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Key Points:

- Concurrent drought in the water source and destination can threaten a water diversion project
- The water source and destination have experienced 5 years of concurrent drought since 1997
- The success of the project faces challenge if the frequently concurrent drought events continue

Supporting Information:

- Supporting Information S1

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Investigation of the probability of concurrent drought events between the water source and destination regions of China's water diversion project

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Abstract In this study, we investigate the concurrent drought probability between the water source and destination regions of the central route of China's South to North Water Diversion Project. We find that both regions have been drying from 1960 to 2013. The estimated return period of concurrent drought events in both regions is 11 years. However, since 1997, these regions have experienced 5 years of simultaneous drought. The projection results of global climate models show that the probability of concurrent drought events is highly likely to increase during 2020 to 2050. The increasing concurrent drought events will challenge the success of the water diversion project, which is a strategic attempt to resolve the water crisis of North China Plain. The data suggest great urgency in preparing adaptive measures to ensure the long-term sustainable operation of the water diversion project.

1. Introduction

A water diversion project is typically constructed to ease water shortage in a region. For example, California's water diversion system consists of several federal, state, and local water diversion projects that have been diverting water from Northern California and the Colorado River to the Central Valley and Southern California since the 1970s and has successfully alleviated water shortage issues while promoting economic development in the Central Valley and Southern California [*Hanak et al.*, 2011]. In China, four fifths of water resources are in the south, while half the people and two thirds of the farmland are in the north. Water scarcity in Northern China has been increasingly severe with rapid economic development [*Liu et al.*, 2001]. The South to North Water Diversion Project (SNWDP) is designed by the Chinese government to funnel 44.8 km^3 of water per year from the Yangtze River to Northern China via western, central, and eastern routes, at a total cost of $62 billion and has resulted in the displacement of about 345,000 people [*Stone and Jia*, 2006]. The central route of SNWDP is designed to divert 13 km^3 of water each year a total distance of 1400 km from the Danjiangkou Reservoir on the Hanjiang River, a tributary of the Yangtze River to the North China Plain (NCP), which includes two mega cities—Beijing and Tianjin [*Liu and Zheng*, 2002]. The NCP, with a population of about 350 million, is called the "Granary of China," providing about 40% and 25% of China's wheat and corn production, respectively [*Liu et al.*, 2001]. The central route of SNWDP has been diverting water since 12 December 2014.

Associated with global warming, the occurrence and duration of drought events show increasing tendencies worldwide [*Dai*, 2013]. Such droughts can reduce the regional available water and place challenges on local water resource management [e.g., *Ciais et al.*, 2005; *Milly et al.*, 2008; *Long et al.*, 2013]. In the southwestern United States, prolonged drought since 2012 has greatly influenced California's water diversion system, whose water sources include the Lake Mead Reservoir, the largest reservoir of United States, as well as Shasta Lake, and Oroville Lake, the two largest reservoirs in California. These historically vast resources are now experiencing low storage levels and do not have enough water to divert [e.g., *Castle et al.*, 2014; *Yang et al.*, 2014; *Danielle*, 2015; *Diffenbaugh et al.*, 2015; *Ficklin et al.*, 2015]. Due to the monsoon climate interactions with complicated geographical landscapes, severe drought of high frequency is one of the most devastating natural disasters in China. The drought damaged area has greatly increased in China during the past 50 years [*Xu et al.*, 2015]. Droughts cause Chinese yuan 15–20 billion of economic losses and affect 200–300 million people on average every year in China [*Zhang et al.*, 2008]. In 2011, extreme drought hit the Hanjiang River, and the water level of the Danjiangkou Reservoir dropped below its dead water level

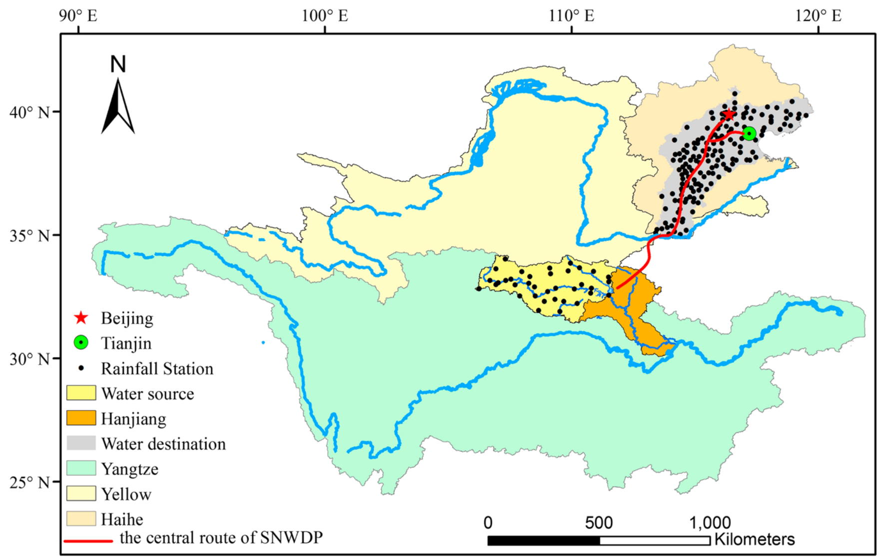

Figure 1. Map of the study area.

on 14 May 2011. This state lasted for 83 days, which brought significant restrictions to irrigation and drinking water allocations in the lower Hanjiang River (China Meteorological Administration, 2011, http://2011.cma.gov.cn/en/speeial/20110218/xunqi_en/xunqiphoto/201105/t20110518_93938.html.) The central route of China's SNWDP, which diverts water from the Danjiangkou Reservoir to the NCP and is in its first year of operation, may also face a dilemma similar to California's water diversion system due to the severe drought which started in 2012. Therefore, estimating the probability of concurrent drought events between the water source and destination regions of SNWDP's central route is crucial for understanding the future operation and sustainability of the diversion project. In this study, the changes in drought events are first analyzed for the water source and destination regions of SNWDP's central route. Then, the probability of concurrent drought is estimated, and the implications of concurrent drought for the water diversion project are investigated. Finally, the relationship between concurrent drought and El Niño–Southern Oscillation (ENSO) is discussed. These results provide a guide for sustainably operating the water diversion project.

2. Study Area and Methodology

The central route of China's SNWDP plans to divert 13 km^3 of water per year from the Danjiangkou Reservoir (water source region) on the Hanjiang River, a tributary of the Yangtze River, to Beijing, Tianjin, Hebei, and Henan provinces, which constitute a majority of the NCP (water destination region) (Figure 1). The Danjiangkou Reservoir, with a drainage area of 96,000 km^2, is located in the eastern monsoon climate zone of China and has dramatic fluctuations in climate and water resources. The annual precipitation varies from 700 to 1100 mm, with 70–80% of the precipitation occurring in the wet months from May to October, and the average mean temperature is 15–17°C. The NCP is also located in the eastern monsoon climate zone of China. Annual precipitation is 500 to 600 mm with about 75% of the precipitation occurring from July to September, and the mean temperature is 9–11°C. Groundwater has been intensively used for irrigation due to water scarcity in the NCP, and the NCP aquifer system has become one of the most overexploited in the world [*Wada et al.*, 2010].

The observed monthly precipitation data from 1960 to 2013 was obtained from the China Meteorological Administration (http://cdc.cma.gov.cn). The Oceanic Niño Index from 1960 to 2013 used to categorize ENSO events was obtained from National Oceanic and Atmospheric Administration (http://www.cpc.ncep.noaa.gov/products). The observed streamflow data from 1960 to 2013 for the Danjiangkou Reservoir were provided by the Ministry of Water Resources of China. We chose five global climate models (GCMs), namely, CanESM2, CSIRO-MK3.6.0, GFDL-ESM2G, HadCM3, and MRI-CGCM3, from the Coupled Model Intercomparison Project phase 5 (http://cmip-pcmdi.llnl.gov/cmip5/) based on their good performance in historical precipitation simulation for China [e.g., *Xu et al.*, 2009]. The high (RCP8.5) and intermediate (RCP4.5) ranges of Representative Concentration Pathways were selected for future scenario analysis.

Droughts are generally classified into three physical types: meteorological, agricultural, and hydrological drought [*Keyantash and Dracup*, 2002], and this study focuses on meteorological drought. Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) are commonly used as statistical indicators to describe meteorological drought events [e.g., *McKee et al*., 1993; *Vicente-Serrano et al*., 2010]. Each of these two indices has their advantages and disadvantages. *Xu et al*. [2015] compared SPI and SPEI in China and concluded that the two indices have similar performance in the relatively humid regions, while SPI has better performance in the relatively arid regions. SPI was chosen to describe meteorological drought conditions in this study, since the NCP is located in the relatively arid region. SPI has different time scales, such as 3 month, 6 month, and 12 month scale. This study focuses on the 12 month SPI because the Danjiangkou Reservoir has the adjustment capability to cope with seasonal dry condition. The detailed calculation procedures of SPI can be found in *McKee et al*. [1993]. Figure S1a in the supporting information shows that SPI has a significant correlation ($R = 0.69$) with annual streamflow anomaly in the study area, indicating that SPI is a good indicator of drought for this study. Table S1 in the supporting information shows drought classification according to the SPI. The SPI temporal trend was analyzed using the modified Mann-Kendall trend test method [*Hamed and Rao*, 1998], which is commonly used for trend detection of SPI [e.g., *Andreadis and Lettenmaier*, 2006; *Vu et al*., 2015].

The water source and destination regions are both located in the eastern monsoon climate zone of China with a distance of about 600 to 1400 km. Figure S1b shows that the correlation coefficient of SPI is 0.37 between the two regions from 1960 to 2013. Drought events in the two regions are not totally independent. Therefore, the probability of concurrent drought events cannot be obtained by simply multiplying the individual drought probabilities. Copula function [*Nelsen*, 1999] is able to calculate the joint probability of dependent events and was used to estimate the probability of concurrent drought events in this study. Since annual SPI is discrete, the distribution of annual SPI was first estimated by Gamma distribution, Pearson type III distribution and generalized extreme value distribution, which are commonly used to fit the distribution of drought and flood events [e.g., *Chang et al*., 2012; *Lott et al*., 2013]. Parameters for these three distributions were estimated using the maximum likelihood estimation method. The Kolmogorov-Smirnov method was used to assess the goodness-of-fit of each distribution and to select the appropriate distribution for the SPI series in each region [*Wilks*, 1999]. The selection process and results are summarized in Text S2 and Table S2 in the supporting information. Pearson type III distribution performed the best and was therefore selected as the appropriate distribution for SPI in this study.

The two dependent variables X and Y (here X and Y refer to SPI in water source and water destination, respectively) with distributions $F_X(x)$ and $F_Y(y)$ and the joint distribution $F(x,y)$ can be described according to the following copula function:

$$F(x, y) = \Pr(X \le x, Y \le y) = C(F_X(x), F_Y(x)) \tag{1}$$

where function C is a copula function representing the bivariate dependence structure of variables X and Y. Considering an event that has a $1/T$ chance of occurrence in any given year represents that the event has a T-year return period [*Cooley et al*., 2007]; the joint return period of variables X and Y can be described as

$$T(X \le x, Y \le y) = \frac{1}{\Pr(X \le x, Y \le y)} = \frac{1}{C(F_X(x), F_Y(x))} \tag{2}$$

The copula functions have many families [*Nelsen*, 1999]; eight types of copula were used in this study to estimate the joint probability distribution of the SPI series in the two regions. The Bayesian model selection method, as described by *Huard et al*. [2006], was used to select the appropriate copula. The Clayton Copula was selected as the most appropriate copula in this study (Table S3 in the supporting information). The selection process and results are summarized in supporting information Text S3 and Table S3.

3. Results and Discussion

3.1. Changes in SPI in the Water Source and Destination Regions

Figures 2a and 2b show the variations of annual SPI in the water source and destination regions during 1960–2013. SPI in the water source and destination regions decreased significantly by $P < 0.1$ and $P < 0.05$, respectively, based on the modified Mann-Kendall trend test, indicating that the dryness of both of the regions have been increasing from 1960 to 2013. Figure 3 shows the SPI probability distributions

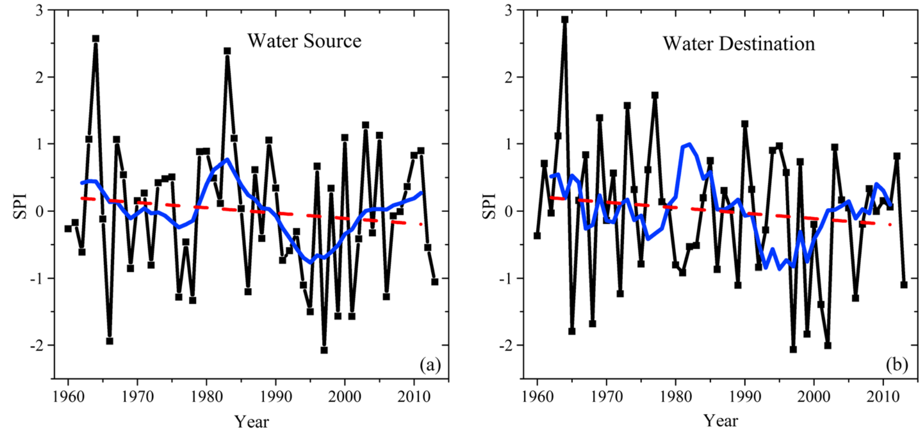

Figure 2. The variation of SPI in the (a) water source and (b) destination regions from 1960 to 2013. The blue line shows the 5 year moving average, and the red dotted lines represent the trend.

fitted by Pearson-III distribution function in the water source and destination regions. The probabilities of drought events (SPI ≤ −1.0) in any given year are 19.8% (a return period of 5.1 years) in the water source region and 19.2% (a return period of 5.2 years) in the water destination region. In the observed record from 1960 to 2013, drought events (SPI ≤ −1.0) occurred 11 and 10 times in the water source and destination regions, respectively (Table 1). In the water source region, there are 5 years with an annual SPI between −1.0 and −1.5 (moderate drought), 5 years with an annual SPI between −1.5 and −2.0 (severe drought), and 1 year (1997) with an annual SPI less than −2.0 (extreme drought). In the water destination region, the years of moderate, severe, and extreme drought events are 5, 3, and 2, respectively, with the driest year also observed in 1997.

3.2. The Probability of Concurrent Drought Events Between the Water Source and Destination Regions

Figure 4 shows the joint probability distribution of the SPI in the water source and destination regions from 1960 to 2013 as estimated using the Clayton Copula. The estimated probability of a concurrent drought event (SPI ≤ −1.0) in the two regions in any given year is 9.1% (a return period of 11.0 years). The estimated probabilities of concurrent severe (SPI ≤ −1.5) and extreme (SPI ≤ −2.0) drought in any given year are 3.6% (a return period of 27.8 years) and 1.1% (a return period of 90.9 years), respectively. In the observed record from 1960 to 2013, there are 5 years when drought events (SPI ≤ −1.0) simultaneously occurred in the water source and destination regions: 1997, 1999, 2001, 2006, and 2013 (Table 1 and Figure 4). Notably, all 5 years of concurrent drought events occurred in or after 1997. In 1997, both the water source and destination regions experienced the most severe drought during 1960 to 2013 (SPI = −2.08 and −2.07, respectively).

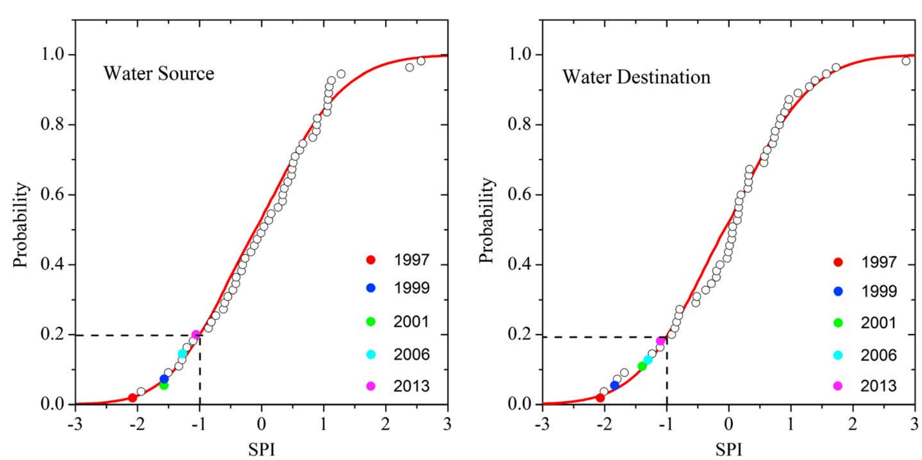

Figure 3. The probability distribution of SPI in the water source and destination regions fitted by Pearson type III distribution. The intersection of the black dotted lines indicates the upper values of drought events (SPI ≤ −1.0).

Table 1. The Observed Drought Events From 1960 to 2013 in the Water Source and Destination Region[a]

Drought Degree	Year	SPI_WS	Year	SPI_WD
Extreme drought (SPI ≤ −2.0)	*1997*[b,c]	−2.08[e]	*1997*[b]	−2.07
			2002	−2.01
Severe drought (−2.0 < SPI ≤ −1.5)	1966	−1.94	**1999**[b]	−1.84
	2001[b]	−1.58	*1965*	−1.80
	1999[b,d]	−1.57	*1968*	−1.68
	1995	−1.51		
Moderate drought (−1.5 < SPI ≤ −1.0)	1978	−1.33	2001[b]	−1.39
	1976	−1.28	2006[b]	−1.30
	2006[b]	−1.28	*1972*	−1.23
	1986	−1.20	1989	−1.11
	1994	−1.10	2013[b]	−1.10
	2013[b]	−1.06		

[a]Note that SPI_WS and SPI_WD indicate the SPI in the water source and destination region, respectively.
[b]Concurrent drought events.
[c]The years in italics indicate El Niño years.
[d]The years in boldface indicate La Niña years.
[e]The years underlined indicate neutral years.

The estimated probability of the 1997 concurrent drought events is 0.94% (Figure 4), and the return period is 106.4 years. Table 2 shows the estimated probability of concurrent drought events (SPI ≤ −1.0) in the two regions in any given year during 2020 to 2050 by the selected GCMs. Under the RCP4.5 emission scenario, all the five GCMs show that the probability of concurrent drought events will increase compared with that during 1960 to 2013. Under the RCP8.5 emission scenario, three of the five GCMs show that the probability will increase. Therefore, the probability of concurrent drought events is highly likely to increase during 2020 to 2050 based on the projection results of GCMs.

3.3. The Implications for the Water Diversion Project

The NCP has been suffering from severe groundwater depletion because of increasing amount of water demand in recent years [*Wada et al.*, 2010]. Beijing's groundwater table has experienced a decrease of 0.90 m each year from 1999 to 2009 [*Yang et al.*, 2010]. The SNWDP's central route is considered as a strategic and ambitious attempt to resolve water scarcity problem in the NCP. However, the introduction of the SNWDP's central route has created widespread controversy. Opponents of the project are mainly concerned about the environment influence on the lower Hanjiang River, into which the Danjiangkou Reservoir currently flows [*Stone and Jia*, 2006]. The lower Hanjiang River is already polluted by industrial wastes, and algal blooms have occurred frequently since the early 1990s. The Danjiangkou Reservoir is the only water source available for flushing algal blooms in the lower Hanjiang River [*Yang et al.*, 2012]. The 13 km^3 of diversion water was chosen based on the annual average streamflow into the Danjiangkou Reservoir from 1954 to 1998, which was 38.9 km^3, and the plan to divert 33% of that streamflow into the Reservoir to the NCP.

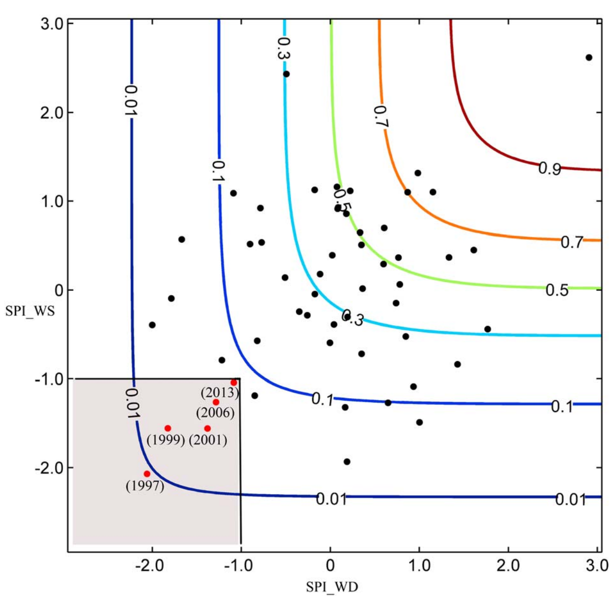

Figure 4. Level curve (isoline) of the joint probability distribution of the SPI in the water source and destination regions from 1960 to 2013. The shaded area indicates where drought events (SPI ≤ −1.0) occurred simultaneously in the water source and destination regions.

Table 2. The Estimated Probability (Unit: %) of Concurrent Drought in the Water Source and Destination Regions in any Given Year During 2020 to 2050 by the Selected GCMs[a]

GCMs	CanESM2	CSIRO-MK3.6.0	GFDL-ESM2G	HadCM3	MRI-CGCM3
RCP4.5	14.7	11.2	17.6	12.1	13.2
RCP8.5	11.3	13.3	23.3	8.3	6.7

[a]Note that RCP4.5 and RCP8.5 indicate high and intermediate ranges of Representative Concentration Pathways, respectively.

Opponents of the project argue that the 33% level of water diversion will aggravate the environment problems and probably lead to an environmental disaster in the lower Hanjiang River [*Stone and Jia*, 2006]. In the concurrent drought years of 1997, 1999, 2001, 2006, and 2013, the annual streamflow into the Danjiangkou Reservoir was 17.2, 17.1, 21.3, 27.1, and 29.1 km^3, respectively, and the amount of 13 km^3 of diversion water would have accounted for 75.6, 76.0, 61.0, 48.0, and 44.7% of the actual streamflow into the Danjiangkou Reservoir in those years, respectively. Considering the environmental and irrigation water needs in the lower Hanjang River, there would not have been enough water to divert from the Danjiangkou reservoir to the NCP in those past concurrent drought years; and there will not be enough in the concurrent drought years expected in the future.

The recent concurrent severe drought of California's water diversion system is a significant warning to the central route of China's SNWDP. Since a prolonged drought in California started in 2012 [*AghaKouchak et al*., 2014], the diversion water from the Lake Mead Reservoir, the largest reservoir of United States and an important water source for California through the Colorado aqueduct, seems to be increasingly important for California. However, water levels of the Lake Mead Reservoir has dropped to record low in 2014 as the Colorado River basin has also been suffering a severe drought during the past years, significantly impacting California's water plan [*Danielle*, 2015]. In the mean time, many reservoirs in Northern and Central California, including Folsom Lake, Shasta Lake, and Oroville Lake, also reached low storage levels at the beginning of 2014 [*Mann and Gleick*, 2015]. Subsequently, on 31 January 2014, California's government announced that farmers will not receive any water allocation from the State Water Project. If a similar concurrent severe drought condition occurs in the central route of China's SNWDP in the future, the responses of government and famers could be different. Famers will keep withdrawing the depleted groundwater to sustain the grain production of the NCP [*Qiu*, 2010], because the NCP is a significant contributor to the food security of China, termed as the Granary of China [*Liu et al*., 2001]. This response will jeopardize the main goal of the central route of China's SNWDP, which is to stop the decline of groundwater table and resolve the water crisis in the NCP [*Stone and Jia*, 2006].

In the last century, water management has been developed under the stationary assumption that natural systems fluctuate within an unchanging envelope of variability and past hydrological experiences provide a good guide to future conditions [*Milly et al*., 2008]. However, significant changes in water cycle associated with global warming challenge the traditional assumption and can alter the reliability [e.g., *Castle et al*., 2014; *Schindler and Hilborn*, 2015]. The impacts of droughts on California and China's water diversion projects further indicate that adaptive measures need to be prepared for regional water management under an uncertain and changing climate. For the central route of China's SNWDP, experts are debating whether it is necessary to build another canal to divert water from the Yangtze River to the middle Hanjiang River to meet the water demands in the lower Hanjiang River. This study indicates that this supporting project can be one of the possible adaptive measures considering the increasing probability of concurrent drought between the Hanjiang River and the NCP. Additionally, improving the long-term streamflow forecasting capability above the Danjiangkou Reservoir will increase management efficiency of the Danjiangkou Reservoir in response to the varying streamflow and further mitigate the negative effects of droughts. Lastly, water conservation practices will remain an important factor for mitigating the NCP's water shortage issue, even after the water diversion project approaches full-scale operation.

3.4. Discussion on the Possible Climate Mechanism of Concurrent Drought Events

The ENSO is widely considered one of the most notable drivers of drought and flood globally [e.g., *Ward et al*., 2014]. According to climate studies in China [e.g., *Li and Zhou*, 2012], an El Niño event usually brings less precipitation and results in drought in Northern China, while a La Niña event usually has significant impacts on extreme temperature and limited impacts on precipitation in China. In the central route of China's SNWDP, the water destination region is located in Northern China, while the water source region is located in the north-south transition zone of China, where ENSO events could also impact the climate [*Huang et al.*, 2000]. The ENSO event from 1960 to 2013 is categorized by the Oceanic Niño Index years (Table S4 in the supporting information). For the water destination region, among the five most severe drought years ($SPI \leq -1.5$), 4 years occurred with an El Niño event (Table 1). For the water source region, three of the six moderate drought years ($-1.5 < SPI \leq -1.0$) occurred with an El Niño event, and El Niño events tended to be associated with moderate drought except the year of 1997. The strongest El Niño event since 1960 occurred in 1997 and lead to the most severe drought experienced in both the water source and destination regions. However, the concurrent drought events in 1999, 2001, 2006, and 2013 did not occur with an El Niño event, as 1999 was categorized as a La Niña year and 2001, 2006, and 2013 were neutral years. Besides ENSO, East Asian monsoons can also impact the climate in China [e.g., *Chang et al.*, 2012]. The East Asian summer monsoon has weakened significantly since 1978, resulting in less precipitation in Northern China and the north-south transition zone of China [*Ding et al.*, 2008]. This could impact the probability of concurrent drought events in the water source and destination regions. The climate mechanism of a concurrent drought event is complex, and various elements may jointly lead to a change in precipitation in the two regions. These complexities need to be further investigated.

4. Conclusion

This study applies the Standard Precipitation Index to calculate drought probability along the central route of China's South to North Water Diversion Project. Meteorological data from 1960 to 2013 revealed that on average, a drought event occurs once every 5.1 years in the water source region, the Danjiangkou Reservoir, and once every 5.2 years in the water destination region, the North China Plain. The probability of a concurrent drought event is 9.1%, or once every 11 years. However, since 1997, these regions have experienced 5 years of concurrent drought events. Moreover, the results of GCM projections show that the probability of concurrent drought events is highly likely to increase during 2020 to 2050. In concurrent drought years, the North China Plain urgently needs the diversion water, while the Danjiangkou Reservoir probably does not have sufficient amounts of water to divert. The impacts of droughts on China's water diversion projects challenge the traditional assumption that past hydrological experiences provide a good guide to future water management. Adaptive measures need to be prepared for water management under the impacts of climate change. For the central route of China's SNWDP, we suggest that building another canal to divert water from the Yangtze River to the middle Hanjiang River could provide an additional source to be used in years of concurrent drought in the Hanjiang River. Additionally, lengthening the lead time of accurate streamflow forecasting is urgent to allow appropriate amount of time to implement necessary adaptations to annual conditions. In particular, water conservation practices will remain important for mitigating the NCP's water shortage issues, even after the water diversion project approaches full-scale operation.

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