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Long-term surface water changes and driving cause in Xiong'an, China: from dense Landsat time series images and synthetic analysis

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ABSTRACT

China's government statement recently reported the plan of constructing Xiong'an New Area, which aims to phase out some extra capital functions from Beijing and to explore an innovative urban development mode with the priority in eco-environmental protection. The New Area is located in the semi-arid North China Plain (NCP) and is home to NCP's largest natural freshwater wetland, Baiyangdian Lake. A comprehensive realization of surface water dynamics would be crucial for policy-makers to outline a sustainable environment development strategy for New Area. In this study, we used a total of 245 time slices of cloud-free Landsat images to document the continuous changes of water bodies within Xiong'an City during 1984–2016 and to provide detailed evidence of water presence and persistency states and changes under the influences of climate change and human actions. Our results reveal that the New Area water body areas varied dramatically during the past 33 years, ranging from 0.44 km^2 in April 1988 to 317.85 km^2 in February 1989. The change of surface water area was not characterized by a monotonically decreasing tendency. The evolution processes can be divided into four sub-stages: the first extreme desiccation in mid-1980s, the wet stage with the most extensive inundation areas and strong inter-annual fluctuations from late-1988 to late 1999, another desiccation stage in early 2000s, and the overall recovering stage between 2007 and 2016. We also mapped the maximum water inundation extents and frequencies of all-season, pre-wet season (February-May) and post-wet season (September-December) for the 33 years and different sub-periods. Although there is good agreement between time series of surface water area evolution in the New Area and station-based precipitation and evaporation variations, multiple lines of evidences reviewed in previous research indicate that the degraded Baiyangdian Lake was also tightly associated with human activities from various aspects, including dam construction, groundwater extraction, agricultural irrigation, etc. We highlighted the current status of exploring the driving mechanism of surface water changes and existing problems, and then offer recommendations.

1. Introduction

The recent joint statement from China's the Central Committee and State Council, reported the plan to construct a New Area city, Xiong'an, which will straddle three counties (Xiongxian, Rongcheng and Anxin) previously belonged to Baoding city, as "a strategy crucial for a millennium to come" (http://politics.people.com.cn/GB/n1/2017/0401/c1001-29185929.html, in Chinese). The New Area, about 100 km southwest of Beijing, will sit at the center of the triangular area formed by Beijing, Tianjin, and Hebei's provincial capital Shijiazhuang (Fig. 1). The move targets at alleviating the present heavy economic, educational, political and residential functions of Beijing, exploring a new mode of optimized development in densely-populated areas, and restructuring the urban layout in the Beijing-Tianjin-Hebei region. The Xiong'an New Area features stable geographical setting, convenient transportation, excellent ecological environment, and relatively sufficient room for development. The new city will cover around 100 km^2 initially and will then be expanded to the double in the near future and about 2000 km^2 in the long term. It is designed as a demonstration area for innovative development with priority in eco-environmental protection and green living environment.

One noticeable characteristic of Xiong'an is that it is located home to Baiyangdian Lake, the largest natural freshwater wetland in the semi-arid North China Plain (NCP). The lake is known as

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"Pearl of North China" and "Kidney of North China" [1,2]. The lake wetland, together with surrounding water bodies, play important roles in maintaining regular circulations of the local ecosystems such as water regulation and supply, reed production, enhancing groundwater recharge, meliorating local climate system, and biodiversity protection [3–5]. In 2002 the Baiyangdian Lake Wetland Nature Reserve Region was established to preserve the freshwater wetland ecosystem, especially for rare and endangered species, most of which are attributed to Class I in the National Key Protected Wild Wildlife List of China [6]. With the development of the new city, it would be crucial to sustain aquatic biodiversity and healthy eco-environmental systems to benefit long-term social, economic, and aesthetic development. Therefore, a comprehensive investigation of surface water bodies, recent dynamics and the driving forces provides important knowledge and reference for policy-makers to outline a sustainable development plan for New Area. In the past several decades, Baiyangdian Lake experienced severe droughts and shrinkage, and nearly dried up several times [3,7,8]. The changes of Baiyangdian Lake led to many ecological problems, such as the reduction of biodiversity, shortage of water resources, degradation of water quality and loss of wetland functions [9,10].

Many efforts have been made to identify ecological problems [6,11], hydrological characteristics and changes [4,12], water resource requirements [13,14] and ecosystem services provided by the wetlands in Baiyangdian Lake [15,16]. Prior research [1,3,5,6,12,17] showed that a series of hydraulic engineering construction projects and the long-term over-exploitation of groundwater had substantially changed the hydrology of the lake during the past few decades. For instance, Li et al. [17] addressed the shrinking areas of water bodies and lasting increases of cultivated land and emergent plants within the Baiyangdian Lake region based on four Landsat MSS/TM images acquired in Sep. 1974, Aug. 1987, Jul. 1996 and Aug. 2007, respectively. Zhuang et al. [6] measured the decreased water area of Baiyangdian Lake from 81 km^2 in 1974 to 47 km^2 in 2007 using Landsat imagery. Additional gauge data collected at hydrological stations also showed significant declining trend in water level from 1950 to 2000s [4,6,12,17]. Most of these studies were based on several epochs of satellite images or water level data from individual stations. The open data access of over 45 years of continuous observations from Landsat satellite series provides an unparalleled record of surface water dynamics [18,19]. The dense time series interpretation of open water inundation extents enables us to detect the decadal, inter-annual and intra-annual variability of Baiyangdian Lake and surrounding water bodies in New Area and to record the time windows of abrupt changes in surface water triggered by extreme climate events or human regulations. We collected all of cloud-free images from Landsat 4/5/7/8 to document the consecutive changes of water bodies within Xiong'an City in the past three decades.

This study mainly aims to fully address the detailed evolution of water inundation areas in Xiong'an New Area, including inter-decadal, inter-annual, seasonal and abrupt changes, and to provide evidence of water presence, persistency states and changes under the influences of climate change and human actions. Besides, many previous studies tried to address what factor dominated the Baiyangdian Lake desiccation and degradation using different evidence and from different perspectives, e.g., climate change or anthropogenic effects, while the conclusions of influencing mechanisms of the lake changes remain large uncertain. Thus we conduct a literature review and synthetic analyses on the driving forces of surface water dynamics of Baiyangdian Lake for the reference of future research. The study is expected to advance the understanding of the change of water resource in New Area and the current state, and to shield lights on water management and policy-making for sustainable development of New Area.

2. Data and methods

2.1. Data and processing method for water body delineation

The Landsat archived images including those from the Landsat 4 & 5 Thematic Mapper (TM), the Landsat 7 Enhanced Thematic Mapper-plus (ETM+) and the Landsat 8 Operational Land Imager (OLI) acquired between 1984 and 2016 are used for detecting surface water dynamics in New Area during the past three decades. The data sets were accessed at http://glovis.usgs.gov. These images have already been radiometrically corrected and projected to the UTM coordinate system. We converted the DN (Digital Numbers) data to top-of-atmosphere (TOA) reflectance imagery. All of used image scenes (245 in total) are completely cloud-free over the water body area. Table S1 shows the temporal sampling information of used images.

In the study area, surface water characteristics is a highly variable in terms of chlorophyll concentration, total suspended solids and colored dissolved organic matter load, water depth and water-body bottom materials, which can result in evident differences in spectral feature at the wavelengths measured by the Landsat sensors [20–22]. In addition, variations in observation conditions (sun-target-sensor geometry, and optical thickness) also contribute to the different spectral properties [23–26]. The variation of spectral features of water on different images poses challenges for automated retrieval of extents of water body. To address the challenges, a two-step NDWI (Normalized Difference Water Index) threshold segmentation scheme was applied in this study to extract the water inundation areas [27–30]. In the first step, all potential waterbody pixels are filtered by a loose initial threshold segmentation (NDWI > -0.1, which is a conservative estimate to mask out various water bodies in different spectral properties at continental or global scale [23]) based on calculated NDWI maps of selected multiple spectral images; the second step is locally iterative segmentation for each potential lake entity, and the iteration goal is to obtain stable lake boundary within consecutive segmentations with the least shifted water area. The NDWI map is generated by the normalized water index between the green (ρ_{green}) and near infrared (ρ_{NIR}) spectral bands proposed by McFeeters [31]. The two-step threshold segmentation method can efficiently improve the accuracy of waterbody extent delineation, compared to the single-threshold segmentation method which uses a fixed threshold to delineate outlines of different lakes which have obviously distinctive spectral features. Eventually an interactive mapping tool was developed to guarantee the mapping accuracy of water body boundaries caused by image "noise" by visual inspection and manual editing [30,32].

2.2. Auxiliary materials

GIS data layers of administrative divisions and topography element data were acquired from the National Geomatics Center of China. Through the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn), we obtained time series of monthly precipitation and daily evaporation data (1980–2016) measured at Baoding weather station to assess climate change and variability over this area (Fig. 1). For some missing evaporation records measured by D20 pan, we interpolated the values based on temporally adjacent observations measured by E601B pan.

3. Satellite-based detection of surface water dynamics of Xiong'an New area

3.1. Analyses on time series of surface water area in Xiong'an

We totally mapped surface water areas of 245 sampling dates from May 1984 to December 2016 (Fig. 2). The total water body

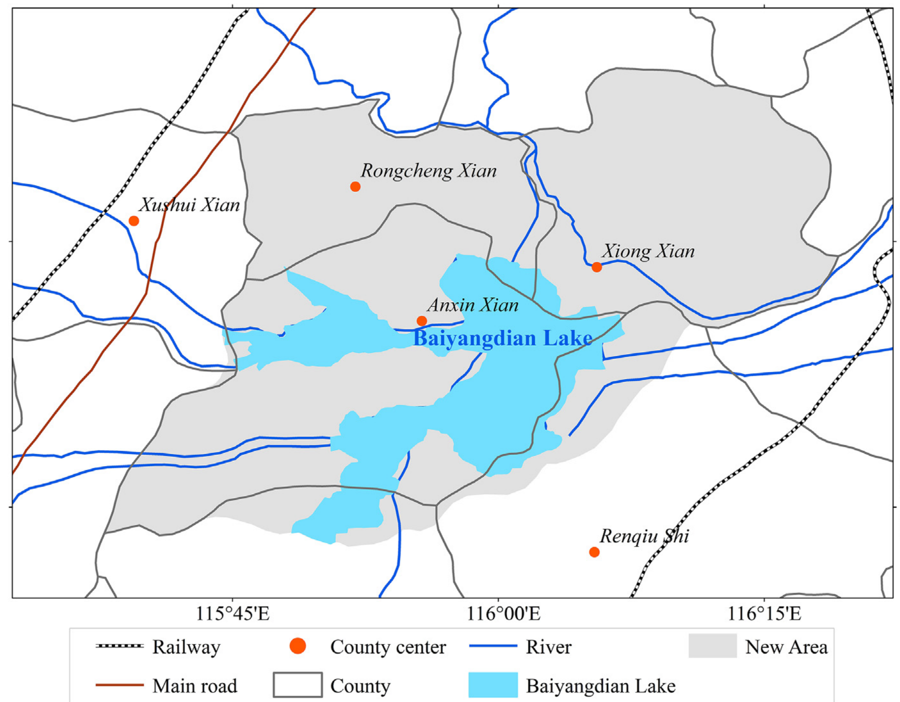

Fig. 1. Maps of geographic location of Xiong'an New Area and Baiyangdian Lake wetland.

area varied dramatically throughout the years, ranging from 0.44 km^2 in April 1988 to 317.85 km^2 in February 1989. It was mainly attributed to the serve drought occurred in the mid-1980s (extremely low precipitation in 1986/1987) and heavy rainfalls in July to August of 1988. To make mapped water body areas comparable at inter-annual timescale, we composited mean water areas in pre-wet season (February-May) and post-wet season (September-December) by averaging all sampled water areas within the corresponding period of the year. The mean water area in pre-wet season showed similar pattern to that in post-wet season (green-blue and green symbolled time series in Fig. 2). The time-series data showed considerable intra-annual and inter-annual area variations through the past three decades and four heterogeneous stages could be observed. The lowest levels and extreme desiccation stage of surface water occurred during 1984 to mid-1988, as the total area kept at the lowest level (S_{mean} = 4.47 km^2, S_{stdev} = 2.52 km^2) and Baiyangdian Lake dried up even in wet seasons. The desiccation stage ended in the late half of 1988 and the surface water area rapidly jumped to ~200 km^2. In the following decade, the water area fluctuated at relatively high levels (S_{mean} = 130.51 km^2), and was characterized by large inter-annual fluctuations (S_{stdev} = 58.41 km^2). Another desiccation stage began in late 1999 and the average total water surface area was mostly below 40 km^2 until 2006 (S_{mean} = 33.25 km^2, S_{stdev} = 11.30 km^2). The inundation area of Baiyangdian Lake nearly dried up in 2000–2002. From 2007 to 2016, there was an overall upward trend of water inundation area, but the total area was still far lower than that in the 1990s (with the mean value of 62.49 km^2), even in wet years.

3.2. Analyses on the spatial patterns of maximum inundation extent and frequency

We mapped the maximum water inundation extents (all locations ever mapped as water, WE) and frequencies (defined as the

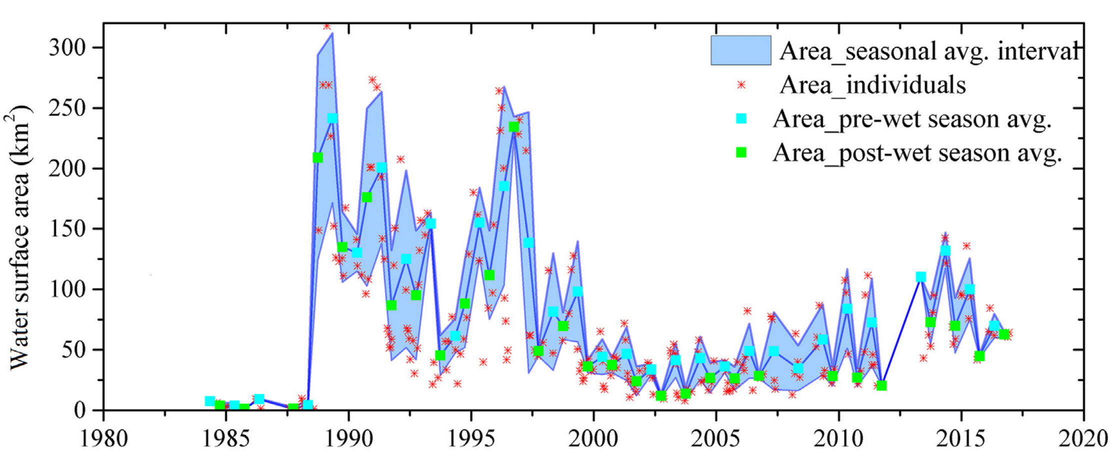

Fig. 2. Time series of Landsat-based surface water area in New Area. The avg. water areas in pre-wet season and post-wet season refer to the composition by averaging all mapped water areas in February-May and September-December.

ratio of the number of that pixel mapped as water to that of total used satellite observations, shorten as WF with value ranging 0–100%) for the 33 years and for three sub-periods as divided in Section 3.1: the wet stage during late-1988 to late-1999 (Sub-period 1), the 2nd desiccation stage during late-1999 to 2006 (Sub-period 2), and the recovering stage during 2007–2016 (Sub-period 3) (the extremely dry sub-period from 1984 to mid-1988 when the surface water was nearly dried up is not analyzed here). To investigate intra-annual dynamics of surface water, the WE and WF for pre-wet and post-wet seasons were also mapped. The WE and WF maps were primarily used to provide a general interpretation of the presence and persistence of surface water in New Area.

Fig. 3 shows water inundation extent of New Area during the whole study period and three sub-periods. The maximum water extents during the study period and Sub-period 1 are basically comparable as extreme wet events all occurred in the 1990s. The maximum water extent based on all valid observations is 409.6 km^2, compared to the areas of ~360 km^2 in pre-wet seasons and ~350 km^2 in post-wet seasons. In the wet sub-period, the water presence located within Baiyangdian Lake has an area of 307.6 km^2, and other small ponds, river channels and agricultural aquatic areas approximately account for 101.9 km^2. In comparison, water extent shrank considerably in Sub-period 2, which indicates that a large fraction of wetland area was totally dried up in this sub-period. In the dry years, many ponds disappeared and Baiyangdian Lake shrank seriously and were separated into small water fragments. The Zaozuodian (northwest part of Baiyangdian Lake) in the west of Anxin city and Mapengdian – Xiaobeidian (southwest tip) were dried up through the seven years. Besides, only a few canal segments were mapped out, which indicates the upstream water supplies to Baiyangdian Lake could dramatically decreased. In Sub-period 3, the maximum water extent recovered to ~210 km^2 over the study area, and the Baiyangdian Lake only recovered back to less than 190 km^2.

Similarly, Fig. 4 shows water frequency maps of Xiong'an in the study period and three sub-periods. Spatial patterns of all sub-maps reveal a gradient of decreasing water inundation frequency from central and eastern Baiyangdian Lake to the lake periphery in both whole-year and seasons, especially in the two extended wetland regions (Zaozuodian and Xiaobeidian) in the east and southwest. Most canals and small ponds out of Baiyangdian Lake are also of seasonal water presence. In the study area, the area of water presence frequency higher than 50% percentile accounts for 8.8% (36.1 km^2) of the total inundation extent (409.6 km^2, the same calculation for the percentages below) during the 33-year period, with higher percentage in the pre-wet season (12.1%) than that in the post-wet season (7.8%). The highest water presence percentage is about 91% at pixel level rather than 100% because of the dry-up stage in the 1980s and near dry-up stage in the early-2000s. Among different sub-periods, obviously higher frequency of water

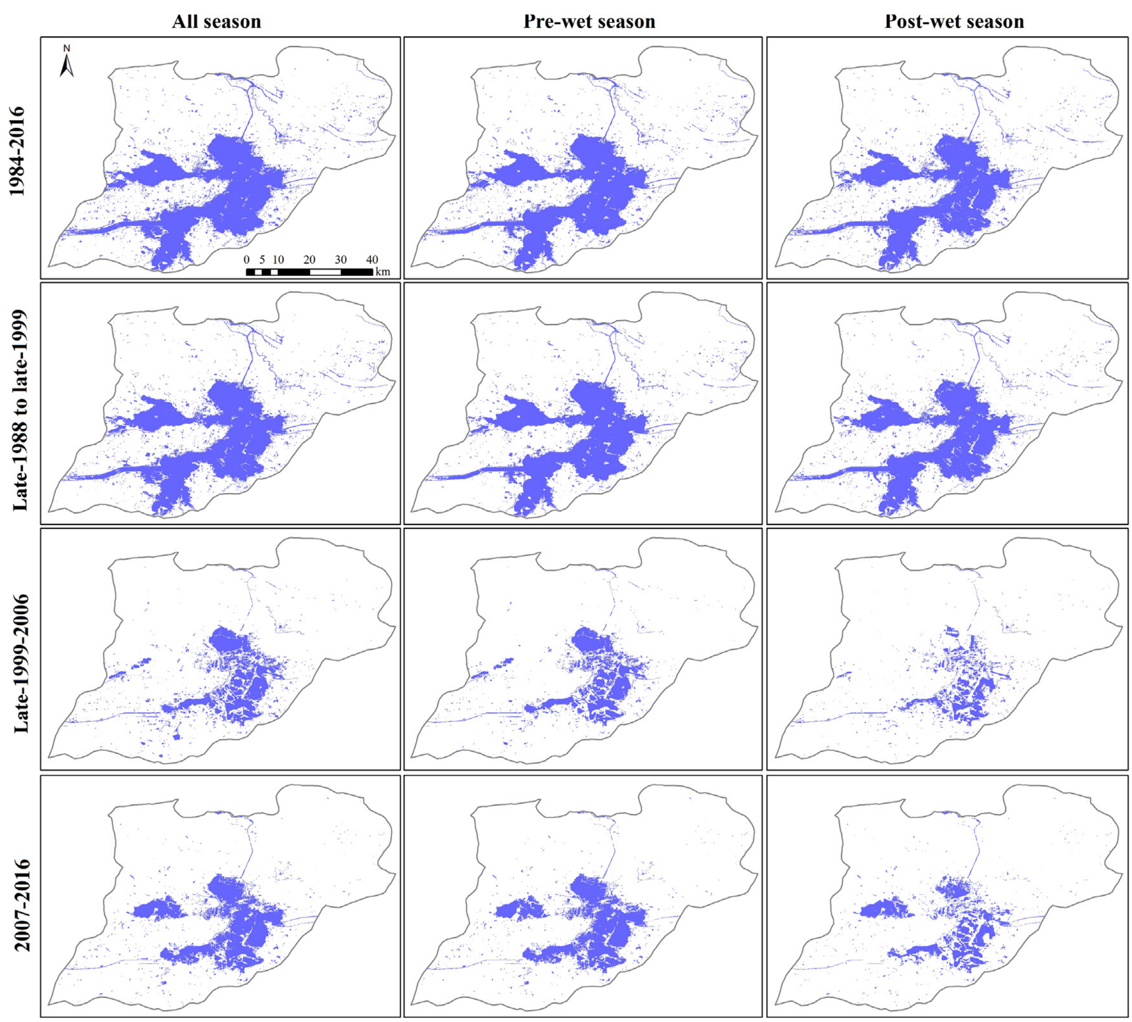

Fig. 3. Water inundation extent (in blue) maps of Xiong'an over the whole study period and three sub-periods (late-1988 to late-1999, late-1999–2006 and 2007–2016) by compositing observations of all-season and pre-wet season and post-wet season. Note: the map direction and scale are consistent as shown in the first sub-map.

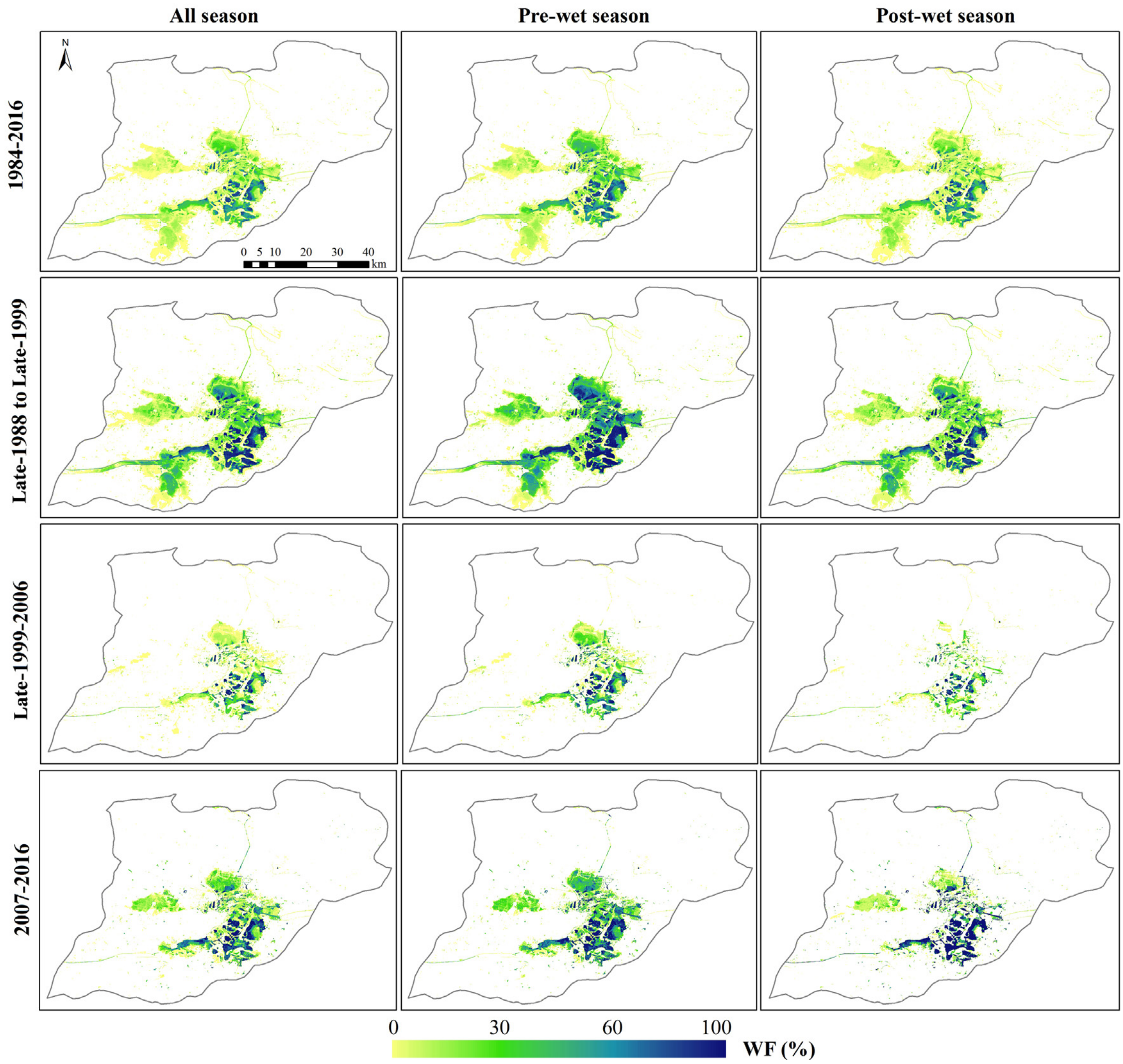

Fig. 4. Water inundation frequency maps of Xiong'an over the whole study period and three sub-periods (late-1988 to late-1999, late-1999–2006 and 2007–2016) by compositing observations of all-season and pre-wet season and post-wet season. Note: the map direction and scale are consistent as shown in the first sub-map.

presence occurred in Sub-period 1 (the 1990s), with the highest frequency of 100%. The area with water presence percentage ≥50% during all season accounts for 18.8% of the total inundation extent. The higher percentage, about 32.2% of water inundation frequency was observed in the pre-wet season, with 10.6 km^2 permanently inundated area (in 100% presence, mainly distributed in the eastern Baiyangdian Lake, including Chiyudian and Fanyudian near the border between Anxin county and Renqiu city) decreasing to 1.6 km^2 in the post-wet season. In comparison, severe shrinking water extent accompanying with rather sporadically and isolated high-frequent water presence in spatial water frequency patterns across the landscape were detected for the sub-period late-1999 to 2006, with about 23.7 km^2 water presence area ≥50%. In Sub-period 3, moderate water presence frequency was observed across the inundation extent, and higher water frequency was observed in the pre-wet season, probably due to the wetter climate in recent years and more frequent external water-division supplying operations in pre-wet seasons.

To better visualize the spatial transitions of water inundation frequency among different sub-periods at synoptic scale, we composite the RGB map of water frequency in Sub-periods P1-P2-P3 (as shown in Fig. 5a), where the reddish color indicates higher percentages of water presence in the first sub-period (the 1990s) than in the two later sub-periods, while the opposite exhibits the bluish color. We can see that the dominated color within the water inundation extent is red and fuchsia, indicating that most of inundated areas during 1988–1999 were desiccated and part of areas were recovered in 2007–2016. The most evident drying area was detected in the southwest of Baiyangdian Lake and intersect region with Tanghe canal (marked with rectangle box). In addition, the brightness can indicate clearly the total water presence percentages as shown by the bright white color for high inundation frequency and dark color for the ephemeral water presence. As circled in Fig. 5a, only the middle section of Baiyangdian Lake and a few scattered ponds within the tourism spots.

For facilitating the identification of water bodies and land use function planning across the entire Xiong'an New Region, we retrieved the areas of water presence frequency higher than 10% in the past 33 years and assigned their attributes by superimposing the water-classified polygons on the high-resolution Google Earth imagery. Fig. 5b shows the main water body within Baiyangdian Lake, the canals, cultivated water area and ponds. It should be noted that many ponds (symbolled in orange color) cannot be identified in the latest images in Google Earth, which indicates that the urbanization and land use change may have caused water surface alterations during the past three decades.

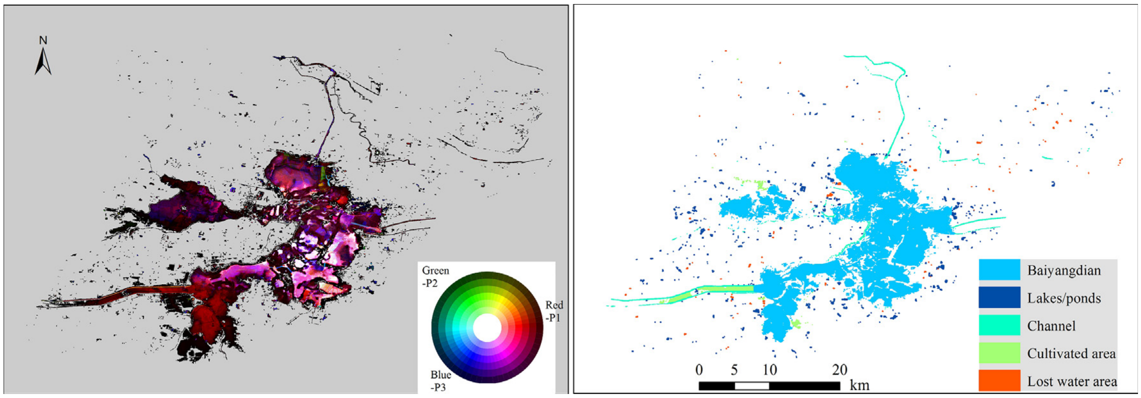

Fig. 5. RGB composite map of water inundation frequency among the three different sub-periods and inventory of water bodies of different attributes across New Area.

3.3. Implication and shortcomings of surface water mapping based on time-series images

The ability to map the spatial distribution and temporal trajectory of surface water bodies is essential to advance our understanding of the hydrological and climate impacts and optimizing water resource developments, especially over watersheds or regions with arid climate and drought disturbances. The long time series of remote sensing imagery from Landsat provides an unparalleled opportunity to measure surface water changes and enables us to detect some fluctuations or abrupt changes of water bodies probably concealed from the investigation only based on several-epoch satellite observations [18,24]. Our study integrated all cloud-free Landsat images to identify and characterize the dynamics of surface water bodies in Xiong'an New Area. We derived spatially and temporally explicit dynamics in surface water and quantified the pixel-based change in extent and water-presence frequency from 1984 to 2016. Continuous time-series of surface water body data are important for analyzing how the water body changes with hydrological seasonality or regime shifts and discriminating the trend and abrupt changes of surface water in response to climate change and anthropogenic intervention [33,34].

In addition, this allowed us to better link the water body area changes with water level time series. Given that the empirical relationship between water area and stage is established, the surface water area (or water level) at any given time step can be estimated based on water level (or area) data, which greatly facilitates the reconstruction of surface water storage (volume) variations and catchment-level water balance modelling. A generally consistent pattern can be found when Baiyangdian Lake water inundation and annual averaged water levels from single station (digitalized from published results in Li et al. [17] and Zhuang et al. [6]) were compared in temporal dimension (Fig. 6a). Specifically, higher water levels were observed at the broader inundation extent and higher water presence frequency in 1986, exposing the lake bathymetry heights below 6 m in (nearly) dry-up stages around 1985 and 2000. Due to the inaccessibility of *in-situ* daily water level data, we here only demonstrate the statistical relationship at annual timescale (Fig. 6b). The regression analysis shows the r^2 values of 0.81 and 0.89 for linear and polynomial relationships that were obtained between annual averaged water level and inundation area in post-west season. The small P value ($P < 0.01$) indicates the statistically significant association.

Fine-scale inventory of New Area water bodies remains a challenge because of the large temporal and spatial variations. Several limitations of our study should be noted. First, our method retrieves water bodies larger than 0.005 km^2 (six or more connected pixel parcels). Thus the estimation of total surface water area may have slight underestimation due to exclusion of small ponds and narrower streams. We manually digitized open water inundation areas based on two dates of high-resolution images from CNES/Airbus that were acquired in October 2002 and April 2016, respectively corresponding to the desiccated and normally inundated stages, and compared them with our Landsat-based automated mapped water body results. The water body maps from high resolution data are provided in Supplementary materials (Fig. S1 online). The mapping results are rather comparable, and the producer's accuracy and user's accuracy for the comparison at normally inundated stage are 79.7% and 95.2%, respectively. The mapping accuracy is relatively lower in desiccated water inundation stage, and the producer's accuracy and user's accuracy

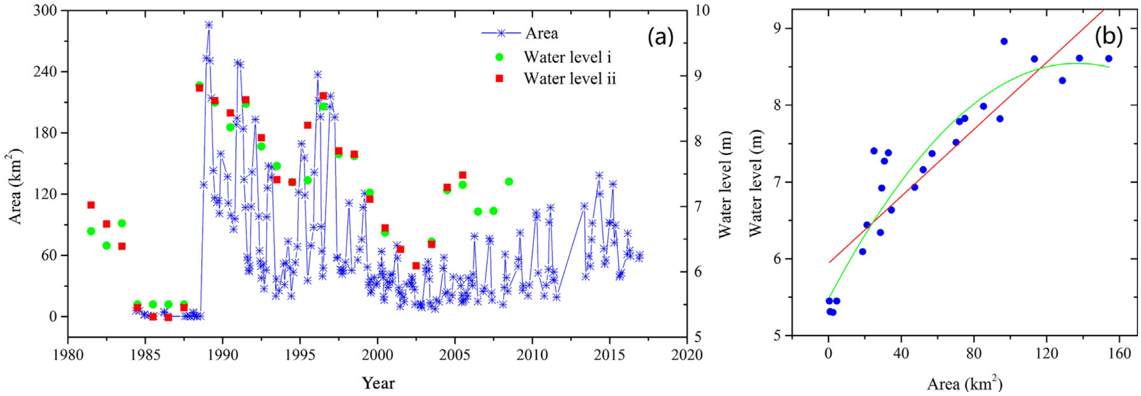

Fig. 6. Comparison of time series of Landsat-derived surface water area and station-based annual averaged water levels of Baiyangdian Lake. The water-level time series i and ii are derived from records in literature Li et al. [17] and Zhuang et al. [6], respectively.

are 61.9% and 79.4%, respectively. The inconsistency could be mainly caused by the scaling issue (narrow channels or tiny ponds) and shallow-water wetlands in dry seasons and periods. Whereas the consistent image resolution of time series of Landsat achieve and the same mapping algorithm may reduce the biases of mapping results in examining the variability of water bodies. Future work should obtain finer sized water bodies and more accurate water body boundary from multi-temporal high-resolution imagery. It would be a useful water reference map and greatly beneficial to the future sustainable urban land use planning and eco-environment conservation within the New Area. Secondly, we mapped the surface water bodies rather than wetlands. However, some wetlands in Xiong'an New Area are shallow-water or reed lands. Thus our analyses only indicate the spatio-temporal variability of open water in this study. Future work should include the mapping of wetland vegetation and to utilize the time-series for understanding the spatially and temporally conversion of surface water area and vegetation wetlands or build-up areas in a changing climate and intensified human interventions. Thirdly, the open water mapping in this study only used completely cloud-free images over the targeted water area since April 1984. The strategy is a little different from that in the recent global water body mapping work by Pekel et al. [24], which includes all of Landsat archive data (including partially cloud-covered) and then masked out cloud-affected area at pixel level. In comparison, the water frequency maps in this study would be more comparable in the spatial domain with coherent mapping times. However, cloud-free images tend to be more available in dry seasons than wet seasons, that is, higher weights are given to the pre-wet season observations in compositing all-season maps. Thus the all-season water frequency maps may be slightly temporal biased in the study.

4. Review and synthesis analyses of the cause of Baiyangdian Lake changes

We compared annual precipitation and pan evaporation variations with the changes of surface water area (Fig. 7). It is obvious to observe that larger water inundation areas coincided with high precipitation and low evaporation anomalies. The lasting dry-up stage during 1984–1988 just followed the extreme drought event of NCP in the early-1980s [35]. The time-series climate data reveal the drought conditions lasted until the late 1980s. In July 1988, the monthly precipitation (from Baoding station) exceeded 400 mm. The heavy rainfalls within the short period probably contributed to the filling of Baiyangdian Lake and other ponds. The peaks and toughs of fluctuated water area time series in the 1990s also corresponded well to the wet and dry years. The correlation analyses between the time series of water body areas (average of sampling points during the post-wet season, S) and climate elements (P, E, and P – E) confirm their strong associations, with correlation coefficients of 0.65, −0.48 and 0.65 for S & P, S & E and S & "P – E", respectively. The strong correlations are statistically significant at the 99% or 95% confidence levels. An interesting note is that, from the climate records, the "precipitation – evaporation" difference anomaly around the year 2000 was even more negative than that in the early-2000s, however, the surface water area was higher than the average during 1984–1988. In particular, Baiyangdian Lake did not completely dry up in the early-2000s despite that the annual precipitation was lower than the level in the early-1980s. It could be partly attributed to the external water division for supplying Baiyangdian Lake. The driving forces of Baiyangdian Lake changes will be discussed below.

Our analyses have revealed the good agreement between time series of surface water area in New Area and gauge-based precipitation and evaporation anomaly. However, it should be noted that the drought stage implies heavier human water demands from the lakes and upstream discharges. Thus we cannot attribute this coherent pattern of climate and water area time series to the dominant control of natural climate factor on surface water dynamics. There have been multiple lines of evidences documented in prior literature to argue that the degraded Baiyangdian Lake was also strongly influenced by human activities from various aspects, including development of reservoir projects, extraction and utilization of groundwater, agricultural irrigation, and land use and land cover change (LULCC), etc.

Water from upstream rivers was the main supply source of Baiyangdian Lake, whereas water supplying Baiyangdian Lake from upstream rivers has decreased dramatically in recent decades. The annual water discharges to Baiyangdian Lake from the entire upstream rivers decreased from 18.27×10^8 m^3 in the 1950s to 0.24×10^8 m^3 in 2000 [9,13]. In the past few decades, a great number of hydraulic engineering projects were constructed in the upstream areas that could have inevitably reduced the runoff and changed the rainfall infiltration condition. About 150 reservoirs, including 6 large reservoirs (Hengshanling, Koutou, Wangkuai, Xidayang, Longmen, and Angezhuang) and 12 medium-sized reservoirs, were built in succession in the basin since the 1950s [17]. It is estimated that the reservoirs, with a total water storage of 3.6×10^9 m^3, controlled more than 50% of the watershed areas

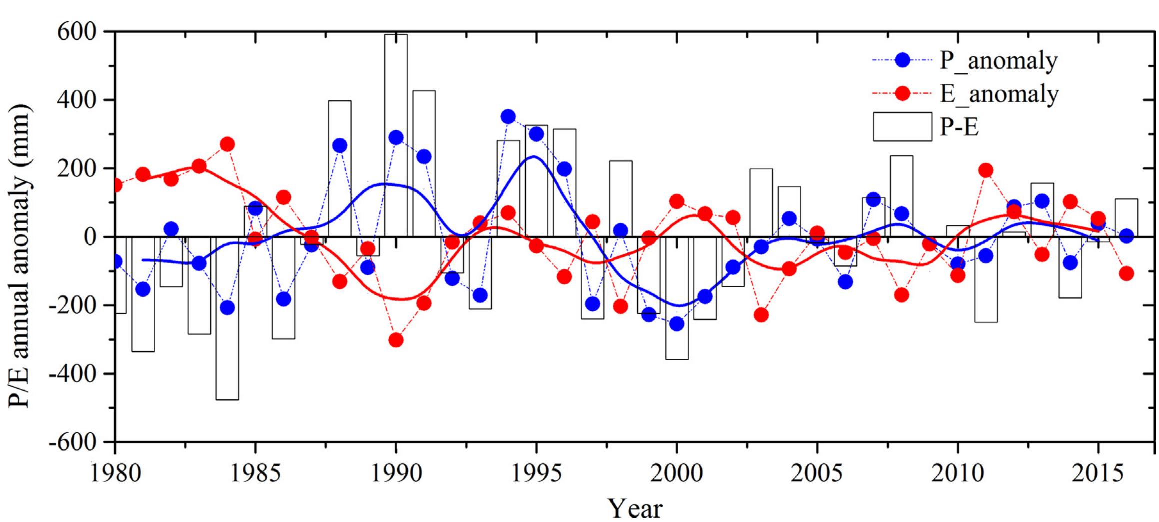

Fig. 7. Time series of precipitation (P)/evaporation (E) anomaly of Baoding station from 1980 to 2016.

and had remarkable effect on intercepting the upstream runoff [17,36,37]. With equivalent water fluxes (expressed as "precipitation-evaporation"), the water flow into Baiyangdian Lake declined significantly after construction of these reservoirs [6,38].

Due to insufficient surface water supply, human water use depended more on exploiting groundwater since the 1970s. Intensive groundwater abstraction especially for agricultural irrigation is another factor contributing to the drastic groundwater drawdown in the lake catchment and the wider North China Plain [4,39,40]. According to the statistics in 2006, groundwater pumped from wells within the basin accounted for 87.5% of the total water consumed. Accumulated overexploitation of groundwater led to substantial decline of water table, which in turn induced more extensive depletion of surface water over the lake region. Measurements in Anxin County evidenced that groundwater declined from an average of underground 6.1 m in 1988 to 11.0 m in 2007. Water loss from well abstraction has not only limited groundwater discharge into the lake, but has also accelerated lake leakage into the underlying aquifer systems.

Baiyangdian watershed is one of the primary grain-production areas in North China Plain. There are four large irrigation districts (Shahe, Tanghe, Yishui, Fanglaizhuo) above 2000 ha and tens of medium irrigation districts within the catchment, with the total effective irrigation cultivated land of ~78,000 ha [17]. Total water use within the catchment got to 46.9×10^8 m^3 in 2006, nearly 80% of which was used for irrigated agricultural land. An interesting phenomenon was found [12] that the abrupt year of streamflow decrease in 1980 happened to the beginning year of China's land policy reform, as the new land policy encouraged farmers to manage their lands more effectively, resulting in the increased agricultural water use and declined streamflow in the catchment.

Other factors such as population growth, urbanization, industrialization, farm irrigation and other forms of land and water use may also contribute to the reduced lake storage. From 1950 to 2007, the population of Baoding City increased from 5.2×10^6 to 1.1×10^7, and per-capita gross domestic product (GDP) of Baoding City increased from ~90 RMB Yuan to 1.2×10^4 RMB Yuan [3,6]. The dramatic growth of population and economy inevitably resulted in an increase of water withdrawal for human use.

By contrast, there have been some human actions taken to mitigate lake water stress. For example, in order to ease the lake desiccation and restore the lake wetland function, water was transferred from upstream reservoirs and external watersheds (e.g. Yellow River) to Baiyangdian Lake 24 times, with the total volume of 1.45×10^9 m^3 between 1991 and 2015 [4,6,17]. Since 2000, the water diverted to the lake has exceeded the natural water discharge from upstream rivers. Without the water transfer project, Baiyangdian Lake could have already dried up. Thus Baiyangdian Lake has been called an "artificial lake" in some sense [6]. The water division project was rather crucial for maintaining ecosystem services of Baiyangdian Lake, such as wildlife habitats, pollution dilution, recreation, and so on. However, the action can only mitigate the problem of water shortage temporarily.

5. Summary and perspectives

The location, persistence, and transition of surface water is both altered by changing climate and human activity, especially in the arid regions, which in turn affects climate, ecosystem diversity, and human society. Here, we employ all of cloud-free Landsat satellite images to examine changes in surface water in Xiong'an New Area at 30-m resolution during 1984 to 2016. A total of 245 valid observations were utilized to extract time series of water inundation areas. The change of surface water area in Xiong'an was not characterized by a monotonically and linear decreasing tendency. During the past 33 years, the New Area water body areas varied dramatically, ranging from 0.44 km^2 in April 1988 to 317.85 km^2 in February 1989. According to the inter-annual change of water inundation area, we divided the whole study period into four sub-stages: the first extreme desiccation during 1984 to mid-1988 when Baiyangdian Lake dried up even in wet seasons, the wet stage from late-1988 to late 1999 with the most extensive inundation areas and strong inter-annual fluctuations, the second desiccation stage since late-1999 and lasting till 2006, and the overall recovering stage between 2007 and 2016.

We mapped the maximum inundation extents and water presence frequencies of all-season, pre-wet season and post-wet season for the study period and different sub-periods. The maximum water extent is 409.6 km^2 occurred in the 1990s, compared with the areas of 164.5 km^2 and 211.3 km^2 in the early 2000s and the recent years, respectively. Spatial patterns of water frequency maps reveal the gradient of decreasing water inundation frequency from central and eastern parts of Baiyangdian Lake to the lake periphery and extended regions in both the whole year and different seasons. Most of mapped canals and small ponds are also seasonally inundated. The area of water presence frequency beyond the 50% percentile approximately accounts for 8.8% (36.1 km^2) of the total inundation extent during the 33-year period, with higher percentage of 12.1% in the pre-wet season compared to 7.8% in the post-wet season. We also delineated the areas of water presence frequency higher than 10% in the past 33 years and assigned their attributes by superimposing the water-classified polygons on the high-resolution Google Earth imagery and revealed that some ponds disappeared probably due to the urbanization and land use change.

As the main water body of Xiong'an New Area, Baiyangdian Lake has undergone enormous changes in hydrology. Prior literatures explored the driving forces of the lake degradation and most highlighted the joint contributions of climate change and human intervention impacting on the lake hydrology and dramatically decreased lake water inputs. Multiple lines of evidences suggest that the upstream flow was strongly influenced by various human activities, including land use and land cover change, reservoir construction projects, agricultural irrigation, and groundwater mining. As many factors jointly affect the lake desiccation together, there has been still no consensus on what is the primary reason. The quantitative modelling work of disassembling the contributions from changing climate and different human actions is still urgently needed with deeper and more comprehensive investigation.

Although more than 20 times of external water division actions have been taken to ease the lake desiccation situation, the situation were mitigated temporally and the eco-environment is still very fragile. The future projected higher occurrence of extreme climate events might make the situation worse. The good news is that the central and local governments are making great efforts to restore the lake hydrology and eco-environment system. Future work is recommended from the following aspects: (1) More quantitative and basin-scale investigations of the climatological, hydrological, geological and environmental processes are needed to promote the comprehensive realization of changes in Baiyangdian Lake and related driving mechanisms [41]. Hence we call on the establishment of geo-spatial data sharing platform, e.g. climatological and hydrological data, environmental monitoring data, remote sensing observations, social-economic statistics etc. We also anticipate to release the result data of surface water change detection for public access for facilitating estimating water storage changes, modelling water balance, and future land use planning. (2) Besides the above-mentioned natural driving factors, human actions should be quantified and integrated into the modelling system to explicitly indicate the different contributing components, which would be the key of scientifically allocate the water resource development and sustain the eco-environment health of New Area. (3) The projected climate change scenarios, especially rising extreme climate events, should be emphasized in the future land use and environmental planning strategy to reduce the lake desiccation risks. (4) It also requires the consideration of balancing the relationships among natural resources, economy and society, e.g., improving agricultural infrastructure for irrigation water-use efficiency, and enhance the cooperation between upstream and downstream to achieve integrated watershed management and shift water resources conservation strategy toward a more sustainable future.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.scib.2018.05.002.

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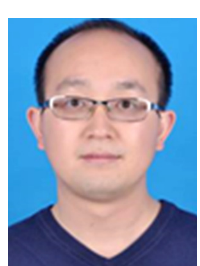

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