Trends in Extreme Drought in China and Its Impact on Urban Water Stress (Postprint)

Authors: Lu Yongqing, Yan Yan, Ding Ding, Zhao Chunli, Song Yang, Zhao Jingzhu

Date: 2018-03-08T00:00:00+00:00

Abstract

With global climate change and alterations in the water cycle, the frequency and intensity of extreme weather events such as uneven precipitation and persistent drought have increased, exerting significant impacts and pressure on water resources, particularly in cities with high population and socioeconomic density. To investigate the changing trends and regional characteristics of drought in China and its impacts on urban water resources pressure, this study employs a daily precipitation dataset from 917 meteorological stations nationwide spanning 1951–2014 to analyze the temporal trends and spatial distribution characteristics of water resources and drought in China. Furthermore, taking 289 major prefecture-level cities as research subjects, we construct an urban water resources pressure assessment methodology based on regional precipitation endowments under climate change scenarios, and project future urban water resources pressure conditions across different time periods and Representative Concentration Pathway (RCPs) scenarios. The results indicate that extreme drought conditions in China have generally increased with global climate change, with the average rate of change in annual maximum consecutive dry days being 2.3 days per 100 years; however, this trend exhibits regional heterogeneity, specifically manifesting as alleviated drought in southern regions and intensified drought in northern regions. Urban water resources pressure in China is influenced by water resource endowments, exhibiting a distribution pattern of high pressure in the north and low pressure in the south. Additionally, large cities with high water consumption also face relatively greater resource pressure. With climate change, overall urban water resources pressure in China in the near term has increased by approximately 2% relative to the current stage. Specifically, water resources pressure has risen in 170 cities, decreased in 110 cities, and the remaining 9 cities have experienced relatively minor impacts from climate change on water resources pressure. Urban water resources pressure under the low-mitigation RCP8.5 scenario is substantially higher than that under the RCP2.6 scenario, demonstrating that climate change mitigation efforts have a positive effect on reducing urban water resources pressure in China. The changes in urban water resources pressure are not uniform, showing a trend of decrease in the south and increase in the north. Cities in North China face the greatest water resources pressure, which continues to increase over time with climate change. This necessitates proactive government action to propose targeted and forward-looking water resources planning schemes and implement measures accordingly to address the increasing urban drought caused by climate change.

Full Text

Preamble

ACTA ECOLOGICA SINICA ChinaXiv Partner Journal
Vol. 38, No. 4, Feb. 2018
DOI: 10.5846/stxb20170711248

Drought Trends and Their Impacts on Urban Water Resource Pressures in China

Lu Yongqing, Yan Ying, Ding Di, Zhao Chunli, Song Yang, Zhao Jingzhu

State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
University of Chinese Academy of Sciences, Beijing 100049, China
Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China

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Abstract

As global climate change progresses, regional precipitation variability and extreme weather events such as droughts have increased in both frequency and intensity, exacerbating water resource shortages—particularly in cities with high population and socioeconomic densities. To investigate drought trends in China and their impacts on urban water resources, we analyzed daily precipitation data from 917 meteorological stations spanning 1951–2014, examined 289 major prefecture-level cities, and developed an evaluation method for urban water resource pressure based on regional precipitation endowment under climate change scenarios. We projected future urban water resource pressures across different time periods and Representative Concentration Pathway (RCP) scenarios.

Our results demonstrate that extreme drought conditions in China are generally increasing with global climate change, with the average rate of change in annual maximum consecutive dry days being 2.3 days per 100 years. However, these trends exhibit strong regional heterogeneity: drought conditions have actually improved in parts of southern China, while becoming more severe in western and northern regions. Water resource pressures are greater in northern cities than in southern cities due to declining precipitation from coastal to inland areas. Metropolises face higher water resource pressures than other areas because of large water consumption by urban populations and active economic activities.

Projections indicate that overall urban water resource pressure in China will increase by approximately 2% after 20 years relative to present conditions. Specifically, 170 cities will experience increased pressure, 110 cities will see decreased pressure, and only 9 cities will remain insensitive to climate change impacts on precipitation. Pressures under the high-emission RCP8.5 scenario are substantially heavier than under the low-emission RCP2.6 scenario, demonstrating that climate change mitigation is beneficial for sustaining urban water supplies. Water resources in North China are projected to decline under future climate change due to reduced precipitation and high consumption. Governments should focus on cities in such areas to adopt prospective policies and formulate implementation plans to ensure that water supply does not limit economic development.

Keywords: urban; climate change; water resources pressure; drought

Introduction

Global climate change significantly impacts the global and regional water cycle, intensifying spatiotemporal precipitation heterogeneity and aggravating drought conditions in some regions [1-2]. China, with its large population and severe water pollution, has a per capita water resource availability of less than 2,500 m^3—only one-quarter of the world average—making it a relatively water-scarce country [3-4]. Compared to rural areas, cities experience amplified losses from drought disasters due to dense economic activity and population concentrations [5-6]. Urban drought reduces river flows, lowers groundwater tables, triggers water use conflicts, and deteriorates personal and environmental sanitation. Coastal cities additionally face saltwater intrusion [7-9]. Drought also diminishes firefighting capacity, increases infectious disease outbreak risks, and causes urban power shortages, affecting residents' production, living conditions, and health [10-11].

China has experienced numerous severe droughts, with affected regions expanding from rural to urban areas and losses becoming increasingly serious [12]. For instance, 1991 and 2009 were years with particularly severe drought conditions, with 111 cities facing water supply shortages and affected populations reaching 52.75 million [5]. As China' s economy develops and urbanization progresses—coupled with global climate change—drought is intensifying in some cities, creating new challenges for ensuring water supply security [13-15].

Research on water resource pressure indices has been extensive. Early studies defined water resource pressure index based on per capita water availability, later establishing supply-demand pressure indices to explore actual water scarcity from regional consumption patterns, and subsequently developing new water security evaluation indices that incorporate water quality and safety [16-20]. These indices facilitate multi-faceted consideration of regional water resource pressures, providing more accurate support for water resource planning. This study focuses on climate change impacts on urban water resource pressure, using regional precipitation to calculate water pressure and compare relative differences across cities to support targeted mitigation efforts.

While cities partially rely on river water and other transboundary water sources, the quantity of such sources is closely related to local climate conditions and geographic location. Precisely measuring transboundary water requires high data demands and technical complexity to clarify interaction processes among these factors. Therefore, using precipitation to measure regional water resource endowment simplifies the spatial scale of water balance accounting. Precipitation-rich regions typically have dense river networks and abundant groundwater, while arid regions have sparse river networks and limited groundwater. Thus, precipitation reasonably abstracts urban water resource endowment and reduces data requirements.

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1. Research Data and Methods

1.1 Research Data

This study utilizes meteorological data and urban statistical data. Meteorological data comprise daily precipitation datasets from 1951–2014 provided by China' s Meteorological Data Center, screened to include only stations with less than 10 days of missing data annually. The study examines 289 major prefecture-level cities in China. Urban statistical data include total urban water supply and municipal district area from the *China Urban Statistical Yearbook*.

1.2 Meteorological Factors

Drought is defined as a prolonged period with no or little rainfall, causing water shortages that lead to economic losses and threaten personal safety [21]. We use annual total precipitation and annual maximum consecutive dry days to characterize regional water resources and drought conditions [22]. Annual total precipitation reflects the precipitation level of a region, indicating drought conditions absent human influence. Annual maximum consecutive dry days reflects the extreme drought level of a city.

1.3 Relative Change Rate of Annual Maximum Consecutive Dry Days

We employ univariate linear regression to calculate the changing rate of annual maximum consecutive dry days under climate change, expressed as:

$$d = a + bx$$

where d represents the maximum consecutive dry days in year i, x is the year, b is the changing rate (days/year), and a is the intercept.

The changing rate b is calculated as:

$$b = \frac{\sum(x_i - \bar{x})(d_i - \bar{d})}{\sum(x_i - \bar{x})^2}$$

The relative change rate of annual maximum consecutive dry days, calculated from the changing rate and average values, represents the relative intensity of climate change impacts on extreme drought compared to normal drought levels:

$$\text{Relative Change Rate} = \frac{b}{\bar{d}}$$

where $\bar{d}$ is the multi-year average of annual maximum consecutive dry days.

1.4 Inverse Distance Interpolation Analysis

We use inverse distance interpolation to obtain spatial distributions of meteorological factors. Based on the first law of geography, this method uses the inverse distance to the power of 2 as weights for weighted averaging.

1.5 Urban Water Resource Pressure Assessment and Projection

Precipitation-Based Urban Water Resource Pressure Index Urban water resources primarily include groundwater and river water. In regions with high precipitation, both river network density and groundwater volume are abundant, whereas low-precipitation regions have scarce river flow and groundwater storage. Therefore, regional precipitation can reflect water resource endowment [23]. Both surface water and groundwater originate from precipitation. Given the complexity of factors affecting actual urban water availability (e.g., regional precipitation patterns, water cycle processes, upstream-downstream relationships, seasonal variations), we directly use urban precipitation to measure water resource endowment, simplifying the spatial scale of water balance accounting.

Based on annual precipitation data, total water supply, and municipal district area from the *China Urban Statistical Yearbook*, we calculate the precipitation-based urban water resource pressure index:

$$P = \frac{W}{R \times A}$$

where P is the water resource pressure index, W is total urban water supply (m^3), R is annual precipitation (mm), and A is municipal district area (km^2). This index reflects long-term water resource pressure.

Extreme Drought Water Resource Pressure Index Beyond regional precipitation impacts, temporal precipitation distribution significantly affects water resource pressure. If precipitation were absolutely uniform temporally (daily precipitation), water resource pressure would remain at baseline levels. However, if precipitation is concentrated and dry periods far exceed national averages, water resource pressure increases substantially. During droughts, more severe and prolonged dry spells cause exponentially greater economic and public health losses. An exponential relationship better describes how consecutive droughts affect urban water resources.

We modify the water resource pressure index by standardizing the annual maximum consecutive dry days using the sample mean across all cities to ensure appropriate magnitude:

$$P_{\text{extreme}} = P \times e^{\frac{d-\bar{d}_{\text{all}}}{\bar{d}_{\text{all}}}}$$

where d is the city' s multi-year average of annual maximum consecutive dry days, and $\bar{d}_{\text{all}}$ is the sample mean across all studied cities.

Climate Change Impact Assessment and Projection Beyond current climate conditions, future climate change impacts on urban water resource pressure cannot be ignored. We project urban water resource pressure for near-term (2030) and long-term (2050) periods under different RCP scenarios.

Since climate change trends are continuous but anthropogenic influences create uncertainty, we assume near-term extreme drought changing rates remain consistent with current rates. For projections, we use Representative Concentration Pathways (RCPs) from IPCC AR5 [25], specifically the low-mitigation RCP2.6 scenario (0.68°C/100yr global temperature rise) and high-emission RCP8.5 scenario (6.59°C/100yr).

Assuming future extreme drought changing directions remain consistent with current patterns but accelerate proportionally with global temperature rise, the relative change rate under RCP scenarios is:

$$\text{Relative Change Rate}_{\text{RCP}} = \text{Relative Change Rate}_{\text{current}} \times \frac{\text{Temperature Rise Rate}_{\text{RCP}}}{\text{Temperature Rise Rate}_{\text{current}}}$$

Future water resource pressure indices are then:

$$P_{\text{future}} = P \times e^{n \times t \times \text{Relative Change Rate}_{\text{RCP}}}$$

where n is the projection time horizon (years) and t is the temperature rise ratio.

Water Resource Pressure Classification To demonstrate relative differences among cities, we use continuous color scales for mapping to reflect regional distribution patterns. All water resource pressure indices are divided into five equal intervals for classification.

2. Spatial Distribution and Trends of Precipitation and Drought in China

Annual precipitation in China shows a northwest-to-southeast gradient, with higher precipitation in the southeast and lower in the northwest, forming a distinct stepwise pattern. The distribution of annual maximum consecutive dry days shows the opposite pattern, with high-latitude and Yangtze River basin regions having relatively uniform precipitation and the lowest dry day counts. Although southern coastal regions have abundant precipitation, pronounced wet and dry seasons make them vulnerable to drought. The highest dry day counts occur in northwestern China and the Tibetan Plateau, followed by Hebei and the Sichuan Basin.

Overall drought conditions are increasing, with the national average rate of change in annual maximum consecutive dry days at 2.3 days per 100 years. However, changes are spatially heterogeneous, generally decreasing in the south and increasing in the north. The fastest increases occur in southern Tibet, Guangdong, and Shandong, while decreasing trends are most evident in the Sichuan Basin, lower Yangtze River, northeast China, and Xinjiang.

The relative change rate of annual maximum consecutive dry days similarly shows a south-low, north-high pattern. Except for Guangdong where extreme drought increases significantly with climate change, most southern regions show decreasing extreme drought. In northern China, except for northeast and northwest where extreme drought mitigation is evident, other areas have high relative change rates. The largest increase rates concentrate in southern Tibet, indicating strong climate change impacts, while the largest decrease rates occur in the Yangtze River basin, showing maximum mitigation effects.

[Figure 1: see original paper] Extreme drought conditions and trends in China during 1951–2014: (a) Average annual precipitation distribution; (b) Average annual maximum consecutive dry days distribution; (c) Extreme drought changing rate; (d) Relative change rate of extreme drought.

3. Urban Water Resource Pressure in China

Precipitation-based urban water resource pressure shows a south-low, north-high pattern, with the highest pressures concentrated in the North China Plain and eastern coastal regions. After accounting for extreme drought conditions, water resource pressure becomes more pronounced, particularly in northwestern inland areas. This occurs because regions with high precipitation generally have shorter consecutive dry periods, while western regions with low precipitation experience longer dry spells.

The difference between precipitation-based and extreme-drought-adjusted pressure is particularly large in the Sichuan Basin and parts of Yunnan, where precipitation is temporally concentrated despite being in humid zones, leading to high water resource pressure during droughts.

Under climate change, urban water resource pressure is projected to increase overall by 2030, with 170 cities experiencing increased pressure, 110 cities seeing decreased pressure, and 9 cities showing little change. The spatial distribution remains similar to current patterns, but with more severe increases in North China and Guangdong. In the RCP2.6 scenario, climate change mitigation significantly alleviates extreme drought in most of southern China, greatly reducing water resource pressure. However, North China and Guangdong still face increasing pressure, particularly large cities with high water consumption.

Under the more severe RCP8.5 scenario, overall water resource pressure increases more substantially, with the most significant increases still concentrated in North China and Guangdong. Notably, Guangdong—originally with good water endowment—will become one of the regions with highest water resource pressure.

[Figure 2: see original paper] Urban water resource pressure in China: (a) Precipitation-based water resource pressure index; (b) Extreme drought water resource pressure index; (c) Near-term urban water resource pressure index; (d) Long-term urban water resource pressure index under RCP2.6 scenario; (e) Long-term urban water resource pressure index under RCP8.5 scenario.

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4. Conclusions and Recommendations

This study reveals that China' s water resource endowment follows a southeast-high, northwest-low stepwise distribution. Although western cities have scarce water resources, their water consumption is relatively low and prefecture-level city density is low, resulting in concentrated water resource pressure in North China. Northern China' s extreme drought shows increasing trends with climate change, while southern China shows opposite trends.

Beyond precipitation endowment, urban development itself creates water supply shortages that significantly impact water resource pressure, as evidenced by metropolitan areas having substantially higher pressure levels than surrounding cities. After accounting for extreme drought, the south-low, north-high distribution of urban water resource pressure becomes more pronounced, as pressure increases exponentially with drought duration. Additionally, the Sichuan Basin and Yunnan—though in humid zones—experience high water resource pressure due to temporally concentrated precipitation.

Projections indicate that by 2030, overall urban water resource pressure will exceed current levels, with particularly notable increases in North China and Guangdong. Under the RCP2.6 scenario, water resource pressure distribution remains similar to current patterns, but climate change mitigation alleviates pressure in southern China, especially reducing pressure in the Sichuan Basin. Under the more extreme RCP8.5 scenario, overall water resource pressure increases more dramatically, with North China and Guangdong showing the most severe increases. Guangdong, originally well-endowed with water resources, will become one of the highest-pressure regions.

For regions where extreme drought shows significant increasing trends with climate change, governments should prioritize urban water crisis management, recognize climate change hazards to urban water supply, and adopt proactive, targeted measures to ensure normal water supply capacity. Policies should be formulated based on regional urban development patterns and relative climate change levels.

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