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Discussions

China's water sustainability in the 21st century: a climate informed water risk assessment covering multi-sector water demands

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Abstract

China is facing a water resources crisis with growing concerns as to the reliable supply of water for agricultural, industrial and domestic needs. High inter-annual rainfall variability and increasing consumptive use across the country exacerbates the situation further and is a constraint on future development. For water sustainability, it is necessary to examine the differences in water demand and supply and their spatio-temporal distribution in order to quantify the dimensions of the water risk. Here, a detailed quantitative assessment of water risk as measured by the distribution of cumulated deficits for China is presented. Considering daily precipitation and temperature variability over fifty years and the current water demands, risk measures are developed to inform county level water deficits that account for both within year and across year variations in climate. We choose political rather than watershed boundaries since economic activity and water use are organized by county and the political process is best informed through that unit. The risk measures highlight North China Plain counties as highly water stressed. Regions with high water stress are typically the regions with high inter-annual variability in rainfall and now have depleted groundwater aquifers. The stress components due to agricultural, industrial and domestic water demands are illustrated separately to assess the vulnerability of particular sectors within the country to provide a basis for targeted policy analysis for reducing water stress.

1 Introduction

Water stress in China is a widely recognized crisis. The simultaneous effects of agricultural growth, industrialization and urbanization coupled with declining surface and groundwater quantity, inefficiency in agricultural water use practices and cross sectoral conflicts over limited water resources are some of the crucial problems (Cai, 2008). The effects of climate variability and change, including increasing frequency of extreme events such as droughts creates additional pressure on the already scarce

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water supplies. Irrigated agriculture is the dominant water user in China, accounting for more than 60 % of all consumptive use (reported in China water resources bulletin in 2011, http://www.mwr.gov.cn/zwzc/hygb/szygb/). China has the highest net irrigated area (6×10^7 ha) in the world and the expansion of agricultural sector through improved irrigation infrastructure has been the key for increased food production for self sustenance and for global trade. In this context, ensuring sufficient water supply across the water sectors is a daunting challenge for sustainability in the 21st century. As competition for water increases across different use sectors and across different states, the temporal variability in available supply leads to increasing pressure to develop surface storage, or to use groundwater resources. Analyses that directly highlight the water stress faced locally relative to endogenous supply within a subregion can highlight the implicit degree of spatial competition for the resource and the impacts of temporal variability relative to an existing or projected demand scenario.

Unlike past work that considers estimates of groundwater recharge and river flow as measures of supply (Oki and Kanae, 2006; Alcamo et al., 2003; Brown, 2011 and references therein), we use local precipitation as the renewable water supply endogenous to the area, and consider natural and human uses of this water, to highlight the degree to which a county is dependent on both endogenous and exogenous water supply for its needs. Our choice is to do an analysis where the renewable supply for each county is considered to be the direct precipitation on that county. This choice is motivated by the need to separate the spatial competition and use of the resource for an analysis of the purely locally induced stress, and to reveal settings where there is a high implicit dependence on external water sources, either through excessive groundwater use locally, or through the use of river waters that may be subsequently captured or depleted for downstream users, as has happened in much of the Yellow River Basin. Within this framework, the impact of within and multiyear droughts on available renewable water supply is explicitly assessed for each county. Here, we apply two metrics presented in Devineni et al. (2013) to capture the influence of within year dry periods (Normalized Deficit Index – NDI) and of shortage across years (Normalized Deficit Cumulated –

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NDC) as measures of water risk and map them for the China at a county level. The computations are done using over fifty years of daily precipitation data and the current reported water use pattern for each county.

Section 2 presents the data sources and methodology. In Sect. 3 we summarize the water stress situation for China using the indices developed. Finally, in Sect. 4, some summary comments are offered.

2 Data and methods

Daily rainfall, maximum temperature, minimum temperature, mean temperature, wind speed, sunshine duration, relative humidity and pressure at 730 stations from 1951–2010 were obtained from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/home.do). Data with good quality at 588 stations from 1960–2009 (50 yr) were spatially interpolated to each of the 2410 counties in mainland China. The renewable water supply was estimated as a fraction (70 %) of daily rainfall available over cropland and a smaller fraction (30 %) of rainfall available from the non-cropped area in the county. This conceptually resembles the process one can model for bare soil evaporation, soil moisture dynamics and runoff generation, and is on average consistent with estimates from physically based models for these processes as applied to China (Feng et al., 2007; Wu, 2007). For computing agricultural water demands, data on harvested crops (total of 18 cultivation patterns are selected for the study) and the total cropland for each county in 1990 were obtained from the EOS-Earth data library (http://eos-earthdata.sr.unh.edu/data/data1.jsp). Estimates on the county level crop sown area and net crop area of most recent year were obtained based on the above dataset, data from the World Bank (http://data.worldbank.org/indicator/AG.LND.ARBL.ZS) and recent cropping pattern changes (changes are small, the largest change is less than 10 % at province level over the past 20 yr) illustrated by Sun (2008). The planting season for each crop in each part of the country were taken according to the FAO and some local farmers. The daily crop water

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requirements for various crops were estimated based on FAO recommended crop coefficients and reference crop evapotranspiration (FAO Penman–Monteith equation, 1990). Industrial water demands are obtained from the 2011 China water resources bulletins (http://www.mwr.gov.cn/zwzc/hygb/szygb/) at the province level. We also got industrial water demand at city level from the latest province specific water resources bulletins. Given industrial water demand at province or city level, we proportioned it among the counties in that province or city. Household water demand for each county was calculated using per-capita water consumption of 160 liters/day and the 2011 population census (http://www.stats.gov.cn/tjgb/rkpcgb/).

The water stress indices presented here were first developed and demonstrated in Devineni et al. (2013). They are based on the computation of the water storage capacity needed to meet the demand for a given sequence of supply (Lall and Miller, 1988; Thomas and Burden, 1963) accounting for temporal variation in supply and demand.

The basic steps for the computation of these two indices are presented below. For the jth geographical unit, define the following quantities:

$$\mathrm{deficit}_{j,t} = \max\ (\mathrm{deficit}_{j,t-1} + D_{j,t} - S_{j,t}, 0) \quad (1)$$

$$\mathrm{SIC}_j = \max_t\ (\mathrm{deficit}_{j,t}; \quad t = 1 : n \cdot 365) \quad (2)$$

$$\mathrm{SII}_j = \max_t\ (\mathrm{deficit}_{j,t(y)}; \quad t = 1 : 365; \quad y = 1 : n) \quad (3)$$

Where $\mathrm{deficit}_{j,t}$ refers to the accumulated deficit, $D_{j,t}$ to total water demand, $S_{j,t}$ to the total water supply volume, for geographical location j, and day t, and y to a calendar or cropping year. The corresponding normalized indices are simply:

$$\mathrm{NDC}_j = \frac{\mathrm{SIC}_j}{\mathrm{AP}_j}; \quad \mathrm{NDI}_j = \frac{\mathrm{SII}_j}{\mathrm{AP}_j} \quad (4)$$

Where AP_j is the average annual rainfall volume (district area · average depth of precipitation) for district j.

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The daily water deficit is defined as the difference between the daily water demand and the daily renewable water supply. The deficits are accumulated while setting negative accumulations to zero. The maximum accumulated deficit in a given year divided by the average annual rainfall across the historical period is the NDI for that year. Similarly the NDC is the maximum accumulated deficit for all 50 yr divided by the average annual rainfall.

The NDI is computed as one number for each year using historical daily rainfall data for the area and current daily water needs. It measures the maximum cumulated water shortage each year during the dry period that needs to be provided for from ground water or from surface water storage or transfers from other areas. The NDC is computed as one number over the historical climate record. It represents the largest cumulative deficit between renewable supply and water use over the entire period. Consequently, it reflects the stress associated with multi-year and within-year shortages at a location. With 50 yr of data, the 5th largest NDI value indicates that there is an approximately 10 % chance that water storage or transfers of that amount may be needed to meet demands at that location in any given year if multi-year droughts were not considered. The NDC indicates the worst case in 50 yr. A detailed description of the mathematical model along with applications and interpretation can be found in Devineni et al. (2013).

3 Results

3.1 Water supply and demand

Rainfall over China has significant variation across regions and across years as shown in Fig. 1. The coastal regions and the southeast are well endowed with precipitation with low inter-annual variability, while the northwest and parts of the North China have low average annual rainfall and high variations from year to year. Much of the country also experiences strong seasonality in rainfall. The monsoon occurs during June and September, and the rest of the year can be dry. Even within the monsoon season, there

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can be long periods of no rain, or monsoon breaks (Panchawagh and Vaidya, 2011; Yan and Wu, 2013), as well as periods of intense rainfall (> 10 cm day^{-1}) even in otherwise arid regions. In a monsoonal climate, one needs to account for the cumulative water deficit for meeting water needs, at least at a daily time step (at which rainfall data and crop water requirements are available), consistent with the farmer's decision making process to irrigate. The NDI and NDC presented here automatically account for the relative difference between average demand and supply over the accounting unit; and the temporal imbalance of supply and demand at a spatial resolution consistent with decision-making.

Figure 2 shows the current cropping pattern for 18 crops identified for this study as a percentage of county area in 2005. The high intensity cropping areas are mainly located in three regions: North China plain (Huang River, Huai River, and Hai River), northeastern plain (Songhua River, Liao River, and Heilongjiang River), and the Yangtze River plain in the middle and lower sections of the Yangtze River. It is notable that much of the dryland areas of the country that have intense agriculture also have a high inter-annual variability in rainfall manifest in the form of persistent droughts or floods. Irrigation from surface or groundwater water reserves is essential in this setting. The progression of intensive agriculture in these regions has led to groundwater depletion (Zheng et al., 2010). Figure 3 shows the water demand for agriculture, industry (including electric power), domestic and the total demand across all the sectors. The agricultural water demand is the sum total of the water requirement as estimated from FAO recommended crop coefficients and reference crop evapotranspiration for 18 crops in each county. High agricultural water demand emerges in South China and parts of Xinjiang. Rice, which is a water intensive crop, is dominant in these regions. Similarly, human settlement and industrial productivity tend to happen in abundant water supply areas (South China and coastland region) or where additional water needs can be easily met from accessible surface water sources, (e.g. Yangtze River Delta and Pearl River Delta in this case).

3.2 Intra-annual and multi-year water stress

The Intra-annual (NDI) and multi-year (NDC) water stress indices described above are computed for each of the 2243 counties (167 counties left black due to lack of sufficient matching data) in China using daily climate records from 1960 to 2009 and the most recent national statistics that inform the current water use attributes for agriculture, industrial, and domestic water withdrawals. The maximum of the Normalized Deficit Index (NDI.max, refers to the highest water stress in any year) and the Normalized Deficit Cumulated (NDC, refers to the inter-annual water stress over the whole period) are shown in Fig. 4a and b respectively. NDI or NDC less than 1 indicates that the magnitude of cumulative deficit is less than the average annual rainfall in the local area. NDI or NDC greater than 1 represents the case where the total shortage is greater than the average annual rainfall. The annual rate of consumption in these regions could also be higher than the average utilizable rainfall rates. From Fig. 4a we see that for the year with the worst deficit (this has a chance of happening once in 50 yr), most of the country has NDI < 1 indicating moderate storage requirements or water stress. As one considers persistence in climate beyond 1 yr, we see from Fig. 4b that the current use patterns portend severe stress over much of the North China plain, middle and lower of Yangtze River, as well as some most arid regions of Xinjiang. Chronic or multi-year stress consequently emerges as the concern in these areas with many locations requiring greater than 5 times the average annual rainfall in the location in storage or to be transferred from other locations to make it. Kashgar in Xinjiang province, located in western of Taklimakan desert has the highest NDI.max (10.6) and NDC (534). This county requires more than 10 times the average annual rainfall almost every year in the past 50 yr since the annual rainfall here is only 60 mm. Yarkant River is the main supplementary water source which maintains the development in this region. Another example is Jieshou county in Anhui province in the North China Plain, where water demand was always greater than renewable supply by 0.3 times of the local average annual precipitation (820 mm or so) over the 50 yr with NDI.max as 0.33 and NDC as

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13.4. Under these conditions, water storage structures and regional water transfers or groundwater pumping play a vital role in augmenting the surface water supply and groundwater recharge. Storage structures constitute one of the major interventions in the massive watershed development programs undertaken recently. If the objective of providing domestic water security is given the highest priority, and is not clubbed with irrigation or industrial requirements, most areas in China would probably come out as self-sufficient (Fig. 4c). If we remove industry, it would have little impact on the total water stress over China apart from Yangtze River Delta and Pearl River Delta (Fig. 4d).

A question that arises is whether there is an opportunity to better allocate the resources across sectors while reducing the overall water stress. The extremely low cost of water encourages the production of crops that are both low-valued and highly water intensive and leads to a disincentive to use water efficiently. While changes in agricultural practices to more efficient techniques would reduce water stress, for a substantial reduction in water stress and effective water allocation across all sectors, one has to explore large scale ideas such as spatial readjustment of crops coupled with dynamic agricultural market mechanisms that are informed by climate. An investigation into the causal mechanisms of such climate induced stress and the ability to develop prognostic climate information based forecasts of the risk up to 6 months ahead could serve as a means to manage regional water allocation through more effective demand and supply management.

3.3 Spatial distribution of cross year water stress and detection of monotonic trends

For each county we developed a map that describes the regions susceptible to persistent shortage resulting from natural variations in climate and existing demand. This is illustrated in Fig. 5. The counties shown in blue have NDC equal to the maximum NDI achieved in any given year, i.e., multi-year shortages do not have an impact worse than that of the driest year on record. This could either be due to the absence of long droughts or due to a relative level of demand that is low enough to not require storage

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across years. Shangcheng County in Henan province had the highest NDC (equal to NDI.max) in the blue category. The most severe water shortage in this region occurred in 2001 and is 0.24 times of local average annual precipitation. The counties marked in yellow have NDC greater than the max NDI, and for the ones marked in red the NDC is more than ten times the max NDI, indicating that multi-year deficit or chronic impacts can be particularly severe. In these cases demand reduction may be particularly beneficial unless a high amount of storage or diversion is available. The red regions reflect demands that exceed total endogenous supply and reflect locations where groundwater mining or imported water is necessary to meet existing demands. These regions are in the North China plain, middle and lower of Yangtze River, Western Xinjiang Province and the Pearl River Delta which have massive storage structures and excessive groundwater extractions.

Based on the 50 yr (1960–2009) time series of NDI estimates we explored the monotonic trends in the incidence of deficits using the Mann–Kendall non-parametric trend test (Mann, 1954; Helsel and Hirsch, 1992). The Mann–Kendall test is a rank based test that is used for detecting trends in extremes with no assumption of the underlying distribution of the data. Figure 6 shows the results from the test for each county. The counties colored red indicate that the NDI has an increasing trend that is statistically significant at the 95 % confidence level. Similarly, the counties colored green have a decreasing trend in NDI that is statistically significant at the 95 % confidence level. The rest of the counties in white have no statistically significant trends. The large contiguous areas with decreasing trends in NDI, which reflect reduced persistence in dry days, are in western China and the Yangtze River basin. Wang et al. (2006) reported increasing rainfall trends in these regions. However, most parts of the North China plain, the most severely stressed region, did not show the sign of deficit reduction.

In addition to the above analyses, we also compare our stress indices (NDI and NDC) to the average water stress measures (i.e. the ratio of average use to average supply) (e.g. Oki et al., 2001; Alcamo et al., 2003) in Fig. 7. The motivation here is to understand the relation between average stress and multiyear stress across the country, and also to explore the opportunity of deriving an empirical relationship that can provide reasonable approximations to climate induced water stress (NDI or NDC) from simple estimates of average supply and average demand thereby avoiding the need for detailed data on all the variables to compute NDC. This will be particularly useful for developing and understanding the real water stress globally using minimal data requirements. We can see that, in areas where average value of NDI is greater than 0.1, the maximum NDI tends to be greater than 0.3 and NDC tends to be greater than 3. In other words, if magnitude of average stress is more than a tenth of mean annual rainfall volume, these counties typically experience a multiyear stress (as computed by NDC) and the cumulative deficit would exceed three times the mean annual rainfall. Similarly, in areas where average stress is greater than 0.3, the maximum NDI tend to be greater than 0.7 and NDC tends to be greater than 15 indicating huge stress. Thus, water stress across years has a non-linear relation with average stress.

4 Discussion and summary

We provide an illustration of water stress over China through presenting the cumulative deficits indices between water demand and water supply and demonstrate that rainfall variability is an important factor for quantifying water stress in a region and for the storage required to reliably meet the current demands. For climate informed analyses of water stress, the index emphasizes that the climate information needs to properly represent the time sequence of supply and demand, and not just average seasonal or annual values, to be of value for decision making. By estimating water needs over seasonal dry spells and across decades, and comparing it with actual rainfall, we find that majority of the areas, which contributes to the food security of the country face chronic stress. Most of these regions, like the North China Plain are also the most agriculturally productive regions. As questions loom over the success of the much acclaimed “South Water to North” project, the additional deficit is being met through groundwater, which

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contributes significantly to the irrigation needs. The region also has heavily subsidized energy prices which lead to a disincentive to improve water use efficiency.

The impact of the South to North water transfer project on the space and time distribution of water stress was not analyzed here. However, a formal consideration of such large scale transfers in the context of the formulation of a policy for institutionalizing water reallocation would better inform the water crisis and its solution. It is well known (Brown and Lall, 2006) that reducing water supply variability through storage can enhance water security, agricultural productivity and economy. For Jieshou County, in Fig. 8, the 50th and 90th percentiles of the NDI are identified as the reference for water storage required meeting the needs at the 50 % and 90 % reliability levels respectively. The probability distribution of stress (storage needed) would also allow consideration of formal risk management strategies or risk exposure analysis relative to existing utilizable storage in an area, offering a new financial risk management option. Since there is much interest in scenarios for future sustainability, one would need plausible daily climate realizations for the future, in conjunction with scenarios for water use. Each of these is feasible to develop under appropriate assumptions, and could be pursued to develop IPCC style scenarios for supply and demand (e.g., assuming conservation programs, or changes in spatial crop allocation), and one could report the storage needed assuming different levels of reliability. Likewise, trade-offs between food and water storage strategies could be examined in a probabilistic framework. This would be very useful as indicators of each region to provide a scientific basis for the water resources allocation. One could also pursue crop allocation optimization at a national scale considering food storage, and water storage as decision variables targeting desired reliability levels and contingency strategies to cover potential failures in food security. Similarly, micro-modification in the distribution of industry can also be done to relieve water stress according to industrial water consuming pattern.

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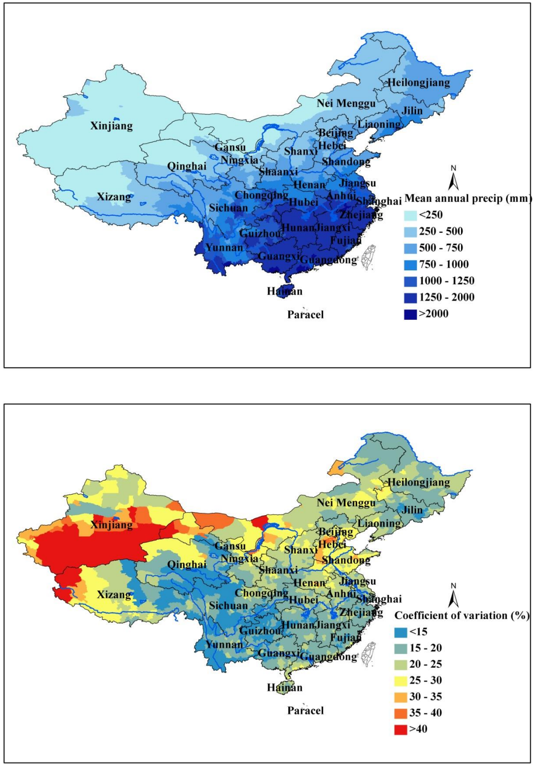

Fig. 1. Mean annual precipitation in mm/year and the associated coefficient of variation as % deviation from the mean.

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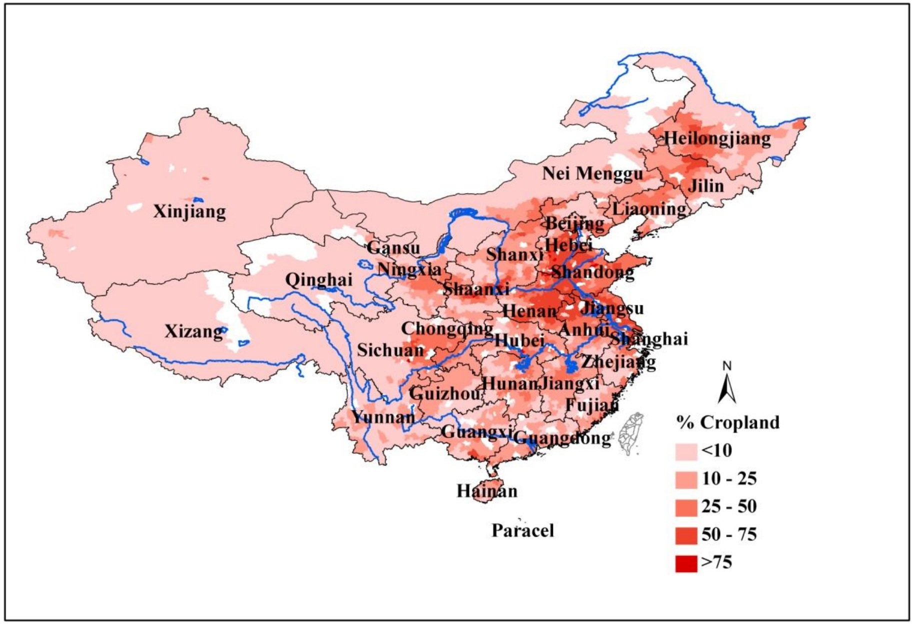

Fig. 2. Current China cropping pattern as net cropped area/county area.

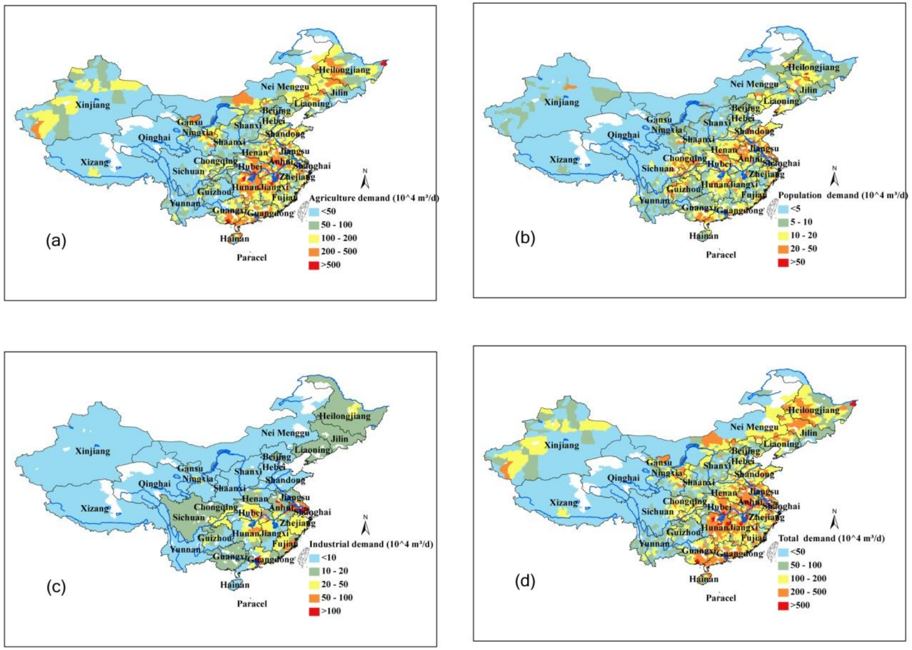

Fig. 3. Average daily water demand (agriculture, population, industry and total demand) for China in most current year at county level.

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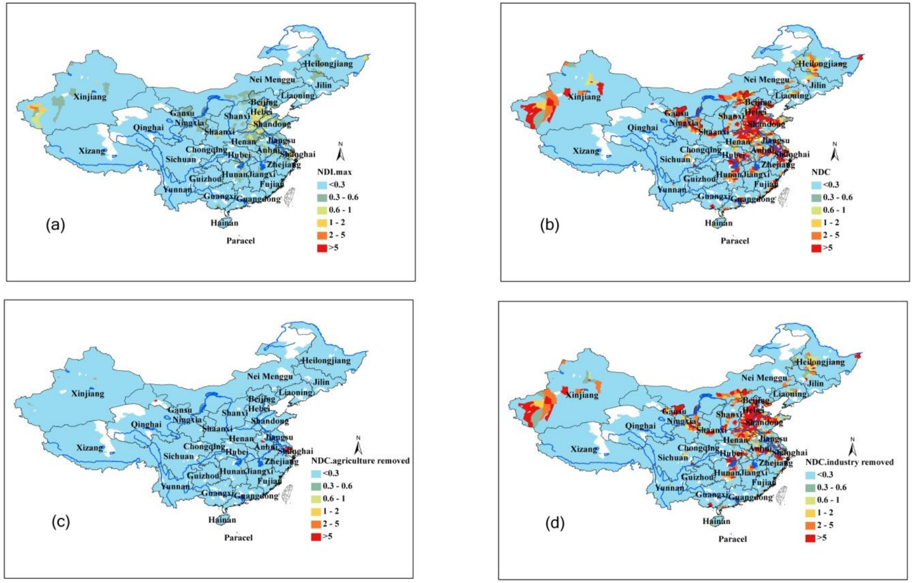

Fig. 4. Magnitude of water stress across China under within year (NDI.max for maximum of NDI, **a**), multiyear cumulative water stress analysis (NDC for total water demand, **b**; NDC.agriculture removed for water stress when agriculture water demand was removed, **c**; NDC.industry removed for water stress when industry water demand was removed, **d**) for 1960–2009 daily supply and demand data (the magnitude 0.3 means that this county need 3 month rainfall volume to fill up the accumulative water deficits, similar, the magnitude 5 means that this county need 5 yr rainfall volume to fill up the accumulative water deficits).

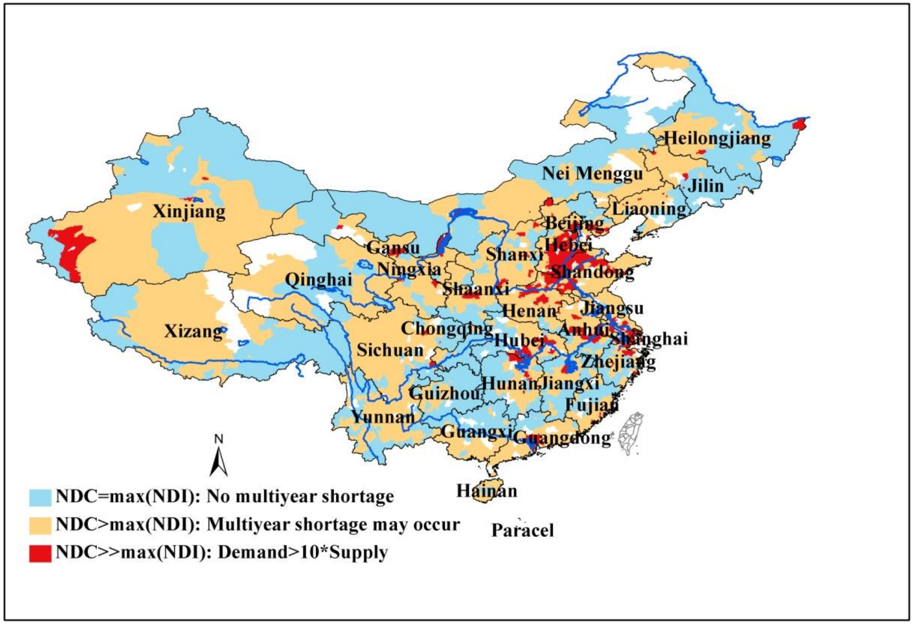

Fig. 5. Spatial categorization of the magnitude and distribution of water deficit risks in China. Blue: multi-year stress = worst single year stress. Yellow: multi-year stress is higher. Red: demand exceeds average annual endogenous supply in the county.

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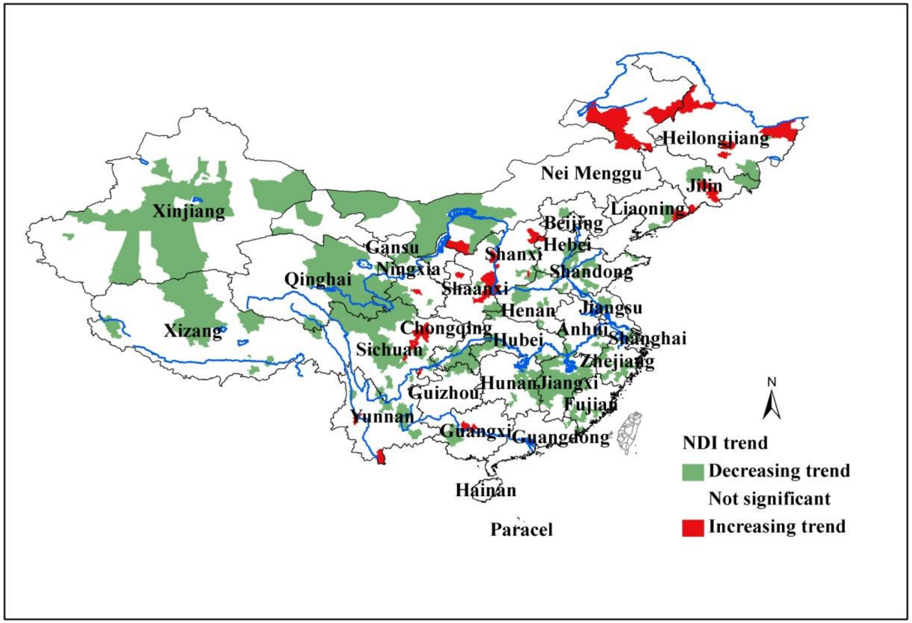

Fig. 6. Time Trends in Water Stress (Significance level = 95 %).

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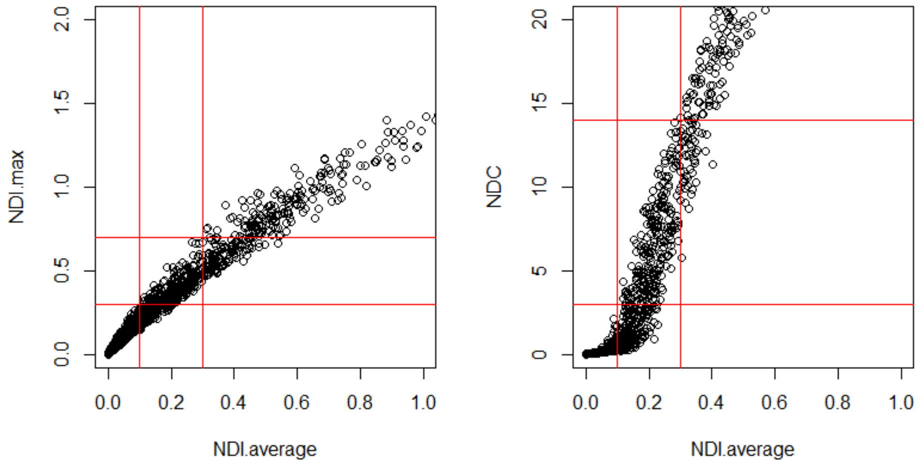

Fig. 7. The statistic relationship between average NDI, maximum NDI and NDC (the mark means how much water volume does this county need to fill up the accumulative water deficits, 0.3 means 3 months rainfall volume in that county, 5 means 5 yr rainfall volume in that county).

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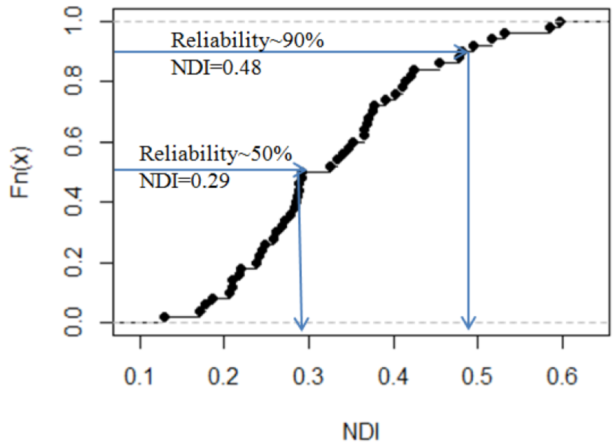

Fig. 8. Cumulative distribution function using the 50 yr of NDI for Jieshou County (NDC is 13.4, located in Anhui province). The 50th and 90th percentiles are highlighted.