or drought, which often affects water supply (Ma *et al.*, 2010). The mean annual precipitation is 535 mm, while annual potential evaporation (PET) is higher than annual precipitation (Zheng and Li, 2009; Dong *et al.*, 2010). Therefore, the dryness index (potential evapotranspiration/precipitation (PET/P)) in the Haihe River Basin is >1.0 . However, an obvious difference

FIGURE 1. The Location and the Nine Subbasins of the Haihe River Basin in China.

FIGURE 2. The Distribution of Land Use in the Haihe River Basin.

FIGURE 3. The Distribution of Dryness Index (PET/P) in the Haihe River Basin.

in dryness is found between the southeast plain and north mountains (Figure 3).

The total population in the Haihe River Basin is over 130 million currently, accounting for about 10% of the nation's population. Therefore, the Haihe River Basin, especially its plain region, has a very high population density (Figure 4), and the region is dominated by intensive agriculture, emerging industries, and rapid urban development. Thus, there is a huge demand for water, and the demand often exceeds

renewable water supply. In the past decade, dropping groundwater level, drying-up rivers, shrinking reservoirs, and diminishing lakes and wetlands were frequently reported in the Haihe River Basin (Fei *et al.*, 2001; Yao, 2003; Zhu *et al.*, 2005; Xia *et al.*, 2006; Xue *et al.*, 2010).

To examine the spatial characteristics of water supply stress, the Haihe River Basin was divided into nine subbasins (or watersheds) mainly based on hydrological characteristics and sub-river system. Among the

FIGURE 4. Distribution of Population Density in 2001 and Total GDP in 1998 of Each County in the Haihe River Basin.

nine subbasins, five subbasins (Luanhe, Beisan, Yongding, Ziya, and Zhangwei) mainly consist of mountain and plateau, and other four sub-basins (Beisi, Daqing, Yundong, and Tuhai) mainly consist of plain (Figure 1).

DATA AND METHODS

The water resource data were collected from the “Haihe River Basin Water Resources Bulletin” that was compiled by a special governmental organization, “the Haihe River Water Resources Commission,” which is responsible for water resource management, and monitoring and collection of hydrological information in the Haihe River Basin. The available data included the volume of the water demand and the water supply in the nine subbasins from 1998 to 2003 except 2000.

The WSSI (Sun *et al.*, 2008) was adopted to evaluate whether water supply could meet the demand of human activities. The WSSI was defined as a ratio of water demand to water supply. Water demand was the water actually used by agriculture, industry, service industries, and daily life in one year. Water supply was the total annual renewable dynamic water in the surface and underground.

$$WSSI = \frac{\text{Water Demand}}{\text{Water Supply}} \quad (1)$$

Therefore, the quantity of water demand included all water volumes used by agriculture, industry,

service industry, and domestic water use at an annual time scale. Water demand from agriculture consisted of irrigation water used for paddy field, cropland, vegetable land, plantation forests, fruit trees and lawns, and filling urban ponds. Water demand from industry consisted of water used by all industries except for service industries, but the reused water in industries was not included. Water demand from the service industry consisted of water used by shopping centers, services, finance, transportation, storage, post and telecommunications, and culture and education organizations. Water demand for domestic use consisted of water used by the public, individual families and livestock drinking water in cities, towns, and villages (Table 1). However, the quantity of water demand was calculated by the original water volume directly taken from three water survey sources: surface water, groundwater, and other water resources. The water demand therefore included the water in transport process due to evaporation, transpiration, soil sorption and production inclusion, etc.

Water demand from surface water resources was the sum of water taken from engineering structures for water storage, diversion, pumping, transfer, and non-engineering facilities. The water volume taken from reservoirs and ponds was summed as the water volume from storage facilities; the water volume overflowing automatically from lakes and rivers was accounted for as the water volume from diversion; the water volume pumped from lakes and rivers was regarded as the water volume from pumping engineering; the water volume transferred from another drainage basin was summed as the water volume from transfer engineering structures; the water volume carried by human beings was summed as the water volume from the non-engineering category.

$$Q_s = Q_{st} + Q_d + Q_p + Q_t + Q_n, \quad (2)$$

where Q_s is the quantity of surface water volume; Q_{st} is the water volume from storage engineering; Q_d is the water volume from diversion engineering; Q_p is the water volume from pumping engineering; Q_t is the transfer water volume; Q_n is the water volume from non-engineering.

Water demand from the groundwater resource was the sum of water volumes taken from well engineering, including shallow well and deep wells. Water demand from other water resources was the sum of water volumes from the reused water after wastewater was treated (except for the reused water within a factory), the rainwater gathered by rainwater harvesting facilities such as cellars, tanks, etc., and the freshwater derived from desalination of sea water.

The quantity of water supply was the sum of surface runoff and infiltration replenishment from the

TABLE 1. The Components of Water Supply and Water Demand, and Their Calculated Methods.

	Types	Components	Calculated Methods
Water demand	Agriculture	Irrigation water for paddy field, cropland, vegetable land, woods, fruit trees, and grassland; Compensatory water for ponds.	Calculated the original water volume directly taken from surface (see Equation 2), groundwater (the estimated water from the number of wells and statistical ponds area and irrigation area)
	Industry	Water used by all industries (reused water was not included).	Calculated the original water volume directly taken from surface (see Equation 2), groundwater (the estimated water from the number of wells used by industries), water from sea water desalination
	Service industry	Water used by shopping centers, services, finance, transportation, storage, post and telecommunications, and culture and education organizations, etc.	Calculated the original water volume directly taken from surface (see Equation 2) and groundwater (the estimated water from the number of wells used by service industries)
	Domestic use	The public, individual families, and livestock drinking water in cities, towns, and villages.	Calculated the original water volume directly taken from surface and groundwater (the estimated water from the statistical public water area, population of people, and livestock)
Water supply	Mountain	River surface flow, total groundwater flow, river base flow.	The drainage method (see Equation 3)
	Plain and plateau	River surface flow, infiltration recharge from precipitation, the total river flow, total groundwater recharge.	The recharge method (see Equations 4 and 5)

local precipitation. However, the quantity of water supply was calculated by different methods in different terrains.

In mountain regions, the total quantity of water supply was calculated using the drainage method by the following equation:

$$W_1 = R + Q_g - R_g, \quad (3)$$

where W_1 is the total quantity of water supply in the mountain basins; R is the river surface flow; Q_g is the total groundwater flow; and R_g is the river base flow.

In plain and plateau regions, the total water supply was calculated using the recharge method:

$$W_2 = R + U_p - Q_{up}, \quad (4)$$

$$Q_{up} \approx Q_r(U_p/U_t), \quad (5)$$

where, W_2 is the total quantity of water supply in plain and plateau; R is the river surface flow; U_p is the infiltration recharge from precipitation; Q_{up} is the river drainage resulting from infiltration recharge; Q_r is the total river flow; and U_t is total groundwater recharge.

The WSSI was used to assess the status of water supply stress. A WSSI value of 1.0 indicates that actual water demand barely meets renewable water supply. If WSSI is <1.0, it indicates annual renewable water is surplus except for meeting actual water demand. If WSSI is >1.0, it implies that actual water

demand exceeds renewable water supply, and the larger the WSSI, the stronger water supply stress is.

RESULTS

Basin-Wide Water Supply Stress

In general, the dynamic renewable water supply was consistently less than the actual water demand in the Haihe River Basin over the entire period of 1998-2003. The annual average demand for water was $404 \times 10^8 \text{ m}^3$, while the annual average supply of renewable water was $245 \times 10^8 \text{ m}^3$. As a result, the natural renewable water supply only met about 60% of water demand, so a reserved water resource would be consumed. The results implied that the Haihe River Basin suffered from a serious water supply stress, because its reserved water resource would be consumed to exhaustion gradually.

To alleviate water supply stress, attempts have been made to reduce actual water demand by adopting many measures. For example, since the largest water consumption in the Haihe River Basin was from agricultural irrigation, the government reduced its water consumption by adopting new irrigation technology, and by turning paddy field into maize land (Wu and Xu, 1997). Though water demand had been cut down to some extent, water demand was still higher than supply (Figure 5). There was an average annual shortage of water $159 \times 10^8 \text{ m}^3$ in the

FIGURE 5. The Water Demand and Supply in the Haihe River Basin During the Period of 1998-2003.

entire Haihe River Basin during the time period of 1998-2003.

The Spatial Variability of Water Supply Stress

The cumulative water supply and water demand at each subbasin during 1998-2003 showed an obvious water supply stress in six subbasins (61.5% area of the Haihe River Basin) out of nine subbasins because their cumulated water demand exceeded cumulated water supply (Figure 6). The average WSSI of each subbasin during 1998-2003 showed an obvious water supply stress in seven sub-basins (79% area of the

FIGURE 6. The Cumulated Water Supply and the Cumulated Water Demand in the Haihe River Basin During 1998-2003 (except 2000).

FIGURE 7. The Spatial Distribution of Water Supply Stress Index (WSSI) in the Nine Subbasins in the Haihe River Basin.

Haihe River Basin) out of nine subbasins with a WSSI higher than 1.0 (Figure 7). These results suggested that most areas of the Haihe River Basin suffered from high water supply stress.

Water supply stress showed an uneven spatial distribution among the nine subbasins. The eastern subbasins suffered from a severe water supply stress. The eastern subbasins had evidently higher water supply stress, since their water demand often exceed water supply, and their WSSI fluctuated in the scope of 2.5-4.3 (Figure 7 and Table 2). For example, subbasins of Beisi, Tuhai, and Yundong in the eastern part of the Basin had a rather high WSSI (>4.0), meaning water demand exceeds fourfold of water supply. However, subbasins in the western mountains had lower water supply stress with WSSI values fluctuating from 0.5 to 2.0 (Figure 7 and Table 2). For example,

TABLE 2. The Water Supply and Water Demand at Nine Subbasins During the Period of 1998-2003.

Terrain	Subbasin	Water Demand $\pm$ SD (10^8 m ³)	Water Supply $\pm$ SD (10^8 m ³)
Mountain	Beisan	10.92 $\pm$ 5.17	20.89 $\pm$ 6.78
	Yongding	20.53 $\pm$ 0.49	21.25 $\pm$ 3.14
	Luanhe	38.75 $\pm$ 2.86	41.23 $\pm$ 17.50
	Zhangwei	43.68 $\pm$ 2.87	38.86 $\pm$ 11.16
	Ziya	64.77 $\pm$ 6.49	34.72 $\pm$ 5.76
Plain	Daqing	69.73 $\pm$ 1.46	28.50 $\pm$ 5.81
	Yundong	29.69 $\pm$ 0.80	10.59 $\pm$ 7.26
	Beisi	51.08 $\pm$ 4.17	15.98 $\pm$ 10.54
	Tuhai	74.60 $\pm$ 4.09	33.53 $\pm$ 24.01

the subbasins of Beisan and Yongding in the north-western part had a lower WSSI, implying a low water supply stress.

To explore the causes of the distribution patterns of water supply stress observed, land use (Figure 2), climatic dryness (Figure 3), population density and GDP (Figure 4) datasets were constructed for each subbasin. The results suggested that although climatic dryness (PET/P) may affect the balance between water supply and water demand, dryness did not contribute to the distribution patterns of water supply stress. There were few similar distribution patterns between the WSSI and the dryness (Figures 3 and 7). The distribution patterns of water supply stress could be explained by land use and population distribution, because there was vast crop land and higher population density in the eastern plain, while the western mountains and plateau were dominated by natural lands, such as forest land, grass land, together with lower population density (Figures 2 and 4). In the eastern plain, the large area of crop land and higher population presumably consumed more water than western mountains and plateaus. Therefore, the eastern plains generated much more GDP than the western regions, likely by consuming more water (Figure 4). As a result, we argue that the key factors that caused the uneven water supply stress should attribute to the distribution of land use and population.

The Temporal Variability of Water Supply Stress

Generally, the interannual fluctuation of WSSI in the Haihe River Basin was large, implying a larger variability of water supply stress. The average annual fluctuation of WSSI in the entire Haihe River Basin ranged around 1.2-2.5 over the period of 1998-2003. However, different annual fluctuation of WSSI was seen among nine subbasins. WSSI in Tuhai Basin had the largest fluctuation between 1.03 and 10.9, but WSSI in Yongding Basin had the smallest fluctuation between 0.78 and 1.13 (Figures 8 and 9).

Interestingly, the interannual fluctuation of WSSI was associated with terrain characteristics. For example, the WSSI in the four subbasins in the eastern plain fluctuated between 1.0-11.0, while the WSSI in the five subbasins in the western mountains fluctuated between 0.2-2 during 1998-2003 (Figures 8 and 9). The results showed that the plain had a larger interannual fluctuation of WSSI than the mountains, so the plain had a larger annual variability of water supply stress than the mountains.

To explore the causes of annual variability of water supply stress, the interannual fluctuation of water supply and demand was studied respectively. Water demand in most subbasins of the Haihe River

FIGURE 8. The Interannual Fluctuation of Water Supply Stress Index (WSSI) in the Subbasins During the Period of 1998-2003.

FIGURE 9. The Interannual Fluctuation Range of Water Supply Stress Index (WSSI) in the Subbasins During the Period of 1998-2003.

Basin had a smaller interannual fluctuation than water supply during 1998-2003 (Table 2). For example, Tuhai Basin had the largest inter-annual fluctuation of water supply, and had smaller fluctuation of water demand (Table 2), so water supply contributed to the largest interannual fluctuation of WSSI (Figures 8 and 9). Therefore, we believed that the interannual fluctuation of water supply stress was mainly controlled by the annual variability of water supply.

Further, the water supply fluctuation was caused by precipitation variability due to a monsoon climate, so it could be further inferred that the interannual

fluctuation of water supply stress was controlled ultimately by the monsoon climate.

DISCUSSIONS

Although we used the similar WSSI concept developed by Sun *et al.* (2008), this study used a different method to calculate water demand and water supply. Water demand in this study was the sum of the original water directly taken from three resources: surface water, groundwater, and other water resources. Water supply in the Sun *et al.* (2008) study was the sum of surface water supply, groundwater supply, and return flow from seven water users. Water supply of WSSI in the paper was the sum of surface runoff and infiltration replenishment due to precipitation, and water supply was calculated by different methods in different terrains. In spite of the differences in water supply and demand accounting, both methods appeared to be working well to address water stress issues.

The data of water supply in WSSI was calculated using the recharge method in the plain (or plateau) and using the drainage method in the mountains, respectively. However, some hydrological and geological parameters were needed. There is different hydrology or different geology even in a subbasin, so the water supply data accuracy would be compromised when water supply was calculated using the same parameters in a subbasin.

The water demand data were derived from the original water volume directly taken from three resources: surface water, groundwater, and other water resources, but some data were estimated indirectly by the statistical datasets of agriculture, industry, service industry, and domestic water use records. Errors might exist in estimating water demand based on the statistical data, such as industry and service industry, which have various categories and sizes. At the same time, the statistical data from agriculture, industry, service, and daily life might have potential errors due to different statistical standards. An improved category system and uniform statistical standards might enhance the quality of water demand data.

Inter-basin transfers (import or export) are often ignored in most water stress indices (Gleick, 1996; Rijsberman, 2006). The water demand in WSSI was calculated by the original water volume directly taken from three resources, so water demand included the imported water from other regions and the dissipative water in the transport process. However, water supply in WSSI was the total annual renewable dynamic water, and the water supply was the sum of surface

runoff and infiltration replenishment due to the local precipitation, without the water imported from other regions.

Reducing the water supply crisis by reducing water demand is becoming increasingly challenging because the increasing population and economy would demand more water in the future. Currently, solving the water shortage problem relies heavily on excessive groundwater withdrawal, which exceeds the renewable groundwater at the same period. Groundwater is excessively pumped up to 70×10^8 to $80 \times 10^8 \text{ m}^3$ per year on average over the renewable groundwater in the Haihe River Basin (Zheng and Li, 2009). Groundwater resources have been depleted to an unsustainable condition in certain areas resulting in a series of environmental and ecological problems (e.g., water quality, biodiversity losses, sea water intrusion) (Zhu *et al.*, 2007).

Water supply stress has been aggravated by climate change in the Haihe River Basin. Annual precipitation showed a slightly decreasing trend in the Haihe River Basin from the 1950s (Chu *et al.*, 2010a; Hao *et al.*, 2010), and streamflow decreased due to the decreasing precipitation (Jia and Zhang, 2003). The extreme climatic events were predicted to become more intense in the future (Chu *et al.*, 2010b). Therefore, the climatic change would also result in greater variability of water supply stress.

To solve the emerging water supply crisis, long-range water transfer from other river basins in southern China, where water is more available due to higher precipitation, has been underway. Approximately 40×10^8 to $60 \times 10^8 \text{ m}^3$ of water have been transferred from the adjacent Huanghe River Basin every year (Wu *et al.*, 2007), and projects are being built to transfer water from the Yangtze River Basin to Beijing, a major water shortage area in the study region.

The temporal and spatial variability maps for WSSI showed where serious water shortage occurred. Management actions to mitigate water crisis through relocating the limited water resources should focus on these areas. The study region is changing rapidly in terms of economic development and land use, so water supply and demand are likely to change. Updated datasets for the recent decade will be useful for further analysis of the trend of water stress in the study basin.

CONCLUSIONS

There was a serious water supply stress in the Haihe River Basin. The annual renewable water supply could not meet the water demand. The water supply stress showed an obvious spatial variability in

the Haihe River Basin. The eastern subbasins suffered from severe water supply stress, while the western subbasins suffered from slight water supply stress. The plain suffered more serious water supply stress than the mountain region. The land use and population were the key causes resulting in the distribution of water supply stress. The water supply stress in the Haihe River Basin also showed a distinct temporal variability. The interannual fluctuation of water supply stress was large. The eastern plain was especially vulnerable to water supply shortage compared to the western mountain areas. Future climate change in precipitation and warming and economic development would likely aggravate the water supply crisis in the study region.

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