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Hydrology and Earth System Sciences
Discussions

Reconstructed natural runoff suggests imbalance in water scarcity between upstream and downstream regions of China's river basins

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Abstract. The increasing conflicts for water resources appeal for chronological insight into the imbalance water scarcity between upstream and downstream regions. While the changes of water scarcity in whole basins have been widely analysed, the divergent development of water scarcity between upstream and downstream regions received little concern. Here non-anthropologically intervened runoff (natural runoff) was first reconstructed in China's 67 basins for the period 1961–2010 using the Fu-Budyko framework and then systematically evaluated in comparison with the observed data. Divergent changes in water scarcity, including water stress and water shortage, between upstream and downstream regions were analyzed for the period of 1980s-2000s. The results showed that surface water withdrawal rapidly increased from 140.8 billion m^3 (9% of natural runoff) in 1980s to 189.7 billion m^3 (14%) in 2000s, with 73% increase occurring in North China (North of the Yangtze River). This led to severe water scarcity of approximately 0.4 billion people (29% of population) in 2000s in comparison with only ~0.2 billion people (17%) in the 1980s, with all increase of water scarcity-threaten population in North China. Since 1990s, the increase of upstream water withdrawal came along with the decrease of downstream surface water availability in most northern basins, leading to slower increase in upstream water scarcity and faster increase in downstream water scarcity. Even though restrict water management policy restrained upstream surface water withdrawal in some northern basins over latest decade, the effect of such a reduction in upstream surface water withdrawal was too little to stop the continued decline in downstream surface water accessibility. Meanwhile, semi-arid/humid basins are following in the footsteps of arid basins by rapidly increasing upstream surface water withdrawal. The Chinese case study provides an all-round observation of the imbalance upstream-downstream development in water scarcity, as well as the experiences and lessons from different water management strategies.

Keywords: Water scarcity, Upstream-downstream imbalance, Historical development, China

1 Introduction

Freshwater scarcity is fast developing into a critical global risk (Wada et al., 2014; WEF, 2015). There is a growing consensus among researchers that increasing economic activity has a much stronger effect on water scarcity than climate

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change, especially in developing countries (Schlosser et al., 2014; Veldkamp et al., 2015). From the 1960s till now, global water consumption has soared from 600 km^3 yr^{-1} to 1,500 km^3 yr^{-1} due largely to socioeconomic development. At the same time the proportion of global population living under water-stress conditions has increased from 27% to 43% (Wada et al., 2011; Kummu et al., 2010, 2016). Given the continuing trends in economic and population growth, the proportion of global population living under water stress is bound to increase to 50% by the end of the 21st century (Arnell, 1999; Vörösmarty et al., 2000; Alcamo et al., 2003; Schlosser et al., 2014; Wada et al., 2014).

A recent study has shown that the impact of anthropologic interventions on water scarcity is not always negative. Water availability in upstream catchments improves while water scarcity becomes worsen in downstream catchments (Veldkamp et al., 2017). Traditionally, studies have focused on the negative impacts of surface water withdrawal on downstream catchments, including deterioration of aquatic ecosystems (Poff et al., 2007; Petes et al., 2012), exacerbation of water quality (Dodds and Oakes, 2008), extra costs for downstream water users (Nordblom et al., 2012). Few studies, however, are specifically concerned with the changes in water availability in upstream and how the imbalance developed in history (Munia et al., 2016, 2018; Veldkamp et al., 2017).

China is facing serious water stress, aggravated by the uneven distribution of its water resources with abundance in the south and scarcity in the north (WB, 2009). The North China Plain (NCP) has the greatest water scarcity, with per capita water availability less than 150 m^3 yr^{-1} (Zhao et al., 2015). Understanding the past trajectories of China's water scarcity in upstream and downstream catchments can help better define pathways to future sustainability by identifying the cause of water scarcity, avoiding further irreversible environmental degradation, and addressing future challenges of climate change and human interventions.

It is difficult to compile historical data on long-term water withdrawal and the related water scarcity in China due to lack of accessibility to data or no long-term data available. As substitution, the gap between observed runoff and modelled non-anthropologically intervened runoff (hereafter called natural runoff) can be treated as surface water withdrawal. There are numerous studies on natural runoff driven by process-based models such as VIC (Variable Infiltration capacity) (Wang et al., 2010; Chang et al., 2015), WBM (Water Balance Model) (Guo et al., 2017), ORCHIDEE (Organizing Carbon and Hydrology in Dynamics Ecosystems) (Piao et al., 2007), SWAT (Soil and Water Assessment Tool) (Luo et al., 2016). However, difficulties in calibrating complex parameters limit model application to one or a few basins (Zhang et al., 2007; Jiang et al., 2015; Zhai and Tao, 2017). By contrast, Budyko frameworks are simple to use at an annual scale with acceptable results, which allows wider application in large spatial scale. Six Budyko frameworks (Zhang et al., 2001; Zheng et al., 2009) were tested here and eventually the one-parameter Fu-Budyko framework was used to reconstruct natural runoff in the catchments because of its optimal performance (Fu, 1981). Fu-Budyko framework has also been successfully validated across the globe (Teng et al., 2012; Zhou et al., 2012; Li et al., 2013; Du et al., 2016). As such, natural runoff was reconstructed for the period 1961–2010 using the one-parameter Fu-Budyko framework and long-term surface water withdrawal data was estimated for 67 catchments (within 12 large basins) in China, covering over 50% of mainland China.

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This was more representative of the national situation as nearly 40% of China's territory is covered by desert, glaciers and plateau.

In this study, we aim to answer that: 1) How did China's surface water scarcity change during the past decades? 2) How did the imbalance in surface water scarcity develop between upstream and downstream regions? and 3) What do we learn from China's water management strategies? The answers will provide experiences and lessons for global water resources management.

2 Materials and Methods

2.1 Hydrological data reliability

Because runoff data are hardly available in China, two-sources of runoff data were used in this study: data from official sources in Hai and Shiyang River Basins and then extracted data from published literatures (Table 1). The reliability of the published data for annual runoff was verified based on the following criteria: a) for a specific gauge station, at least two related published data sources of overlapping study periods were prepared. Then the annual runoff data was extracted and a cross validation conducted to limit errors below 5%. b) The published annual runoff data were further verified by comparing the trends in the processed data and in others published coincidentally; e.g., published work by Yang et al. for Dongting lake (Yang et al., 2015), Shi and Wang for Huangpu river (Shi and Wang, 2015), etc.

Insert Table 1 here

The annual runoff measured in a total of 132 gauge stations was verified. Based on the length and spatial distribution of the data, however, only 67 gauge stations were qualified for runoff analysis. While data from 54 out of 67 basins spanned for a period of 50 year (1961–2010), data from other 13 basins only spanned for over 40 years. The basin boundaries were based on the delineations in "Data Sharing Infrastructure of Earth System Science" (http://www.geodata.cn/) and sub-basin boundaries were delineated in ArcHydro tool.

2.2 Climatic factors

Gridded monthly precipitation and temperature (maximum, minimum and mean temperature) for 1961–2010 were downloaded from "China Meteorological Data Sharing Service System" (http://cdc.nmic.cn/). The spatial resolution of the gridded dataset is 0.5° ×0.5°. Also daily climate data at point-scale (maximum and minimum temperature, wind speed, relative humidity and sunshine hours) from 563 national weather stations for the period 1961–2010 were downloaded from the same website.

2.3 Fu-Budyko framework

The parameter of Fu-Budyko framework is related to catchment characteristics, e.g., vegetation cover (Li et al., 2013), aridity index (Du et al., 2016), soil (Gerrits et al., 2009), vegetation and topography (Sun et al., 2007). Model calibration in

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this study showed that parameter θ was greatly influenced by topography. The steeper the catchment, the smaller was the parameter. The average bias between natural and observed runoff in 67 catchments in this study was 6.9% for the calibration period (1961-1970), showing the reliability of the method. Note that Fu-Budyko framework was suitable for annual or mean annual studies while the application in finer temporal scale was restrained.

The Fu-Budyko framework is expressed as:

$$F(\varphi) = 1 + \varphi - \left(1 + \varphi^{\theta}\right)^{1/\theta} \quad (1)$$

where $F(\varphi)$ is evaporation rate; φ is the ratio of potential evapotranspiration (ET_0) to precipitation (P) on annual scale; and the θ parameter is related to catchment characteristics. Studies have shown that anthropologic interventions had intensified across China since the 1980s, driven by the economic reform and opening up (Yang and Tian, 2009; He et al., 2013; Jiang et al., 2015). We therefore assumed that the observed runoff for 1961–1970 was natural and not (or less) disturbed by human activities. As such, the θ parameter was calibrated for the period 1961–1970 and used to reconstruct natural runoff for the period 1971–2010.

Annual natural runoff was calculated in mm/a as $P(1-F(\varphi))$ and then changed into 10^8 m^3/a for the catchment area. For Hai, Shiyang, Hei and Tarim River Basins, natural runoff at the outlet gauge stations was the sum of the upstream tributaries. This is because most of the water was subsequently consumed and therefore little runoff generated in the downstream regions in these basins (Zhang et al., 2015; Zhang et al., 2016).

The annual ET_0 was aggregated at monthly scale and the gridded monthly ET_0 calculated by Hargreaves equation as (Allen et al., 1998):

$$ET_0 = 0.0023(T_{mean} + 17.8)(T_{\max} - T_{\min})^{0.5} R_a \quad (2)$$

where T_{mean} is the ith-month mean temperature; $T_{\max}$ is the ith-month mean maximal temperature; $T_{\min}$ is the ith-month mean minimal temperature; and R_a is net radiation for the middle day of the ith-month. The unit for both ET_0 and R_a is mm/day and then ET_0 was multiply by the number of days in the ith-month to get monthly ET_0.

To validate the gridded annual Hargreaves ET_0, point-scale daily ET_0 was calculated by the FAO56 Penman-Monteith equation (Allen et al., 1998) and then scaled up to annual value. The annual Hargreaves ET_0 was adjusted by multiplying the gridded coefficient (interpolated by the IDW method) as the ratio of the Penman-Monteith ET_0 to Hargreaves ET_0.

The gridded annual precipitation was aggregated from the gridded monthly precipitation data and then adjusted by the point-scale data as mentioned above.

The basin-scale annual P and ET_0 were the average values of the grids in the basin. For grids that were partially within the basin boundary, weighting was done based on the fraction covered.

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Aridity Index (AI) of each catchment was calculated as ET_0 / P, where ET_0 and P are the average values for 1961–2010. The basins were classified into humid, semi-humid, semi-arid and arid for AI less than 1, 1–2, 2–3 and greater than 3, respectively.

2.4 Trend analysis

Trend and significance of P, ET_0 and runoff was tested using the non-parametric Mann-Kendal method, and magnitude of change over the 50 years was calculated as:

$$Change = (V_{2000s} - V_{1960s}) / V_{1960s} * 100\% \quad (3)$$

where V_{2000s} and V_{1960s} represent P, ET_0 and runoff in 2000s and 1960s. respectively.

2.5 Water stress and shortage

The surface water scarcity analysis was done at decadal scale using indicators — water stress and water shortage (Kummu et al., 2016). Water stress (*WTA*) for this purpose is defined as the percent ratio of surface water withdrawal (*WW*) to water availability (*WA*) in a basin or sub-basin. Moderate or high stress occurs when over 20% or 40% of the available water is consumed, respectively (Vörösmarty et al., 2000). This demand-driven scarcity of water can occur even in regions with low population (Kummu et al., 2010, 2016). Water shortage is measured in per capita surface water availability per year, defined as *WA* devided by population. Moderate, high and extreme water shortages occur when water availability drops below 1,700, 1,000 and 500 m^3 cap^{-1} yr^{-1}, respectively. A demographic-driven scarcity of water can occur when large populations compete for limited water resources, leading to disputes (Falkenmark, 1997). The combined use of these two indicators provide a complete picture of water scarcity in a river basin. The calculation was conducted in decadal scale for 1970s, 1980s, 1990s, and 2000s respectively.

WW for the whole basin is the difference between observed runoff and natural runoff at the hydrological outlet station. For the upper reaches, *WW* is the aggregate of *WW* from all the upstream tributaries. For the middle and lower reaches, *WW* was calculated as the difference in *WW* between a station at main stem and its corresponding immediately upstream station.

$$WW_{whole} = abs(Q_{nat} - Q_{obs}) \quad (4)$$

$$WW_{up} = \sum_{i=1}^{n} abs(Q_{nat,upi} - Q_{obs,upi}) \quad (5)$$

$$WW_{middle} = abs(Q_{nat,middle} - Q_{obs,middle}) - WW_{up} \quad (6)$$

$$WW_{down} = abs(Q_{nat,down} - Q_{obs,down}) - WW_{middle} \quad (7)$$

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where Q_{nat} is mean natural runoff in each decade from the 1970s to 2000s; Q_{obs} is mean observed runoff in the same decade, the subscripts whole, up, middle and down respectively represent whole basin, upper reach, middle reach and lower reach of the basin.

WA for the upper reaches is the aggregation of natural runoff from all the tributaries. Then for the middle and lower reaches, it is the incoming discharge from former reaches and locally generated runoff.

$$WA_{up} = \sum_{i=1}^{n} Q_{nat,upi} \quad (8)$$

$$WA_{middle} = \sum_{i=1}^{n} Q_{obs,upi} + (Q_{nat,middle} - WA_{up}) \quad (9)$$

$$WA_{down} = Q_{obs,middle} + (Q_{nat,down} - Q_{nat,middle}) \quad (10)$$

The population count data from Gridded Population of the World (GPW) (http://sedac.ciesin.columbia.edu/data/collection/gpw-v4) was used to the basin-scale population. Given the limitation of the data length, the GPW data for 1990, 2000 and 2010 were respectively used to get the population for the 1980s, 1990s and 2000s. The resolution was ~5 km for 1990 and 2000 datasets and ~1 km for 2010 dataset.

3 Results

3.1 Observed and natural runoff

The degree of suitability of the Fu-Budyko Framework for use in reconstructing annual natural runoff is shown in Figure 1. It well captures temporal trends in humid basins (Yangtze, Pearl, Min and Qiantang River Basins) in south China. Increasing gaps between the observed and natural runoff, however, are observed in other basins, especially those arid basins. We hypothesis that the gaps could be caused by water withdrawals for anthropologic activities.

Insert Figure 1 here

There was a dominant decreasing trend (55 out of 67 basins) in observed runoff for 1961–2010 compared with the reconstructed estimates of natural runoff, with 31 basins showing significant decrease and only 1 with a significant increase (Fig. 2a,b). The decrease in observed runoff (recorded at downstream outlet gauge station) in most of the basins in the north exceeded 60%. This was particularly true for Hai River Basin, where there was over 80% decrease in runoff at most of the gauge stations in both the upstream and downstream reaches. There was increasing observed runoff in 12 gauge stations, mainly in southeast China and the upstream region of northwest China where there was a significant increase in rainfall (Fig. 3a,b).

Insert Figure 2 here

Contrary to observed runoff, basins with an increasing natural runoff (38) slightly outnumbered those with a decreasing natural runoff (29), 16 of which showed a significant increase (mainly in northwest China) and only one had a significant

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decrease (a basin mainly in Sichuan Province of southwest China) in the face of the recent global warming trend (Fig. 2c,d). There was a strong decrease in natural runoff in both Hai River Basin and middle-reach of Yellow River Basin (of ~ 40%), which could be largely correlated to the decreasing precipitation (Fig. 3c,d).

Insert Figure 3 here

3.2 Water stress trajectories

Generally, the degree of surface water stress in the 12 large basins increased for the study period from 37% to 54%, though the increase magnitudes were different in different climate zones (Fig. 4). For basins in humid climate (AI<1) where water stress was less than 20%, water stress level increased from ~4% to ~9%. For basins in semi-humid climate (1<AI<2) with moderate or slightly high water stress level, water stress level increased from ~20% to ~48%. For basins in semi-arid (2<AI<3) and arid (AI>3) climate with high water stress level, water stress level increased from ~55% and 75% to ~77% and 94%, respectively. Interestingly, there was a period of rapid increase in water stress in most of the basins, followed by a period of steady increase. The period of rapid increase was the 1980s for Pearl, Qiantang, Hai, Shiyang and Tarim River Basins, the 1990s for Huai River Basin and the 2000s for Songhua and Liao River Basins. The Yellow River Basin had bimodal period of rapid increase (the 1980s and the 1990s) and then no further increase, due mainly to governmental regulation since 1998 (Xia and Pahl-Wostl, 2012).

Insert Figure 4 here

Given the inaccessibility of observed runoff data in the downstream region of Liao, Huai and Qiantang River Basins, only nine large basins were selected to analyze past changes in surface water withdrawal in the upstream, midstream, and downstream reaches. For Yangtze, Pearl and Min River Basins in southern China and Songhua River Basin in the north, surface water stress increased continuously in the upstream, midstream and downstream reaches (Fig. 5). For some northern basins (including Hai, Shiyang, and Hei River Basins), surface water stress increased in both upstream and downstream reaches in 1980s, then continued with an increase in upstream and a large decrease in the downstream region in 1990s. For other northern basins (including Yellow and Tarim River Basins), the decrease of surface water stress in downstream region occurred in 2000s. In total, the proportion of water withdrawal in upstream and downstream reaches showed divergent trend in northern basins, identifying lack of water availability in downstream regions of northern basins (Fig. 6).

Insert Figure 5 here

Insert Figure 6 here

3.3 Water shortage trajectories

During the study period, the surface water availability had decreased from 1,361 m^3 cap^{-1} yr^{-1} in 1980s to 1,190 m^3 cap^{-1} yr^{-1} in 2000s (Fig. 4). Apart from Yangtze, Pearl and Min River Basins with over 1,700 m^3 cap^{-1} yr^{-1} of surface water availability, most of the basins in the north had surface water shortage. While Songhua, Hei and Tarim River Basins had moderate water shortage (of over 1,000 m^3 cap^{-1} yr^{-1} surface water), the other six remaining basins in the north had high water shortage (of

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less than 1,000 m^3 cap^{-1} yr^{-1}). Hai River Basin had the most severe surface water shortage (of less than 100 m^3 cap^{-1} yr^{-1}). In fact, water supply in the middle and downstream reaches of the basin was largely supplemented by groundwater (Water Resources Bulletin of Hai River Basin, 2015), resulting over-exploitation of groundwater.

Insert Figure 7 here

Generally, there was a dominant decrease in surface water availability in most of the reaches and basins. As shown in Figure 7, surface water availability in the upstream regions of the basins in the south and the Songhua River was always lower than that in the downstream regions, driven mainly by the gradual accumulation of runoff in downstream regions. Conversely, in the basins in the north except Songhua River, surface water availability in the downstream regions was significantly lower than that in the upstream regions.

Population was another important factor influencing surface water availability (Fig. 8). For most of the basins in coastal or the eastern regions, population increase (driven by rapid urbanization) resulted in decreasing water availability in the downstream region (e.g., Pearl, Yangtze, Min, Hai and Songhua River Basins). Since the end of 1990s, the rate of decrease in water availability in downstream regions was faster than that in upstream and middle-stream regions. This was due to the rapid development in downstream metropolis such as Beijing, Shanghai and Guangzhou (Yang and Chen, 2014). However, for basins in the northwest, big cities were usually located in midstream oasis such as Wuwei, Zhangye, Jiuquan, Aksu, etc. Thus surface water availability generally decreased in midstream of the basins in the northwest.

Insert Figure 8 here

3.4 Water scarcity (stress/shortage) trajectories

The combined analysis of water stress and water shortage has shown aggravation of water scarcity in China: higher water stress induced by higher surface water withdrawal and less per capita water availability induced by increasing population (Fig. 9a). For basins in humid regions, water scarcity was still low after endurable increase in water withdrawal and decrease in water availability, which was due to rich water resources. For basins in the arid northwest and Hai River Basin where water stress was already at the highest level, the slight increase of water scarcity could be attributed to strict water managements such as water saving or water transfer from basins in the south (Barnett et al., 2015). Note that large increase in water scarcity happened in semi-humid/arid basins with dramatic increase of surface water stress and little change of surface water availability, suggesting that the exacerbation in water scarcity was driven by socioeconomic development.

Insert Figure 9 here

Comparison of Figures 9b and 9c clearly showed the competition for water between upstream and downstream regions in five water-scarce basins, including Hai, Yellow, Shiyang, Hei and Tarim River Basins. Water withdrawal increased in upstream region while decreased in downstream region. In Hai basin, for instance, surface water withdrawal in the upstream region increased from 65% to 88%, while surface water withdrawal in the downstream regions was reduced from 44% to 28%. Yellow and Hei River Basins began to decrease their water withdrawal in upstream region, however, little decrease of upstream water withdrawal in such extent could not stop the continued decrease of downstream water availability. The less

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accessibility to surface water resources in downstream region had led to ecological migration in northwestern basins and over-exploitation of groundwater in northern basins.

4 Discussions

This study showed that climate change was the major driver of runoff, as change in precipitation corresponded with the reconstructed natural runoff. For instance, both precipitation and natural runoff increased in the coastal regions in the southeast and in the upper reaches of the northwest, decreased in Hai River Basin, middle-reaches of the Yellow River Basin, middle reaches of Yangtze River Basin and in basins in the southwest. However, anthropologic interventions had greatly changed river runoff across northern China over past decades. Human disturbances have resulted in significant runoff decline against marginal precipitation decline in Hai River Basin and in the middle reaches of Yellow River Basin. Moreover, runoff decreased even when precipitation marginally increased in northeast China and significantly increased in northwest China.

In most water-limited basins, increasing water use in the up and middle reaches increased water stress and over-exploitation of groundwater in the downstream regions (China Water Resources Bulletin, 2016). To stop the imbalance in water use, scarcity and shortage, the cautious choice of governmental interventions, through water governance and economic compensation, should be further evaluated and made.

Across the vast water-scarce northern China, two different policies are adopted to relieve water scarcity: Water allocation accompanying with water right, and transboundary water transfer. The former policy is currently applying in northwestern catchments including Shiyang, Hei and Tarim River Basins. While the latter policy is mainly applying in Hai River basin, which is the destination of famous "South-to-North Water Transfer" project. Yellow River Basin is trying to relieve its water scarcity by the combination of both two policies.

In this study, we consider the per capita water availability as a key factor in making the choice of policies. In northwestern catchments, the water resources are rich and population density is low, leading to high per capita water availability. For example, per capita water availability is 3,295 m^3 for five northwestern provinces of China in 2016 (National Bureau of Statistics of China, 2016). The main problem is that the dramatic increase of water withdrawal in up and middle reaches causes water scarcity in lower reaches, and the consequent terminal lake vanishing, vegetation death, and desertification. Together with the montane terrains which impedes the construction of water transfer projects, therefore water allocation accompanying with water right and water price might be the optimal choices for northwestern catchments to solve problems in lower reaches. Similar regions over globe include Sub-Saharan Africa with 3,969 m^3 per capita water availability, Central Asia with 12,375 m^3 per capita water availability, and so on (WB, 2014).

Conversely, for Hai River Basin, poor water resources and large population lead to extreme low per capita water availability with 279.7, 161.6, 121.6 m^3 in 2016 for Hebei provinces, Beijing, and Tianjin, respectively (National Bureau of Statistics of China, 2016). Water allocation is not feasible here because water scarcity happens everywhere. If more surface water is

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forced to release to downstream, the upstream regions will face more severe water resources shortage and consequent environmental deterioration. For example, Shanxi province, the upstream province of Hebei, Beijing and Tianjin, haven't had enough surface water to satisfy itself demand in long run. Consequently, the development of Shanxi province heavily relied on groundwater at amount of 3.6 billion m^3, or 64% of total water use, in 2004 (National Bureau of Statistics of China, 2004). The excessive exploitation of groundwater has resulted in a series of environmental and geological problems, such as land subsidence, earth fissures, and great reduction of river water flow to the downstream (Sun et al., 2016). Moreover, considering the higher economic value per unit water in downstream regions, for instance, 15.6 and 58.4 $m^3/10^4$ GDP in 2016 in Beijing and Shanxi, respectively (National Bureau of Statistics of China, 2016), the increase of water supply is more feasible policy, including water recycling, transboundary water transfer and sea water desalinization. Similar regions over globe include Singapore with 110 m^3 per capita water availability, Saudi Arabia with 78 m^3 per capita water availability, and so on (WB, 2014).

Overall, the formulation of water governance policies is challenging. The analysis of past trajectories of water scarcity in upstream, midstream and downstream provided a sound basis for developing and implementing water governance in China and across the world.

5 Conclusions

The unconstrained water consumptive uses in upstream of a river basin lead to negative impacts on economy, society, and ecosystems in downstream. However, the spreading of water scarcity from upstream to downstream is still unclear in China due to lack of long-term water uses data. By comparing observed runoff (1961-2010) and reconstructed theoretical runoff in 67 catchments, we analyzed trajectories of surface water withdrawal and per capita surface water availability in upstream, midstream and downstream of China's major river basins. Results showed that the rapid increase of water scarcity mainly happened in northern basins from 1980s to 2000s. Since 1990s, the increase of upstream surface water withdrawal came along with the decrease of downstream surface water accessibility. Although upstream water withdrawal was restrained in some northern basins since 2000s under new water management policy, however, the extent of decrease of upstream water withdrawal was too little to stop further decline of downstream water availability. Moreover, some of semi-arid and humid basins are following the footsteps of arid basins, increasing upstream surface water withdrawal rapidly. The results provide experiences and lessons in developing new management strategies/policies to reduce negative impacts of over withdrawal and enhance water availability by considering whole river basin as one system.

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Figure 5 Water stress trajectories for the period from the 1970s to 2000s for the whole basins and reaches. WTA is defined as the percent ratio of surface water withdrawal to available water, referring a demand-driven scarcity of water.

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Basin	Hydrologic station	Reference
Yangtze	Pingshan1, Yichang, Hankou, Datong, Gaochang, Wulong, Beibei, Huangzhuang, Chenglingji, Hukou	Changjiang Sediment Bulletin (2010); Chinese river sediment Bulletin (2002-2010)
Yellow	Tangnaihai, Toudaoguai,Huayuankou, Lijin, Huangpu, Wenjiachuan, Huaxian, Baijiachuan, Ganguyi, Hejin, Heishiguan, Wuzhi, Hongqi	Yellow River Sediment Bulletin (2000-2010); Chinese river sediment Bulletin (2002-2010)
Hai	Zhangjiafen, Xiangshuibao, Xiahui, shixiali	Official source, Chinese river sediment Bulletin (2002-2010)
	Daomaguan, Xiaojue, Pingshan2	Official source
	Haihezha	Chinese river sediment Bulletin (2002-2010); Dai et al., 2007a; Wei et al., 2016
Hei	Yingluoxia, Zhengyixia	Chinese river sediment Bulletin (2002-2010); Niu et al., 2011
	Langxinshan	Niu et al., 2011; Ren et al., 2015
Shiyang	Huangyanghe, Zamusi, Gulanghe, caiqi, Hongyashan	Official source
Tarim	Tongguziluoke, Kaqun, Xidaqiao, Alaer	Chinese river sediment Bulletin (2002-2010); Zhao et al., 2010; Yang and He, 2003
	Yingbazha, Qiala	Zhao et al., 2010; Yang and He, 2003
Huai	Xixian, Bengbu	Chinese river sediment Bulletin (2002-2010); Pan et al., 2013; Dai et al., 2007a

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Pearl	Gaoyao, Liuzhou, Qianjiang, Nanning, Shijiao, Boluo	Chinese river sediment Bulletin (2002-2010); Dai et al., 2007a,b
Min	Zhuqi, Qilijie, Yangkou, Shaxian	Chinese river sediment Bulletin (2002-2010); Dai et al., 2007a
Qiantang	Huashan, Zhuji, Quxian	Chinese river sediment Bulletin (2002-2010)
Liao	Xinglongpo, Tieling	Chinese river sediment Bulletin (2002-2010); Zhang et al., 2014; Dai et al., 2007a
Songhua	Dalai, Jiangqiao, Fuyu, Haerbin, Jiamusi	Chinese river sediment Bulletin (2002-2010); Tu et al., 2012; Song et al., 2009

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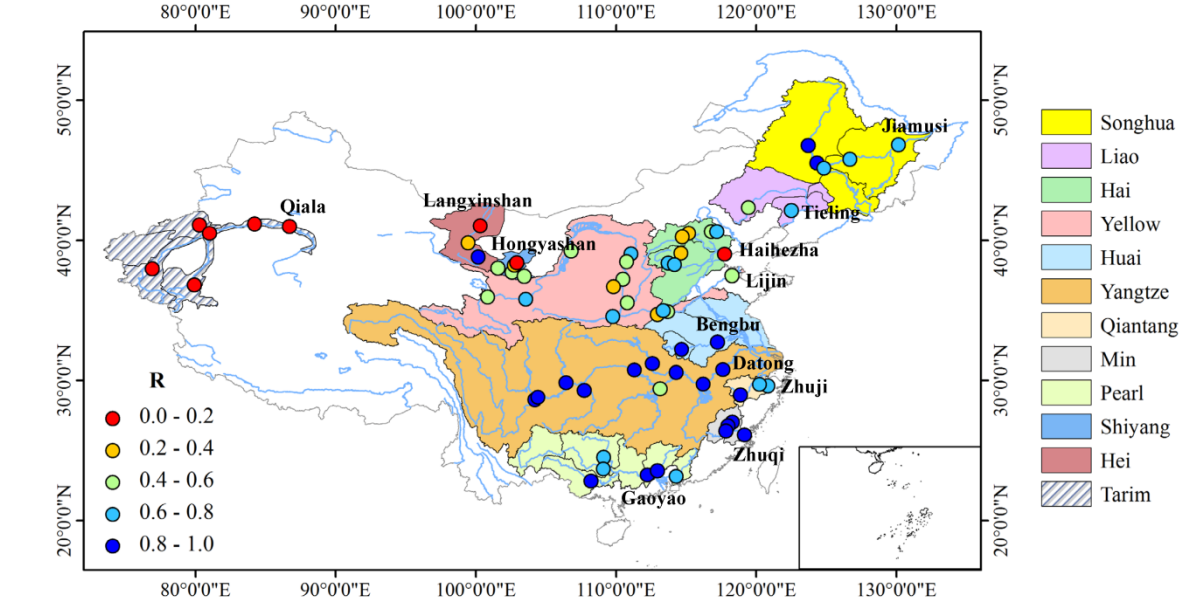

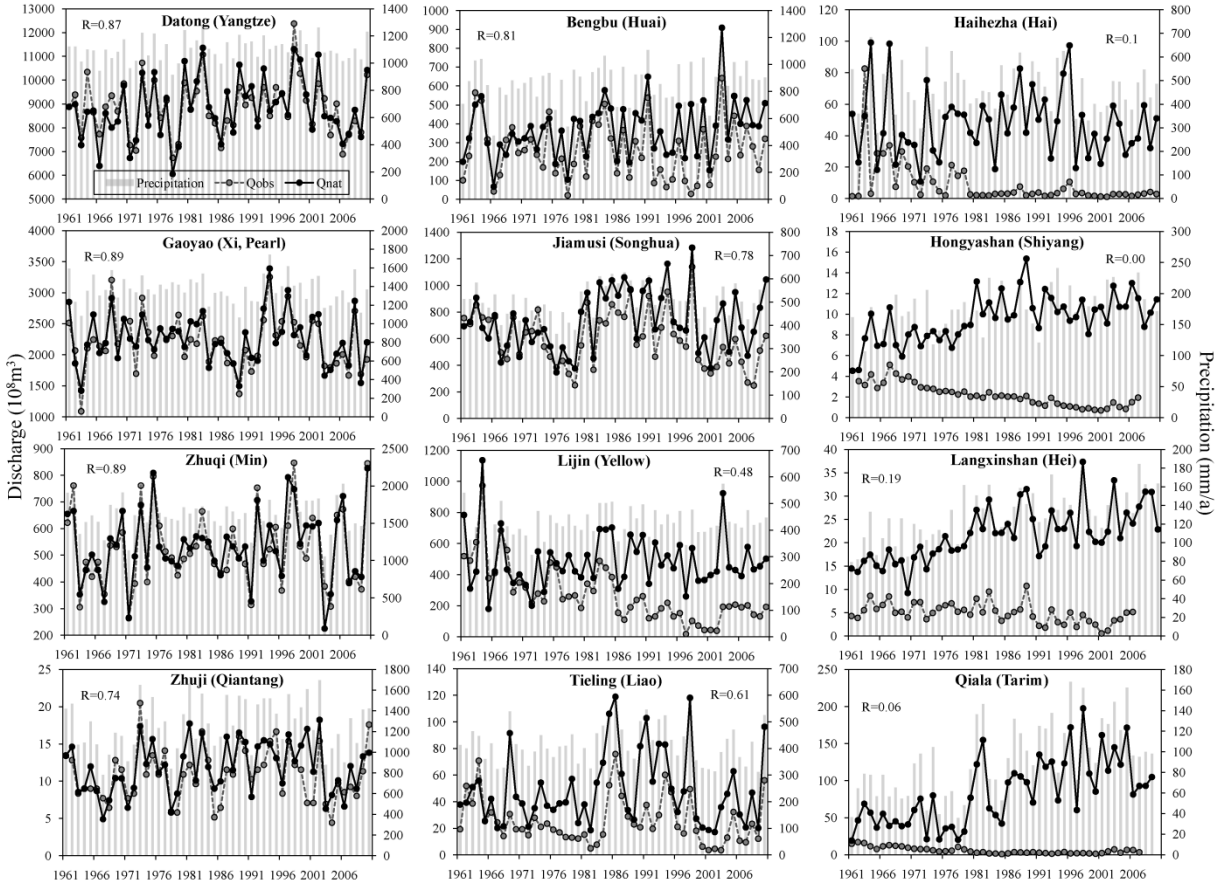

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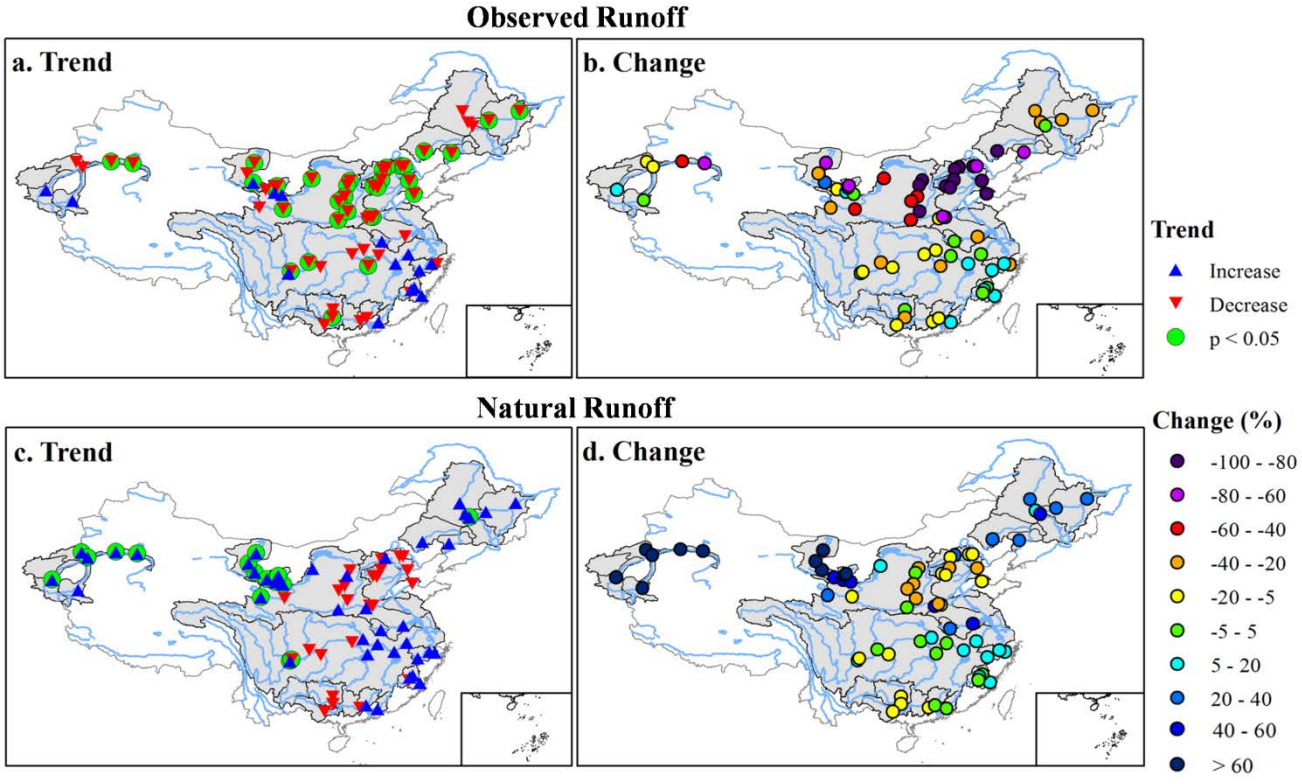

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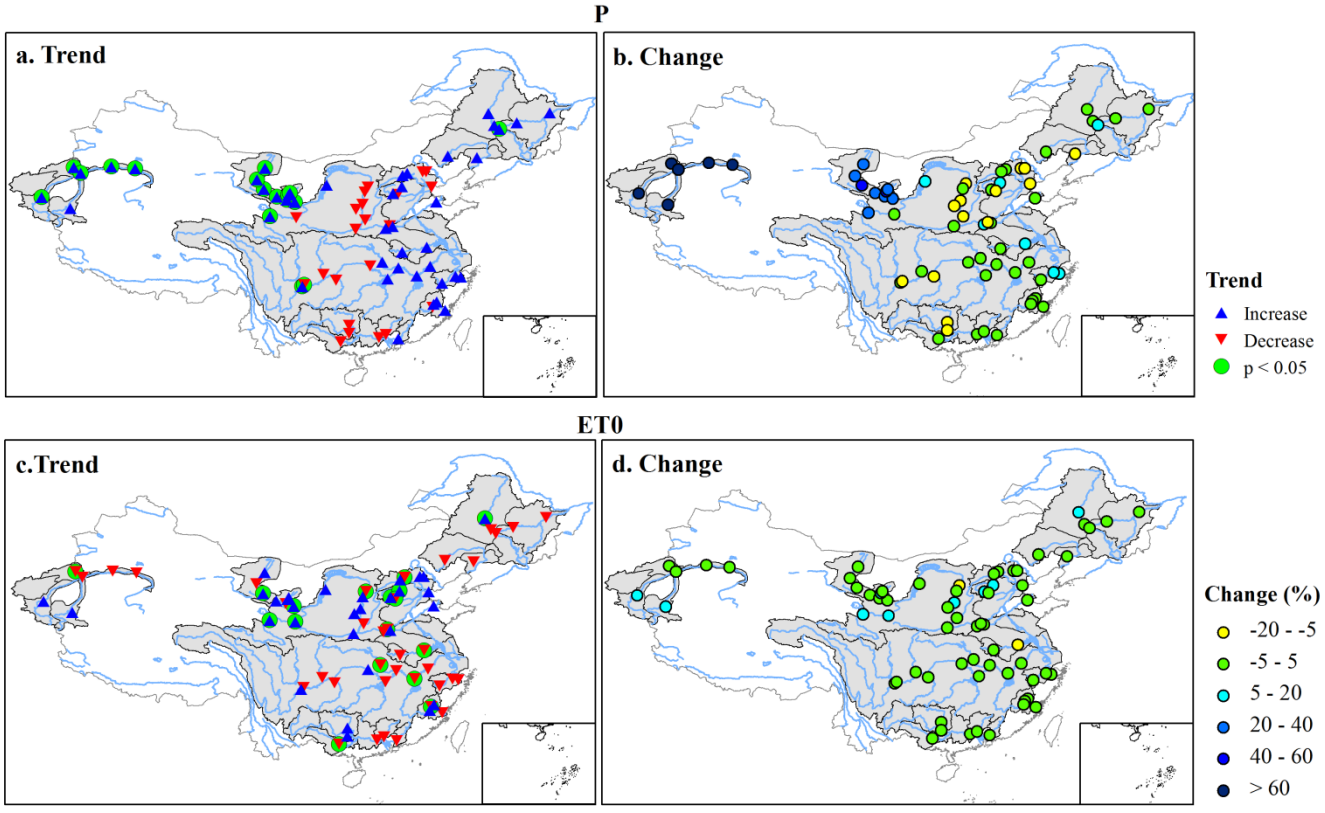

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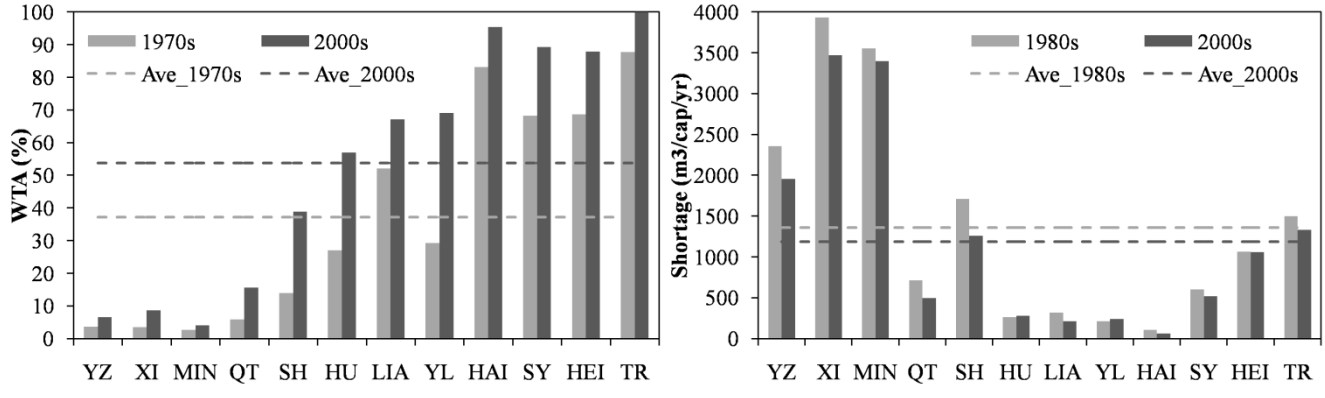

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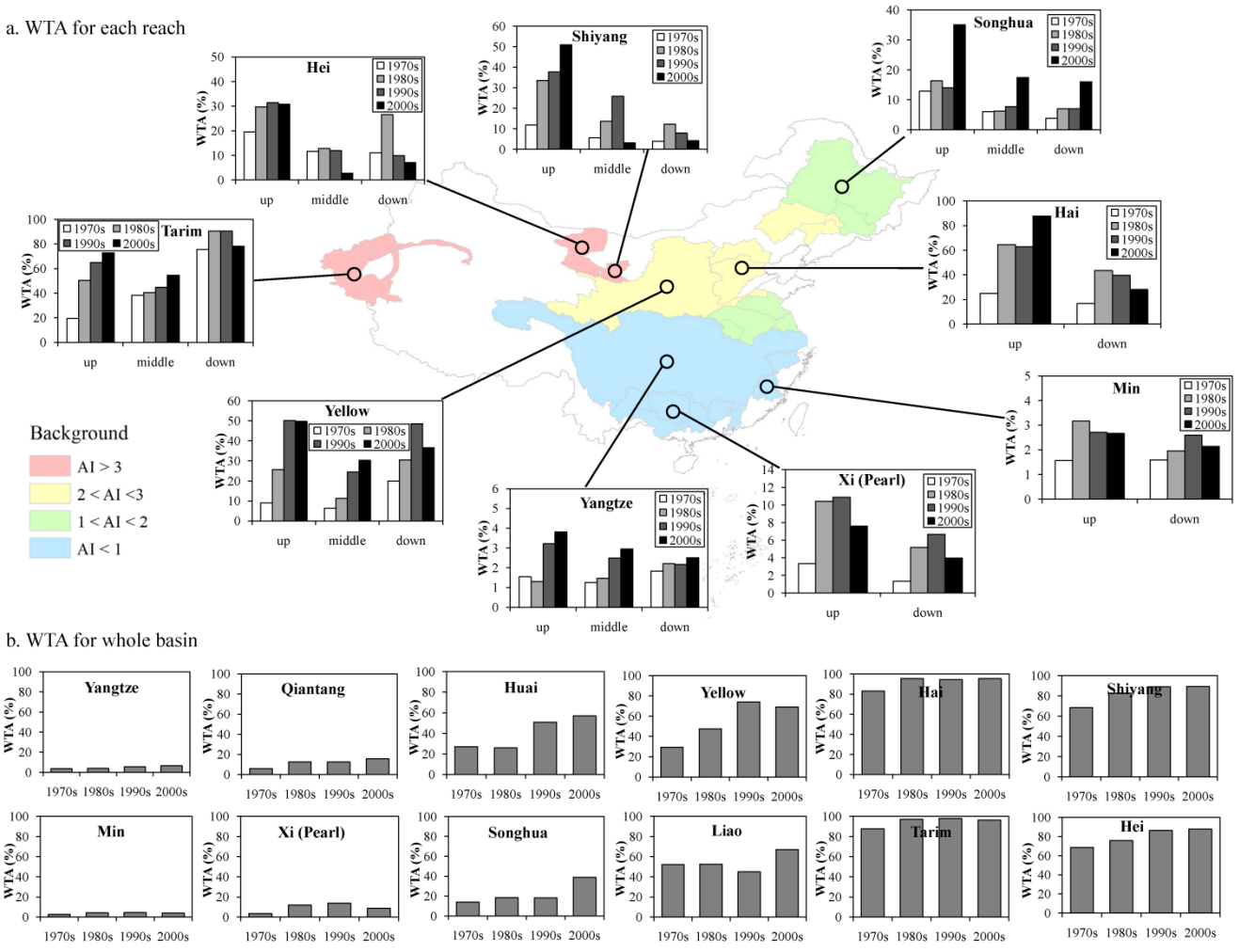

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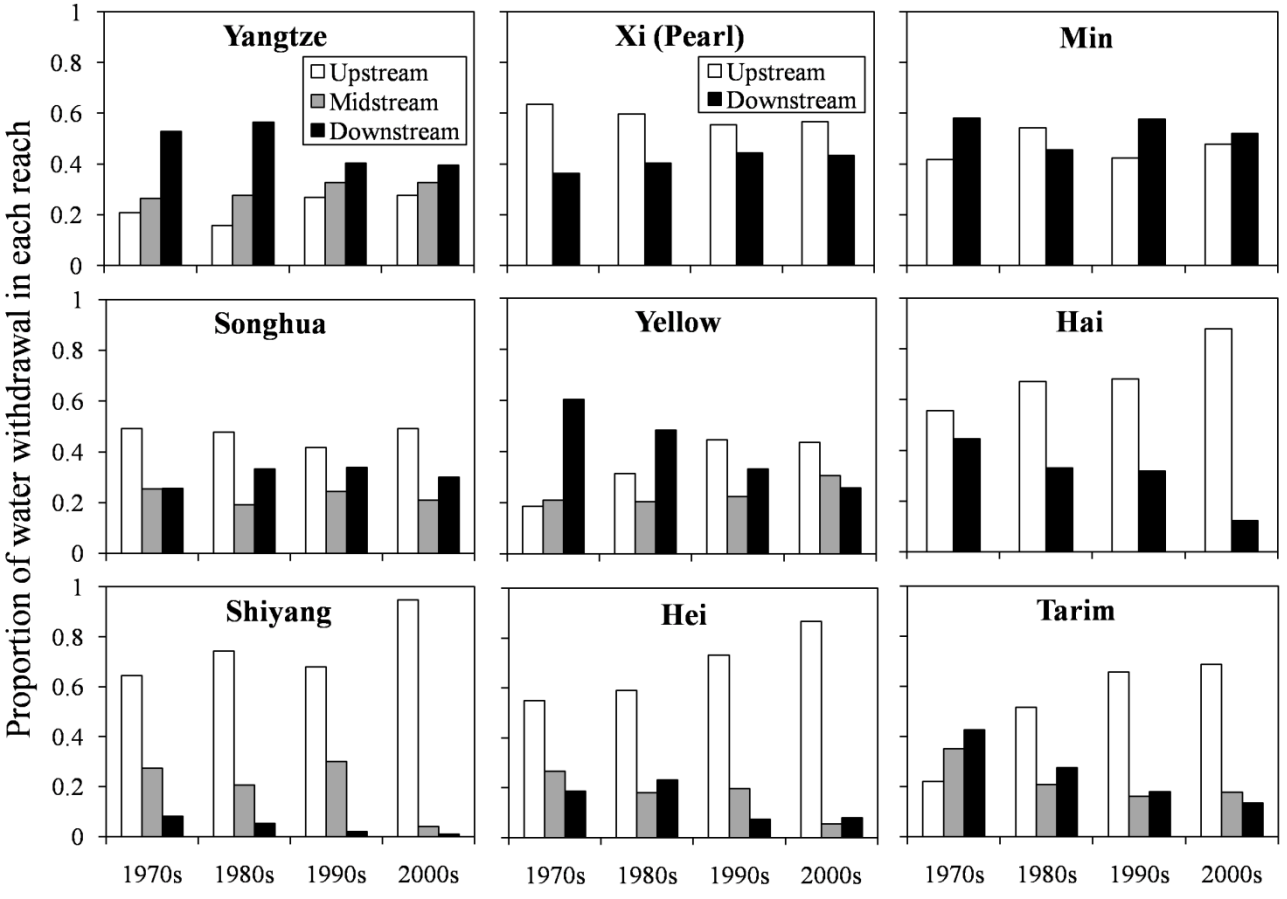

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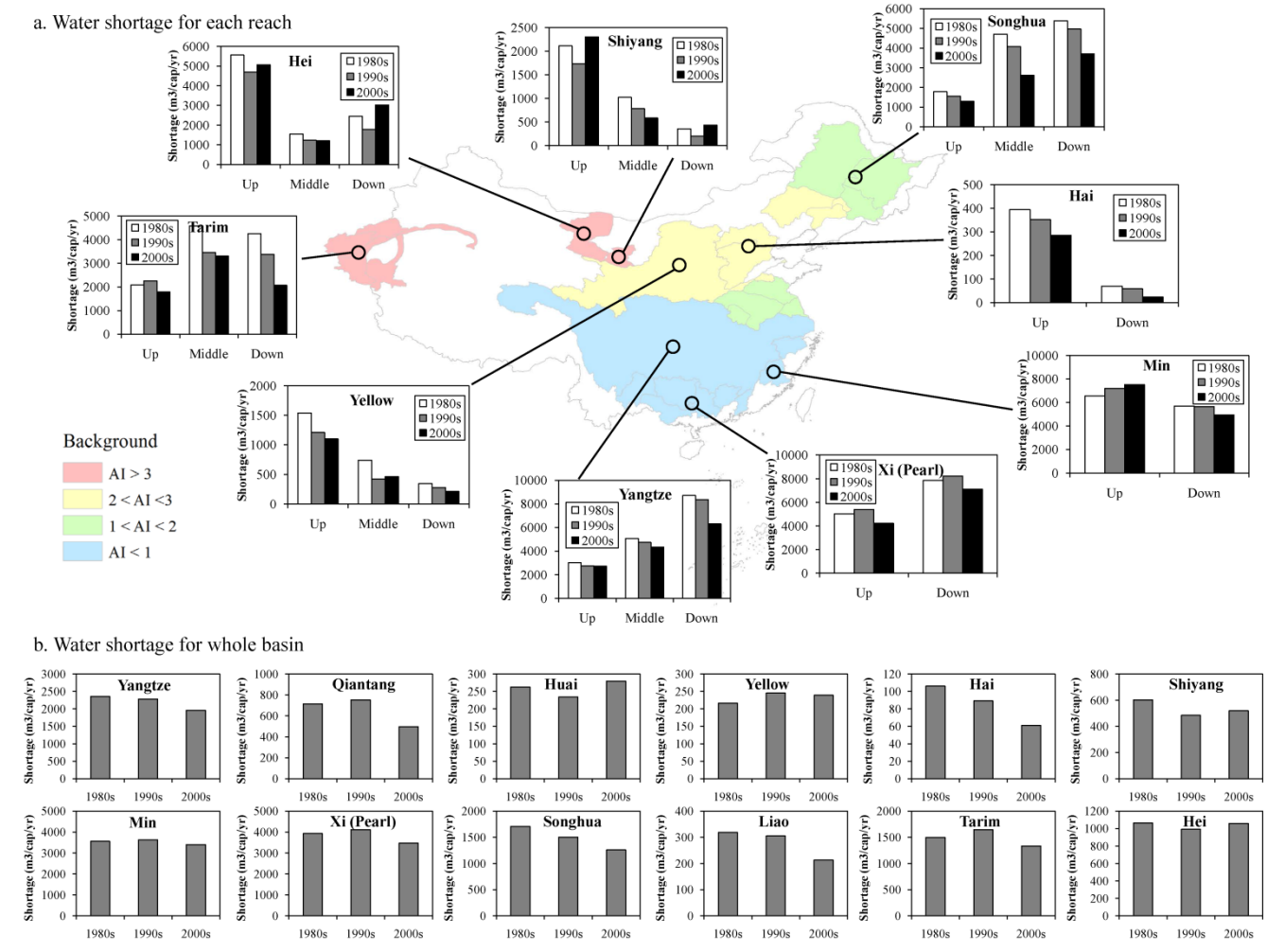

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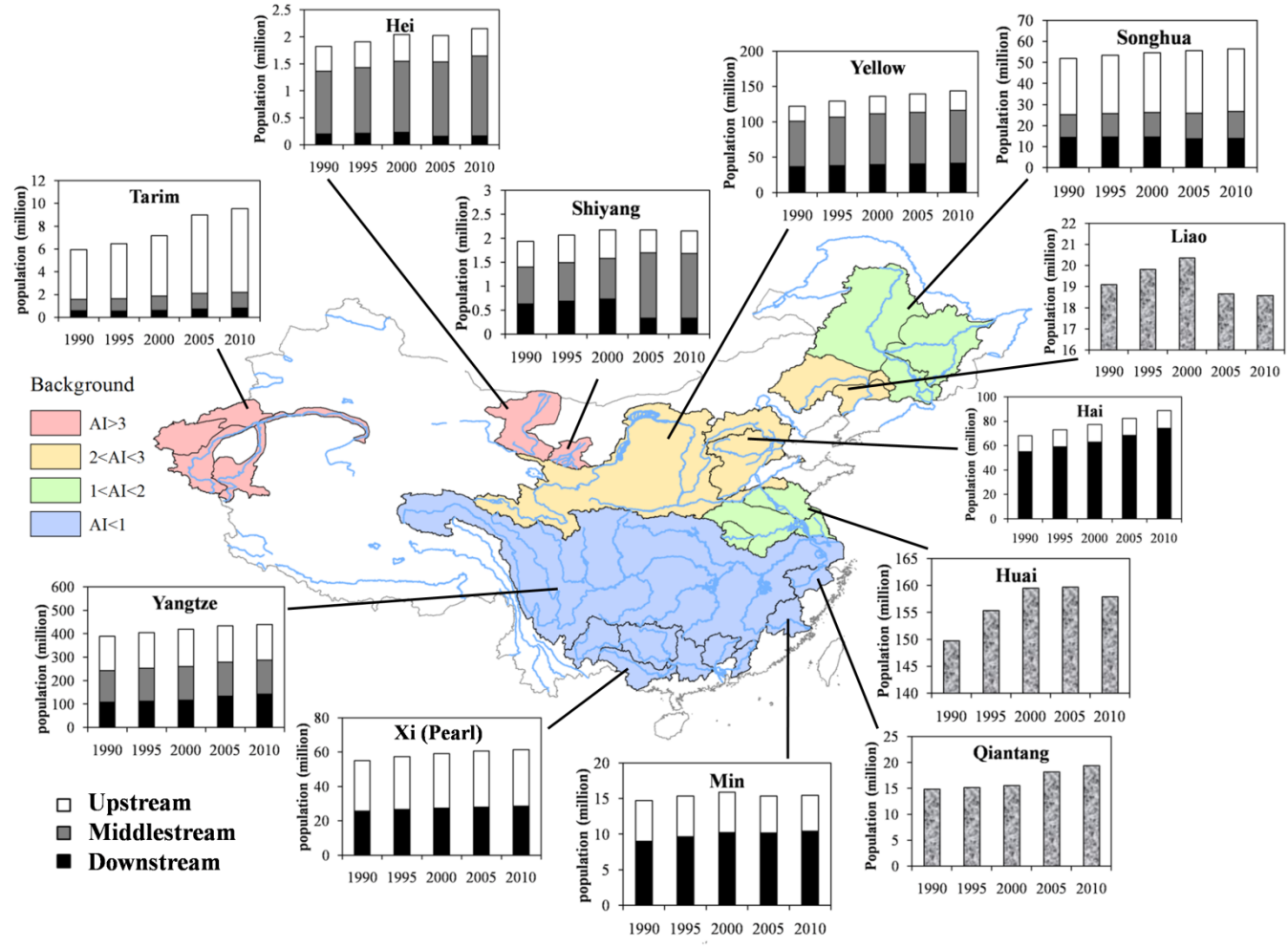

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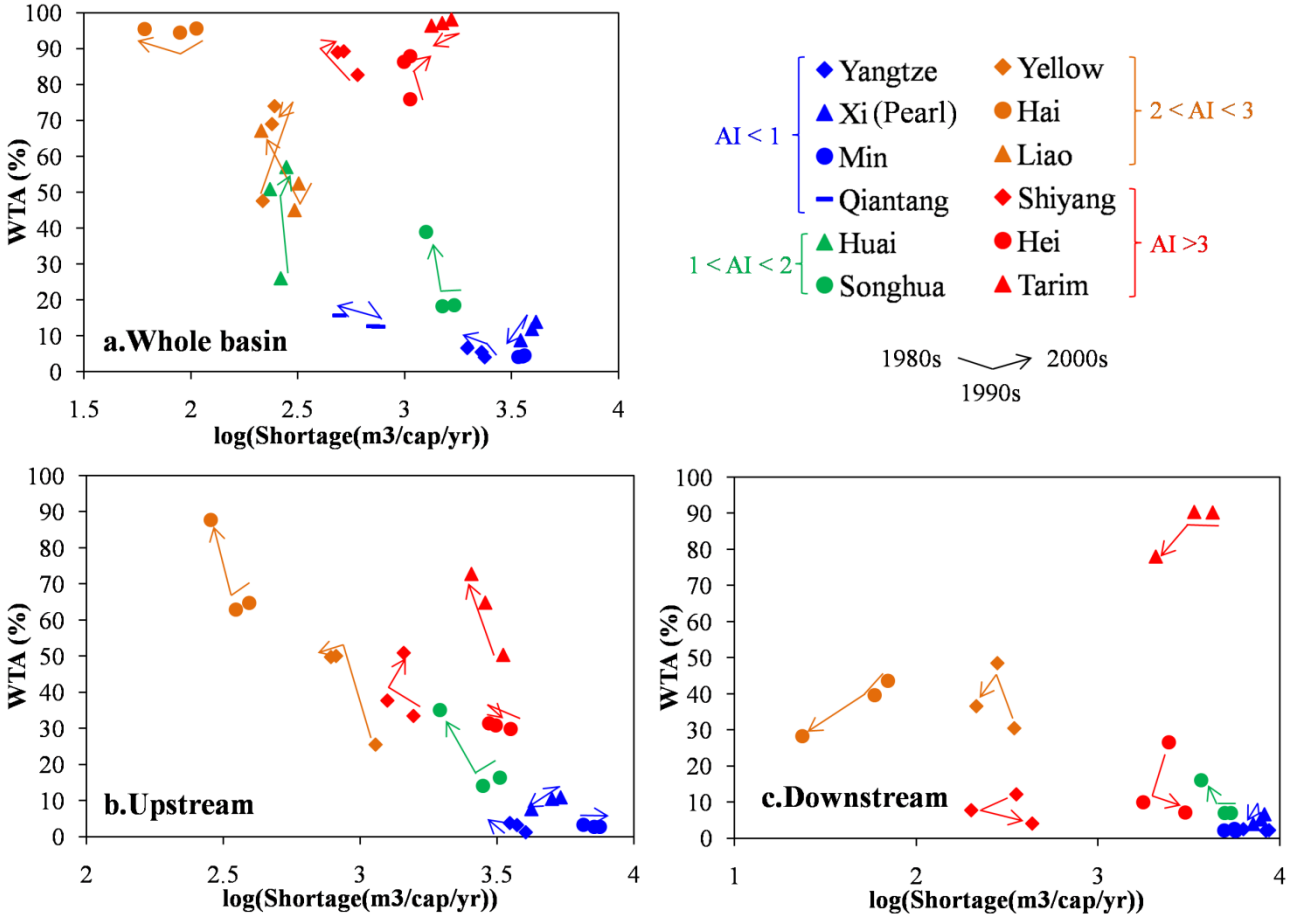

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