Changes in China's water resources in the early 21st century

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Nearly 19% of the world's population lives in China, yet the country contains only 7% of the planet's fresh water. Combining remotely sensed data and ground-based measurements, we conducted a comprehensive assessment of recent changes in China's water resources. Beginning in the 21st century, glaciers in western China have been melting at very high rates; lakes on the Tibetan Plateau have been expanding rapidly, but lakes in other regions have been severely impacted by humans; and groundwater in the North China Plain is increasingly being depleted. Overall, the nation's water resources have been decreasing at an annual rate of ~9.6 billion cubic meters. Precipitation was the dominant factor controlling the observed changes in water resources, but human activities and rising temperatures have also been major drivers in the decline of water resources in the North China Plain and Tibet, respectively. From a global perspective, the changes in China's water resources are among the most pronounced on Earth, and water policies should be re-evaluated and revised in light of the findings presented here.

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Fresh water is an essential resource for life on Earth, and is becoming increasingly important as a result of climate instability and human population growth (Vörösmarty *et al.* 2000). This is particularly true in China, where 19% of the world's population shares only 7% of the Earth's global freshwater resources (Yang and Pang 2006; Cheng *et al.* 2009). Despite this limited supply, China's water resources – lakes, rivers, groundwater, and glaciers – have sustained diverse socioecological systems. In the semi-arid northern parts of China, the lakes and rivers dotting the grasslands provide key water supplies to nomadic herders and endangered species; in the North China Plain (Figure 1a; WebFigure 1), large, densely populated cities rely heavily on groundwater for domestic, agricultural, and industrial uses; and on the Tibetan Plateau, the mountain glaciers that form among the planet's highest peaks (Figure 1b) not only serve as crucial sources of fresh water but also are of cultural and religious importance to local communities.

Yet China's water resources have undergone major changes since the beginning of the 21st century. Shifting monsoon patterns are transforming the distribution and intensity of precipitation over mainland China (Zhang *et al.* 2011), while warming is occurring across the Tibetan Plateau at a rate far exceeding the global average (Kuang and Jiao 2016). Against this backdrop of climate change, China's growing population and rapid economic development are consuming massive amounts of water (Jiang 2009), in turn aggravating regional water scarcity.

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China's water issues are expected to become even more complex with the implementation of the world's largest water-transfer and tree-planting projects across the country (WebFigure 2a). The yet-to-be-completed South-to-North Water Transfer project aims to divert water from the Yangtze River in the south to Beijing and its surroundings through systems of artificial channels, in an effort to alleviate water scarcity in northern China (WebFigure 2b; Cheng *et al.* 2009). The goal of the Three North Shelter Forest Program, which started in the 1970s, was to plant trees throughout northern China in an attempt to slow the expansion of degraded drylands (WebFigure 2c). Although intended to combat environmental degradation, it has been argued that this forestation project has depleted local groundwater levels (Cao 2008).

Limited water resources, pronounced changes to the climate, increased human demand for water, and the implementation of large-scale water-related projects are not unique to China, and therefore examining changes in China's water resources can inform water management and policy decisions elsewhere in the world. Here, we provide a comprehensive assessment of the changes in China's water resources, beginning in the early 21st century, focusing on terrestrial water storage (TWS; that is, all forms of water stored on the Earth's surface) and its two key components: groundwater and lake water. We also investigate the possible driving forces behind observed changes in water resources, and propose policy recommendations for achieving a sustainable water future in China.

Methods

Several remote-sensing techniques and an extensive dataset of ground-based measurements were used in this study. We analyzed data from various sources described below; these data were collected over different time spans but largely occurred between 2000 and 2016.

Changes in terrestrial water storage (TWS)

To examine changes in China's TWS, we relied on data from the Gravity Recovery and Climate Experiment (GRACE) project (available from 2002), whose mission involves measuring variations in Earth's gravitational field associated with changes in groundwater, snow and ice, river waters, and lake waters (Tapley *et al*. 2004; Rodell *et al*. 2018). We obtained monthly Center for Space Research Land Mass Grids from the GRCTellus Land Product center (vRL05, 1-degree resolution; https://grace.jpl.nasa.gov/data/get-data/monthly-mass-grids-land). Temporal trends in TWS for different regions within and for the country as a whole were then calculated (Figure 2; WebFigure 3). Ground-measured TWS data collected by China's Ministry of Water Resources were used to validate the GRACE data (WebFigure 4; WebTable 1). Because the unit of GRACE TWS is equivalent water depth but that of ground-measured TWS is water volume, we converted ground-measured TWS into equivalent water depth by dividing it by land surface area (WebTable 1). Finally, using precipitation data collected from ~2400 meteorological stations across China, we investigated whether changes in TWS were being driven by climatic factors (WebFigure 5).

Figure 1. Water resources support diverse socioecological systems in China but are undergoing rapid changes. Two typical examples are shown here. (a) Population growth and rapid economic development are consuming massive amounts of water in the North China Plain. (b) A warming climate is driving the retreat of glaciers and consequent expansion of lakes on the Tibetan Plateau. Large-scale water projects further complicate China's existing water issues (see WebFigure 2).

Changes in groundwater

We evaluated changes in groundwater in China by creating a database of groundwater monitoring wells. The database was composed of data compiled from two sources: literature reviews and national monitoring wells. We searched Google Scholar and the China National Knowledge Infrastructure (CNKI; www.cnki.net) database using a combination of selected city names in China and "groundwater" as keywords; a total of 134 monitoring wells were compiled. We also identified an additional 671 monitoring wells with temporal coverage over the period 2005–2016 from China's national statistical yearbooks. The final database consisted of 805 wells located throughout China, possibly the largest database of its kind (WebDatabase 1). For each monitoring well, we then calculated the rate of change in groundwater level, and also used measurements from the nearest meteorological station to assess changes in annual precipitation (WebDatabase 1).

Changes in lakes

We compared Landsat images from two years – 2000 and 2016 (with exceptions; see below) – to quantify changes in the number and areal extent of selected lakes over time. We focused on lakes with areal extents >10 km^2, because large lakes like these comprise most of the country's total lake area (Ma *et al*. 2011; Tao *et al*. 2019), and because such lakes hold massive amounts of water and are therefore more suitable for evaluating changes in TWS. We acquired Landsat images from the US Geological Survey (https://earthexplorer.usgs.gov) for the summers of 2000 and 2016. In cases where images in 2000 or 2016 were contaminated by clouds, we used cloud-free images from the year closest to 2000 or 2016. The classical normalized difference water index method (McFeeters 1996) was used to extract lake area and number of lakes from the Landsat images (WebTable 2).

In addition, changes in lake water level were quantified using Geoscience Laser Altimeter System (GLAS) data. The GLAS sensor was affixed to NASA's Ice, Cloud, and land Elevation Satellite (ICESat), operated from 2003 to 2009, and provided repeated measurements of elevation over the Earth's surface. We downloaded the GLAH14 data from the US National Snow and Ice Data Center (https://nsidc.org/data/icesat/data.html). Because GLAS data were collected via laser

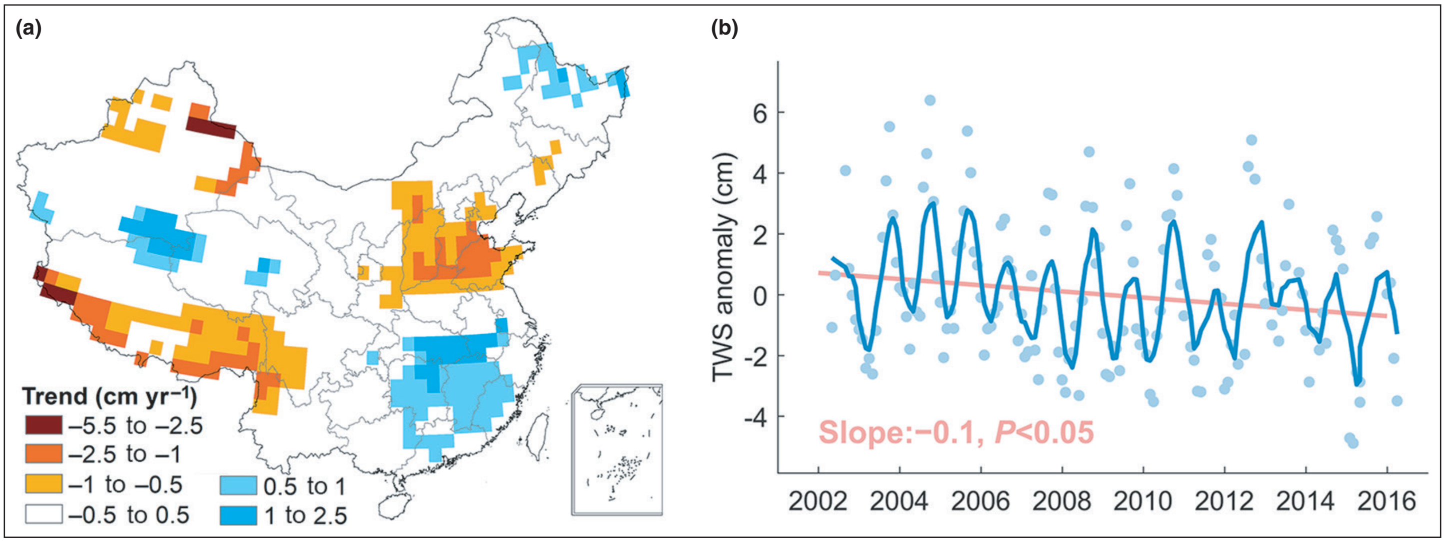

Figure 2. Changes in China's terrestrial water storage (TWS) in the early 21st century (2002–2016), including (a) temporal changes in TWS at the pixel (~100-km-wide and ~100-km-long) level and (b) temporal changes in the monthly anomaly of TWS at the national scale, based on data from the Gravity Recovery and Climate Experiment (GRACE) program. Each point represents a monthly GRACE value averaged across the whole country. The monthly anomaly was defined as the deviation from the long-term average value. The blue line indicates the moving window average over 6-month periods; the red line is the fitted trend. See WebFigure 3 for details about temporal changes in TWS at the regional level.

pulses that captured discrete ~70-m "footprints", only a few lakes in China were captured by the GLAS sensor. To ensure data quality, we excluded GLAS data containing cloud contamination, signal saturation, or more than one signal peak (Wang *et al.* 2013). In total, 184 lakes with high-quality GLAS measurements were identified, and changes in water level were calculated for each (WebFigure 6). To better understand the changes in several of China's large lakes, we also calculated the areal extent of those lakes over the same period (2003–2009), and then compared changes in lake area with changes in lake water level (WebFigure 7).

Results

As measured by GRACE, TWS in China decreased at a rate of –0.1 cm yr^{-1} at the national level (Figure 2), equivalent to a national loss of 9.6 billion cubic meters of water every year. Large regional disparities in TWS were observed (Figure 2a; WebFigure 3), with increases in northeast China, south China, and the north Tibetan Plateau but rapid decreases in the North China Plain, Inner Mongolia, and the glacier regions of western China. Such trends in TWS were confirmed by ground-based measurements (WebFigure 4). Although TWS closely tracked precipitation dynamics observed in most regions (WebFigure 5), high levels of precipitation failed to slow the rapid decline in TWS in the North China Plain and Tibetan regions.

With respect to groundwater, we found that 63% (510 out of 805) of groundwater-monitoring wells exhibited decreasing trends in groundwater levels (Figure 3a; WebDatabase 1). The spatial patterns of changes in groundwater were generally consistent with those of TWS, where increasing trends were observed in northeast and south China but decreasing trends predominated in most other regions. Of the monitoring wells that exhibited decreasing trends, 45% (233 out of 510) were located in regions receiving less precipitation (WebDatabase 1), indicating that declining groundwater levels were not always linked with changes in precipitation regimes but were likely attributed to human activities. The North China Plain region was particularly severely impacted, with most monitoring wells showing marked declines in groundwater levels.

Finally, we identified 643 lakes with areal extents >10 km^2 in the year 2000, covering an area of 69,792 km^2 (WebTable 2). Although the number of lakes did not change substantially between 2000 and 2016 (from 643 to 641), lake area increased by 5099 km^2 (WebTable 2). Increases in lake area were concentrated in the Tibetan Plateau (+4434 km^2), whereas decreases in lake area were most pronounced in north China (–552 km^2). Changes in lake water levels, as revealed by the GLAS sensor and despite a limited sample size, were consistent with changes in lake area, both spatially and temporally (WebFigures 6 and 7). However, considerable differences were observed between changes in lake area and TWS (Figure 3b), where most lakes on the Tibetan Plateau increased in size while TWS decreased or was largely unchanged, and where changes in lake area in the North China Plain and the Yangtze Plain in southern China were inversely related to changes in TWS.

Discussion

Changes in China's water resources and their driving forces

Using satellite-based and ground-measured data, we provide – to the best of our knowledge – the first comprehensive evaluation of changes that have occurred in China's water

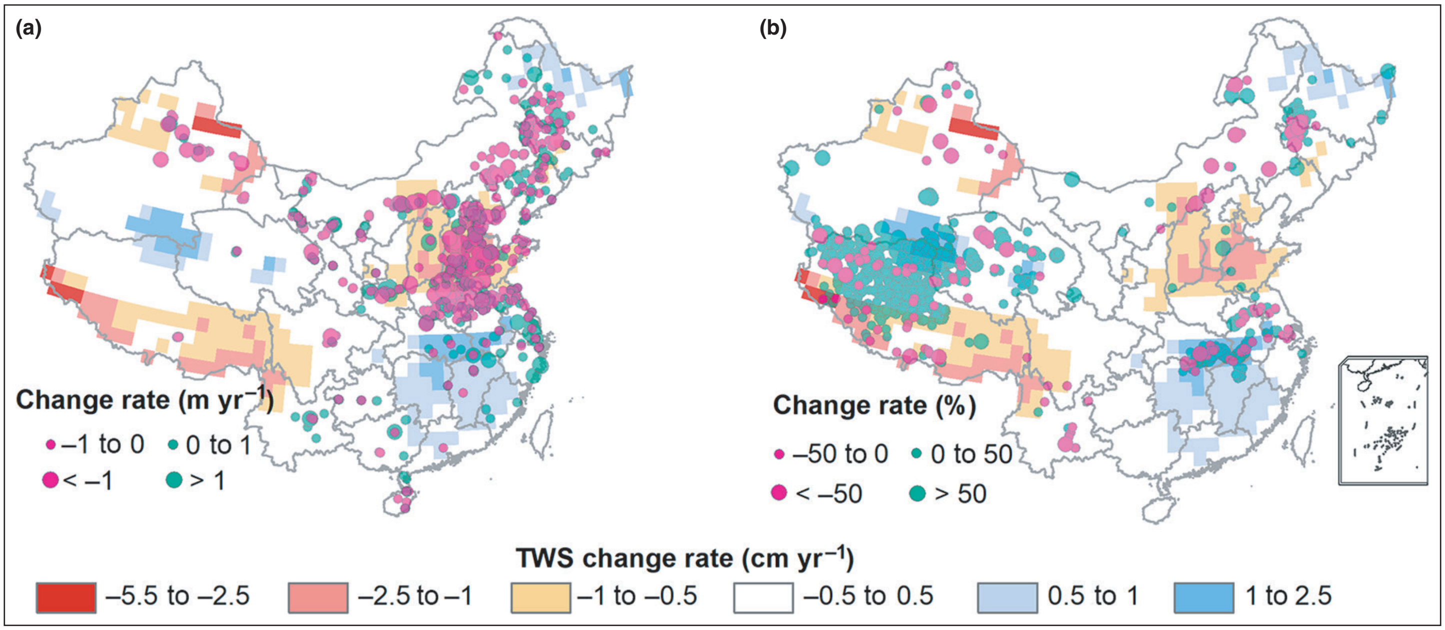

Figure 3. Changes in China's (a) groundwater and (b) lakes (both expressed as solid circles) as compared to changes in TWS (pixels) in the early 21st century.

resources in the early 21st century. Our analysis detected changes in TWS that differed by region, as revealed by comparing GRACE satellite-based images and ground-based measurements (WebFigure 4). TWS increased in northeastern and southern China, and in the north Tibetan Plateau, but decreased in other regions (WebFigure 3), resulting in an overall decline in TWS at the national level (Figure 2b) and demonstrating a clear contrast between China's dry north and water-rich south. Precipitation played a major role in the observed changes in TWS (WebFigure 5), with the exception of Tibet and the North China Plain, where the most severe reductions in TWS were observed (Figure 2; WebFigure 3). Consistent with earlier studies (Jiang 2009; Song *et al*. 2015), our observations suggest that the decreases in TWS in Tibet and the North China Plain (Figure 3a) were mainly caused by warming-induced glacier melting and anthropogenic groundwater exploitation, respectively.

A second key finding is the discordance between changes in TWS and changes in China's lakes. In southern Tibet, TWS showed an overall decline because of glacial melting, but part of the glacial meltwater flowed into nearby lakes and caused an increase in volume for these lakes (Zhang *et al*. 2015). Permafrost melt and increased precipitation also contributed to the expansion of Tibetan lakes, especially in the central and northern parts of the Plateau (Li *et al*. 2014). In the Yangtze Plain of southern China, many lakes are smaller in area despite an increase in local TWS. Similarly in northern China, many lakes are also considerably smaller, although the change in TWS was insignificant (between –0.5 and 0.5 cm yr^{-1}), due primarily to human activities. Many lakes in the Yangtze Plain have been subjected to lake impoldering – a type of land-cover conversion that encroaches on lakes and their associated wetlands for agricultural purposes, through the construction of dikes (see Fang *et al*. 2005). Numerous rivers in northern China have been diverted for irrigation and industrial purposes (Fang *et al*. 2005, 2018; Tao *et al*. 2015), reducing freshwater inputs to lakes; segments of the Yellow River have even run dry due to water overallocation (Tang *et al*. 2008). Notably, in a few cases, human activities resulted in enlarged lakes, with most occurring in the North China Plain, where lake conservation practices are being carried out by local governments (Song *et al*. 2018).

A global perspective of the changes in China's water resources

From a global perspective, the changes in China's water resources are among the most pronounced on Earth. Several major aquifers around the world are experiencing very high rates of groundwater depletion, including that of the North China Plain (Famiglietti 2014; Rodell *et al*. 2018). Glacier retreat is occurring on a planetary scale, but rates of warming in Tibet are substantially higher than the global average (Kraaijenbrink *et al*. 2017), and the resulting expansions in Tibetan lakes are clearly observable in maps of changes in global surface waters (Pekel *et al*. 2016). National, regional, and local policies are required to confront these extensive changes in water resources if the worst of the consequences for the environment and for human populations are to be avoided, or at least minimized.

Implications for policy making

Our analysis indicates that different regions of China face different water challenges. We suggest that the dominant changes in water resources within and between regions should be considered in policy making at regional and national scales, respectively. We illustrate this point with three examples:

(1) On the Tibetan Plateau, glacier retreat and lake expansion are the dominant water resource changes, and therefore policies should center on establishing hazard-warning systems to protect local Tibetan communities against glacial hazards, such as portions of glaciers at risk of collapse and sudden "outburst" floods from glacial lakes. Over the longer term, policies that secure water supplies will also be needed because many Tibetan glaciers are predicted to disappear before the end of the century (Kraaijenbrink *et al.* 2017).

(2) In northern China, because groundwater depletion and lake shrinkage are the dominant water resource changes, policies should encourage efficient industrial and agricultural water use, with the goal of halting overexploitation of groundwater and lake–river systems. Given the ongoing loss of water in northern China (WebFigure 3), the Three North Shelter Forest Program may need to be reconsidered.

(3) National water policies should try to alleviate the increasing disparity in water availability between China's north and south. "Virtual water trading" provides a promising solution, where "virtual water" represents the water used for producing key water-intensive commodities such as agricultural products (Allan 2002). China's northern regions are water-scarce but have been exporting agricultural products (ie "virtual water") to the water-rich south and east (Zhao *et al.* 2015). The South-to-North Water Transfer project then physically transfers water to the north at a considerable cost in terms of manpower and material resources (WebFigure 2). Better planning of the interprovincial trade of virtual water could prove to be more efficient and sustainable over the long term.

These policy suggestions are by no means exhaustive, and several have already been or are in the process of being implemented in China. Although China's water resources will be further affected by future climate change and anthropogenic interventions (Cheng *et al.* 2009), sustainable water management in China is expected to be achieved, given the continuing efforts from Chinese scientific community and policy makers.

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Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.2164/suppinfo

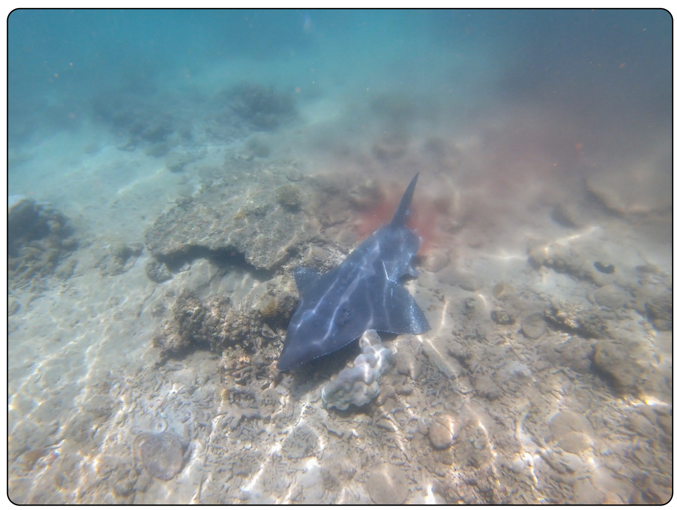
FrontiersEcoPics

Rare great hammerhead predation of a wedgefish

Many species of sharks are apex predators, exerting top-down control on coral reef communities via predation and behavioral modification of prey. The great hammerhead (*Sphyrna mokarran*) is broadly distributed in tropical waters, with a varied diet composed of crustaceans, cephalopods, bony fish, and other elasmobranchs. Gut-content analysis has indicated a preference for rays and skates, including larger taxa such as guitarfish; however, direct observations of predation are rarely witnessed.

At noon on 7 Nov 2019, we observed a large great hammerhead shark (~3.5–4 m total length) preying on a bottlenose wedgefish (*Rhynchobatus australiae*) (~2–2.5 m total length) at a depth of 2.5 m in a shallow bay off Enderby Island (top photo), in the Dampier Archipelago, along the north coast of Western Australia.

The initial bite resulted in the hammerhead shark shearing the wedgefish in half behind the first dorsal fin before subsequently consuming the rear portion. Afterwards, the hammerhead circled in the shallows for approximately 5 minutes before consuming the remainder of the carcass (bottom photo). While the "pin and pivot" behavior has been recorded for hammerheads predating on rays (ie using their heads to restrain prey on the substrate), in this instance the depredation event was initiated at the surface and the hammerhead used the force of its tail to twist and shear the wedgefish in half (WebVideo 1). This observation supports previous stomach-content data and documents a unique predator–prey interaction, including a ray-hunting style that differs from previously recorded techniques.



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