RESPONSE TO REVIEWER #1

General comments

The study used a well-known framework to analyze the water scarcity in some large basins in China. Although the method is not new, the topic is interesting. However, some details about the method should be added (please see the following point-to point remarks), and the presentation of the results should be improved. In the results part, I found that the analysis was not complete for each basin, the results were not well organized, and the figures are hard to follow. These limitations made me a little bit hard to understand the results and conclusions (some are due to a lack of quantitative analysis, and some are due to a lack of complete summary and necessary discussions; particularly, the result about water scarcity was not well interpreted). Finally, the authors had three objectives, but the imbalance between upstream and downstream regions was not well quantified, and the third one was only discussed in a very simple way.

Response: We appreciate reviewer #1's constructive comments which help us improve our manuscript a lot. According to the comments, we thoroughly redrafted the manuscript: a scenario analysis has been added to quantify the impact of upstream water use on downstream water scarcity, and anew water scarcity indicator was defined to explore the main driver of water scarcity. The objectives changes correspondingly. In addition, the discussion part has been rewritten and the related water policy was fully discussed. We hope the new version will satisfy the criterion of publication. The point-to-point reply is listed below.

Specific comments:

P4L1: how did you do the model calibration to show that theta is most sensitive to topography? The details about the model calibration were missing. The theta value was constant for all the basins?

Response: We realized that the model calibration was not necessary in this study. As the P, ET0 and observed runoff are known variables, the ordinary least squares method was adopted to fit the model parameter using the P, ET0 and observed runoff in the period of 1961-1970, then the fitted parameter was used to calculate the natural runoff in the following period. Only the upstream, middlestream and downstream gauge stations were kept and the irrelevant tributaries were removed. Although the parameter was recalculated in the new manuscript, the upstream regions still have lower value compared to its downstream counterpart, which is probably related to the steeper terrains in upstream regions. The explanation has been added in the P5L13-15 as "*Using the observed ET0, P and observed discharge, the parameter θ was calculated using the least-square data fitting method for the period 1961–1970, then the fitted parameter was used to reconstruct decadal natural runoff for the period 1971–2010.*"

P4L2: the uncertainty of the model should be evaluated more completely. 6.9% was only the average. However, how about the spatial distribution of the uncertainty? Which basins had the largest uncertainty?

Response: Given the auto-fitted parameters, the biases were quite small with less than 1% for humid basins (Pearl, Min and Qiantang River Basins), 1% for semi-humid basins (Yangtze, Songhua and Huai River Basins), -3% for semi-arid basins (Yellow, Hai and Liao River Basins) and 3% for the upstream of arid basins (Hei, Shiyang and Tarim River Basins).

P4L3: please give references to show this framework can be suitable for annual studies. In my experience, this frame is only suitable for mean annual studies.

Response: A reference has been added in the discussion part in P11L12-15 as "*This has been proved by Zhang et al. (2008), who has tested the Budyko model over 265 Australian catchments at different time scales, including mean annual, annual, monthly and daily. They found at annual scale, the model works well for most of the catchments with 90% of them having values of the coefficient of efficiency greater than 0.5 and less than 3% of the catchments have bias values greater than 10%.*"

P4L17: here, why was ET0 calculated by the Hargreaves equation rather than the Penman equation? The gridded meteorological data can be also obtained by interpolating the station-based data to grids.

Response: A explanation of the combined use of HG-ET0 and PM-ET0 was added in section 2.2.2 in P5L17-23 as "*Two equations – Hargreaves (HG) and Penman-Monteith (PM) – were used to estimate ET0 (Allen et al., 1998). The HG-ET0 was based on gridded dataset at monthly scale while PM-ET0 was based on pointed dataset at daily scale. The PM equation ranked as the best equation for estimating ET0 but the sparse distribution of climate stations limited its application in western China. The continuous spatial coverage of gridded dataset can provide full estimation of HG-ET0 in western China. However, large discrepancies between HG-ET0 and PM-ET0 were found in different regions over the world in previous studies (Temesgen et al., 2005; Gavilan et al., 2006; Trajkovic, 2007; Bautista et al., 2009; Sivaprakasam et al., 2011; Berti et al., 2014). Thus more accurate ET0 can be obtained by combining two estimations.*"

P5L2, please give the reference for the classification method of AI.

Response: The classification has been added in P5L6-9 as "*In this study, AI of each catchment was calculated at mean annual scale for the period of 1961-2010 and the catchments were classified into humid, semi-humid, semi-arid and arid for AI ranging from 0.375~0.75, 0.75~2, 2~5 and 5~12, respectively (Ponce et al., 2000; Arora, 2002).*"

P5L5, according to Figs. 4 to 9, I think you focused more on the changes, so maybe the trend was less important. Please consider to delete the trend analysis contents to make the results more coherent.

Response: Thank you for your suggestion. The reason for keeping the trend analysis in the manuscript was in case someone is interested in the trends. After careful consideration of your suggestion, we have deleted all the trend analysis contents to make the results coherent.

P5L9, the definition of water scarcity is expressed by two indicators, but this is not very easy to follow, especially in Fig. 9. I suggest define a new indicator, e.g., WS=WTA/Shortage? Maybe it is easier to compare this indicator among different decades, basins, and reaches.

Response: Thank you for the useful comment. We redefined a new water scarcity indicator in section 2.2.5 and the explanation of the new indicator was listed as "*Kummu et al. (2016) used per capita water use (WTA×FI) to show the variation of water scarcity. However, it probably failed to describe water scarcity variation because of the cancelling out of the two indicators: The increase of water scarcity was indicated by higher WTA but lower FI. Hence we proposed a new water scarcity definition, per capita remaining available water, which is described as (1-WTA) ×FI. The new definition of water scarcity can better show the change of water scarcity through the consistent change of (1-WAT) and FI.*"

P6L15, the correlation coefficient of natural and observed runoff means what? As defined by the authors, natural runoff and observed runoff could be totally unrelated, so I don't know what R means. 1961-1970 was the period for model calibration, so why did you show the degree of suitability of the model during 1961-2010? If the authors assumed that period from 1961-1970 was nearly natural, you should divide the period into two sub-periods: one for calibration and the rest one for validation. I noticed that the model's performance in some basins listed in the right most column of Figure 1 was very poor during 1961-1970. Is the framework suitable for these basins?

Response: In the new manuscript, the ordinary least squares method was used to fit the parameter using the known P, ET0 and observed runoff in the period of 1961-1970, then the fitted parameter was used to calculate the natural runoff in the following period. The explanation has been added in the P5L13-15 as "*Using the observed ET0, P and observed discharge, the parameter θ was calculated using the least-square data fitting method for the period 1961–1970, then the fitted parameter was used to reconstruct decadal natural runoff for the period 1971–2010.*"

“Some basins in the right most column of Figure 1” refers to arid basins and Hai River Basin. For those basins, Budyko framework usually performs poor. Here we only calculated the upstream natural runoff and assume there is no local-generated runoff in the downstream regions. The explanation of the runoff calculation in arid basins has been added in section 4.1 in P11L16-22 as “*What is more, previous studies proved that Budyko framework performed badly in arid and cold basins where snow and glacier melt contribute a lot to runoff. Here we found that Du et al. (2016) successfully applied a Budyko framework in Hei River Basin by dividing the basin into six sub-basins. They calibrated the model separately in different sub-basins and found the model performed quite well in the upper mountainous regions with little human interventions while the model was almost impossible to validate in downstream sub-basins. Thus we also divided the arid basins (including Hai, Shiyang, Hei and Tarim River Basins) into upper mountainous sub-basins and downstream sub-basins. The Fu-Budyko framework was directly applied in the mountainous* *sub-basins.”*

P6L24, it is very difficult to see which gauges are in the upstream and which gauges are in the downstream. The authors should think about how to present the locations of the gauges clearly.
Response: Thank you for the comments. The locations of upstream, middlestream and downstream and corresponding gauge stations have been marked in new Figure 1.

P6L25, can you explain why a gauge with a positive trend in rainfall can have a negative change (Fig. 3)?
Response: Here the rainfall's change was not calculated as the trend (mm/year) * year, instead it was calculated as the differences between two periods - 2000s and 1960s. Thus the change of a gauge was only dependent on the differences between 2000s and 1960s but not the trend. Meanwhile, Figure 3 has been deleted in the new manuscript.

P6L29, in northwest of China, such as Heihe, Tarim, river runoff is mostly contributed by snow melt. Is the framework suitable for these basin?
Response: The explanation of the runoff calculation in arid northwestern basins has been added in section 4.1 in P11L16-22 as “*What is more, previous studies proved that Budyko framework performed badly in arid and cold basins where snow and glacier melt contribute a lot to runoff. Here we found that Du et al. (2016) successfully applied a Budyko framework in Hei River Basin by dividing the basin into six sub-basins. They calibrated the model separately in different sub-basins and found the model performed quite well in the upper mountainous regions with little human interventions while the model was almost impossible to validate in downstream sub-basins. Thus we also divided the arid basins (including Hai, Shiyang, Hei and Tarim River Basins) into upper mountainous sub-basins and downstream sub-basins. The Fu-Budyko framework was directly applied in the mountainous sub-basins.”*

P6L25, P71, the authors gave subjectively the reasons for the trend (a significant increase in rainfall, recent global warming), I don't see any supporting analysis.
Response: All the trend analysis parts have been removed in the new manuscript according to the previous comment.

P7L11-15, from Figure 4, I can't see these interesting analyzes. And, please add the AI in this figure.
Response: The figure has been redrawn and the description of Figure 4 has been thoroughly rewritten in section 3.2.1.

P7L14-15, this is also too subjective.
Response: Figure 4 has been redrawn and the description of Figure 4 has been thoroughly rewritten in section 3.2.1.

P7L20, in Figure 5a, I suggest add an average of 1970s~2000s for each basin. Here, how did you define "continuously"? Obviously, WTA in the Yangtze, Pearl, Min River and Songhua did not increase monotonously.
Response: Figure 5 has been redrawn and the description of Figure 5 has been thoroughly rewritten in section 3.2.2.

P7L17-25, these results should be discussed to give the possible reasons.
Response: Section 4.2 fully discussed the changes of water policy in China, which shows that the excessive water use was encouraged in 1980s and 1990s while limited in 2000s. Please see the section 4.2 for details.

P8L5, Figure 7 is about water shortage, so I don't know why the authors were talking about surface water availability.
Response: Figure 7 has been replaced by Figure 4 and Figure 5, and the term “water shortage” was substituted by “per capita water availability”. Please see section 3.2 for the details.

P8L11, water availability is determined by natural runoff, so I can't understand why population can affect water availability.
Response: We are sorry for the unclear description. Water availability is determined by natural runoff, while per capita water availability (FI) is related to population.

P8L19, from Figure 9a, I can't see the aggravation of water scarcity in China. This figure is not visual to show this aggravation trend.
Response: Figure 9 was replaced by Figure 7 and 8 and a new definition of water scarcity was used to identify the main driver of water scarcity changes. Please see the section 3.4 for the detailed explanation.

P8L25, water scarcity is defined with water stress and water shortage, here, why is it related to surface water availability?
Response: In the new manuscript, the term of “water shortage” was replaced by “per capita water availability”, which is considered as better expression of “water shortage”.

P8L28, fig. 9a and 9c cannot show this competition (at least I don't know how to interpret). And this paragraph was about water scarcity, but the authors were talking about water withdrawal. So it is very hard to understand these sentences.
Response: Figure 9 was replaced by Figure 7 and 8 and a new definition of water scarcity was used to identify the main driver of water scarcity changes. Please see the section 3.4 for the detailed explanation.

In Figure 8: in the Liao, Huai, and Qiantang, why were there no upstream, middle, and downstream?

Response: The explanation has been added in P7L4-9 as "*It is noted that only nine large basins were selected to analyze past changes in surface water scarcity in all three reaches (upper, middle and lower) because runoff data were not available in the downstream regions of Liao, Huai and Qiantang River Basins. For example, hydrological data at outlet station in Liao River Basin is available in 1984-2010; there were no hydrological data at outlet station in Huai River Basin; streamflow data were only available in tributary stations in Qiantang River Basin. For the above-mentioned three basins, we only used the available data from upper stream or tributaries for estimating WTA and FI.*"

P9L4-5, no analysis supporting the statement here.
Response: The climate-related content has been removed in the new manuscript.

P9L16, the possible impacts of the policies on water scarcity in all the basins were not fully discussed.
Response: The water policies from after the reform and opening were fully discussed in section 4.2 in the new manuscript, which shows that the excessive water use was encouraged in 1980s and 1990s while limited in 2000s. Please see the section 4.2 for details.

RESPONSE TO REVIEWER #2

General comments

Here, the authors presented a framework for quantifying the change in water scarcity at major river basins of China. Although, the study is interesting the methodology is not new and the manuscript is poorly written. For publishing purpose, the entire manuscript should be presented in a high quality format. The details of methodology is also not clear. In addition, the authors did not provided equal importance for all the objectives mentioned in the study.

Response: Thank you for reviewer #2's comments which greatly polished our manuscript. We used some new methods and thoroughly rewritten the manuscript. The detailed responses are as below.

Specific comments:

Introduction

The introduction should be improved with proper citations and sentences which shows the importance of the current study.

Response: The introduction has been rewritten and the review of literatures proved that our study is an important supplement for quantitative analysis of upstream-downstream water nexus.

Page 2 second paragraph is confusing. The sentences should be clear. Please add references for "A recent study has shown that the impact of anthropologic interventions on water scarcity is not always negative".

Response: The paragraph has been rewritten and the reference has been summarized in P2L16-20.

Line 21-22 (page2) is confusing. Please correct the sentence. Line 26 is not clear. Please rewrite the entire paragraph.

Response: The paragraph has been thoroughly rewritten. Please see the introduction part for the details.

Page 3. The presentation of objects is poor and not clear. Please write with specific reasoning. In addition, the sentence "The answers will provide experiences and lessons for global water resources management" is not matching here.

Response: The new objectives were proposed in revised manuscript in P3L24-29 as "In this study, we aim to answer following three questions, and provide experiences and lessons for global water resources management. They are:

i. How surface water scarcity developed in upstream and downstream regions of selected basins in China during the past decades;
ii. How to quantify the influence of upstream water use on downstream water scarcity; and
iii. What is the main driver for the change of China's water scarcity."

Overall, the introduction is too short and not clearly written. Please provide more information on the importance of water scarcity analysis by using different indices such as, water stress and water shortage. Please try to link the importance of Fu-Budyko in water scarcity analysis in a river basin scale.

Response: We have thoroughly rewritten the introduction part which includes the points mentioned above. Please see the introduction part for the details.

Materials and methods

The manuscript needs more explanation on method section.

Response: More explanations has been added into the method section accordingly.

Starting the paragraph with 'because' is not recommended. In table 1 provide the lat/lon for gauge locations. Need more explanation on the section Hydrological data reliability.

Response: The first sentence has been corrected and lat/lon information has been added into Table 1. More information about the extracting and processing observed runoff has been provided to explain the data reliability. Please see the section 2.1.1 for details.

Line 29 - please replace e.g. by such as.

Response: All “e.g.” has been replaced in the revised manuscript.

Page 4. The sentence "The steeper the catchment, the smaller was the parameter" is not clear. Need more explanation on the catchment parameter (theta) used in the study?

Response: In the new manuscript, the ordinary least squares method was used to fit the parameter. The explanation has been added in P5L13-15 as “*Using the observed ET0, P and observed discharge, the parameter θ was calculated using the least-square data fitting method for the period 1961–1970,thenthe fitted parameter was used to reconstruct decadal natural runoff for the period 1971–2010.*”

The equation 1 shows the Fu-Budyko framework, and it is a function of aridity index. But the authors did not mention it here. But in page 5 authors introduced the AI (aridity index). It will make confusion to the readers. Please rewrite the section accordingly.

Response: Thank you for pointing out the mistake. The introduction of AI has been moved to P5L5-9 as “*Where $F(\varphi)$ is evaporation ratio, φ is the Aridicity index (AI), calculated from ratio of potential evapotranspiration (ET0) to precipitation (P) on annual scale, the θ parameter is related to catchment characteristics with the range of $1\sim\infty$. In this study, AI of each catchment was calculated at mean annual scale for the period of 1961-2010 and the catchments were classified into humid, semi-humid, semi-arid and arid for AI ranging from 0.375~0.75, 0.75~2, 2~5 and 5~12, respectively (Ponce et al., 2000; Arora, 2002).*”

Expand the unit mm/a (line 13)

Response: The unit of “mm/a” has been corrected to mm/year.

Hargreaves is not a suitable method for quantifying the potential ET hence it is only based on Tmax and Tmin. Please mention the drawback in the manuscript.

Response: The disadvantages of Hargreaves equation has been pointed and the combination of HG-ET0 and PM-ET0 was used to improve the accuracy. Please see P5L17-23 for details as "*Two equations – Hargreaves (HG) and Penman-Monteith (PM) – were used to estimate ET0 (Allen et al., 1998). The HG-ET0 was based on gridded dataset at monthly scale while PM-ET0 was based on pointed dataset at daily scale. The PM equation ranked as the best equation for estimating ET0 but the sparse distribution of climate stations limited its application in western China. The continuous spatial coverage of gridded dataset can provide full estimation of HG-ET0 in western China. However, large discrepancies between HG-ET0 and PM-ET0 were found in different regions over the world in previous studies (Temesgen et al., 2005; Gavilan et al., 2006; Trajkovic, 2007; Bautista et al., 2009; Sivaprakasam et al., 2011; Berti et al., 2014). Thus more accurate ET0 can be obtained by combining two estimations.*"

What does the value 17.8 indicates in the equation 2. Be more specific.

Response: The explanation of the parameters has been added in the revised manuscript in P5L27-28 as "*The standard values of empirical parameters are 0.0023, 17.8 and 0.5.*"

Then line 23-27 is not clear. Please rewrite.

Response: The paragraph has been rewritten in P6L6-10 as " *The monthly gridded HG-ET0 and daily pointed PM-ET0 were scaled up to annual value. At the annual scale, HG-ET0 was adjusted by multiplying the gridded coefficient (interpolated by the IDW method) as the ratio of the PM-ET0 to HG-ET0. 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 ET0 were obtained by weighting average of grid data within each basin.*"

Page 5. Line 2-3. What is the basis of this classifications? Include references.

Response: The classification and its basis have been added in P5L6-9 as "*In this study, AI of each catchment was calculated at mean annual scale for the period of 1961-2010 and the catchments were classified into humid, semi-humid, semi-arid and arid for AI ranging from 0.375~0.75, 0.75~2, 2~5 and 5~12, respectively (Ponce et al., 2000; Arora, 2002).*"

The trend analysis section is not clear. Need more explanation including the equations used.

Response: In the new manuscript, the trend analysis relative contents have been removed.

Line 12-13 is not clear. Rewrite. Line 10-19 please rewrite. Please rewrite the section 'water stress and shortage'.
Response: The "Water stress and shortage" section has been rewritten as "Water stress and availability". Please see section 2.2.3 for details.

Line 17 Populations or population
Response: Populations has been changed to population.

The definition of WW is confusing. Please explain the Qnat and Qobs more specifically.
Response: The "WW" has been changed to "WU" and the detailed explanation was added in section 2.2.3. Please see the section for detailed explanation.

Page 6. Is it population count data or population data?
Response: It is population count data here.

Overall, the methodology section is not clearly written and confusing for the readers. Please improve the section.
Response: We thoroughly rewrote the method section and the explanation was clearer in the revised manuscript.

Results
The first sentence is not clear. What does the term sustainability indicates. Why did the authors calculate the correlation between observed and natural runoff? Need a clear explanation for this section.
Response: The improper term of "sustainability" has been replaced by "reliability" and the correlation coefficient was no longer calculated in the new manuscript. Please see the first paragraph of section 3.1 and P5L13-15 for the detailed explanation.

Page 6. The line 15-18 is not written well. Please improve the writing quality.
Response: The paragraph has been rewritten as "*The reliability of the Fu-Budyko framework in reconstructing annual natural discharge is summarized in Figure 2. The model captures well the fluctuations of observed discharge in both time and space during the simulation period of 1971-2010 in humid and semi-humid catchments, with small gaps between the observed and natural discharge (Fig. 2). Increasing gaps between the observed and natural discharge, however, are observed in semi-arid and arid basins, especially the Hai, Hei, Shiyang and Tarim River Basins. These gaps are regarded as water use from anthropologic activities.*"

Page 7. Line 18 shows that the authors selected only 9 large river basins for analysis. Please explain the reasons.
Response: The explanation for the selection of 9 river basins was added in P7L4-9 as "*It is noted that only nine large basins were selected to analyze past changes in surface water scarcity in all three reaches (upper, middle and lower) because runoff*

data were not available in the downstream regions of Liao, Huai and Qiantang River Basins. For example, hydrological data at outlet station in Liao River Basin is available in 1984-2010; there were no hydrological data at outlet station in Huai River Basin; streamflow data were only available in tributary stations in Qiantang River Basin. For the above-mentioned three basins, we only used the available data from upper stream or tributaries for estimating WTA and FI."

The explanation for the questions "How did the imbalance in surface water scarcity develop between upstream and downstream regions? and What do we learn from China's water management strategies?" are not sufficient in the manuscript.

Response: The old objectives have been replaced by the new ones. Please see the last paragraph of Introduction section for the details. In the discussion section, we fully discussed the China's water policies since 1980s and linked the policies to the water scarcity. Please see the discussion section for the details.

Explain how the model framework is performing for different regions such as, snow regions in the manuscript.

Response: The suitability of Budyko framwork has been described in discussion section. Please see the section 4.1 for details.

The discussion on percentage decrease in surface water withdrawal is not clear. Please explain the possible reasons.

Response: The section 4.2 fully discussed the changes of China's water policies and their links to water scarcity. Please see the section 4.2 for the detailed explanation.

Page 9. Line 26-29 is not clear. The discussion section is not sufficient and well written.

Response: We have thoroughly rewritten the discussion section. The changes of water policies and their links to water scarcity has been fully discussed. Please see the discussion section for details.

Reconstructed natural runoff helps quantifying the relationship between upstream water use and downstream water scarcity in China's river basins

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Abstract. The increasing conflicts for water resources between upstream and downstream regions appeal for chronological insight across the world. While the negative consequence of downstream water scarcity has been widely analysed, the quantification of influence of upstream water use on downstream water scarcity received little attention. Here non-anthropologically intervened runoff (natural runoff) was first reconstructed in upstream, middle stream and downstream regions in China's 12 large basins for the period of 1970s to 2000s using the Fu-Budyko framework, and then compared with the observed data to obtain the developmental trajectories of water scarcity, including water stress (WTA) and per capita water availability (FI) in decadal scale. Furthermore, a contribution analysis was used to investigate the main drivers of water scarcity trajectories in those basins. The results show that China as a whole has experienced a water-scarce period with surface water use rapidly increasing from 161 billion m^3 (12% of natural runoff) in 1970s to 256 billion m^3 (18%) in 2000s, approximately 65% increase occurring in North China. In 2000s, the increase of upstream surface water scarcity and the decrease of downstream surface water scarcity occurred simultaneously for semi-arid and arid basins, which was caused by the increasing upstream water use and the consequent decreasing surface water availability in downstream regions. The influence of upstream surface water use on downstream water scarcity was less than 10% in both WTA and FI for humid and semi-humid basins during the study period, but with an average of 26% in WTA and 32% in FI for semi-arid and arid basins, and the ratio kept increase from 10% in 1970s to 37% in 2000s for WTA and from 22% in 1980s to 37% in 2000s for FI. The contribution analysis shows that the WTA contribution greatly increases in 2000s mainly in humid and semi-humid basins while decreases mainly in semi-arid and arid basins. The trajectories of China's water scarcity are closely related to the socioeconomic developments and water policy changes, which provides valuable lessons and experiences for global water resources management.

Keywords: Water scarcity, Upstream-downstream water nexus, Quantitative analysis, contribution analysis, China

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1 Introduction

Water scarcity is one of major challenges for hampering the United Nations sustainable development goals. This is particular important for downstream areas where local-generated water resources often cannot meet water demand, and water inflow from upstream becomes critical for relieving regional water scarcity. It was estimated that up to 1 billion people would have water scarcity problem if upstream water was not provided for downstream areas (Oki et al., 2001). Upstream drought and excessive water use would exacerbate downstream water scarcity, causing the consequent cooperative or conflictive events (Munia et al., 2016). These facts make it critical to understand the upstream-downstream water nexus under a changing climate and with intensified human activities.

There are lots of studies conducted to analyse the negative impacts of upstream water use on downstream environment (Poff et al., 2007; Arfanuzaman and Syed, 2018), biology (Brown and King, 2006; Petes et al., 2012), water quality (Dodds and Oakes, 2008), and socioeconomic issues (Jack, 2009; Nordblom et al., 2012; Al-Faraj and Tigkas, 2016). Despite the widespread recognition of the negative impacts, only limited quantitative researches have been performed to unravel the upstream-downstream interactions on water resources and water scarcity. Munia et al. (2016) simulated water use and water availability by PCR-GLOBWB (PCRaster Global Water Balance) model in global transboundary river basins in 2010, and found that 288 out of 298 middle-stream and downstream sub-basin areas experienced some change in stress level after accounting for upstream water use, affecting 0.29-1.13 billion people in transboundary river basins. Veldkamp et al. (2017) used global multi-model assessment to examine the impact of different human interventions (HI) on monthly water scarcity over the period 1971-2010. Their results showed that HI was the main drivers of water scarcity, aggravating water scarcity for 8.8% of the global population but alleviating it for another 8.3%. Positive impacts of HI mostly occur upstream, whereas HI aggravates water scarcity downstream. Duan et al. (2018) investigated the water availability and water stress over the conterminous United States (CONUS) from 1981 to 2010 using statistical water use data and simulated water supply by WaSSI (Water Supply Stress Index) model. They found that 12% of the CONUS land relied on upstream incoming flow for adequate water supply, while local water alone was sufficient to meet the demand in another 74% of the area. Munia et al. (2018) developed a framework to quantify the dependency of downstream water stress on upstream water supply and applied the framework to global transboundary river basins. Surprisingly, they found that the majority (1.15 billion) of those people (1.18 billion) currently suffer from water stress only because they excessively use water and the water use from upstream does not have impact on the downstream stress status. These studies preliminarily quantified the upstream-downstream relationship in water withdrawal and water scarcity, however, they either focused on only transboundary river basins or dependency analysis. There is a great need for further quantification of influence of upstream water use on downstream water scarcity in river basins as a whole.

As one of three countries with greatest water risk hotspots, China is facing serious water stress, especially in its northeastern regions (OECD, 2017). Meanwhile, the downstream environment has been severely deteriorated in some arid basins (Li et al., 2013; Lu et al., 2015; Zhao et al., 2016). Therefore, this study selected China to quantify the impact of upstream water

删除的内容: 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 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

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use on downstream water scarcity. Understanding the past trajectories of China's water scarcity in upstream and downstream catchments and quantifying the relationships between upstream water use and downstream water scarcity can help better define pathways to future sustainability, avoid further irreversible environmental degradation, and address future challenges of climate change and human interventions.

Water scarcity can be divided into two aspects: availability and stress (Kummu et al., 2016). Per capita water availability is a “demographic-driven scarcity” when a large population compete for limited water resources, leading to disputes (Falkenmark, 1997). Water stress is defined as water use to water availability and refers to a “demand-driven scarcity” which potentially occurs with low population and high water use (Kummu et al., 2010). The combined use of the two indicators can therefore provide a complete picture to describe water scarcity.

It is difficult to compile historical data on long-term water use and the related water scarcity in China due to lack of data accessibility 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 use. 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), and 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). In comparison, Budyko framework is widely used at an annual to decadal scale and in a large spatial scale (Zhang et al., 2001; Zhang et al., 2009;Zheng et al., 2009). Six Budyko framework models were tested here and eventually the one-parameter Fu-Budyko model was used to reconstruct natural runoff in the catchments because of its optimal performance (Fu, 1981). Fu-Budyko model 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, this study used this model to reconstruct decadal natural runoff for the period of 1961–2010 in upstream and downstream regions within 12 large basins in China, which cover over 50% of mainland China.

In this study, we aim to answer following three questions, and provide experiences and lessons for global water resources management. They are:

i. How surface water scarcity developed in upstream and downstream regions of the selected basins in China during the past decades;

ii. How to quantify the influence of upstream water use on downstream water scarcity; and

iii. What are the main drivers contributing China’s water scarcity change.

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2 Materials and Methods

2.1 Materials

2.1.1 Hydrological data

Since digital runoff data are hardly available in China, we obtained runoff data from the following two-sources: official sources in Hai and Shiyang River Basins and published literatures (Table 1). The reliability of the published annual runoff data was verified based on the following two criteria. First, 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%. Second, the published annual runoff data were further verified by comparing the trends in the processed data and in others published coincidentally, such as published work for Dongting lake by Yang et al. (2015), for Huangpu river by Shi and Wang (2015) and so on.

Insert Table 1 here

The annual runoff measured in a total of 132 gauge stations was verified. Based on the record length and spatial distribution of the data, 37 gauge stations that are representative for upper, middle and lower reaches were used in this analysis. While the length of data from 29 out of 37 basins spanned for an entire period of 1961–2010, data from other 8 basins 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 (Fig. 1).

Insert Figure 1 here

2.1.2 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.

2.1.3 Population count

The population count data from Gridded Population of the World (GPW) (http://sedac.ciesin.columbia.edu/data/collection/gpw-v4) was used to estimate the basin-scale population. Given the limitation of the data record 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.

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2.2 Methods

2.2.1 Fu-Budyko framework

The Fu-Budyko framework is expressed as:

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

where $F(\varphi)$ is evaporation ratio, φ is the Aridity index (AI), calculated from ratio of potential evapotranspiration (ET_0) to precipitation (P) on annual scale, the θ parameter is related to catchment characteristics with the range of 1~∞. In this study, AI of each catchment was calculated at mean annual scale for the period of 1961-2010 and the catchments were classified into humid, semi-humid, semi-arid and arid for AI ranging from 0.375~0.75, 0.75~2, 2~5 and 5~12, respectively (Ponce et al., 2000; Arora, 2002). Annual natural runoff was calculated in unit of mm/year as $P*(1-F(\varphi))$, and then changed into discharge in unit of 10^9 m^3/year by multiplying the catchment area.

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. Using the observed ET_0, P and observed discharge, the parameter θ was calculated using the least-square data fitting method for the period 1961–1970, then the fitted parameter was used to reconstruct decadal natural runoff for the period 1971–2010.

2.2.2 Estimation of ET_0 and P

Two equations – Hargreaves (HG) and Penman-Monteith (PM) – were used to estimate ET_0 (Allen et al., 1998). The HG-ET_0 was based on gridded dataset at monthly scale while PM-ET_0 was based on pointed dataset at daily scale. The PM equation ranked as the best equation for estimating ET_0 but the sparse distribution of climate stations limited its application in western China. The continuous spatial coverage of gridded dataset can provide full estimation of HG-ET_0 in western China. However, large discrepancies between HG-ET_0 and PM-ET_0 were found in different regions over the world in previous studies (Temesgen et al., 2005; Gavilan et al., 2006; Trajkovic, 2007; Bautista et al., 2009; Sivaprakasam et al., 2011; Berti et al., 2014). Thus more accurate ET_0 can be obtained by combining two estimations.

Hargreaves equation is described as (Allen et al., 1998):

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

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 the net radiation for the middle day of the ith-month. The standard values of empirical parameters are 0.0023, 17.8 and 0.5. The unit for both ET_0 and R_a is mm/day and then ET_0 was multiplied by the number of days in the ith-month to get monthly ET_0.

FAO56 Penman-Monteith equation is described as below (Allen et al., 1998):

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$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1+0.34u_2)} \qquad (3)$$

where R_n is the net radiation at the crop surface [MJ m^{-2} day^{-1}], G is the soil heat flux density [MJ m^{-2} day^{-1}], T is the mean daily air temperature at 2 m height [°C], u_2 is the wind speed at 2 m height [m s^{-1}], e_s is the saturated vapour pressure [kPa], e_a is the actual vapour pressure [kPa], e_s-e_a is the vapour pressure deficit [kPa], $\Delta$is the slope of vapour pressure-temperature curve [kPa °C^{-1}], γ is the psychrometric constant [kPa °C^{-1}]

The monthly gridded HG-ET_0 and daily pointed PM-ET_0 were scaled up to annual value. At the annual scale, HG-ET_0 was adjusted by multiplying the gridded coefficient (interpolated by the IDW method) as the ratio of the PM-ET_0 to HG-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 obtained by weighting average of grid data within each basin.

2.2.3 Water stress and availability

Two indicators – WTA (Water use To Availability) and FI (Falkenmark Index) – were used for the developmental analysis in surface water scarcity. WTA refers to water stress, which is moderate or high when over 0.2 or 0.4 of the available water is consumed, respectively (Vörösmarty et al., 2000). FI refers to per capita water availability which indicates moderate, high and extreme water stresses when it drops below 1,700, 1,000 and 500 m^3 cap^{-1} yr^{-1}, respectively (Falkenmark, 1997). The calculation of WTA was conducted in decadal scale for 1970s, 1980s, 1990s, and 2000s, respectively, while FI was calculated in decadal scale for 1980s, 1990s, and 2000s due to the limited access of population count data.

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

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

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

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

where WU and WA indicates surface water use and water availability in each decade from the 1970s to 2000s, Q_{nat} and Q_{obs} are natural and observed discharge in the same decade, Q_{in} is the incoming observed discharge from upper reach, WU_{local} and WU_{former} are the surface water use in middle/downstream regions and its former regions, respectively.

For Hai, Shiyang, Hei and Tarim River Basins, natural discharge at the middle and lower reaches was taken as the discharge of the upper reaches or the aggregate discharge from upstream tributaries. This is because most of the water was

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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:

$$Change = (V_{2000s} - V_{1960s}) / V_{1960s} \qquad (3)$$

where V_{2000s} and V_{1960s} represent P, ET_0 and runoff in 2000s and 1960s. respectively.
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subsequently consumed and therefore little runoff was generated in the downstream regions (Zhang et al., 2015; Zhang et al., 2016).

It is noted that only nine large basins were selected to analyze past changes in surface water scarcity in all three reaches (upper, middle and lower) because runoff data were not available in the downstream regions of Liao, Huai and Qiantang River Basins. For example, hydrological data at outlet station in Liao River Basin is available in 1984-2010; there were no hydrological data at outlet station in Huai River Basin; streamflow data were only available in tributary stations in Qiantang River Basin. For the above-mentioned three basins, we only used the available data from upper stream or tributaries for estimating WTA and FI.

2.2.4 Quantitative analysis

To quantify the influence of upstream water use on downstream water scarcity, an experiment was designed by involving in two scenarios: one with upstream water use (S1) and another without upstream water use (S2). In the first scenario (S1), the downstream water availability was the sum of local natural discharge and incoming observed flow; in the second scenario (S2), the downstream water availability was the aggregation of local natural discharge and natural discharge from the upper reaches.

2.2.5 WTA Contribution in water scarcity change

The contribution rate of WTA change in water scarcity change is estimated as follow:

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

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

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

where ΔWTA and ΔFI indicate the absolute difference in standardized (zscore) WTA and FI between two periods, respectively. zscore is calculated as $(X_i - \overline{X}) / std(X)$.

3 Results

3.1 Reliability of Fu-Budyko framework

The reliability of the Fu-Budyko framework in reconstructing annual natural discharge is summarized in Figure 2. The model captures well the fluctuations of observed discharge in both time and space during the simulation period of 1971-2010.

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in humid and semi-humid catchments, with small gaps between the observed and natural discharge (Fig. 2). Increasing gaps between the observed and natural discharge, however, are observed in semi-arid and arid basins, especially the Hai, Hei, Shiyang and Tarim River Basins. These gaps are regarded as water use from anthropologic activities.

Insert Figure 2 here

The magnitude of gaps between observed and natural discharge varies in different reaches and different periods as shown in Figure 3. For humid regions with large discharge, the natural discharge is quite consistent with the observed one, leading to small gaps during all the study periods in both upstream and downstream regions. However, situations are different for arid basins with small discharge, where the gap between observed and natural discharge in upstream and middle stream regions is relatively small from the beginning of the study period, and increases as time goes by. While in downstream regions, the gap is large from the beginning, and rapidly increases with time going by, especially in 1980s and 1990s.

Insert Figure 3 here

3.2 Water scarcity trajectories

3.2.1 National range overview

Generally, the surface water has become scarcer from 1970s to 2000s in China, with national WTA increasing from 0.12 to 0.18 and surface water use increasing from 161 billion m^3 in 1970s to 256 billion m^3 in 2000s (Fig. 4). The 65% increase of surface water use occurs in northern basins, including Songhua, Huai, Yellow, Liao, Hai, Hei, Shiyang and Tarim River Basins. Meanwhile national per capita water availability decreases from 1,534 to 1,265 m^3. The change magnitudes are different in different climate zones. For humid (Xi, Min and Qiantang River Basins), semi-humid (Yangtze, Songhua and Huai River Basins), semi-arid (Yellow, Liao and Hai River Basins) and arid basins (Hei, Shiyang and Tarim River Basins), WTAs have increased from 0.1, 0.1, 0.36 and 0.81 in 1970s to 0.14, 0.15, 0.7 and 0.95 in 2000s, respectively. Per capita water availability has decreased from 1,943 in 1980s to 1,680 in 2000s for humid basins, and from 239 m^3 to 226 m^3 for semi-arid basins, but it has increased from 1,740 in 1980s to 1,772 m^3 in 2000s for semi-humid basins and from 866 m^3 to 1,255 m^3 for arid basins.

Stress level changes in WTA and FI

According to FI, Xi River Basin changed from no water stress to moderate water stress and Tarim River Basin changed from high water stress to moderate water stress from 1980s to 2000s, while the stress level remained almost unchanged for all the other basins. According to WTA alone, water stress level changed from low stress to high stress for Songhua River Basin (even though no overall water stress), from low stress to moderate stress for Huai River Basin, from moderate stress to high stress for Yellow, Liao and Shiyang River Basins from 1970s to 2000s, while the rest remained at their stress levels.

Critical period

For most basins, 1980s is a critical period with rocketing WTA, for instance, 40% increase for Yangtze River Basin, 56% increase for Xi River Basin, 64% increase for Songhua River Basin, 52% increase for Yellow River Basin, 31% increase in Hai River Basin, 67% increase in Shiyang River Basin and 50% increase in national ranges. Meanwhile, per capita water

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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).

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availability changed little in the same period. The changes have probably linked to the water use increase because of China's reform and opening up policy at the end of 1970s.

Insert Figure 4 here

3.2.2 Upstream and downstream relationship

Meanwhile, different basins experienced different developmental trajectories in water scarcity for upstream, middle stream and downstream regions. From the FI perspective the Hei, Min, Songhua, Tarim and Yangtze Rivers and Pearl upstream are not stressed, however elevated water use could lead the Hei, Songhua, Tarim rivers into water scarcity from a non-scarcity status. Humid basins, for example the Min, Pearl and Yangtze Rivers, show the fluctuations in WTA for both upstream and downstream regions. Songhua River Basin shows continuous increase in WTA for both upstream and downstream regions, with dramatic increase in 2000s. For semi-arid and arid basins, the increase in WTA in upstream and middle stream regions and the decrease in WTA in downstream regions occurred simultaneously in 2000s (Hei River Basin shows the decrease in middle stream). The decrease in WTA for downstream regions is caused by the reduced incoming discharge from upstream regions, which forces the downstream water users to exploit groundwater as a supplement source for water supply (Water Resources Bulletin of Hai River Basin, 2015).

Insert Figure 5 here

The decreasing trend is dominant in per capita water availability in both upstream and downstream regions. Per capita water availability has largely decreased in downstream regions compared to its upstream counterparts for eastern basins, however, the reverse is observed in western basins. This is driven by the migration during the study period. Since the end of 1990s, the rapid urbanization has formed some metropolis in downstream regions in eastern China, such as Beijing in the downstream of Hai River Basin, Shanghai in the downstream of Yangtze River Basin, Guangzhou in the downstream of Pearl River Basin, leading to population concentration and per capita water availability decrease in those regions (Yang and Chen, 2014). However, for northwestern inland basins, big cities are usually located in middle reach oasis such as Zhangye in middle stream regions of Hei River Basin, Aksu in middle stream regions of Tarim River Basin. Meanwhile, the exacerbated degradation of the downstream ecological environment has driven downstream inhabitants migrating to middle stream. Thus per capita surface water availability generally decreases in middle stream region while it increases in downstream in northwestern river basins.

3.3 Quantifying upstream-downstream water nexus

Scenario analysis shows the quantitative influence of upstream water use on downstream water scarcity (Fig. 6). For humid and semi-humid river basins (except Songhua River Basin), the influence of upstream water use on downstream water scarcity is negligible during the study period, with less than 10% difference in both WTA and FI between two scenarios. The influence of upstream water use on downstream water scarcity rapidly enlarged in 2000s for Songhua River Basin, with the WTA difference between two scenarios increasing from 12% in 1990s to 27% in 2000s and the FI's impact doubled from around 700 m^3 cap^{-1} year^{-1} in 1990s to 1400 m^3 cap^{-1} year^{-1} in 2000s.

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Insert Figure 6 here

In contrast, upstream water use largely exacerbates downstream water scarcity in semi-arid and arid basins, and the influence of upstream water use on downstream water scarcity kept increasing from 1970s to 2000s. On average, the WTA impact extent for all the five semi-arid and arid basins increased from 10% in 1970s to 37% in 2000s and the FI impact extent increased from 22% in 1980s to 37% in 2000s. Among the five basins, Tarim River Basin is the largest human-intervened basin with the WTA increasing from 51% in 1970s to 86% in 2000s and FI increasing from 75% in 1980s to 86% in 2000s. Hai River Basin is the fastest scarcity-exacerbated basin with WTA's contribution increasing from 7% in 1970s to 87% in 2000s for WTA and FI increasing from 59% in 1980s to 87% in 2000s.

3.4 Driven factors of water scarcity trajectories

The combined analysis of WTA and FI (Fig. 7) shows that the Hai, Shiyang, Yellow River Basins, the upstream of Pearl and the middlestream of Hei River Basins are in the FI stress, while Hai, Yellow, Shiyang River Basins and the middlestream of Hei River Basins are in the WTA stress simultaneously. The other basins have plenty available water but the excessive water use makes the Tarim River Basin, the downstream of Hei River Basin and the upstream of Songhua River Basin experiencing WTA stress. The water scarcity trajectories of stressed basins show that the WTA stress is still increasing in downstream of Hei, Tarim and Hai river basins and middle stream of Yellow River Basin, while decreasing in downstream of Yellow River Basin and upstream of Songhua and Hei River Basins.

Insert Figure 7 here

The contribution analysis shows that the WTA's influence greatly increases in 2000s mainly in humid and semi-humid basins (Xi, Min, Songhua, and Tarim River Basins) while decreases mainly in semi-arid and arid basins (Yangtze, Yellow, Hai, Hei and Shiyang River Basins). The same change direction in WTA contribution in upstream, downstream and whole basins happens in Yangtze, Songhua and Shiyang River Basins. The upstream WTA change is the main driver of water scarcity trajectories for Min, Yellow and Hei River Basins, while the downstream WTA change is the main driver of water scarcity for Tarim River Basin. For Hai and Xi River Basins, the inconsistent change of WTA contribution in upstream/downstream and whole basin implies other water supply as the supplements of surface water resources.

Insert Figure 8 here

4 Discussions

4.1 Suitability of Fu-Budyko framework

The fitted parameter θ was greatly influenced by topography. Taking three basins with different climates – humid Yangtze River Basin, semi-arid Yellow River Basin, and arid Hei River Basin – as example, the values of θ are 1.7, 1.7 and 1.3 respectively for upstream regions while those are 2.0, 2.3 and 2.0 respectively for downstream regions. Given the fact that steeper terrains in upstream and flatter terrains in downstream, the values of θ are probably related to topography. The result

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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 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.

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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. 9

is consistent with that from Sun et al. (2007), who found that three factors – infiltration rate, water storage capacity and average slope – had impact on θ in Fu-Budyko framework. Other influential factors were also indicated in other studies, such as vegetation cover (Li et al., 2013), aridity index (Du et al., 2016), and soil characteristic (Gerrits et al., 2009).

Note that Fu-Budyko framework was suitable for annual or mean annual studies while the application in finer temporal scale was restrained. This has been proved by Zhang et al. (2008), who has tested the Budyko model over 265 Australian catchments at different time scales, including mean annual, annual, monthly and daily. They found at annual scale, the model works well for most of the catchments with 90% of them having values of the coefficient of efficiency greater than 0.5 and less than 3% of the catchments have bias values greater than 10%.

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What is more, previous studies proved that Budyko framework performed badly in arid and cold basins where snow and glacier melt contribute a lot to runoff. Here we found that Du et al. (2016) successfully applied a Budyko framework in Hei River Basin by dividing the basin into six sub-basins. They calibrated the model separately in different sub-basins and found the model performed quite well in the upper mountainous regions with little human interventions while the model was almost impossible to validate in downstream sub-basins. Thus we also divided the arid basins (including Hai, Shiyang, Hei and Tarim River Basins) into upper mountainous sub-basins and downstream sub-basins. The Fu-Budyko framework was directly applied in the mountainous sub-basins.

4.2 The link between China's water policies and water use changes

After the end of 1970s when China's reform and opening started, economic development was set as the primary goal, leading to rapid economic increase in the 1980s, with the GDP fourfold from 364.5 billion RMB in 1978 to 1699.2 billion RMB in 1989 (National Bureau of Statistics of China, 2017). Our study showed that with rapid economic increase, surface water use also rocketed from 79 billion m^3 in 1970s to 138 billion m^3 in 1980s for the 12 basins, with the increase in surface water use of 25.4 billion m^3 (63%) for humid basins, 18.6 billion m^3 (120%) for semi-arid basins, 9.8 billion m^3 (59%) for semi-humid basins and 5.1 billion m^3(90%) for arid basins. Meanwhile, the increase of surface water use simultaneously occurred in both upstream and downstream regions in this period, and the increase magnitude in surface water use was higher in upstream regions from humid to arid basins. In some cases, the expansion of arable land was the main driver for the increase of surface water use (Yang and Tian, 2009). While in another case, the share of agricultural water use decreased from 64% to 35% from 1985 to 2001 due to the lower priority, leading to industrial sector being the major contributor in water use increase (Lohmar et al., 2003). In summary, the water resources management was fragmented and sector-oriented due to overlapping responsibilities and lack of effective coordination, leading to rocketed increase in surface water use and conflicts between upstream and downstream and different sectors.

Aiming to address conflicts and shortfalls of the deficient and fragmented system that arose during the 1970s and early 1980s, the 1988 Water Law was implemented as the first fundamental legislation regulating water activities (Shen, 2014). By encouraging utilization of water resources rather than water saving, the law facilitated the booming of thousands of engineering projects but failed to effectively address water shortages and environmental degradation in China's water resources during the period of 1990s (Jiang, 2017). Our study showed that total surface water use continuously increased from 138 billion m^3 in 1980s to 178 billion m^3 in 1990s, with 23.8 billion m^3 increase (36%) from humid basins, 7.4 billion m^3 increase (28%) from semi-humid basins, 6.2 billion m^3 increase (18%) from semi-arid basins and 2.6 billion m^3 increase (25%) from arid basins. Meanwhile, the surface water use in upstream regions also increased, while that in downstream regions were divergent with upward trend in humid and semi-humid basins and downward trend in semi-arid and arid basins due to decrease in water availability. Consequently, 1990s was known as a period with the frequent outbreaks of water-related crisis, such as the disappeared inland Juyanhai Lake of Hei River Basin in 1992 (Jiang, 2017), the annual average of 107 dry days of the main channel of Yellow river in 1990s (CPSP, 2005), the rapid drop of groundwater table in North China Plain (Jia, 2011), the severe pollution in surface water and ground water in major rivers (Wu et al., 1999). To summarize, the 20-years rapid development and the neglect of environmental issues caused the extremely tense water-human relationship and threatened the human well-beings and regional sustainable development in 1990s.

When entering into 2000s, in view of the failure of the traditional principle of water use, how to manage water resources in a sustainable and efficient manner was of increasing significance (Shen, 2014; Jiang, 2017). Reflecting a significant thinking transition in water governance from construction and utilization (project oriented) to conservation and protection (resource oriented), Chinese government has initiated an ambitious water reform "Building a water-saving society", which aims to achieve "harmonious coexistence between man and nature" (Wang, 2006). Our study showed that surface water use slightly decreased from 178 billion m^3 in 1990s to 177.6 billion m^3 in 2000s, with 10.7 billion m^3 decrease in humid basins, 9.2 billion m^3 increase in semi-humid basins, 270 million m^3 increase in semi-arid basins and 870 million m^3 increase in arid basins. Noteworthy, the decrease in surface water use mainly occurred in downstream regions in most basins expect Songhua and Yangtze River Basins, while surface water use continuously increased in upstream regions at a slower rate. The theory of water rights and water markets was viewed as a fundamental policy regime in the water reform. For example, the water deal between Dongyang and Yiwu counties in Zhejiang Province in 2000, the water rights trading in Zhangye city in 2002 and water allocation in Yellow River Basin in 2000s (Jiang, 2017). Meanwhile, the statistic data starting in 2000 suggested the still increasing total water use and rising water stress between 2000 and 2010 across China (Wang et al., 2017; China Water Resources Bulletin, 2000-2010).

The story in post-2000s looks encouraging. The strictest water resources management strategy – three redlines – was implemented in 2012 and statistic data showed that it began to show slightly decrease in total water use over China and each basin (China Water Resources Bulletin, 2011-2016). Our future study will keep tracing the changes of water use and water availability and their links with water policy.

4.3 The lessons and experiences from China's water governance

The section 4.2 showed that the lagging of water governance behind water crisis. Hence we would like to raise a question: What is the most suitable water governance for each region?

There are two different policies adopted to relieve water scarcity across the vast water-scarce northern China: Water allocation accompanying with water right, and transboundary water transfer. The former policy is currently being applied in northwestern catchments including Shiyang, Hei and TarimRiver Basins. Meanwhile, the latter policy is mainly being applied in Hai River basin, which is the destination of famous "South-to-North Water Transfer" project. The two policies are being combined in Yellow River Basin to relieve its water scarcity.

This study suggested that appropriate/optimized water allocation should be adopted in regions with high WTA and FI, while physical water transfer should be applied in regions with high WTA and low FI. For the situation of high WTA and FI, the main problem is that the imbalanced increase of water use in up and middle reaches, leading to the consequent terminal lake vanishing, vegetation death, and desertification in downstream regions. Moreover, considering that the upstream complex terrains would increase the difficulties of construction of water projects, it is appropriate to adopt water allocation accompanied with water right and water price for solving environmental problems in lower reaches.

For the situation of high WTA and low FI, water allocation is not feasible here because water scarcity happens everywhere. If more surface water is forced to be released 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 their own 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 alternative water supply is a more feasible policy, including water recycling, transbasin water transfer and brackish water/sea water desalinization.

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

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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.

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5 Conclusions

The unconstrained water use in upstream of a river basin has led to negative impacts on economy, society, and ecosystems in downstream regions. However, the upstream-downstream water nexus remains still unclear in China due to lack of long-term water use data. By comparing observed runoff (1970s to 2000s) and reconstructed theoretical runoff, we analyse the trajectories of surface water use and per capita surface water availability in upstream, middle stream and downstream of China's major river basins. The scenario analysis further quantifies the impact of upstream water use on downstream water scarcity. Finally, the contribution analysis is used to identify the main drivers of water scarcity changes. Our results show

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that some river basins in China have experienced a water-scarce period from 1970s to 2000s and the rapid increase of water scarcity mainly occurs in northern basins. In 2000s, the increase of upstream surface water scarcity and the decrease of downstream surface water scarcity occurs simultaneously, which is probably caused by the increasing upstream water use and the consequent decrease of downstream water availability outpaced by the decrease of downstream surface water use. The influence of upstream water use on downstream water scarcity is less than 10% for humid and semi-humid basins, while it is quite large for semi-arid and arid basins with WTA-impact increase from 10% in 1970s to 37% in 2000s and FI-impact increase from 22% in 1980s to 37% in 2000s. The contribution analysis shows that the WTA contribution greatly increases in 2000s mainly in humid and semi-humid basins, but decreases mainly in semi-arid and arid basins. The trajectories of China’s water scarcity are closely related to the socioeconomic development and water policy, which thus provides valuable lessons and experiences for global water management.

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Acknowledgements

We sincerely thank Professor Keith Richards from Cambridge University for the constructive suggestion given on the study. This work was supported by the National Natural Science Foundation of China under Grant 41671021.

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Figure captions

Figure 1 The locations of the 12 basins and 37 hydrologic stations. Upstream, middle stream and Downstream were identified by red, green and yellow, respectively.

Figure 2 The comparison of observed and natural annual discharge at the outlet stations in 12 basins. Natural discharge in most of the basins was measured at the outlet stations, but that in four basins (Hai, Shiyang, Hei and Tarim) was the discharge in the upstream tributaries because of negligible runoff generated in the downstream regions.

Figure 3 The comparison of observed and natural annual discharge (log10 transformed) in upper, middle and lower reaches. Black triangles indicate 1960s, black dots indicate 1970s, dark grey dots indicate 1980s, light grey dots indicate 1990s and white dots indicate 2000s.

Figure 4 Changes of WTA and FI in 12 basins and China from 1970s/1980s to 2000s. YZ, XI, MIN, QT, SH, HUA, YL, LIA, HAI, HEI, SY, TA and NA represent Yangtze, Xi (Pearl), Min, Qiantang, Songhua, Huai, Yellow, Liao, Hai, Hei, Shiyang, Tarim River Basins and National range, respectively.

Figure 5 Trajectories of WTA and FI in upstream, middle stream and downstream regions for 9 large basins from 1970s/1980s to 2000s.

Figure 6 Quantitative impact of upstream water use on downstream surface water stress (a) and per capita surface water availability (b). S1 is a scenario that downstream WTA (FI) is contributed by upstream water use while S2 is a scenario that downstream WTA (FI) is not contributed by upstream water use. S1-S2 (S2-S1) indicates the upstream water use. YZ represents Yangtze River Basin, XI represents Pearl River Basin, MIN represents Min River Basin, SH represents Songhua River Basin, YL represents Yellow River Basin, HAI represents Hai River Basin, SY represents Shiyang River Basin, HEI represents Hei River Basin, and TR represents Tarim River Basin. Asteroid sign indicates that the values are enlarged by 100 times for Hai River Basin to make them visible for comparison purpose.

Figure 7 The combined analysis of WTA and FI showing the water scarcity trajectories in 9 river basins in the period of 1980s - 2000s.

YZ represents Yangtze River Basin, XI represents Pearl River Basin, MIN represents Min River Basin, SH represents Songhua River Basin, YL represents Yellow River Basin, HAI represents Hai River Basin, SY represents Shiyang River Basin, HEI represents Hei River Basin, and TR represents Tarim River Basin.

Figure 8 The WTA contribution in water scarcity trajectories for whole basin, upstream and downstream between different periods.

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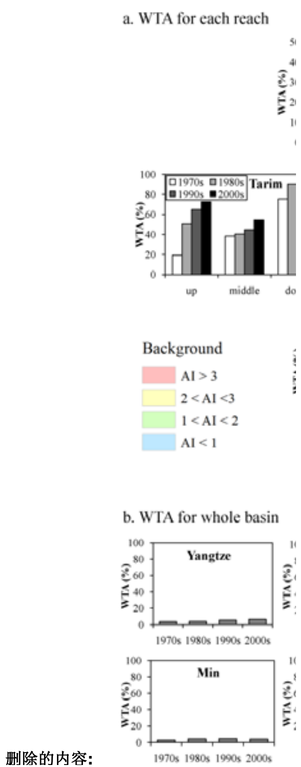

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Table1: Sources of hydrological data from office and published literatures.

Basin	Hydrologic station (lat/lon)	Reference
Yangtze	Yichang^{u}(30.75/111.3), Hankou^{m}(30.58/114.28), Datong^{d}(30.77/117.6)	Changjiang Sediment Bulletin (2010); Chinese river sediment Bulletin (2002-2010)
Yellow	Toudaoguai^{u}(39.25/106.78),Huayuankou^{m}(34.9/113.66), Lijin^{d}(37.5/118.25)	Yellow River Sediment Bulletin (2000-2010); Chinese river sediment Bulletin (2002-2010)
Hai	Zhangjiafen^{u}(40.62/116.78), Xiangshuibao^{u}(40.51/115.18), Xiahui^{u}(40.62/117.17), shixiali^{u}(40.25/114.73)	Official source, Chinese river sediment Bulletin (2002-2010)
	Daomaguan^{u}(39.08/114.63), Xiaojue^{u}(38.38/113.72), Pingshan^{u}(38.25/114.17)	Official source
	Haihezha^{d}(39.02/117.73)	Chinese river sediment Bulletin (2002-2010); Dai et al., 2007a; Wei et al., 2016
Hei	Yingluoxia^{u}(38.8/100.17), Zhengyixia^{m}(39.82/99.45)	Chinese river sediment Bulletin (2002-2010); Niu et al., 2011
	Langxinshan^{d}(41.03/100.32)	Niu et al., 2011; Ren et al., 2015
Shiyang	Caiqi^{u}(38.21/102.75), Hongyashan^{d}(38.41/102.9)	Official source
Tarim	Alar^{u}(40.5/80.99)	Chinese river sediment Bulletin (2002-2010); Zhao et al., 2010; Yang and He, 2003
	Yingbazha^{m}(41.17/84.22), Qiala^{d}(40.97/86.7)	Zhao et al., 2010; Yang and He, 2003
Huai	Bengbu(32.74/117.23)	Chinese river sediment Bulletin (2002-2010); Pan et al., 2013; Dai et al., 2007a
Pearl	Liuzhou^{u}(24.53/109.11), Qianjiang^{u}(23.68/109.1), Nanning^{u}(22.82/108.19), Gaoyao^{d}(23.26/112.22)	Chinese river sediment Bulletin (2002-2010); Dai et al., 2007a,b
Min	Qilijie^{u}(27.01/118.29), Yangkou^{u}(26.77/117.97), Shaxian^{u}(26.4/117.83), Zhuqi^{d}(26.12/119.15)	Chinese river sediment Bulletin (2002-2010); Dai et al., 2007a
Qiantang	Huashan(29.62/120.83), Zhuji(29.72/120.23), Quxian(28.98/118.87)	Chinese river sediment Bulletin (2002-2010)
Liao	Tieling(42.14/122.48)	Chinese river sediment Bulletin (2002-2010); Zhang et al., 2014; Dai et al., 2007a
Songhua	Harbin^{u}(45.8/126.67), Jiamusi^{d}(46.83/130.13)	Chinese river sediment Bulletin (2002-2010); Tu et al., 2012; Song et al., 2009

Superscript: ^{u} represents upstream gages, ^{m} represents middle stream gages, and ^{l} represents downstream gages.

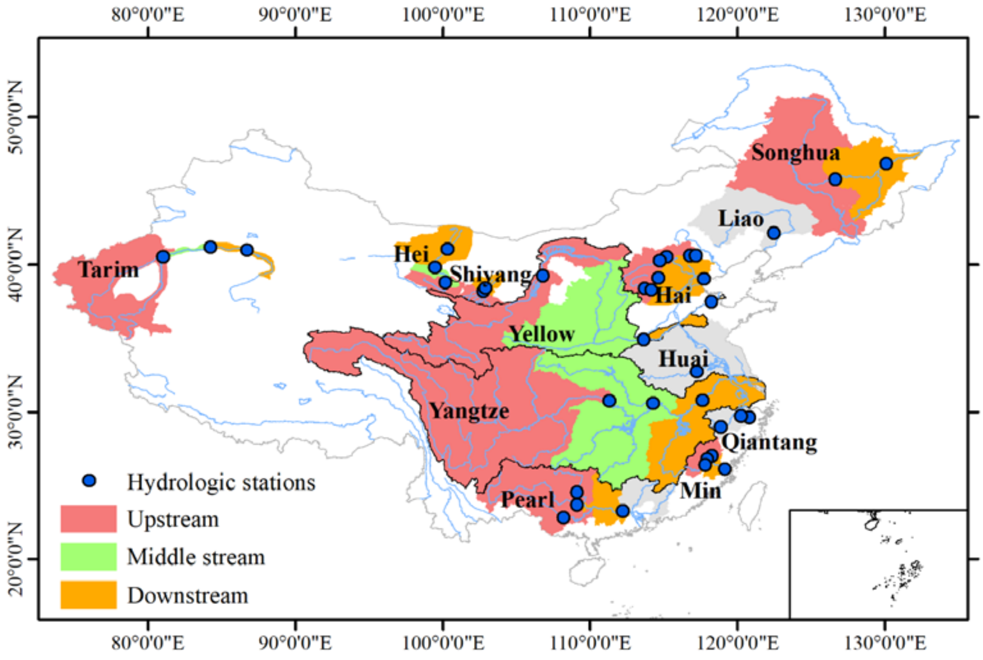

Figure 1: The locations of the 12 basins and 37 hydrologic stations. Upstream, middle stream and Downstream were identified by red, green and yellow, respectively.

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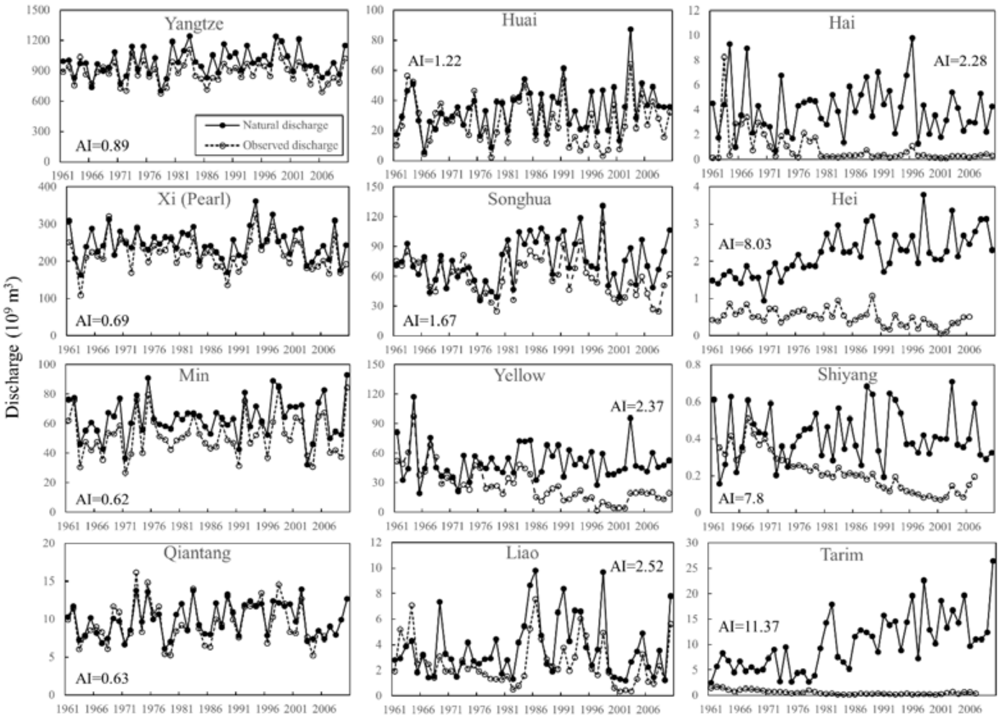

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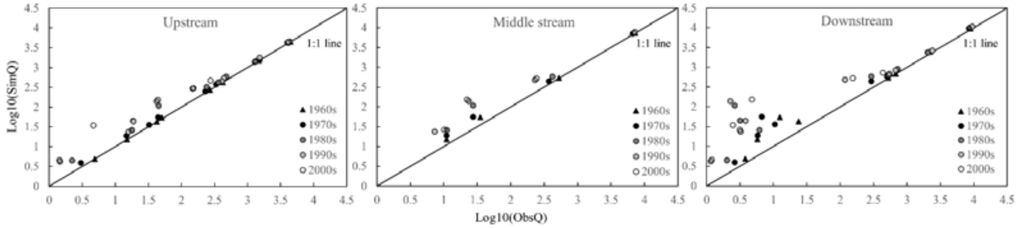

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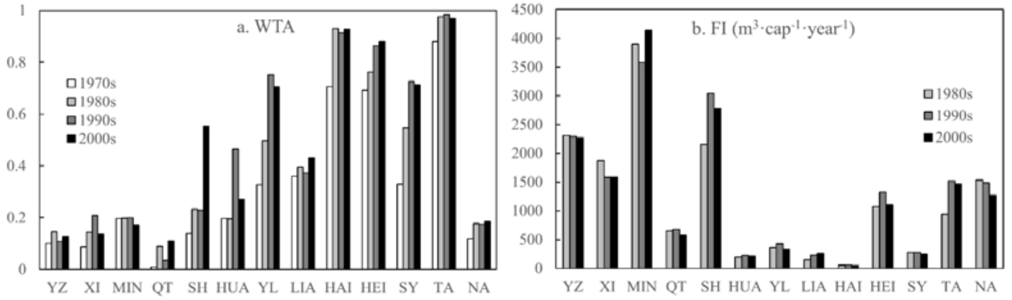

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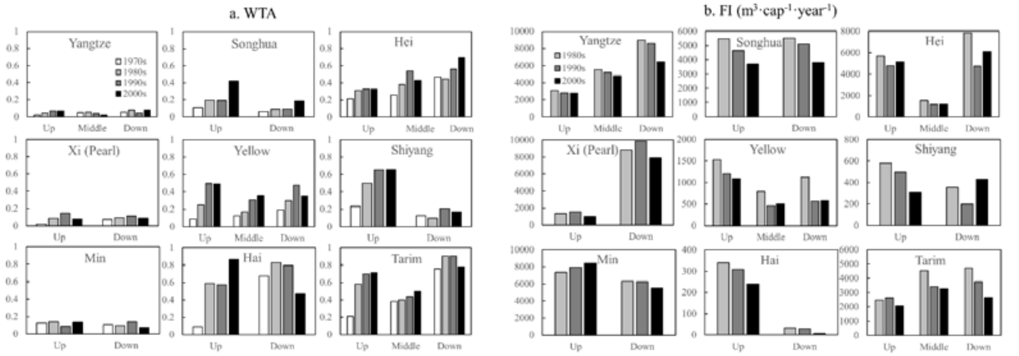

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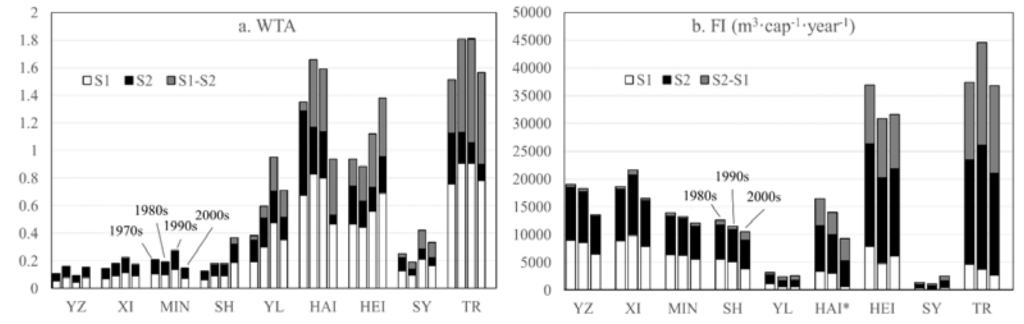

Figure 6: Quantitative impact of upstream water use on downstream **surface water** stress (a) and per capita surface water availability (b). S1 is a scenario that downstream WTA (FI) is contributed by upstream water use while S2 is a scenario that downstream WTA (FI) is not contributed by upstream water use. S1-S2 (S2-S1) indicates the upstream water use. YZ represents Yangtze River Basin, XI represents Pearl River Basin, MIN represents Min River Basin, SH represents Songhua River Basin, YL represents Yellow River Basin, HAI represents Hai River Basin, SY represents Shiyang River Basin, HEI represents Hei River Basin, and TR represents Tarim River Basin. Asteroid sign indicates that the values are enlarged by 100 times for Hai River Basin to make them visible for comparison purpose.

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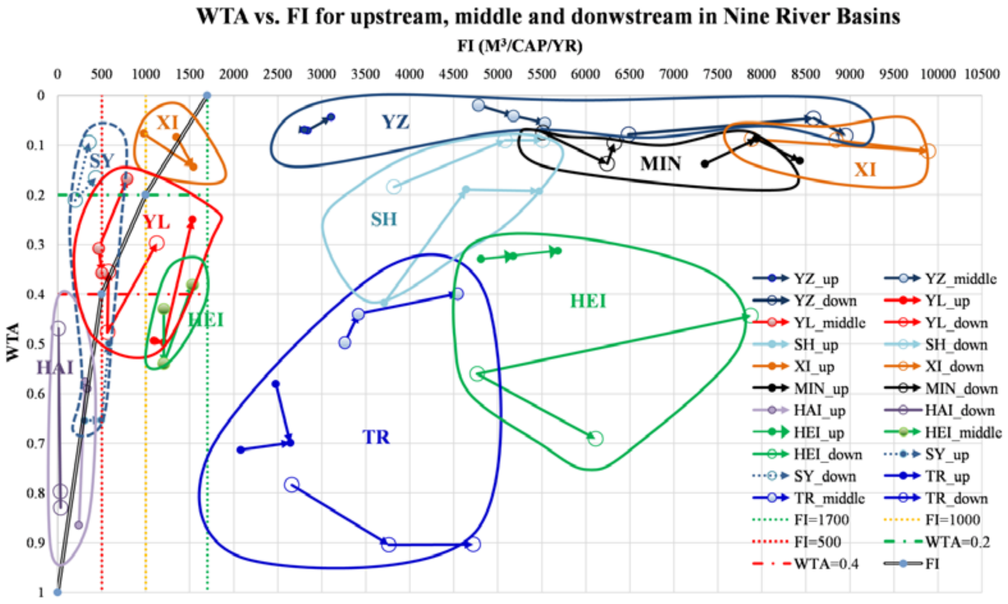

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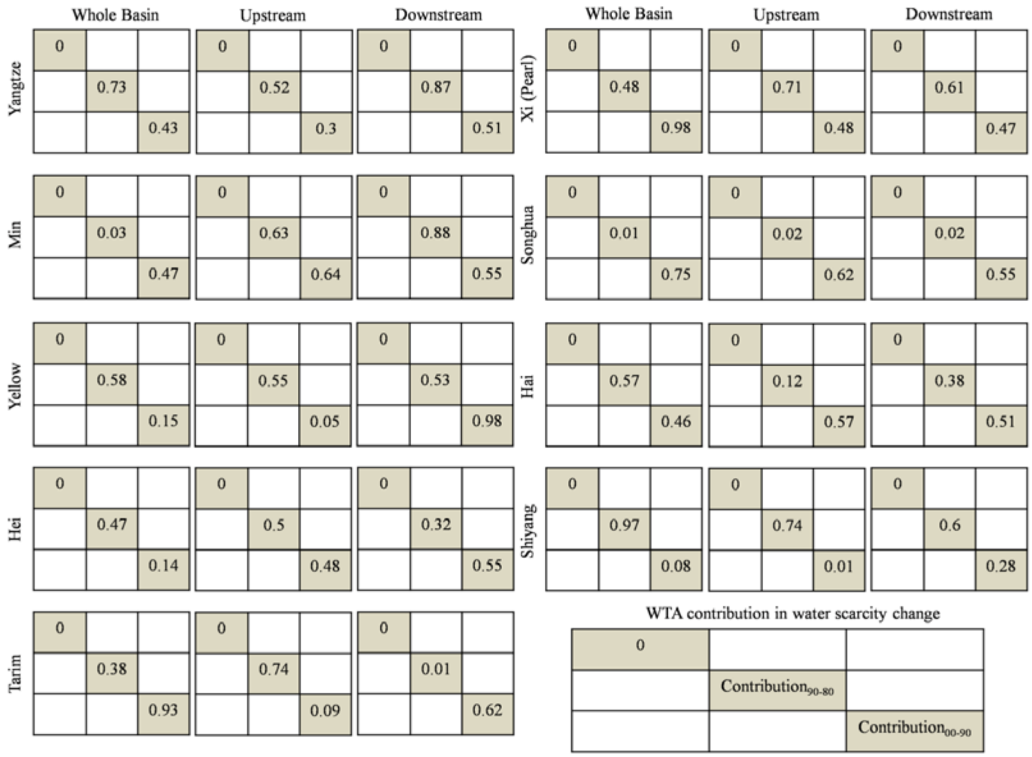

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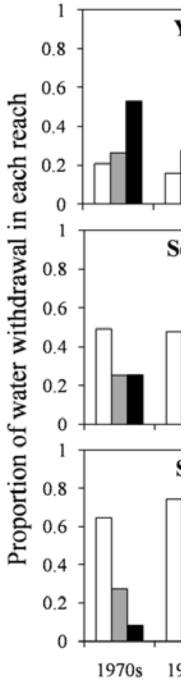

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Figure 6: Proportion of water withdrawal of upstream, midstream and downstream in total water withdrawal during different periods. .

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