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The Impact of Precipitation Deficit and Urbanization on Variations in Water Storage in the Beijing-Tianjin-Hebei Urban Agglomeration

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Abstract: Depletion of water resources has threatened water security in the Beijing-Tianjin-Hebei urban agglomeration, China. However, the relative importance of precipitation and urbanization to water storage change has not been sufficiently studied. In this study, both terrestrial water storage (TWS) and groundwater storage (GWS) change in Jing-Jin-Ji from 1979 to the 2010s were investigated, based on the global land data assimilation system (GLDAS) and the EartH2Observe (E2O) outputs, and we used a night light index as an index of urbanization. The results showed that TWS anomaly varied in three stages: significant increase from 1981 to 1996, rapid decrease from 1996 to 2002 and increase from 2002 to the 2010s. Simultaneously, GWS has decreased with about 41.5 cm (500% of GWS in 1979). Both urbanization and precipitation change influenced urban water resource variability. Urbanization was a relatively important factor to the depletion of TWS (explains 83%) and GWS (explains 94%) since the 1980s and the precipitation deficit explains 72% and 64% of TWS and GWS variabilities. It indicates that urbanization coupled with precipitation deficit has been a more important factor that impacted depletion of both TWS and GWS than climate change only, in the Jing-Jin-Ji region. Moreover, we suggested that the cumulative effect should be considered when discussing the relationship between influence factors and water storage change.

Keywords: terrestrial water storage; groundwater storage; urban agglomeration; Beijing-Tianjin-Hebei

1. Introduction

As an important resource, terrestrial water storage (TWS) is jointly influenced by climate change and anthropogenic activities [1]. In the past three decades, the Beijing-Tianjin-Hebei region has experienced a rapid urban expansion [2,3]. During the process, extensive cultivated land was converted to built up and the soil was replaced by impervious surface [4]. Land cover change has immediate impacts on the urban hydrological cycle [5,6]. The depletion of TWS and groundwater storage (GWS) was significant in this region, attributed to groundwater extraction and climate change. Thus, it is necessary to analyze variability in water storage, which, at present, is crucial to urban water resource management.

Conventionally, changes in TWS and GWS were measured by ground-based observation. Being sparsely distributed, the measurement is impractical for water storage change studies on either global or regional scales [1,7]. In the recent decade, remotely sensed data have been widely used

in examining terrestrial water storage change, since the Gravity Recovery and Climate Experiment satellites (GRACE) launched in 2002. GRACE offers an effective way to detect TWS change both globally and regionally, with a spatial resolution of $1 \times 1°$ [8–11]. However, the study area chosen must be larger than 200,000 km^2 when using GRACE, so there are many limitations and uncertainties when referring to water storage change in a small region [12]. In addition, hydrological models and land surface models were also used to investigate water storage change. For instance, outputs derived from Global Land Data Assimilation System (GLDAS) have been widely used in water storage change researches with $0.25 \times 0.25°$ and $1 \times 1°$ resolutions [13]. Outputs derived from WaterGAP Global Hydrological Model (WGHM), including soil moisture storage (SMS), surface water storage (SWS) and GWS, are simulated comprehensively by natural groundwater recharge and discharge, human-induced groundwater abstractions and return flow with a resolution of $0.5 \times 0.5°$ [1,14]. Spatially, TWS derived from GLDAS is more detailed than GRACE and WGHM, but GWS is not included. Furthermore, the EartH2Observe (E2O) project integrates observation-based data, models and assesses global water resources, with a resolution of $0.5 \times 0.5°$. Although outputs derived from E2O have certain advantages, this dataset has not been widely used to study regional water storage change.

Both natural and anthropogenic factors influence water resources. Precipitation and recharge from rivers are the main sources of water storage, while evapotranspiration, runoff and human water use are outputs of water storage at a regional scale [15]. Changes in precipitation and temperature could cause variability in water storage [15,16]. Mo et al. suggested that both precipitation and runoff show large impacts on water storage change [17]. Anthropogenic activities such as irrigation also impact water storage change by increasing evapotranspiration and groundwater abstraction [9,18]. Furthermore, the increased population also enhances the pressure on water supply [19] and land cover change. Previous research suggested that land cover change has a strong effect on the global hydrological cycle [6,20].

The Beijing-Tianjin-Hebei urban agglomeration (the Jing-Jin-Ji region), one of the world's largest agglomerations, is the political, economic and cultural centre of China, and has an area of about 214,900 km^2 [21]. During the past 30 years, the Jing-Jin-Ji region has rapidly experienced an urbanization process [22]. It contains approximately 8% of China's total population and contributes to approximately 11% of the Gross Domestic Product (GDP) [23]. The Jing-Jin-Ji region is located at the edge of China's ecologically fragile environment and suffers from a serious water resource shortage [22,24]. Due to the excessive demand, groundwater was overexploited, resulting in a series of ecological problems, such as groundwater drawdown cones [23,25] and land subsidence [26]. The South-to-North Water Diversion project has been carried out in an effort to alleviate water stress, and has been supplying water to Jing-Jin-Ji since late 2014 [27].

In the context of urbanization and climate change, water resource management is critical, especially for the Jing-Jin-Ji region. However, the relative importance of precipitation change and urbanization to water storage change is not clear now. To support water resource management, long-term water storage changes must be investigated and influencing factors should be identified. In this paper, we aimed to (1) investigate spatial and temporal changes in TWS and GWS of the Jing-Jin-Ji region in the most recent 30 years with GLDAS and E2O datasets; and (2) evaluate the relative importance of land cover change and climate change to variability in TWS and GWS, respectively.

2. Materials and Methods

2.1. Study Area

The Beijing-Tianjin-Hebei urban agglomeration is one of the fastest urbanized areas with rapid population growth and dramatic land cover change since 1978, located at the North China Plain [28] and covers the majority of the Haihe River Basin. This study examines the urban agglomeration, including Beijing, Tianjin and Hebei Province, thirteen main cities in total (Figure 1). This region belongs to the semi-arid temperate continental monsoon climate with an annual average precipitation

of 500–600 mm and an annual potential evaporation of 1100–2000 mm [23]. The precipitation mainly occurs in summer and the climate is typically dry during spring and winter. Lying north of the North China Plain with mountains behind and facing the Bohai Sea in front, the study area consists of diverse topography. Most of the cultivated land is located south of Hebei province. Since 1979, urbanization has occurred mainly within plains, and a large region of cultivated land has been replaced with urbanized land.
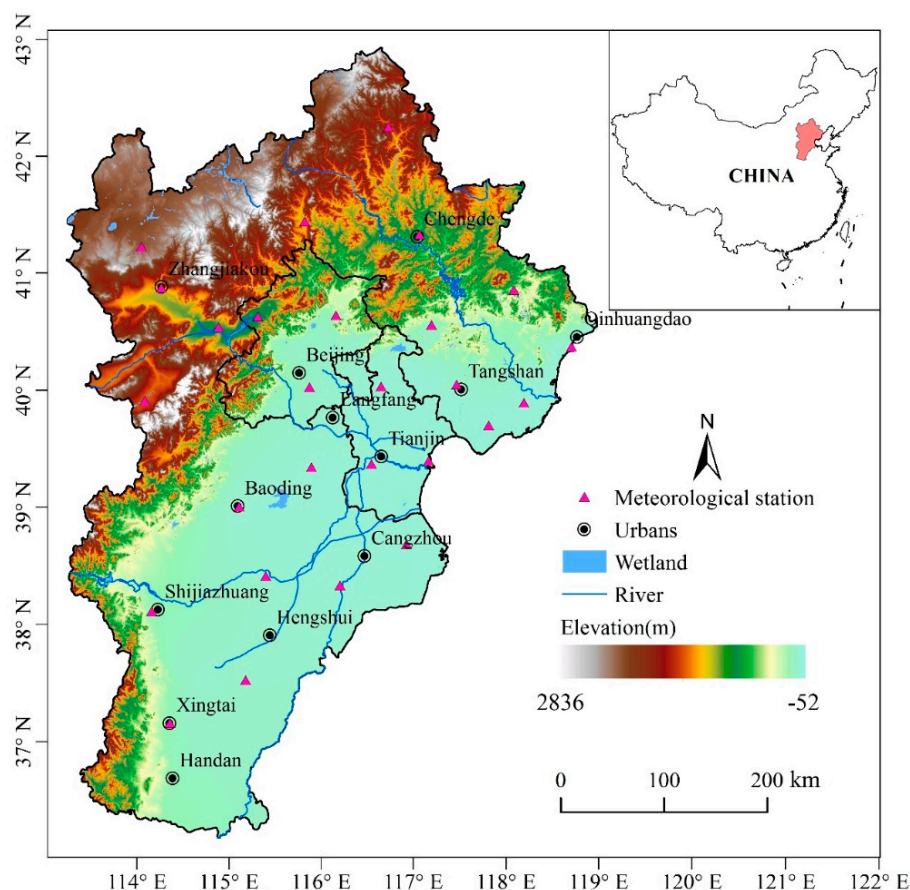
Figure 1. The location of the Jing-Jin-Ji region and main cities observed in this study.

2.2. Data Sources

GLDAS was jointly developed by National Aeronautics and Space Administration (NASA) and the US National Oceanic and Atmospheric Administration (NOAA), incorporated satellite and ground based observations [13]. It drives four land surface models: Mosaic, Noah, Community Land Model (CLM) and Variable Infiltration Capacity (VIC) [17]. We obtained GLDAS2.0 and GLDAS2.1 Noah outputs to investigate TWS change in the Jing-Jin-Ji region from 1979–2010s for its high spatial resolution of $0.25 \times 0.25°$. E2O is a collaborative project funded under the European Commission Directorate-General (DG) Research Framework Programme 7 (FP7) programme [29]. The overall object is to contribute to the assessment of global water resources through the use of new earth observation datasets and techniques. We obtained the data from the Centre for Ecology and Hydrology (CEH) and Joint Research Centre (JRC) at a spatial resolution of $0.5°$ to detect GWS variability from 1979–2010s. WGHM was developed by Döll et al. in 2003. It is a submodel of the global water use and availability model WaterGAP 2 and computes surface runoff, groundwater recharge and river discharge at a spatial resolution of $0.5°$ and is able to calculate reliable and meaningful indicators of water availability at a high spatial resolution [14]. Outputs from all three of the datasets above partially contain surface water storage components (such as snow water equivalent and canopy water storage) as well as SMS,

and WGHM and E2O also provide additional GWS data. As suggested by Long et al. [1], TWS anomaly (TWSA) changes derived from WGHM showed the lowest uncertainty compared with those derived from GLDAS and GRACE in sixty basins. Thus, we obtained the outputs from WGHM between 2003 and 2014 to evaluate TWS and GWS derived from GLDAS and E2O.

The Operational Line-scan System (OLS), running from 1992 to 2012 on the Defense Meteorological Satellite Program (DMSP) has the capacity for detecting city lights, gas flares and fires at night, benefitting from a low-light detecting capability [30]. It provides an effective way for analyzing the relationship between urbanization and anthropogenic activities and was widely used in urban studies [31,32]. In this paper, the DMSP/OLS dataset was used to present the dynamics of urbanization in the Jing-Jin-Ji region from 1980 to 2015. Additionally, the population and water consumption were obtained from yearbooks of Beijing, Tianjin and Hebei as extra data.

The precipitation data obtained from the National Climatic Centre of the Chinese Meteorological Administration was used to inform precipitation changes from 1979 to 2015. To analyze trends, only meteorological stations without missing data were selected (33 stations in total).

2.3. Methods

In this study, we obtained calculated TWS by summing up the total soil moisture (SM), snow water equivalent (SWE) and canopy surface water (CSW) from GLDAS, E2O and WGHM and calculated TWSA by subtracting the average TWS from 1979 to 2015:

$$TWS = SM + SWE + CSW, \tag{1}$$

$$TWSA = TWS_{ij} - \overline{TWS}, \tag{2}$$

where TWS_{ij} is TWS in month i of year j and $\overline{TWS}$ is average TWS from 1979 to 2015. The accumulated yearly TWSA, GWSA and precipitation anomaly are calculated by the following equation:

$$\begin{aligned} S_{it} &= W_{1t} + W_{2t} + \cdots + W_{it} \\ S_{ig} &= W_{1g} + W_{2g} + \cdots + W_{ig} \\ S_{ip} &= W_{1p} + W_{2p} + \cdots + W_{ip}, \end{aligned} \tag{3}$$

where S_{it}, S_{ig}, S_{ip} is the accumulated yearly TWSA, GWSA and precipitation anomaly, respectively, and W_{it}, W_{ig}, W_{ip} is the annual average TWSA, GWSA and precipitation anomaly, respectively.

The Theil–Sen median trend analysis (TS) and Mann–Kendall test (MK) methods were used to analyze TWS and GWS change trends within the Jing-Jin-Ji region. The Pearson correlation coefficient (r) was utilized to describe the relationship between water storage change and influencing factors. The relative contribution was estimated using a coefficient of determination (R^2).

The Theil–Sen Median trend analysis method can be effectively combined with a Mann–Kendall test to evaluate the trend of long-term data [33]. As a robust statistical method for identifying trends, the TS method calculates the median slopes between all $n(n-1)/2$ pair-wise combinations of the time series data [33]. The value of TS median ranges from -1 to 1 and a value of 0-1 indicates that water storage increased, and any other value indicates water storage decreased. The MK method has been widely used to analyze trends and variability at sites with hydrological and meteorological time series due to its advantages in the description of the significance of changing trends [33]. In this study, a trend is considered significant if the value (*p*) is less than 0.05.

As an effective measure of the linear correlation between two variables, the Pearson correlation coefficient (r) has been widely used to study the degree of linear dependence between different variables [34]. When r values range from 0 to 1, the variables have a positive correlation, while any negative value indicates a negative correlation between the two variables.

3. Results

3.1. Changes in Water Storage

We evaluated TWS changes derived from GLDAS by the results derived from WGHM and E2O, as seen in Figure 2a. All TWS variation patterns derived from GLDAS, WGHM and E2O are similar. However, the amplitude of WGHM was more intense than GLDAS and E2O. From 2008 to 2010, there were significant differences among TWSAs derived from GLDAS, WGHM and E2O. From 2008 and 2010, GLDAS and E2O reach maximum values in August or September, while WGHM reaches maximum values in January or February. Furthermore, GLDAS and E2O decreases from February 2006 to June 2007, while WGHM increases during this period. Overall, E2O and GLDAS agree well (r = 0.92) while WGHM is discordant with GLDAS and E2O (r = 0.4 and r = 0.37). WGHM-based TWSA changes show more uncertainty in the smaller region of Jing-Jin-Ji. Additionally, GLDAS was selected to analyze TWSA change in the Jing-Jin-Ji region because it covers the period from 1979 to 2010s.

The evaluation of GWS was based on E2O and WGHM. As Figure 2b shows, GWS decreases from 2003 to 2012 in both E2O and WGHM datasets. Although both datasets reveal a trend in the same direction, WGHM decreases rapidly, while E2O decreases slightly during 2003 to 2012. Moreover, between 2008 and 2012, E2O has almost no significant change, while WGHM continues to decrease. According to Li et al. [35], GWS varies slightly after 2000 (Figure S1). In this case, E2O was more available in our study.
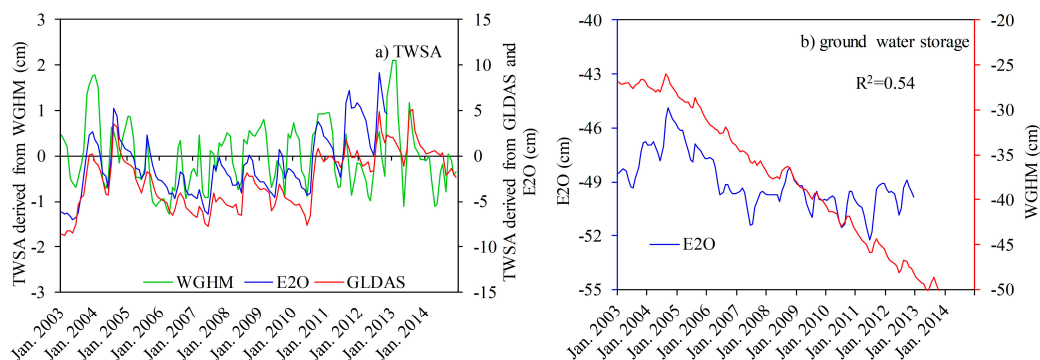

Figure 2. Evaluation of TWSA and GWS derived from GLDAS and E2O, respectively. (**a**) evaluation of TWSA derived from GLDAS with that derived from WGHM and E2O; (**b**) evaluation of GWS derived from E2O with that derived from WGHM.

TWS and GWS changes were analyzed from 1979 to the 2010s. The results show that TWS varies at three different stages: first, there was a significant increase in water storage from 1981 to 1996, and then a rapid decrease from 1996 to 2002. Finally, there was an increase in water storage from 2002 to 2015 (Figure 3a). Although TWSA increased slightly from 1979 to 2010s, TWSAs were less than the annual average in 29 years. The accumulated yearly TWSA was less than 0 from 1980 to 2015, and water storage deficit had been increasing continuously (Figure S2). This suggests that water storage in the Jing-Jin-Ji region is at a deficit, although that state was distinctly ameliorated from 1992 to 1995. GWS is another important factor of water resources. As can be seen, GWS has decreased rapidly and continuously between 1979 and the 2010s, with a total decline of approximately 41.5 cm (500% of GW in 1979) (Figure 3b). According to Li et al. [35], the water table depth in the Jing-Jin-Ji plain area increased rapidly between 1981 and 1997, at a rate of about 0.62 m/yr, then decreased slightly from 1998 to 2010. This therefore suggests that groundwater resources in the Jing-Jin-Ji region have been decreasing rapidly and continuously, although the loss of GWS has slowed down in the recent decade.

The results in Figure 4 spatially illustrate monthly trends in TWS and GWS estimated by TS and MK methods. TWS and GWS have declined significantly in the Jing-Jin-Ji urban agglomeration between 1979 and the 2010s. Moreover, changes in both TWS and GWS revealed declining trends in

the majority of the Jing-Jin-Ji region. TWS decreased significantly in 62.6% of the Jing-Jing-Ji region, especially in the middle area (TWSA decreased at a rate of more than 0.01 cm/yr, and the area accounts for more than 20% of the entire region) (Figure 4a). In the southern region, TWS increased significantly (about 14.3%), and it covers over 60% of the increased area (where TWSA increased at a rate of less than 0.01 cm/yr). Changes in GWS revealed significant declines in the whole plain area (about 66.3% of the Jing-Jing-Ji region), including the entirety of Beijing, Tianjin, Tangshan, and the southern region of Hebei Province (Figure 4b). In Southern Hebei Province (part of the Jing-Jin-Ji plain), GWS declined rapidly and obviously, at a rate of about 0.22 cm/yr, while it showed a slightly increasing trend (less than 0.002 cm/yr) in the northeast area.
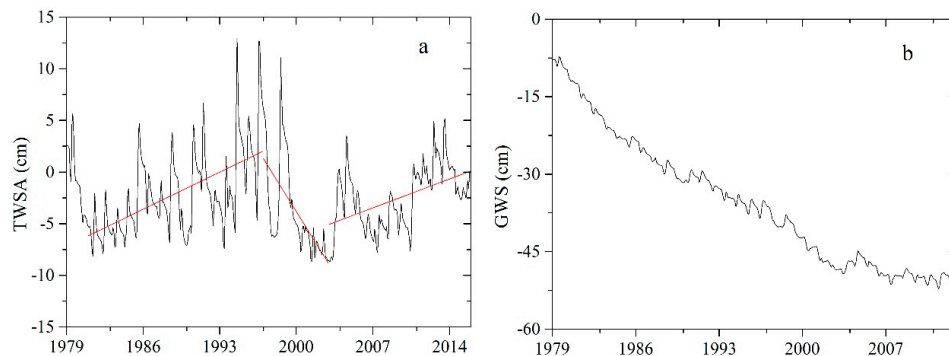
Figure 3. Variation patterns of TWSA and GWS in the Jing-Jin-Ji region. (**a**) changes of monthly TWSA from 1979 to 2010s, where red lines indicate linear fitting results of three various stages; (**b**) changes in monthly GWS from 1979 to the 2010s.
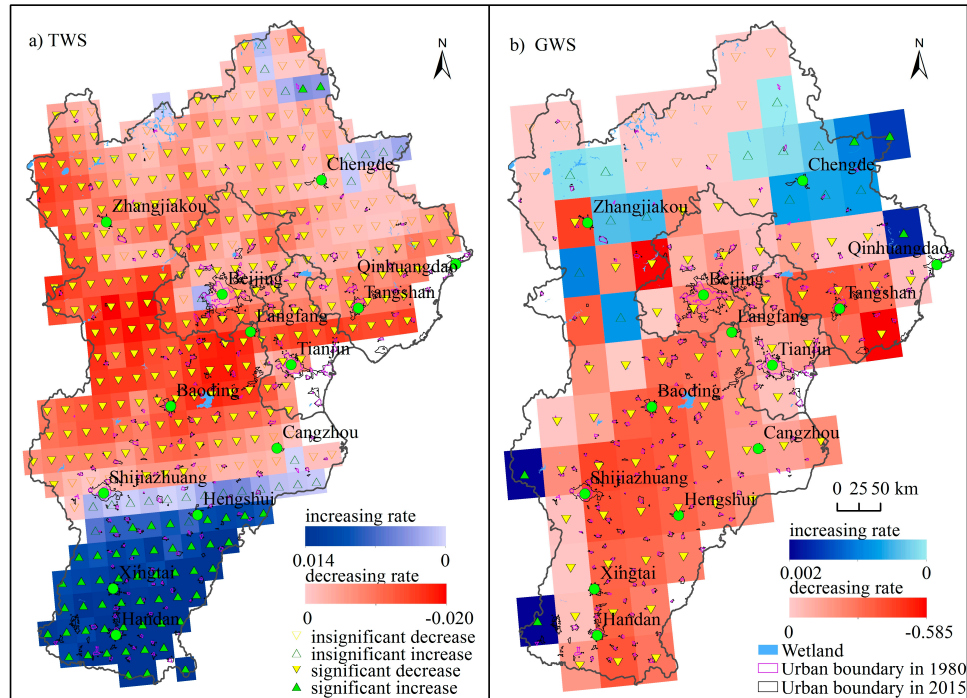

Figure 4. Spatial patterns of changes in TWS and GWS in the Jing-Jin-Ji region estimated by TS and MK methods, respectively, with statistical significance at the 5% level. (**a**) monthly trends in TWS from 1979 to the 2010s; (**b**) monthly trends in GWS from 1979 to the 2010s.

3.2. Precipitation and Water Storage Change

Precipitation is an important factor that influences water storage change directly. In this study, the correlation between precipitation and water storage change is estimated by the Pearson correlation coefficient. Results indicate that precipitation in the Jing-Jin-Ji region has changed in three stages: first, there was a significant increase from 1981 to 1995, and then a rapid decrease from 1996 to 2002, and, finally, there was an increase from 2002 to 2010s (Figure S3a). Spatially, precipitation increased in the southern area but decreased in the Beijing-Tianjin-Tangshan (Jing-Jin-Tang) region (Figure S4).

As Figures 3 and 4 demonstrate, precipitation change pattern is corresponding to TWSA and there is a significant positive correlation between TWSA and precipitation (r = 0.56, $p < 0.01$) (Figure 5a). The only difference is that TWSA increased while precipitation decreased in 1996. Whereas, although precipitation tended to decrease from 1996, but it was still larger than annual average level and that could be the reason why TWSA increased in 1996. Moreover, the accumulated yearly precipitation anomaly is in deficit almost over the whole period, except 1996 (Figure S3b). The increase in the annual precipitation anomaly from 1984 to 1996 relieved depletion of TWS. The accumulated yearly precipitation anomaly explains about 72% of accumulated yearly TWSA change (Figure 5b).
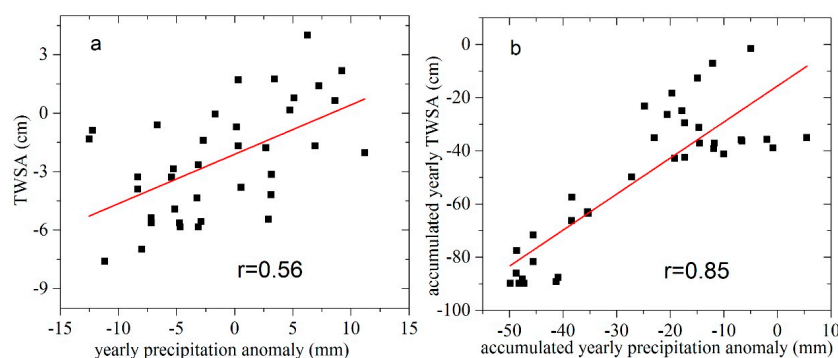

Figure 5. The relationship between precipitation and TWS as evaluated by the Pearson correlation coefficient at the 5% level. (**a**) The relationship between the precipitation anomaly and TWSA (r = 0.56, $p < 0.01$); (**b**) The relationship between accumulated precipitation anomaly and TWSA (r = 0.85, $p < 0.01$).

As shown in Figure 6a, the relation between GWS and precipitation changes is not significant. It seems that precipitation change has little influence on GWS variability. However, precipitation is an important factor to GWS variability. The result shows a high positive correlation between accumulated yearly precipitation anomaly and accumulated yearly GWSA and precipitation change explains 64% of the depletion of GWS (Figure 6b).
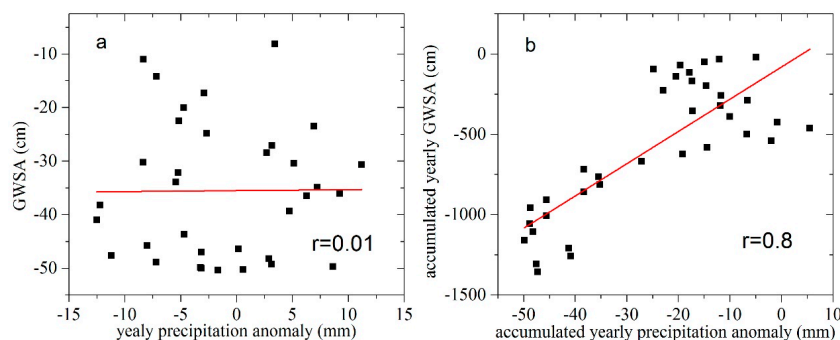

Figure 6. The relationship between precipitation and GWS anomaly (GWSA) as evaluated by the Pearson correlation coefficient at the 5% level. (**a**) the relationship between the precipitation anomaly and GWSA (r = 0.01, $p > 0.05$); (**b**) the relationship between accumulated precipitation anomaly and GWSA (r = 0.80, $p < 0.01$).

3.3. Urbanization and Water Storage Change

Variation in water storage was also affected by human activities. Since 1980, urbanization is one of the most important human activities in China. Between 1980 and the 2010s, the Jing-Jin-Ji urban agglomeration developed rapidly by about 5651 km^2, making urban regions 268% as big as they were in 1980 (Figure S5). Cities in Hebei Province have experienced a slower urbanization process (urban area increased about 1.8%), but urban area increased the most with about 3391 km^2 (Figure S6). Beijing had the highest rate of urbanization, with urban areas increasing by about 1538 km^2 (approximately 9.2%) during the same period. Urbanization and residential growth increased residents living water consumption (Figure S7). The demand of water supply has led to more groundwater extraction in the last 20 years. Nevertheless, most of the new urban area (about 75%) was converted from cultivated land, and the loss of cultivated land, in turn, resulted in a decrease of agricultural water consumption. Ultimately, total water consumption decreased in the past 20 years as the decreased agricultural and industrial water consumption overcame the water consumption demand arising from the increased population.

The average night light index (NLI) from 1980 to 2015 (exception of 1992 to 2012) was estimated by the significant positive linear relationship between NLI and population (r = 0.97, *p* < 0.01, Figure S8a). This revealed that urbanization was the direct result of population growth. There is not a significant trend of TWSA with urbanization, but urbanization explains 83% of TWSA deficit (Figure 7). Moreover, soil water storage is the major component of TWS and urbanization has affected it seriously because most of the soil was replaced by an impervious surface during urbanization. However, the accumulated yearly TWSA stops decreasing when urbanization reaches a relative high level.
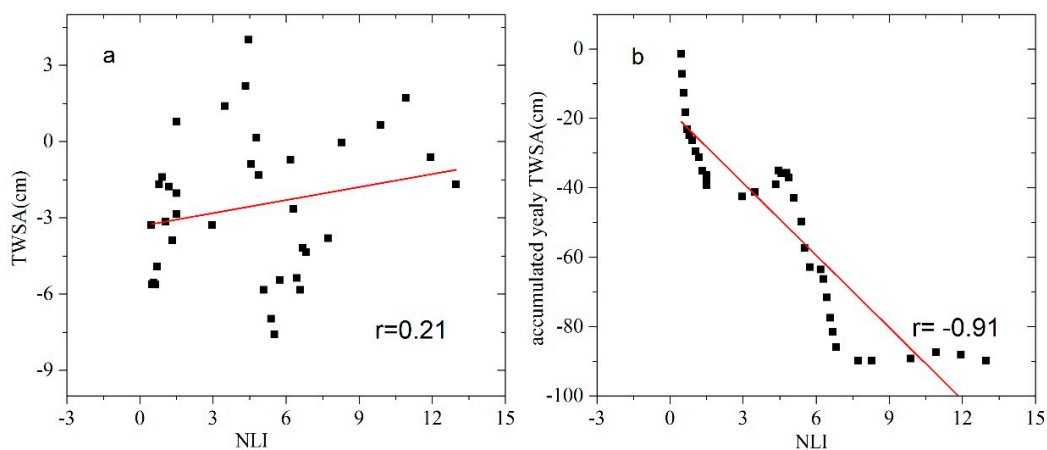

Figure 7. The relationship between night light index (NLI) and TWSA as evaluated by the Pearson correlation coefficient at the 5% level. (**a**) the relationship between NLI and TWSA (r = 0.21, *p* > 0.05); (**b**) the relationship between NLI and accumulated yearly TWSA (r = −0.91, *p* < 0.01).

Urbanization affects GWS more seriously than TWS. Population growth is the major reason for urbanization. In the past 30 years, population growth explains 98% of cumulative groundwater abstraction increase (Figure S8b), despite water supplied by groundwater decreased from 1998 to 2015 (Figure S7). As illustrated in Figure 8a, there is a significant negative correlation between GWSA and urbanization (r = −0.92, *p* < 0.01), which indicates that urbanization causes GWS decrease in the Jing-Jin-Ji region. Additionally, urbanization is a cumulative process. A large fraction of variation in accumulated yearly GWSA can be explained by urbanization (94%, Figure 8b).
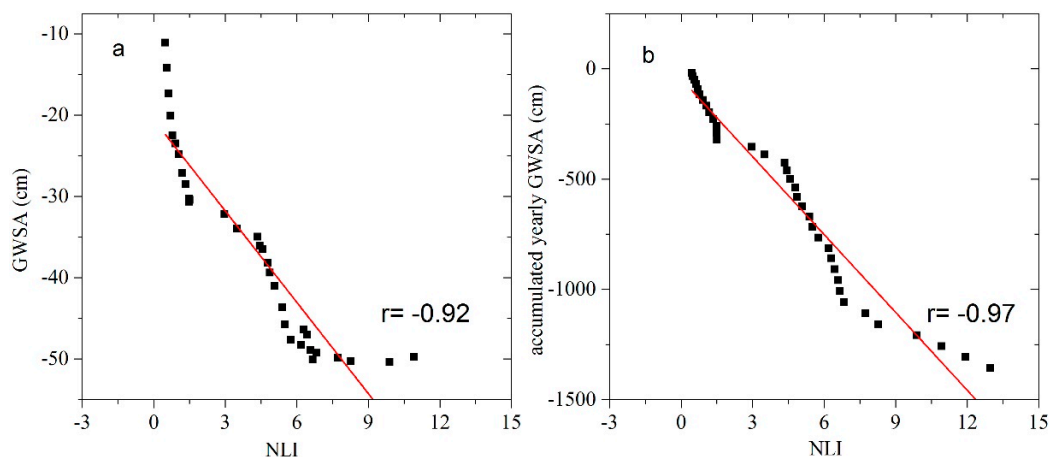
Figure 8. The relationship between night light index (NLI) and GWSA as evaluated by the Pearson correlation coefficient at the 5% level. (**a**) the relationship between NLI and GWSA (r = −0.92, *p* < 0.01); (**b**) the relationship between NLI and accumulated yearly GWSA (r = −0.97, *p* < 0.01).

Overall, urbanization is the relative important factor to variability in total water storage in the Jing-Jin-Ji region. Firstly, urbanization increased groundwater deficit. Secondly, land use/land cover change (LUCC) changed land surface characteristics and water permeability and the groundwater recharge decreased during urbanization development.

4. Discussion

Water storage variability has been studied at global scale and regional scale. Most previous studies focused on the hot-spot area, such as the Tibet plateau, and there are few studies of water storage change in urban areas. On the one hand, urban areas are small in general. Most of the datasets are too coarse to study water storage change in the urban areas. On the other hand, fresh water shortage in urban areas attracts more attention than other water resources. However, total water storage change is also an important factor for large urban agglomerations.

Between 1979 and the 2010s, water storage decreased significantly [36], and GWS decreased more significantly than TWS. As shown in Figure 3a, the number of TWSAs is less than 0 in most years. Even so, difference values between two years are small and cannot reflect the depletion of water storage. Moreover, the rate of recharge of GWS is slow and GWS cannot vary immediately when the precipitation rate changes. It needs a relatively long time to recover GWS, and the depletion of GWS is a cumulative result. Thus, the cumulative effect was considered in our work, including precipitation anomaly yearly accumulation, TWSA yearly accumulation, GWSA yearly accumulation and urbanization. In the previous studies, the cumulative effect is usually ignored [15]. The accumulated precipitation anomaly, TWSA and GWSA illustrate water shortage in the Jing-Jin-Ji region very well. In addition, cumulative effect could affect estimation of the relationship between water storage change and driving factors. In this condition, we found that precipitation deficit is important to both of TWS and GWS shortage. In this paper, soil water storage is the major component and affected by precipitation change easily. Moreover, the precipitation deficit reduced the recharge of groundwater and the abstraction further intensified the depletion of GWS.

In addition, LUCC was found to influence the hydrological cycle including precipitation, evapotranspiration, infiltration and runoff [37]. Evapotranspiration decreased rapidly from 1980 to 1998, and then decreased slightly from 1999 to 2015 (Figure S9a). This study examined the nonlinear relationship between evapotranspiration and land cover change by Spearman's rank correlation coefficient. Results revealed a significant correlation between evapotranspiration variation and LUCC (Figure S9b,c). The annual average of evapotranspiration decreased with the reduction of cultivated land, which indicates a significant positive relationship between them (r = 0.86, *p* < 0.01).

Since irrigation is common in the Jing-Jin-Ji plain area, the reduction of irrigation arising from the loss of cultivated land during urbanization resulted in a decrease in evapotranspiration [38]. Therefore, it formed a highly significant negative relationship between the evapotranspiration anomaly (annual average) and urban area (r = -0.93, $p < 0.01$). This finding is derived from the fact that the evaporation capacity decreased as the surface became more impervious during the urbanization process [39]. It also confirms that the runoff increase is highly correlated with urban expansion [5].

Overall, both urbanization and precipitation change influence the urban hydrological cycle and water storage change. The findings suggest that urbanization coupled with precipitation deficit has a stronger impact on the depletion of both TWS and GWS than climate change only in the Jing-Jin-Ji region. Additionally, TWS is influenced more easily by precipitation than GWS, while urbanization has more impact on GWS than TWS.

5. Conclusions

The Beijing-Tianjin-Hebei urban agglomeration (the Jing-Jin-Ji region) was selected as the study area for investigating water storage change and its correlation with climate change and anthropogenic activity. The GLDAS and E2O outputs were used to detect the variation patterns of water storage between 1979 and the 2010s.

It was found that the TWSA decreased slightly and varied in three stages: first, there was a significant increase in water storage from 1981 to 1996, and then there was a rapid decrease from 1996 to 2002. Finally, there was an increase in water storage from 2002 to 2010s. TWSA in the Jing-Jin-Ji region was in a deficit, although this state was distinctly ameliorated from 1992 to 1995. Spatially, TWSA declined significantly in the middle of the Jing-Jin-Ji region and increased in the southern region of Hebei Province. From 1979 to the 2010s, GWS decreased rapidly and continuously, declining about 41.5 cm (500% of GW in 1979). Change in GWS showed significant declines in the whole plain area that was observed (about 66.3% of the Jing-Jing-Ji region), including the entirety of Beijing, Tianjin, Tangshan, and the southern region of Hebei Province. In the southern region of Hebei Province (part of the Jing-Jin-Ji plain), GWS declined rapidly and, obviously, at a rate of approximately 0.22 cm/yr, while in the northeast area, groundwater storage showed a slightly increased trend (less than 0.002 cm/yr).

To further investigate the relationship among water storage change, urbanization and precipitation, the accumulations of TWSA, GWS and precipitation yearly anomaly were also examined. Results indicate that urbanization coupled with precipitation deficit have a stronger impact on the depletion of both TWS and GWS in the Jing-Jin-Ji region than climate change. TWS is influenced more easily by precipitation than GWS, and urbanization has more impact on GWS than TWS.

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Conflicts of Interest: The authors declare no conflict of interest.

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