Impacts, Causes and Countermeasures of Extreme Drought in Poyang Lake: Postprint

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Abstract

Under changing environmental conditions, the hydrological regime of Poyang Lake has undergone significant adjustments over the past two decades, characterized by continuously declining water levels and a severe aridification trend. In 2022, Poyang Lake experienced an extreme drought event, with water levels reaching a historic low. The extreme drought in Poyang Lake has exerted significant impacts on the socio-economy and ecological environment of the lake region, drawing high-level attention and widespread concern from both government and society. This article analyzes the impacts and causes of drought in Poyang Lake based on long-term meteorological and hydrological data analysis, existing research findings, and hydrological prediction simulations, and proposes corresponding countermeasures and recommendations.

Full Text

Impacts, Contributing Factors and Countermeasures of Extreme Droughts in Poyang Lake

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Abstract

Over the past two decades, the hydrological regime of Poyang Lake has undergone significant alteration under a changing environment, characterized by continuously declining water levels and a severe trend toward aridification. In 2022, Poyang Lake experienced an extreme drought event, with water levels reaching a historic minimum. This extreme drought has profoundly impacted the regional economy, society, and ecological environment, drawing substantial attention and widespread concern from both government and the public. Based on long-term meteorological and hydrological data series, existing research findings, and hydrological prediction modeling, this study analyzes the impacts and contributing factors of drought in Poyang Lake and proposes corresponding countermeasures and recommendations.

Keywords: climate change, extreme droughts, synergistic regulation of hydraulic engineering, water safety, Poyang Lake

Introduction

Poyang Lake is the largest freshwater lake in China, with an average maximum water surface area of 2,818 km^2 and a maximum storage capacity of 1.32×10^{10} m^3 [1]. As a critical river-connected lake in the middle reaches of the Yangtze River, the lake drains a catchment area of 162,000 km^2. According to measured runoff data from hydrological stations provided by Jiangxi Province, the average annual discharge from Poyang Lake into the Yangtze River during 1960–2022 was 1.47×10^{11} m^3, accounting for 16.7% of the runoff at the Datong hydrological station in the lower Yangtze. The lake contains high-quality water resources and serves as a strategic water source for the middle and lower Yangtze region. Poyang Lake also harbors rich biodiversity and provides critical habitat for numerous rare species, including an average of 340,000 migratory birds that overwinter there annually [2]. The lake is also an important habitat for the "smiling angel" Yangtze finless porpoise, with approximately 500 individuals residing in the lake—nearly half of the total Yangtze River population. Both national and local authorities have prioritized ecological conservation of Poyang Lake.

On April 26, 2018, President Xi Jinping stated at the symposium on promoting the development of the Yangtze River Economic Belt that "the ecological and environmental situation of the Yangtze River remains severe" and that "the Yangtze River's 'two kidneys'—Dongting Lake and Poyang Lake—frequently dry up, with nearly 30% of important lakes and reservoirs remaining in a eutrophic state." Since 1983, Jiangxi Province has implemented the "Mountain-River-Lake" project, which adopts a systematic approach to coordinate the relationships among "catchment—Yangtze River—lake" and has achieved positive results in water source conservation, water quality protection, and ecological conservation in Poyang Lake.

Over the past 20 years, under the influence of global climate change and intensive human activities such as water resource development, the river-lake relationship in the middle Yangtze has continuously adjusted, and the hydrological regime of Poyang Lake has undergone profound changes. These changes are primarily manifested as: the lake entering the dry season earlier, prolonged dry periods, rapid water level decline during dry seasons, and record-low water levels showing signs of increasing aridification [3-6]. Climate change has triggered extreme hydrological events in the Poyang Lake basin. In 2020, the Yangtze River experienced an extraordinary flood that approached the scale of the catastrophic 1998 flood in both duration and intensity, affecting 6.733 million people across the basin, inundating 742,000 hectares of crops, causing complete crop failure on 192,000 hectares, and resulting in approximately 31.33 billion yuan in direct agricultural economic losses. In 2022, the Yangtze River basin experienced a historically rare "dryness during flood season" event. On September 23, 2022, the water level of Poyang Lake dropped to 7.1 m (Wusong elevation), marking a record low since observations began in 1951. The lake area shrank to 244 km^2 with a storage capacity of only 7.8$\times10^{8}$ m^3, leaving the lake nearly completely dry [Figure 1: see original paper]. By the end of October 2022, drought conditions necessitated assistance for over 407,000 people in Jiangxi Province, including more than 19,000 experiencing drinking water difficulties, affecting 530.6 million people across 1,504 townships and causing severe ecological damage [7]. Throughout 2023, water levels in Poyang Lake remained persistently low, averaging 2.6 m lower than the same period (January–August) during 1953–2022. On July 20, 2023, the water level at the Xingzi representative station dropped to around 12.0 m, signaling the early onset of the dry season for Poyang Lake [Figure 2: see original paper], making 2023 the earliest dry season on record—103 days earlier than the historical average and 15 days earlier than 2022.

This study analyzes the impacts and causes of hydrological drought in Poyang Lake based on measured meteorological and hydrological data from Jiangxi Province during 1960–2022, and proposes corresponding countermeasures and recommendations.

1. Characteristics of Historical Extreme Water Level Changes in Poyang Lake

The trend of water level changes in Poyang Lake shifted significantly around the year 2000. Using the Xingzi station as a representative site, analysis of annual maximum and minimum water levels from 1960–2022 reveals distinct patterns in anomalies and cumulative anomalies [Figure 3: see original paper]. Annual maximum water levels experienced regime shifts in 1987, 1999, and 2014. The period 1960–1987 showed a non-significant decreasing trend ($p>0.05$), 2000–2014 exhibited a significant decreasing trend ($p<0.01$), while 1988–1999 ($p<0.01$) and 2015–2022 ($p<0.05$) showed significant increasing trends. The trend for annual minimum water levels was more pronounced, with significant increases during 1980–2003 ($p<0.01$) and significant decreases during 1960–1979 and 2004–2022

($p<0.01$).

Since the 21st century, anomalies in maximum water levels have alternated between positive and negative values, fluctuating around the 1960–2022 mean of 19.22 m. In contrast, anomalies in minimum water levels have predominantly been negative, with cumulative anomaly curves declining—indicating persistently decreasing minimum water levels. In 2022, the minimum water level anomaly reached a historic low of -1.48 m, with the actual minimum water level dropping to 6.48 m, which is 1.48 m lower than the 1960–2022 average of 7.96 m and below the previous record low of 7.11 m (recorded on February 4, 2004). Analysis of return periods for minimum water levels before and after 2003 shows that the 100-year low water level decreased from 7.59 m to 7.15 m, indicating an increasingly severe low-water trend over the past two decades.

Following the operation of the Three Gorges Project in 2003, the onset of the dry season in Poyang Lake (defined as water level below 12 m at Xingzi station) advanced from early November to early October—approximately one month earlier.

2. Typical Drought Events in Poyang Lake and Their Impacts

Poyang Lake has experienced numerous severe high-temperature drought events throughout its history. During July to mid-August 2013, anomalously strong and northward-shifted Western Pacific Subtropical High (hereinafter referred to as "WPSH") caused the rain belt to move northward, resulting in high temperatures and low rainfall over the Poyang Lake basin. Drought conditions persisted until late August. In 2019, severe autumn-winter continuous drought also occurred, with annual rainfall close to the multi-year average but extremely unevenly distributed—rainfall from August to December accounted for less than 20% of the annual total. Since the 21st century, the frequency and severity of droughts in Poyang Lake have increased. Operation of large upstream reservoirs in the Yangtze River has caused channel degradation of the main stem, lowering water levels and significantly weakening the backwater effect on Poyang Lake, leading to reduced storage. Additionally, since 2000, when sand mining was banned in the main Yangtze channel, extensive mining shifted to Poyang Lake, causing channel incision in the northern river-connected section and enhancing the lake' s drainage capacity, thereby increasing outflow. Under climate change, human activities have exacerbated drought conditions in Poyang Lake [8].

Droughts have caused substantial impacts on Jiangxi Province, a major agricultural region. Based on factors including affected crop area, complete crop failure area, affected population, and direct economic losses from 1978–2022, the most severe drought years were 1978, 1986, 1991, 2003, 2007, 2011, and 2019 . The year 1978 ranked last in annual rainfall for the 1960–2022 period [Figure 4: see original paper] and consequently caused the most severe agricultural damage. The year 2003 incurred the largest direct agricultural economic losses due to a typical summer-autumn-winter continuous drought. From late June to early September 2003, over half of Jiangxi' s counties experienced daily maximum temperatures exceeding 40°C, with rainfall 40% below historical averages. This high-temperature, low-rainfall period coincided with critical growth stages for early rice (grain filling) and late rice (seedling development), causing severe agricultural damage. Although the 2022 drought set a new record for lowest water levels [Figure 4: see original paper], it did not cause the most severe agricultural economic losses due to: (1) improved construction and operation strategies of basin water conservancy projects—by early July 2022, medium-sized reservoirs in the Poyang Lake basin had storage rates of 84%, providing some drought relief, and upstream Yangtze River reservoirs repeatedly increased outflow to supplement downstream water, effectively raising main stem water levels and alleviating drought; and (2) continuous optimization of crop planting structure. According to the "Jiangxi Province Rice Industry Development Survey," rice planting patterns changed significantly from 1980–2021, with the area planted to medium rice and single-crop late rice increasing more than threefold by 2021, reaching 27.5% of total rice area. The irrigation period for these crops avoids the peak water demand period of August–September, thereby reducing agricultural economic losses [7,9].

Drought has also significantly impacted the lake's ecological environment. First, overwintering migratory birds depend on the extensive floodplain wetlands that contain numerous dish-shaped lakes as critical habitats. Remote sensing monitoring shows that in mid-July 2022, dish-shaped lakes larger than 1 km^2 had a total water surface area of 930 km^2, but by early August, the number of dish-shaped lakes decreased by 36% and their total storage area shrank by 86% [7], substantially reducing habitat area for overwintering birds. Second, declining water levels in dish-shaped lakes reduce hydrological connectivity, leading to increased spatial variation in water quality and deterioration [10]. Third, falling lake levels compress the living space for aquatic organisms, causing mortality among fish, mussels, and benthic organisms. According to the "Bulletin of Aquatic Biological Resources and Habitat Conditions in the Yangtze River Basin," fish resource abundance in Poyang Lake in 2022 decreased by approximately 6.3% compared to 2020 [11]. Fourth, groundwater in floodplains is a crucial water source for wetland vegetation. Lake drought increases groundwater depth in floodplain wetlands, causing the living space of submerged vegetation to be severely encroached upon by mesophytic plant communities. Vegetation such as carex advances its growth period and senesces rapidly, potentially creating food shortages for migratory birds that primarily feed on carex and aquatic plant tubers [12,13].

3. Causes of the 2022 Extreme Drought in Poyang Lake

The 2022 extreme drought in the Yangtze River was associated with both the influence of consecutive La Niña events on China' s climate and abnormal seasonal variation of the WPSH, as well as thermal anomalies over the Tibetan

Plateau and record-breaking high temperature events. Multiple influencing factors intertwined, creating complex and uncertain causes. During summer 2022, anomalous atmospheric circulation caused the entire Northern Hemisphere to experience high temperatures and droughts, with severe drought events occurring in Europe, America, and Asia, and temperatures in the normally ice-covered Arctic Circle soaring to 32.5°C [14]. The WPSH is the most important atmospheric circulation system controlling summer climate in the middle and lower Yangtze River, and its anomalies can lead to extreme high temperatures, droughts, and floods [15,16]. The unusually strong WPSH in summer 2022 was a major cause of high-temperature and drought conditions in the middle and lower Yangtze. Beginning in mid-June, the WPSH continuously extended westward and northward, dominating the Yangtze River basin throughout July–August. The extreme anomalous WPSH in August caused prevailing subsidence over the Yangtze basin, leading to surface warming and extreme high-temperature drought conditions that broke historical records [17,18]. Additionally, the continental subtropical high over the Arabian Peninsula to Iran extended eastward and northward, merging with the WPSH for an extended period to form a strong, broad subtropical high control zone that prevented moisture transport from the south to mid-latitudes, reducing rainfall in the Yangtze basin. These factors combined to cause an extreme drought event in Poyang Lake exceeding the 100-year return period.

Flow reduction in the "Five Rivers" of the Poyang Lake basin (Gan, Fu, Xin, Rao, and Xiu Rivers) also contributed significantly. These rivers contribute approximately 80% of the outflow at the lake outlet (Hukou station). In 2022, total inflow from the Five Rivers was 95% of the 1960–2021 average, ranking 34th in the historical sequence, but with highly uneven seasonal distribution. From July to November 2022, the combined inflow was only 1,098 m^3/s, just 38% of the 1960–2021 average (a 62% reduction) [Figure 5: see original paper]. This represented the lowest flow on record for August–November since 1960. By late October, over 30 rivers with catchment areas exceeding 10 km^2 had dried up, large reservoirs had effective storage reduced to 8.23×10^{9} m^3 (a 20% decrease from July levels), and medium-small reservoirs experienced storage reductions exceeding 50%, with approximately 30% of medium-small reservoirs falling to dead storage levels [7].

Reduced inflow from the upper Yangtze River also played a crucial role. The river-lake hydrological relationship significantly affects seasonal water level variations in Poyang Lake. Depending on the relative water level difference between the Yangtze main stem and Poyang Lake, the Yangtze can produce "draining," "backwater," or "reverse flow" effects on the lake. From July to November 2022, the average discharge at Jiujiang station on the Yangtze main stem was only 11,994 m^3/s, just 44% of the historical average (1993–2021) [Figure 6: see original paper]. This reduction caused a significant draining effect on Poyang Lake. At Hukou station, July–November outflow averaged 2,197 m^3/s, more than double the concurrent inflow from the Five Rivers (1,098 m^3/s), substantially draining the lake' s storage and causing dramatic water level declines.

4. Countermeasures and Suggestions for Addressing Drought Issues in Poyang Lake

Facing increasingly severe water-related disasters under global change impacts, adaptive water management measures are urgently needed, combining both engineering approaches (e.g., reservoir regulation) and non-engineering measures (e.g., forecasting, early warning, scheduling, insurance, and regulations).

(1) Comprehensive utilization of Yangtze River basin reservoir groups for scientific synergistic regulation to effectively alleviate drought in Poyang Lake, ensure socioeconomic water use, and maintain lake ecological security. Joint operation of Yangtze River reservoirs has demonstrated substantial benefits in flood control and drought relief, effectively reducing economic losses from floods and droughts in the middle and lower Yangtze [19]. From August 1–15, 2022, controlled reservoirs in the basin systematically released approximately 5.30×10^{9} m^3 of water to the middle and lower reaches, including 1.09×10^{9} m^3 from the Three Gorges Reservoir, which partially alleviated drought conditions. Simulations show that although the Three Gorges Reservoir has considerable storage capacity and some water replenishment capability, its effectiveness for Poyang Lake is limited, with low replenishment efficiency and only short-term emergency supplementation possible. Therefore, while implementing upstream Yangtze River water replenishment, various water conservancy projects in the lake basin and lake area should be jointly operated to scientifically implement coordinated regulation of rivers, lakes, and tributaries, rationally allocate water resources between upstream and middle reaches, ensure water demand, reduce drought impacts on the economy and society, and maintain ecological security.

(2) Scientific regulation of Poyang Lake' s dish-shaped lake groups to maintain hydrological connectivity between dish-shaped lakes and the main lake and rivers, thereby sustaining wetland ecological water levels and ensuring ecological security. Approximately 3,000 km^2 of floodplain in Poyang Lake contains over 100 dish-shaped lakes ranging from 1 to 71 km^2 in area. At high water levels, they are inundated and integrated with the river-connected water body; at low water levels, they become disconnected, forming unique lake groups within the exposed floodplain. Research indicates that 77 dish-shaped lakes collectively account for 18.5% ($\pm$6.8$\pm$2.0%) of its storage capacity during the dry season [1], playing an important role in alleviating local drought. Based on natural hydrological rhythms, scientific regulation of hydrological connectivity between dish-shaped lakes and the river-connected lake body and rivers can be achieved using existing dikes and gates [20,21], thereby mitigating drought severity during dry seasons and extreme drought years and maintaining wetland ecological water security.

(3) Appropriate development and utilization of groundwater resources in the Poyang Lake plain area to compensate for water shortages caused by lake drought. The Poyang Lake plain area, defined as the catchment downstream of the seven hydrological observation stations on the Five Rivers , covers 24,023.6 km^2 (approximately 15% of the total basin area). Groundwater depth in this area varies significantly throughout the year, ranging from 0–10 m during the dry season with an average depth of 2 m. The shallow aquifer consists primarily of medium-coarse sand and gravel with intermittent clay layers, exhibiting strong hydraulic conductivity and significant water exchange with the lake. From May to July, the lake recharges groundwater, while from August to April, groundwater discharges into the lake. During dry seasons, groundwater discharge accounts for nearly half of the lake' s storage change [22]. Considering the substantial storage capacity of the plain area' s aquifer, its abundant recharge sources, and rapid groundwater circulation, it can serve as a backup water source for appropriate development to supplement water supply for domestic and production uses during extreme lake drought events.

(4) Detailed demonstration of the operation scheme for the proposed Poyang Lake water conservancy hub project. The hub project would fully open its gates during the flood season (April–August) to maintain complete free connection between the river and lake, while using gate regulation from September to March to intercept outflow and adjust lake water levels, thereby utilizing flood resources at the end of the flood season and restoring the lake' s autumn-winter hydrological rhythm. Studies show the hub project could effectively raise lake water levels by an average of 3 m across the entire lake [23]. For different hydrological years, the project could restore dry-season water levels to early historical averages and delay the release of stored water by half a month, alleviating downstream Yangtze drought while ensuring lake storage. However, for extreme drought years like 2022, emergency operation schemes require further demonstration. Additionally, the operational scheme must fully consider joint operation with various existing water conservancy projects.

(5) Enhancing predictive capabilities for extreme meteorological and hydrological events at the basin scale, promoting data sharing, improving information dissemination mechanisms, and strengthening drought prevention and disaster reduction systems. There is an urgent need to improve forecasting capabilities for extreme hydrological events at the basin scale. This includes adopting advanced technologies, intensifying meteorological and hydrological observations, integrating various observation data, improving spatial and temporal resolution and reliability of observations, developing new integrated models of lake-catchment hydrological processes [24], extending forecast lead times, strengthening data sharing and collaborative mechanisms, promoting information exchange, improving early warning systems for extreme meteorological and hydrological events (including warning release mechanisms, information transmission channels, and emergency response plans), and maximizing the reduction of flood and drought disaster impacts.

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The seven hydrological stations are Wanjiabu, Hushan, Waizhou, Lijiafu, Meigang, Qiujin, and Dufengkeng stations.

Note: Figure translations are in progress. See original paper for figures.