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Dramatic decrease in streamflow from the headwater source in the central route of China's water diversion project: Climatic variation or human influence?

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[1] The Danjiangkou Reservoir is the headwater source of the central route of China's South to North Water Diversion Project (SNWDP). Average annual streamflow into the Reservoir was 40.97 km^3 from 1951 to 1989, while it was 31.64 km^3 from 1990 to 2006. Between the two periods, the average annual streamflow was reduced by 9.33 km^3, accounting for 71.8% of the proposed amount of water diversion of the central route (13 km^3 per year). The sharply decreasing streamflow would inevitably have negative impacts on the implementation of the SNWDP. The reasons for the decrease in streamflow should be investigated before developing any adaption strategies. In this study, the impacts of climatic variation and human activities on streamflow were evaluated by a climate elasticity method. The results show that the impact of climatic variation (indicated by precipitation and potential evapotranspiration) was responsible for 84.1–90.1% of the streamflow reduction, while human activities or other indentified uncertainties contributed 9.9–15.9% of the streamflow reduction. The observed 69.89 mm decrease in average annual precipitation contributed 81.6–87.3% of the decrease in streamflow. According to the observed data during the study period, the planned water diversion could lead to an ecological disaster of the downstream area of the Danjiangkou Reservoir in certain years. We suggest that the water diversion from the Danjiangkou Reservoir should be conducted in an adaptive manner to avoid such an adverse consequence, instead of the current plan of a fixed annual amount of water.

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1. Introduction

[2] The South to North Water Diversion Project (SNWDP) is a multidecade infrastructure project of China, which is considered as a strategic and ambitious approach to resolve the water shortage in northern China [*Liu and Zheng*, 2002]. The project is designed to funnel 44.8 km^3 of water per year from Yangtze River to the northern China via its western route, central route, and eastern route, with a total cost of about $62 billion and the expected displacement of 0.345 million people [*Stone and Jia*, 2006]. The central route is planned to divert 13 km^3 of water per year from the Danjiangkou Reservoir on the Hanjiang River, a tributary of the Yangtze River, to Beijing and Tianjin, the two largest cities in northern China. The 13 km^3 of diversion water was partially designed according to the annual average streamflow into the Danjiangkou Reservoir from the year 1954 to 1998. The central route has been basically completed and will be ready to divert water since the year 2014 (http://www.nsbd.gov.cn/).

[3] In the last century, water management has been developed and implemented under the stationary assumption that natural systems fluctuate within an unchanging envelope of variability [*Milly et al.*, 2008]. However, a number of studies have reported apparent changes in streamflow associated with climate change and human activities in many regions of the world in recent years [e.g., *Marengo et al.*, 1998; *Hanna et al.*, 2008; *Zheng et al.*, 2009; *Wang and Hejazi*, 2011]. The hydrologic cycle at the watershed scale is a complex process and affected by climate, land use practices, vegetation types, soil properties, geology, terrain, and spatial patterns of interactions among these factors [*Tomer and Schilling*, 2009]. While evaporation is likely to increase globally with anthropogenic climate change, precipitation trends are likely to be highly heterogeneous, which could lead to change in streamflow [e.g., *Christensen et al.*, 2004; *Zheng et al.*, 2009]. In addition, several studies find climate change alone is insufficient to explain streamflow trends in some watersheds, and human activities such as land use/cover change (LUCC)

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can also alter hydrological processes and impact the generation of streamflow [e.g., *Fu et al.*, 2004; *Zhang and Schilling*, 2006; *Raymond et al.*, 2008; *Tomer and Schilling*, 2009]. For example, *Raymond et al.* [2008] suggested that land use change and management were more important than climate change for explaining increasing water from the Mississippi River. *Wang et al.* [2009] also concluded that human impacts such as water conservation and land use change exerted a dominant influence upon runoff decline compared to climate change in the Chaobai River, China.

[4] It is evident that both climate change and human activities are important drivers of changes in watershed streamflow. The climate elasticity method is an effective way to quantitatively separate the impacts of climate change and human activities on streamflow [e.g., *Schaake*, 1990; *Dooge et al.*, 1999; *Sankarasubramanian et al.*, 2001; *Arora*, 2002]. The climate elasticity method measures the contribution of climate change on streamflow change, and assumes that the remaining change of streamflow would come from human influence (LUCC) or other unidentified factors such as the uncertainties in measuring hydro-climatic variables and LUCC. *Li et al.* [2007] used the method in the Wuding River basin of the Loess Plateau of China and estimated that the soil conservation measures accounted for 87% of the reduction in streamflow and climate change accounted for 13% of that from 1972 to 1997. *Zheng et al.* [2009] applied the method in the headwater catchments of the Yellow River Basin and concluded that the effects of climate change and human activities on the reduction in streamflow were about 30% and 70%, respectively, in the 1990s. *Jiang et al.* [2011] used the method in the Laohahe Basin of China and revealed that human activities were the main factors of the reduction in streamflow and explained 89–93% of the reduction in streamflow from 1980 to 2008.

[5] Climatic variation was observed in the regions of the central route of the SNWDP during the past 50–100 years. Mean surface air temperature increased significantly, and obvious decadal variations of precipitation, dryness–wetness index and pan evaporation were also detected [*Ren et al.*, 2011]. In addition, change in land use and land cover has been observed in Hanjiang River Basin [*Yu et al.*, 2010]. Change in streamflow was reported at the Danjiangkou Reservoir [*Chen et al.*, 2007]. However, the existing studies mainly focused on the decadal variation of streamflow and the future scenario of streamflow predicted by GCMs [*Yuan et al.*, 2004; *Chen et al.*, 2007], while analysis on the temporal trend of streamflow into the Danjiangkou Reservoir and the impacts of change in streamflow on the water diversion project were not conducted. In addition, the decomposition of the impacts of climatic variation and human activities on streamflow into the Reservoir were also not available in the literature. In this study, the temporal change of streamflow into the Danjiangkou Reservoir is analyzed and the impacts of climatic variation and human activities on the streamflow are evaluated by a climate elasticity method. This study is aimed to evaluate the relative contributions of climatic variation and human impact to the change in annual streamflow, and assess the impacts of change in streamflow on the operation of the SNWDP.

2. Study Area and Data

[6] The Danjiangkou Reservoir (111.5E, 32.7N) is located on the middle reaches of the Hanjiang River, the largest tributary of the Yangtze River. The Hanjiang River Basin is located in the sub-tropical monsoon climate zone and has dramatic fluctuation in climate and water resources during the year. The mean annual temperature is about 15–17°C. The maximum mean monthly temperature is about 22–24°C in July, while the minimum mean monthly temperature is about 1–3°C in January. The annual precipitation varies from 700 to 1100 mm, and 70–80% of the precipitation occurs in the wet months from May to October. The streamflow between July and October accounts for about 65% of the total annual streamflow. The Danjiangkou Reservoir has a drainage area of 96,000 km^2. For the implementation of the SNWDP, the dam of the Danjiangkou Reservoir has been heightened from 162 m to 176.6 m in 2009. Accordingly, the reservoir capacity has been increased from 17.45 km^3 to 29.05 km^3 (http://www.nsbd.gov.cn/).

[7] Daily meteorological records of 11 national meteorological stations from 1951 to 2006 from the National Climatic Centre (NCC) of China Meteorological Administration (CMA) were used in the study (Figure 1). The meteorological data included daily precipitation (P), air temperatures (T), wind speed, vapor pressure and sunshine duration. The observed sunshine duration of a day is defined as the sum of hours for which the direct solar irradiance exceeds 120 W/m^2 [*World Meteorological Organization*, 1996]. Potential evapotranspiration (E_0) was calculated by the Penman-Monteith method [*Allen et al.*, 1998]. The monthly streamflow (1951$\sim$2006) into the Danjiangkou Reservoir was provided by the Bureau of Hydrology of the Yangtze Water Resources Commission. The land use maps of the year 1980 and 2000 used to identify the land use change were provided by the Chinese Academy of Sciences. The maps have a resolution of 1 km $\times$ 1 km and were also used in other hydro-climatic studies [e.g., *Wang et al.*, 2009; *Zheng et al.*, 2009].

3. Methodology

3.1. Statistical Analysis

[8] Temporal trend in the annual streamflow into the Danjiangkou Reservoir was analyzed based on the rank-based non-parametric Mann–Kendall statistical test [*Mann*, 1945; *Kendall*, 1975]. The method has been commonly used for trend detection due to its robustness for non-normally distributed data, which are frequently encountered in hydro-climatic time series [e.g., *Yue and Wang*, 2002; *Zheng et al.*, 2009]. Results of the test indicated that there was a generally decreasing trend ($P < 0.10$ for annual data; and $P < 0.05$ for 5-year moving average) on the streamflow into the Danjiangkou Reservoir during 1950–2006. Changes in temperature and evaporation are considered to occur in a transient manner, while other climatic variables such as precipitation are likely to change abruptly. In both cases, the magnitudes or relative contributions to the total detected changes in a certain period vary from year to year. Therefore, a "breakpoint" of the change may be statistically determined. The existence of a statistical significant breakpoint indicates that the study period should be segmented into sub-periods for trend analyses and other investigations. This approach was widely used for similar studies on hydrology and climatic change in many regions [e.g., *Partal and Kahya*, 2006; *Smadi and Zghoul*, 2006; *Wang et al.*, 2009; *Zheng et al.*, 2009; *Wang et al.*, 2011]. The existence and significance of

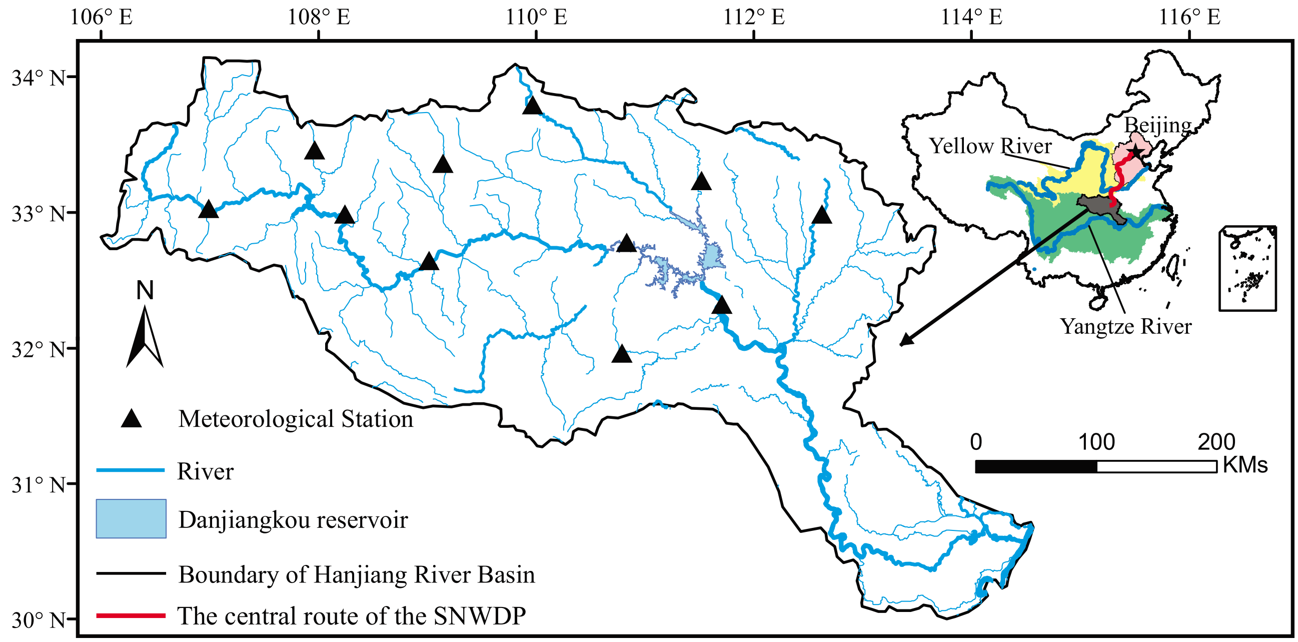

Figure 1. Map of the study area.

a breakpoint may vary with the study locations and periods. By characterizing the hydrologic conditions in a specific watershed configuration, therefore, this approach is anticipated to provide useful information to support regional management for water resources. In this study, the sequential version of the Mann-Kendall test [*Mann*, 1945; *Kendall*, 1948] was conducted to analyze the change point of the hydro-climatic time series [e.g., *Douglas et al.*, 2000; *Modarres and Sarhadi*, 2009].

[9] Given a data series composed of $x_1, x_2 \ldots x_n$, for each element, the Mann–Kendall rank statistic (d_k) is calculated as the summation of m_i, which is the number of later terms in the series whose values exceed x_i:

$$d_k = \sum_{i=1}^{k} m_i \qquad (2 \le k \le n) \tag{1}$$

The mean and variance of the test statistic d_k are:

$$\begin{cases} E[d_k] = k(k-1)/4 \\ \mathrm{var}[d_k] = k(k-1)(2k+5)/72 \quad (2 \le k \le n) \end{cases} \tag{2}$$

The sequential values of the statistic $u(d_k)$ are then calculated as:

$$u(d_k) = (d_k - E[d_k])/\sqrt{\mathrm{var}[d_k]} \tag{3}$$

The terms of the $u(d_k)$ ($1 \le k \le n$) constitute a forward sequence curve (C_1). The same method is then applied to the inversed series and gets a backward sequence (C_2). The intersection point of C_1 and C_2 located between the confidence interval is the time when a change point occurred.

3.2. Estimation of the Impacts of Climatic Variation on Streamflow

[10] The climate elasticity method was used to assess the impacts of climate change on streamflow [e.g., *Dooge et al.*, 1999; *Arora*, 2002; *Zheng et al.*, 2009]. The streamflow record into the Danjiangkou Reservoir from 1951 to 2006 was divided into two periods by the Mann–Kendall method. For a hydrologically isolated region such as a river watershed, the change in streamflow between the two periods (ΔQ) can be estimated as:

$$\Delta Q = \Delta Q_C + \Delta Q_H \tag{4}$$

where ΔQ_C and ΔQ_H are changes in streamflow due to climatic variation and human activities, respectively. ΔQ_C can be approximately estimated as the follows [e.g., *Dooge et al.*, 1999; *Milly and Dunne*, 2002]:

$$\Delta Q_C = \Delta Q_P + \Delta Q_{E_0} = (\varepsilon_P \Delta P/P + \varepsilon_{E_0} \Delta E_0/E_0)Q \tag{5}$$

where ΔQ_P and ΔQ_{E0} are the contributions of change in P and E_0 to change in Q, respectively. ΔP and ΔE_0 are the change in P and E_0 between the two periods, respectively. ε_P and ε_{E0} are climate elasticity of streamflow to P and E_0, respectively, and can be estimated as the follows [e.g., *Dooge et al.*, 1999; *Arora*, 2002] by the six water balance models based on the Budyko hypothesis [*Budyko*, 1948]:

$$\varepsilon_P = 1 + \frac{\phi F'(\phi)}{1 - F(\phi)}, \mathit{and}\ \varepsilon_P + \varepsilon_{E_0} = 1 \tag{6}$$

where ϕ is the aridity index ($\phi = E_0/P$) and calculated at yearly timescale in this study. $F(\phi)$ is the function of ϕ (Figure 2) and $F'(\phi)$ is the derivative of $F(\phi)$ with respect to ϕ. The detailed expressions of $F(\phi)$ and $F'(\phi)$ are listed in Table 1. ΔQ_H is calculated as ($\Delta Q_H = \Delta Q - \Delta Q_C$), and presented in the study as the change of streamflow due to human activities and other unidentified uncertainties.

4. Results

4.1. Changes in Annual Streamflow, Precipitation and Potential Evaporation

[11] Figure 3a shows the variation of annual streamflow into the Danjiangkou Reservoir from 1951 to 2006. The

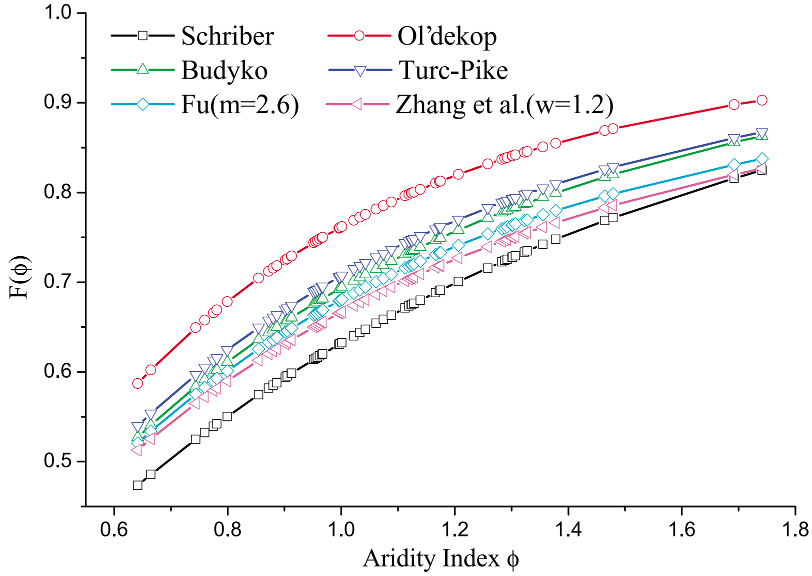

Figure 2. Relationship between F(ϕ) and aridity index (ϕ) by the six forms of F(ϕ) based on the Budyko hypothesis (formulas were listed in Table 1).

annual streamflow series fluctuated intensely. The wettest year was observed in 1964 with annual streamflow of 79.49 km^3, while the driest year was in 1999 with annual streamflow of 17.09 km^3. The former is about 4.6 times larger than the latter. It can be seen from Figure 3b that a change point for annual streamflow time series was identified around the year 1990 ($P < 0.05$) based on the sequential version of the Mann-Kendall test. The average annual streamflow was 40.97 km^3 from 1951 to 1989 (period I), while it was 31.64 km^3 from 1990 to 2006 (period II). The average annual streamflow in period II decreased by 9.33 km^3 compared to that of period I, and the relative change was −22.8% (Table 2). Figures 3c and 3d show the variations of streamflow in wet season (May to October) and dry season (November to April of next year) from 1951 to 2006. The average streamflow in wet season decreased from 32.03 km^3 in period I to 23.72 km^3 in period II, while that in dry season decreased from 8.94 km^3 to 7.92 km^3. The change rate in wet season and dry season was −25.9% and −11.4%, respectively. The streamflow in wet season accounted for about 77.3% of the total annual streamflow, and decrease of streamflow in wet season accounted for 89.1% of the total annual decrease in streamflow. Figure 4 shows the variations of annual precipitation, temperature and E_0 from 1951 to 2006. Compared to period I, the average annual precipitation decreased by 69.89 mm in period II, while precipitation in wet season and dry season decreased 47.45 mm and 22.44 mm respectively. The average annual temperature increased by 0.33°C, and the annual E_0 slightly increased by 4.01 mm. In addition, the annual precipitation and streamflow were positively correlated with $R^2 = 0.84$ from 1951 to 2006 (Figure 4d).

4.2. Impacts of Climatic Variation and Human Activities on Streamflow

[12] Table 3 shows the climate elasticity index of annual streamflow to precipitation (ε_P) and E_0 (ε_{E0}). The ε_P varied from 2.25 to 2.41, while ε_{E0} varied from −1.41 to −1.25.

[13] It indicated that 10% increase in precipitation would result in 22.5–24.1% increase in streamflow, while 10% increase in E_0 would result in 12.5–14.1% decrease in streamflow. Therefore, the annual streamflow was more sensitive to the change in precipitation than to the change in E_0. Following the formula of *Zhang et al.* [2001], the 64.89 mm decrease in precipitation led to a 7.66 km^3 decrease in streamflow, while the 4.01 mm increase in E_0 resulted in a decrease in annual streamflow of 0.24 km^3. Change in precipitation and E_0 led to 82.1% and 2.6% of decrease in annual streamflow, respectively. The changes in precipitation and E_0 together led to 84.7% of decrease in streamflow, while human activities or other indentified uncertainties led to 15.3% of decrease in streamflow. Therefore, decrease in

Table 1. Expressions for Estimating Annual Evapotranspiration Based on the Budyko Hypothesis[a]

Reference	$F(\phi)$	$F'(\phi)$
Schreiber [1904]	$F(\phi) = 1 - e^{-\phi}$	$F'(\phi) = \phi e^{(-\phi-1)}$
Ol'dekop [1911]	$F(\phi) = \phi \tanh(\omega)$	$F'(\phi) = \tanh(\omega) - 4/[\phi(e^{-\omega} + e^{\omega})^2]$
Budyko [1948]	$F(\phi) = [\phi \tanh(\omega)(1 - e^{-\phi})]^{1/2}$	$F'(\phi) = \frac{(\tanh(\omega)-\omega \sec h^2(\omega))(1-e^{-\phi})+\phi \tanh(\omega) e^{-\phi}}{2[\phi \tanh(\omega)(1-e^{-\phi})]^{1/2}}$
Turc [1954] and *Pike* [1964]	$F(\phi) = 1/\sqrt{1+\phi^{-2}}$	$F'(\phi) = 1/[\phi^3(1+\phi^{-2})^{3/2}]$
Fu [1981]	$F(\phi) = 1 + \phi - (1 + \phi^m)^{1/m}$, $m > 1$	$F(\phi) = 1 - \phi^{m-1}(1 + \phi^m)^{1/m-1}$, $m > 1$
Zhang et al. [2001]	$F(\phi) = (1 + w\phi)/(1 + w\phi + 1/\phi)$	$F(\phi) = (\phi^{-2} + 2w\phi^{-1} + w - 1)/(1 + w\phi + 1/\phi)^2$

[a]The variables m and w were set to 2.6 and 1.2, respectively, to be comparable with other four forms in this study.

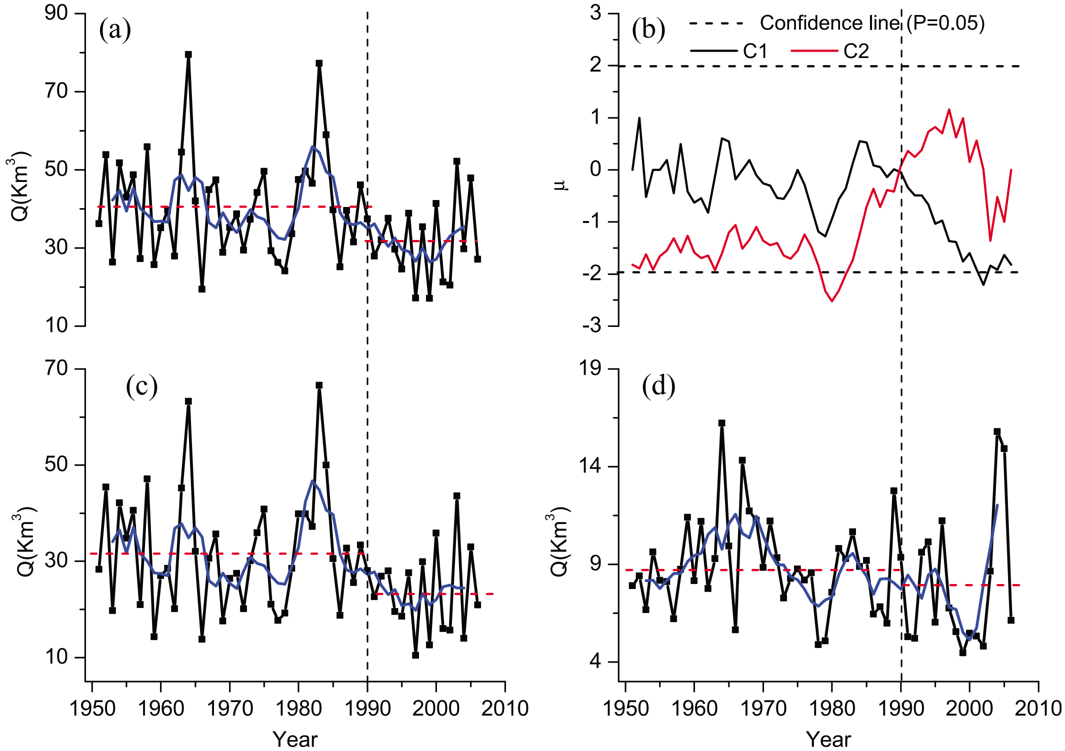

Figure 3. (a) Variation of annual streamflow into the Danjiangkou Reservoir and (b) the Mann-Kendall analysis of annual streamflow from 1951 to 2006. The black horizontal dotted lines represent the critical values corresponding to the 5% significance level. The cross point of C1 and C2 (backward sequence) at 1990 was a start point of abrupt change in the streamflow time series. Variation of annual streamflow into the Danjiangkou Reservoir in (c) wet season and (d) dry season from 1951 to 2006. The blue line shows the five year moving average and the red horizontal dotted lines represent the averages of the corresponding period.

precipitation was the main factor of decrease in streamflow, and contributed 81.6–87.3% of the decrease as calculated by the six formulas based on the Budyko hypothesis. The climatic variation (changes in precipitation and E_0 together) contributed 84.1–90.1% of decrease in annual streamflow.

[14] Table 4 shows the land use of the drainage area of the Danjiangkou Reservoir in the year of 1980 and 2000. Largest change rate was observed for cultivated land, which increased by only 0.19% between 1980 and 2000. The forest was dominant and its area almost remained the same. Therefore, the impacts of changes in land use and land cover on streamflow were not significant. In addition, there were no activities of dam construction or water transfer in the area since the 1990s. As a result, the impacts of human activities on streamflow were relatively small compared to the impacts of changes in climatic variables.

4.3. Impacts of Decreasing Streamflow on the Central Route of the SNWDP

[15] The introduction of the SNWDP has created widespread controversy [*Stone and Jia*, 2006]. Opponents of the project are mainly concerned about the influence on the Hanjiang River, where about 31% of the water will be diverted based on the average annual streamflow during 1951–1989. However, data analysis on the streamflow from 1990 to 2006 shows that about 41% of the water will be diverted if the proposed 13 km^3 diversion water is required (Figure 5). In the driest year of 1999, annual streamflow into

Table 2. Hydro-climatic Statistics of the Two Periods[a]

Period	Streamflow (km^3)			Precipitation (mm)				
	Q	Q_{wet}	Q_{dry}	P	P_{wet}	P_{dry}	T(°C)	E_0 (mm)
I: 1951∼1989	40.97	32.03	8.94	846.53	672.34	174.19	14.27	859.56
II: 1990∼2006	31.64	23.72	7.92	776.64	624.89	151.75	14.6	863.57
Change(Δ)	−9.33	−8.31	−1.02	−69.89	−47.45	−22.44	0.33	4.01
Relative change (%)	−22.8	−25.9	−11.4	−8.3	−7.1	−12.9	2.3	0.5

[a]Change (Δ) means the difference of hydro-climatic variables between the period I and II, and relative change is the ratio between Δ and the mean value in the period I. Q indicates annual average streamflow. P indicates annual average precipitation. T indicates annual average temperature. E_0 indicates annual average potential evapotranspiration. Q_{wet} and Q_{dry} indicate streamflow in wet season (May to October) and dry season (November to April of next year), respectively. P_{wet} and P_{dry} indicate precipitation in wet season and dry season, respectively.

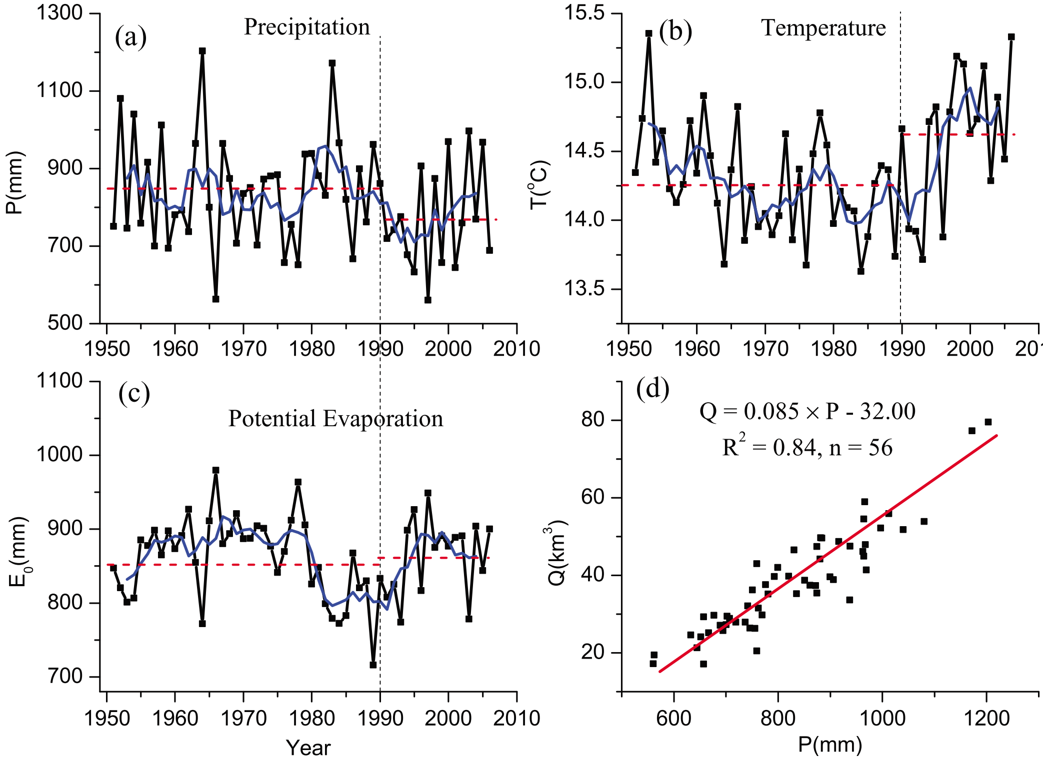

Figure 4. Variation of annual (a) precipitation, (b) temperature and (c) potential evapotranspiration from 1951 to 2006. The blue line shows the five year moving average and the red horizontal dotted lines represent the averages of the corresponding period. (d) The relationship between annual streamflow and precipitation from 1951 to 2006.

the Danjiangkou Reservoir was only 17.09 km^3 and diversion water would account for 76.1% of the annual streamflow in a similar future year. Thus, consistently diverting 13 km^3 of water could cause the Hanjiang River to suffer from water shortages, and probably lead to an environmental disaster in certain years [*Stone and Jia*, 2006]. Therefore, building another canal to divert water from the Yangtze River to the middle Hanjiang would be one of the possible adaptive projects considering the risk of impacts of climatic variation on streamflow. In addition, global change challenges the traditional assumption that past hydrological experience provides a good guide to future conditions, and could alter the reliability. Therefore, the water diversion from the Danjiangkou Reservoir should be conducted in an adaptive manner to avoid an ecological disaster of the downstream Hanjiang River, instead of the current plan of a fixed annual amount of water.

5. Discussion

5.1. Uncertainties

[16] The uncertainties of evaluating the climatic variation effects on streamflow by climate elasticity method existed in this study. First, the empirical formulas based on the Budyko

Table 3. Impacts of Climate Change and Human Activities on Streamflow Into the Danjiangkou Reservoir Estimated By the Six Forms of $F(\phi)$ Based on the Budyko Hypothesis[a]

	Schreiber [1904]	*Ol'dekop* [1911]	*Budyko* [1948]	*Turc* [1954] and *Pike* [1964]	*Fu* [1981]	*Zhang et al.* [2001]
ε_P	2.25	2.41	2.30	2.32	2.26	2.26
ε_{E0}	−1.25	−1.41	−1.30	−1.32	−1.26	−1.26
$\Delta Q_P(km^3)$	−7.61	−8.15	−7.77	−7.83	−7.65	−7.66
$\Delta Q_{E0}(km^3)$	−0.24	−0.27	−0.25	−0.25	−0.24	−0.24
ΔQ_C (km^3)	−7.85	−8.41	−8.02	−8.08	−7.89	−7.90
$\Delta Q_P/\Delta Q$(%)	81.6	87.3	83.2	83.9	81.9	82.1
$\Delta Q_{E0}/\Delta Q$(%)	2.6	2.9	2.7	2.7	2.6	2.6
$\Delta Q_C/\Delta Q$(%)	84.1	90.1	85.9	86.6	84.5	84.7
$\Delta Q_H/\Delta Q$(%)	15.9	9.9	14.1	13.4	15.5	15.3

[a]ΔQ means the change in streamflow between the two periods; ΔQ_C and ΔQ_H mean changes in streamflow due to climatic variation and human activities, respectively. ΔQ_P and ΔQ_{E0} are the contributions of change in precipitation and potential evapotranspiration to change in streamflow, respectively. ε_P and ε_{E0} are climate elasticity of streamflow to precipitation and potential evapotranspiration, respectively.

Table 4. Land Use Change in the Drainage Area of the Danjiangkou Reservoir Between 1980 and 2000[a]

Land Use	Area (km^2)		Proportion (%)		Change Rate (%)
	1980	2000	1980	2000	
Forest	45139.01	45148.82	47.02	47.03	0.01
Grassland	26870.30	26726.41	27.99	27.84	−0.15
Cultivated	22368.02	22550.22	23.30	23.49	0.19
Water bodies	979.21	883.23	1.02	0.92	−0.10
Residential	624.02	671.88	0.65	0.70	0.05
Sandy land	9.60	9.60	0.01	0.01	0.00

[a]The land use data were provided by the Chinese Academy of Sciences.

hypothesis (Table 1) express the relationship between evapotranspiration and precipitation at the annual timescale. Therefore, equation (6) can only be applied to the annual streamflow responding to climatic variation. It cannot be used to analyze the response to the sub-annual (e.g., monthly or seasonal) time step. However, the rainfall-runoff relationship may vary between different months due to the fluctuation of climate system during the year in the region, which is located in the monsoon climate zone.

[17] Second, the impacts of changes in precipitation and potential evapotranspiration on streamflow were separated with the assumption that they are independent in equation (5). However, precipitation and potential evapotranspiration impacted each other, and they were not totally independent. Potential evapotranspiration is defined as the amount of evaporation and transpiration that would occur if sufficient water source were available, and is the function of temperature, vapor pressure, wind speed and solar radiation [*Allen et al.*, 1998]. For example, increase in precipitation could lead to an increase in vapor pressure, thus lead to a decrease in potential evapotranspiration.

[18] At last, climate elasticity method measures climatic variation influence on streamflow and assumes that the remaining change would come from human influence or other unidentified uncertainties. However, climatic variation influence evaluated by the climate elasticity method could be associated with uncertainties. Even the attribution results calculated by different empirical formulas based on the Budyko hypothesis had slight differences. For example, the relative attribution of climatic variation to the decrease in streamflow calculated by the equation of *Schreiber* [1904] was 84.1%, while it was 90.1% by the equation of *Ol'dekop* [1911] (Table 3). Therefore, the derived contribution of human influence to streamflow change could be also associated with uncertainties. In addition, uncertainties could come from the measurements of precipitation and streamflow, especially when assuming that a limited number of gauges are representative of a large region. However, the uncertainties will not substantially change the conclusion that climatic variation is the main reason of the decrease in streamflow.

5.2. Change in E_0

[19] E_0 reflects an integrated effect of temperature, solar radiation, vapor pressure and wind speed. The decrease in E_0 or pan-evaporation along with global warming in last century have been reported in many regions of the world [e.g., *Peterson et al.*, 1995; *Roderick and Farquhar*, 2002; *Liu et al.*, 2004], which is called "Evaporation Paradox" [*Brutsaert and Parlange*, 1998]. The significant decreases in wind speed ("stilling") and/or solar radiation ("dimming"), which offset the effect of increasing air temperature on E_0, were widely considered as the main reasons of decrease in E_0 and/or pan-evaporation [e.g., *Rayner*, 2007; *Roderick et al.*, 2007; *Zheng et al.*, 2009].

[20] Pan-evaporation decreased significantly since the mid-1960s at the Danjiangkou Reservoir, and the decreasing trend appeared to have ended in the early 1990s [*Ren et al.*, 2011]. Figure 4c also shows the similar trend in E_0 at the Danjiangkou Reservoir. Our previous study [*Liu et al.*, 2011] found that E_0 in China decreased from 1960s to the early 1990s, but began to increase since the early 1990s. We

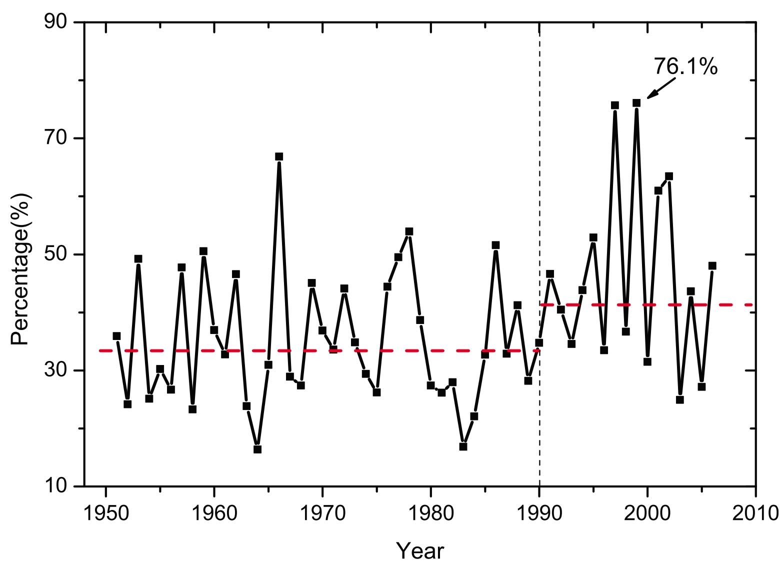

Figure 5. Variation of the proportion of annual proposed diversion water (13 km^3 per year) to annual streamflow into the Danjiangkou Reservoir from 1951 to 2006. The red horizontal dotted lines represent the averages of the corresponding periods.

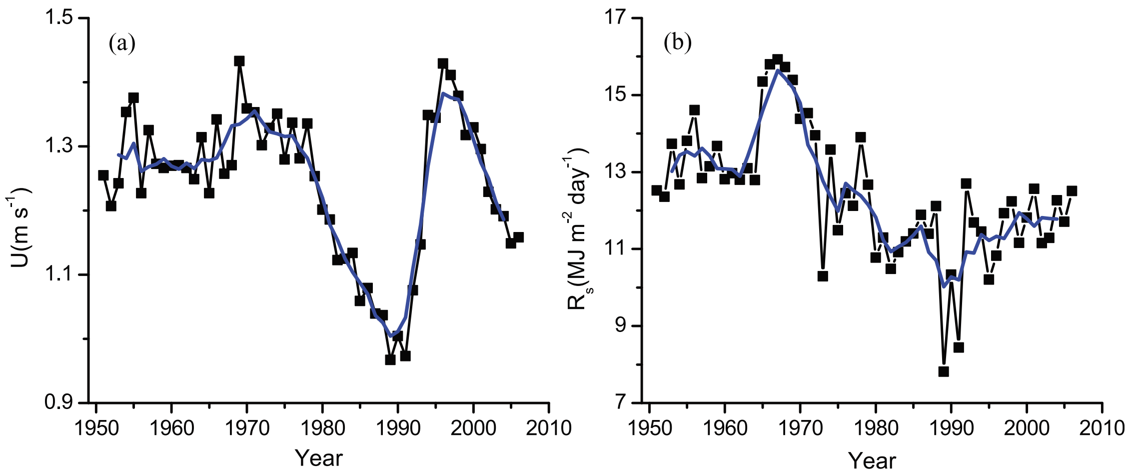

Figure 6. Variations of annual (a) wind speed and (b) solar radiation from 1951 to 2006. The blue line shows the five year moving average.

showed that the amplitude of increase in air temperature rose seriously, while the amplitude of decrease in wind speed declined and solar radiation even increased (from "dimming" to "brightening") since the early 1990s. We concluded that increasing air temperature dominated the change in E_0, which offset the effect of wind speed on E_0 and led to the increase in E_0 since the early 1990s. Figure 4b shows that air temperature increased dramatically since the early 1990s at the Danjiangkou Reservoir, and *Ren et al.* [2011] also found the similar change in air temperature. In addition, Figure 6 shows that the decrease in wind speed stopped, while solar radiation increased at the Danjiangkou Reservoir since the early 1990s. The observed change in air temperature and wind speed may support the conclusion that dramatically increase in air temperature could be the reason for the increase in E_0 since the early 1990s.

5.3. Change in Precipitation

[21] Figure 4a shows that precipitation fluctuated dramatically on decadal time scales at the Danjiangkou Reservoir, and precipitation decreased both in dry season and wet season from 1990 to 2006 compared to the period 1951–1989 (Table 2). *Chen et al.* [2007] also found the decadal fluctuation of precipitation in the Hanjiang River Basin, and showed that precipitation decreased substantially since the 1990s in the drainage area of the Danjiangkou Reservoir. The observed change in precipitation in China was widely interpreted in the literature. Change in sea surface temperature (SST) anomalies which leads to the El Niño–Southern Oscillation (ENSO) and El Niño Modoki can influence the precipitation in southern China significantly [e.g., *Zhang et al.*, 1999; *Wu et al.*, 2003; *Feng and Li*, 2011; *Zhou*, 2011]. In addition, the large-scale circulation over East Asia and East Asian monsoon can also impact the precipitation in China [e.g., *Wang and Zhou*, 2005; *Zhou and Wu*, 2010]. *Cheng et al.* [2005] show a warming of the SST in the South China Sea and the Indian Ocean, and a strengthening of the West Pacific Subtropical High in the early summer led to the drought in southern China (includes the Danjiangkou Reservoir). However, the reason for change in precipitation in China is complicated, and various elements may together lead to the change in precipitation at the Danjiangkou Reservoir, which needs to be further investigated.

[22] It is noticeable that there was a slightly increasing trend for precipitation since the 2000s (Figure 4a), even though the average precipitation from 2000 to 2006 (which is 827.98 mm per year) is still below the average from 1951 to 1989 (846.53 mm per year). It is hard to determine whether this means the drought will be alleviated due to the fluctuation of climate system since the 2000s, which needs a longer period of observed data to verify in the future. However, the worst drought in 50 years hit the middle and lower reaches of the Yangtze River in 2011, and water level of the Danjiangkou Reservoir dropped drastically to 4.23 m below its dead water level on May 14, 2011 (China Meteorological Administration, http://2011.cma.gov.cn/en/speeial/20110218/xunqi_en/xunqiphoto/201105/t20110518_93938.html). Therefore, considerable attention should be given to the climatic background in assessing the planning and management program of the SNWDP.

5.4. Human Activities

[23] During the 1990s, China has experienced rapid urbanization, and the land use and land cover have changed dramatically. Large areas of woodlands, grasslands and wetlands were converted to croplands in northern China, while large areas of croplands were converted to urban areas in southern China [*Liu et al.*, 2005]. The impacts of land use and land cover change were considered to be the main reasons of decrease in streamflow in many regions of China [e.g., *Li et al.*, 2007; *Zheng et al.*, 2009; *Jiang et al.*, 2011]. However, the Hanjiang River Basin is located in mountainous areas and has low population density. The land use and land cover in the drainage area of the Reservoir almost remained the same between 1980 and 2000. Therefore, the impacts of land use and land cover change on streamflow were not obvious.

6. Conclusion

[24] Change in streamflow into the Danjiangkou Reservoir from 1951 to 2006 was analyzed in this study. The Mann-Kendall test showed that the streamflow time series had a

change point around the year 1990. Annual average streamflow into the Reservoir was 40.97 km^3 from 1951 to 1989, while it decreased to 31.64 km^3 from 1990 to 2006. The results of elasticity analysis showed that climatic variation (indicated by precipitation and potential evapotranspiration) was responsible for 84.1–90.1% of the streamflow reduction, while human activities or other unidentified uncertainties contributed 9.9–15.9% of the reduction. The average annual precipitation from 1990 to 2006 decreased 69.89 mm when it was compared to that from 1951 to 1989, which contributed 81.6–87.3% of the streamflow reduction. Decrease in streamflow into the Danjiangkou Reservoir challenges the water diversion plan of the central route of the SNWDP. About 41% of the annual streamflow into the Danjiangkou Reservoir will be diverted if the 13 km^3 diversion water per year is required. The water diversion from the Danjiangkou Reservoir should be conducted in an adaptive manner to avoid an ecological disaster of the downstream Hanjiang River, instead of the current plan of a fixed annual amount of water.

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References

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith (1998), Crop evapotranspiration: Guidelines for computing crop requirements, *Irrig. Drain. Pap.*, *300*(56), 1–15.

Arora, V. K. (2002), The use of the aridity index to assess climate change effect on annual streamflow, *J. Hydrol.*, *265*, 164–177, doi:10.1016/S0022-1694(02)00101-4.

Brutsaert, W., and M. B. Parlange (1998), Hydrologic cycle explains the evaporation paradox, *Nature*, *396*, 30, doi:10.1038/23845.

Budyko, M. I. (1948), *Evaporation Under Natural Conditions*, Gidrometeorizdat, Leningrad, translated from Russian, Isr. Program for Sci. Transl., Jerusalem.

Chen, H., S. Guo, C. Xu, and V. P. Singh (2007), Historical temporal trends of hydro-climatic variables and runoff response to climate variability and their relevance in water resources management in the Hanjiang basin, *J. Hydrol.*, *344*, 171–184, doi:10.1016/j.jhydrol.2007.06.034.

Cheng, Y. J., U. Lohmann, J. H. Zhang, Y. F. Luo, Z. T. Liu, and G. Lesins (2005), Contribution of changes in sea surface temperature and aerosol loading to the decreasing precipitation trend in southern China, *J. Clim.*, *18*(9), 1381–1390, doi:10.1175/JCLI3341.1.

Christensen, N. S., A. W. Wood, N. Voisin, D. P. Lettenmaier, and R. N. Palmer (2004), The effects of climate change on the hydrology and water resources of the Colorado River Basin, *Clim. Change*, *62*, 337–363, doi:10.1023/B:CLIM.0000013684.13621.1f.

Dooge, J. C. I., M. Bruen, and B. Parmentier (1999), A simple model for estimating the sensitivity of runoff to long-term changes in precipitation without a change in vegetation, *Adv. Water Resour.*, *23*, 153–163, doi:10.1016/S0309-1708(99)00019-6.

Douglas, E. M., R. M. Vogel, and C. N. Kroll (2000), Trends in floods and low flows in the United States: Impact of spatial correlation, *J. Hydrol.*, *240*, 90–105, doi:10.1016/S0022-1694(00)00336-X.

Feng, J., and J. Li (2011), Influence of El Niño Modoki on spring rainfall over south China, *J. Geophys. Res.*, *116*, D13102, doi:10.1029/2010JD015160.

Fu, B. P. (1981), On the calculation of the evaporation from land surface (in Chinese), *Sci. Atmos. Sin.*, *5*, 23–31.

Fu, G. B., S. L. Chen, C. C. Liu, and D. Shepard (2004), Hydro-climatic trends of the Yellow River Basin for the last 50 years, *Clim. Change*, *65*, 149–178, doi:10.1023/B:CLIM.0000037491.95395.bb.

Hanna, E., P. Huybrechts, K. Steffen, J. Cappelen, R. Huff, C. Shuman, T. Irvine-Fynn, S. Wise, and M. Griffiths (2008), Increased runoff from melt from the Greenland ice sheet: A response to global warming, *J. Clim.*, *21*, 331–341, doi:10.1175/2007JCLI1964.1.

Jiang, S., L. Ren, B. Yong, V. P. Singh, X. Yang, and F. Yuan (2011), Quantifying the effects of climate variability and human activities on runoff from the Laohahe basin in northern China using three different methods, *Hydrol. Processes*, *25*, 2492–2505, doi:10.1002/hyp.8002.

Kendall, M. G. (1948), *Rank Correlation Methods*, Hafner, New York.

Kendall, M. G. (1975), *Rank Correlation Measures*, Charles Griffin, London.

Li, L., L. Zhang, H. Wang, J. Wang, J. Yang, D. Jiang, J. Li, and D. Qin (2007), Assessing the impact of climate variability and human activities on streamflow from the Wuding River basin in China, *Hydrol. Processes*, *21*, 3485–3491, doi:10.1002/hyp.6485.

Liu, B. H., M. Xu, M. Henderson, and W. G. Gong (2004), A spatial analysis of pan evaporation trends in China, 1955–2000, *J. Geophys. Res.*, *109*, D15102, doi:10.1029/2004JD004511.

Liu, C. M., and H. X. Zheng (2002), South-to-north water transfer schemes for China, *Int. J. Water Resour. Dev.*, *18*(3), 453–471, doi:10.1080/0790062022000006934.

Liu, J., H. Tian, M. Liu, D. Zhuang, J. M. Melillo, and Z. Zhuang (2005), China's changing landscape during the 1990s: Large-scale land transformations estimated with satellite data, *Geophys. Res. Lett.*, *32*, L02405, doi:10.1029/2004GL021649.

Liu, X., Y. Luo, D. Zhang, M. Zhang, and C. Liu (2011), Recent changes in pan-evaporation dynamics in China Recent changes in pan-evaporation dynamics in China, *Geophys. Res. Lett.*, *38*, L13404, doi:10.1029/2011GL047929.

Mann, H. B. (1945), Non-parametric tests against trend, *Econometrica*, *13*, 245–259, doi:10.2307/1907187.

Marengo, J. A., J. Tomasella, and C. R. Uvo (1998), Trends in streamflow and rainfall in tropical South America: Amazonia, eastern Brazil and northwestern Peru, *J. Geophys. Res.*, *103*, 1775–1783, doi:10.1029/97JD02551.

Milly, P. C. D., and K. A. Dunne (2002), Macroscale water fluxes: 2. Water and energy supply control of their inter-annual variability, *Water Resour. Res.*, *38*(10), 1206, doi:10.1029/2001WR000760.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kudzewicz, D. P. Lettenmaier, and R. J. Stouffer (2008), Climate change: Stationarity is dead: Whither water management?, *Science*, *319*, 573–574, doi:10.1126/science.1151915.

Modarres, R., and A. Sarhadi (2009), Rainfall trends analysis of Iran in the last half of the twentieth century, *J. Geophys. Res.*, *114*, D03101, doi:10.1029/2008JD010707.

Ol'dekop, E. M. (1911), On evaporation from the surface of river basins (in Russia), *Trans. Meteorol. Obs. Univ. Tartu 4*, Univ. Tartu, Tartu.

Partal, T., and M. Kahya (2006), Long-term trend analysis using discrete wavelet components of annual precipitations measurements in Marmara region (Turkey), *Phys. Chem. Earth, Parts A/B/C*, *31*(18), 1189–1200, doi:10.1016/j.pce.2006.04.043.

Peterson, T. C., V. S. Golubev, and P. Y. Groisman (1995), Evaporation losing its strength, *Nature*, *377*, 687–688, doi:10.1038/377687b0.

Pike, J. G. (1964), The estimation of annual runoff from meteorological data in a tropical climate, *J. Hydrol.*, *2*, 116–123, doi:10.1016/0022-1694(64)90022-8.

Raymond, P. A., N. H. Oh, R. E. Turner, and W. Broussard (2008), Anthropogenically enhanced fluxes of water and carbon from the Mississippi River, *Nature*, *451*(24), 449–452.

Rayner, D. (2007), Wind run changes are the dominant factor affecting pan evaporation trends in Australia, *J. Clim.*, *20*(14), 3379–3394, doi:10.1175/JCLI4181.1.

Ren, G., et al. (2011), Multi-time-scale climatic variations over eastern China and implications for the South-North Water Diversion Project, *J. Hydrometeorol.*, *12*, 600–617, doi:10.1175/2011JHM1321.1.

Roderick, M. L., and G. D. Farquhar (2002), The cause of decreased pan evaporation over the past 50 years, *Science*, *298*, 1410–1411.

Roderick, M. L., L. D. Rotstayn, G. D. Farquhar, and M. T. Hobbins (2007), On the attribution of changing pan evaporation, *Geophys. Res. Lett.*, *34*, L17403, doi:10.1029/2007GL031166.

Sankarasubramanian, A., R. M. Vogel, and J. F. Limburner (2001), Climate elasticity of streamflow in the United States, *Water Resour. Res.*, *37*, 1771–1781, doi:10.1029/2000WR900330.

Schaake, J. C. (1990), From climate to flow, in *Climate Change and U.S. Water Resources*, edited by P. E. Waggoner, chap. 8, pp. 177–206, John Wiley, Hoboken, N. J.

Schreiber, P. (1904), Über die Beziehungen zwischen dem Niederschlag und der Wasserführung der Flüße in Mitteleuropa, *Z. Meteorol.*, *21*(10), 441–452.

Smadi, M. M., and A. Zghoul (2006), A sudden change in rainfall characteristics in Amman, Jordan during the mid 1950s, *Am. J. Environ. Sci.*, *2*, 84–91, doi:10.3844/ajessp.2006.84.91.

Stone, R., and H. Jia (2006), Going against the flow, *Science*, *313*, 1034–1037, doi:10.1126/science.313.5790.1034.

Tomer, M. D., and K. E. Schilling (2009), A simple approach to distinguish land-use and climate-change effects on watershed hydrology, *J. Hydrol.*, *376*(1–2), 24–33.

Turc, L. (1954), Le bilan d'eau des sols. Relation entre la precipitation, l'evaporation et l'ecoulement, *Ann. Agron.*, *5*, 491–569.

Wang, D., and M. Hejazi (2011), Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States, *Water Resour. Res.*, *47*, W00J12, doi:10.1029/2010WR010283.

Wang, G., J. Xia, and J. Chen (2009), Quantification of effects of climate variations and human activities on runoff by a monthly water balance model: A case study of the Chaobai River basin in northern China, *Water Resour. Res.*, *45*, W00A11, doi:10.1029/2007WR006768.

Wang, Y., and L. Zhou (2005), Observed trends in extreme precipitation events in China during 1961–2001 and the associated changes in large-scale circulation, *Geophys. Res. Lett.*, *32*, L09707, doi:10.1029/2005GL022574.

Wang, Z., Y. Luo, C. Liu, J. Xia, and M. Zhang (2011), Spatial and temporal variations of precipitation in Haihe River Basin, China: Six decades of measurements, *Hydrol. Processes*, *25*, 2916–2923, doi:10.1002/hyp.8055.

World Meteorological Organization (1996), *Guide to Meteorological Instruments and Methods of Observation*, 6th ed., Geneva, Switzerland.

Wu, R., Z. Hu, and B. Kirtman (2003), Evolution of ENSO-related rainfall anomalies in East Asia, *J. Clim.*, *16*, 3742–3758, doi:10.1175/1520-0442(2003)016<3742:EOERAI>2.0.CO;2.

Yu, G., Q. Zeng, S. Yang, L. Hu, X. Li, Y. Che, and Y. Zheng (2010), On the intensity and type transition of land use at the basin scale using RS/GIS: A case study of the Hanjiang River Basin, *Environ. Monit. Assess.*, *160*(1–4), 169–179, doi:10.1007/s10661-008-0666-y.

Yuan, F., Z. Xie, Q. Liu, H. Yang, F. Su, X. Liang, and L. Ren (2004), An application of the VIC-3L land surface model and remote sensing data in simulating streamflow for the Hanjiang River basin, *Can. J. Rem. Sens.*, *30*(5), 680–690, doi:10.5589/m04-032.

Yue, S., and C. Y. Wang (2002), Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test, *Water Resour. Res.*, *38*(6), 1068, doi:10.1029/2001WR000861.

Zhang, L., W. Dawes, and G. Walker (2001), Response of mean annual evapotranspiration to vegetation changes at catchment scale, *Water Resour. Res.*, *37*, 701–708, doi:10.1029/2000WR900325.

Zhang, R. H., A. Sumi, and M. Kimoto (1999), A diagnostic study of the impact of El Niño on the precipitation in China, *Adv. Atmos. Sci.*, *16*(2), 229–241, doi:10.1007/BF02973084.

Zhang, Y. K., and K. E. Schilling (2006), Increasing streamflow and baseflow in the Mississippi River since the 1940s: Effect of land use change, *J. Hydrol.*, *324*, 412–422, doi:10.1016/j.jhydrol.2005.09.033.

Zheng, H., L. Zhang, R. Zhu, C. Liu, Y. Sato, and Y. Fukushima (2009), Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin, *Water Resour. Res.*, *45*, W00A19, doi:10.1029/2007WR006665.

Zhou, L.-T. (2011), Interdecadal change in sea surface temperature anomalies associated with winter rainfall over South China, *J. Geophys. Res.*, *116*, D11101, doi:10.1029/2010JD015425.

Zhou, L.-T., and R. Wu (2010), Respective impacts of the East Asian winter monsoon and ENSO on winter rainfall in China, *J. Geophys. Res.*, *115*, D02107, doi:10.1029/2009JD012502.

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