Remote Sensing of Environment 248 (2020) 111998

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Anthropogenic transformation of Yangtze Plain freshwater lakes: patterns, drivers and impacts

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ARTICLE INFO

Keywords:
Lake reclamation
Landsat
Remote sensing
Yangtze
Sustainability
Freshwater
Policy

ABSTRACT

Over the past half century, the Yangtze Plain of China has experienced rapid economic development. Lake reclamation (i.e., conversion of natural lake/wetland areas to agricultural/urban land or aquaculture, thereby reducing the area of natural waters) in particular has greatly contributed to meeting the increasing demands for food and urban development. However, until now, a comprehensive quantification and understanding of historical anthropogenic lacustrine exploitation in this region has been lacking, prohibiting assessment of the impacts of these activities. We used Landsat observations from 1973 to 2018 to track reclamation-induced changes in 112 large lakes (97.8% of the total lake area) in the Yangtze Plain. We show that 41.6% (6056.9 km^2) of the total lake area has been reclaimed since the 1970s. The expansion of agricultural and built-up lands dominated the reclamation activities in the 1970s, while the increase of aquaculture zones has prevailed since the mid-1980s. Reclamation activities were closely connected to government policies and major socio-economic events and had strong impacts on lake hydrology, flood risk mitigation capacity, and water quality as revealed by satellite and in situ observations. This new quantitative understanding of anthropogenic reclamation and its associated impacts on Yangtze Plain freshwater lakes can underpin the development of strategies to reduce the impacts of lake reclamation on environmental quality. The study has also demonstrated the unique strength of using long-term series satellite images in tracking historical environmental changes in a substantial region of the world, and the methods used here are potentially extendable to other inland and coastal areas to understand similar human-environment interaction problems.

1. Introduction

The Earth's surface water bodies have witnessed dramatic changes in recent decades (Donchyts et al., 2016), such as global warming induced alpine lake expansion and human-induced freshwater lake shrinkage (Lewis et al., 2015; Ma et al., 2010a; Pekel et al., 2016; Prigent et al., 2012; Roach et al., 2011; Tao et al., 2020). Many of these changes have had significant negative environmental, ecological and economic consequences (Jia et al., 2018; Zhang et al., 2017). This highlights the need for a better understanding of the tradeoffs between development and the environment, as well as improved strategies for sustainable development. Lake reclamation is a prominent example of such changes, in which the undisturbed open-water lake areas are converted to agricultural/urban land or aquaculture to meet the increasing demands for food and living space from a growing population (Donchyts et al., 2016; Fang et al., 2005). Globally, more than 50% of natural wetlands have been lost since the 20th century, which has been accompanied by severe deterioration of environmental quality (e.g., eutrophication, pollution) and the loss of ecosystem services (e.g., potable water, biodiversity) (Fang et al., 2006; Zeng et al., 2013). The highest wetland loss rates over the past half century have occurred in Asia, with inland wetlands more seriously affected than coastal

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https://doi.org/10.1016/j.rse.2020.111998
Received 17 March 2020; Received in revised form 16 June 2020; Accepted 8 July 2020

wetlands (Davidson, 2014). In China's Yangtze Plain, lakes and low-lying lands have been exploited for millennia. With the population expanding from 160 million in 1953 to 340 million in 2018 (i.e., 24% of China's and 4.4% of the world's population), this plain has rapidly urbanized and become a global hotspot of human-environment interaction (Cui et al., 2013; Xie et al., 2017).

Lake reclamation has been widely used to boost scarce land resources to support agri-food production and urban development in the Yangtze Plain (Cui et al., 2013; Fang et al., 2005; Xie et al., 2017), but this has had serious and widespread environmental impacts, such as biodiversity losses (Fang et al., 2006), wetland degradation (Zhou et al., 2014), and water quality decline (Zhu et al., 2019). In response, the Chinese government has recently established specific programs to preserve freshwater ecosystems under its commitment to the United Nations' Sustainable Development Goals (SDGs) (Gao et al., 2018). However, a detailed and accurate assessment of lake reclamation, which is necessary for understanding the environmental impacts of human development as well as supporting policy and decision-making, does not exist.

Previous research has quantified historical land-use changes of selected lakes in the Yangtze Plain using remote sensing, reporting the conversion of large lake areas to agricultural land, built-up land, and aquaculture (see Table S1 for a complete list of studies on lake changes). However, due to the substantial heterogeneity and complexity of lacustrine hydrological processes over space and time, long-term high-resolution spatiotemporal dynamics of lake reclamation patterns over the entire Yangtze Plain have not been quantified. In general, most existing studies have only focused on the changes of the lakes' physical properties (i.e., inundation area) and few attempts have been made to examine their functional transition. A major limitation of these studies for example, is the lack of consideration of the conversion of natural lake areas to aquacultural production, which remain inundated but are separated from the main lakes. Indeed, the absence of a comprehensive assessment of lake reclamation has impeded the understanding of the potential environmental consequences of large-scale human activities on regional lacustrine and wetland systems, not to mention the design and implementation of effective sustainability policy and programs.

In this study, we undertake a comprehensive assessment of anthropogenic reclamation of Yangtze Plain lakes over the past half century, assessing the influence of policy on reclamation and its hydrological and ecological impacts. We used Landsat images from 1973 to 2018 to examine changes to 112 large lakes (with lake area ranging between 7 and 4267 km^2 and representing 97.8% of the total lake area in 1973) in the Yangtze Plain, China (see Fig. 1 and Table S2). We mapped three lake cover types, (1) Natural water (i.e., undisturbed open water), (2) Aquaculture zone and (3) Agricultural/built-up land (see Fig. 2). We summarized the spatial and temporal patterns of lake cover changes and explored the influence of policies and major socio-economic events. We also assessed the impacts of observed lake cover changes on water quality and hydrology using satellite observations and in-situ measurements. The results not only provide the first comprehensive picture of large-scale anthropogenic environmental change and the associated impacts on Yangtze Plain lakes but also demonstrate how human activities can transform the Earth's surface at the regional scale. The information presented is crucial for underpinning effective policies for freshwater lake conservation in China to meet its commitment to the UN SDGs.

2. Materials and methods

2.1. Study area

The Yangtze Plain, which refers to the alluvial plain in the middle and lower reaches of the Yangtze River, has an area of ~140,000 km^2 and covers five provinces (Hubei, Hunan, Jiangxi, Anhui, and Jiangsu) and one municipality (Shanghai) (Fig. 1). As an essential area for grain, oil, and cotton production, the Yangtze Plain accounts for ~51% of rice production and ~57% of freshwater aquaculture production in China (Ge and Jin, 2009; Zhu, 1995). Lakes and ponds are spread throughout this region, accounting for 18.8% of the lake area in Asia and ~ 54% of the freshwater resources in China (Ma et al., 2010b; Wang et al., 2014). The codes, names, and locations of these lakes are listed in Table S2. The lakes primarily originated following sea-level rise during the last postglacial age when the water level of the Yangtze River increased, causing floods and persistent inundation of low-lying areas along the two banks (Yang, 1986). Hence, the Yangtze Plain lakes are mostly shallow, with a water depth of < 5 m (Yang et al., 2008). Historically, the lakes were naturally linked to the Yangtze River, but most of these natural connections have been blocked over the past century due to the intensive construction of hydraulic projects (Xie, 2017). Currently, there are only three Yangtze-connected lakes in the Yangtze Plain (i.e., Poyang Lake, Dongting Lake, and Shijiu Lake), in which a seasonal inundation regime dominates and lakes dry out forming large floodplains during the dry season (Fig. 2). Two major types of reclamation occurred in the Yangtze Plain lakes. The first type is physical development from Natural water to Agricultural/built-up land (see Fig. 2). The second type includes reclamation from Natural water to Aquaculture zone. Although Aquaculture zones are still covered with water, they are generally diked from the main lake and are mostly used for fishery cultivation. Satellite remote sensing has been used to track the historical changes of reclamation in selected lakes in the Yangtze Plain (Table S1). However, previous studies suffer from the following two major limitations: 1) spatial and/or temporal constraints regarding the satellite data that were used and 2) only a partial study of one or a few lakes. Comprehensive assessments of lake exploitation and reclamation

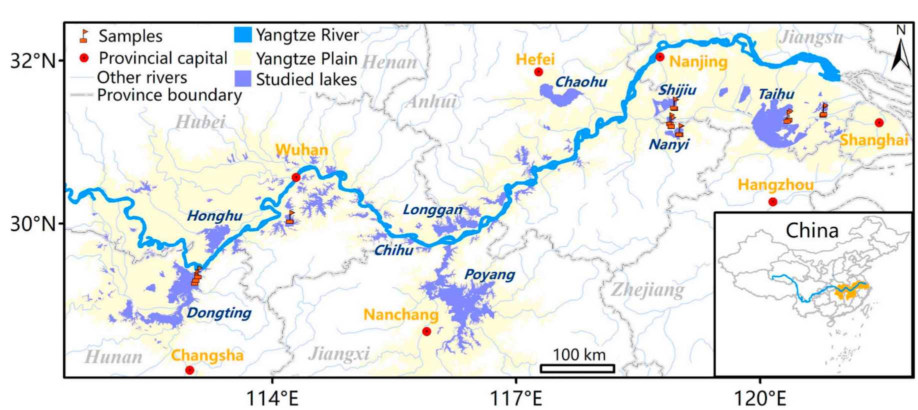

Fig. 1. Locations of the 112 studied lakes in the Yangtze Plain. Red flags show the locations where water samples were collected. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

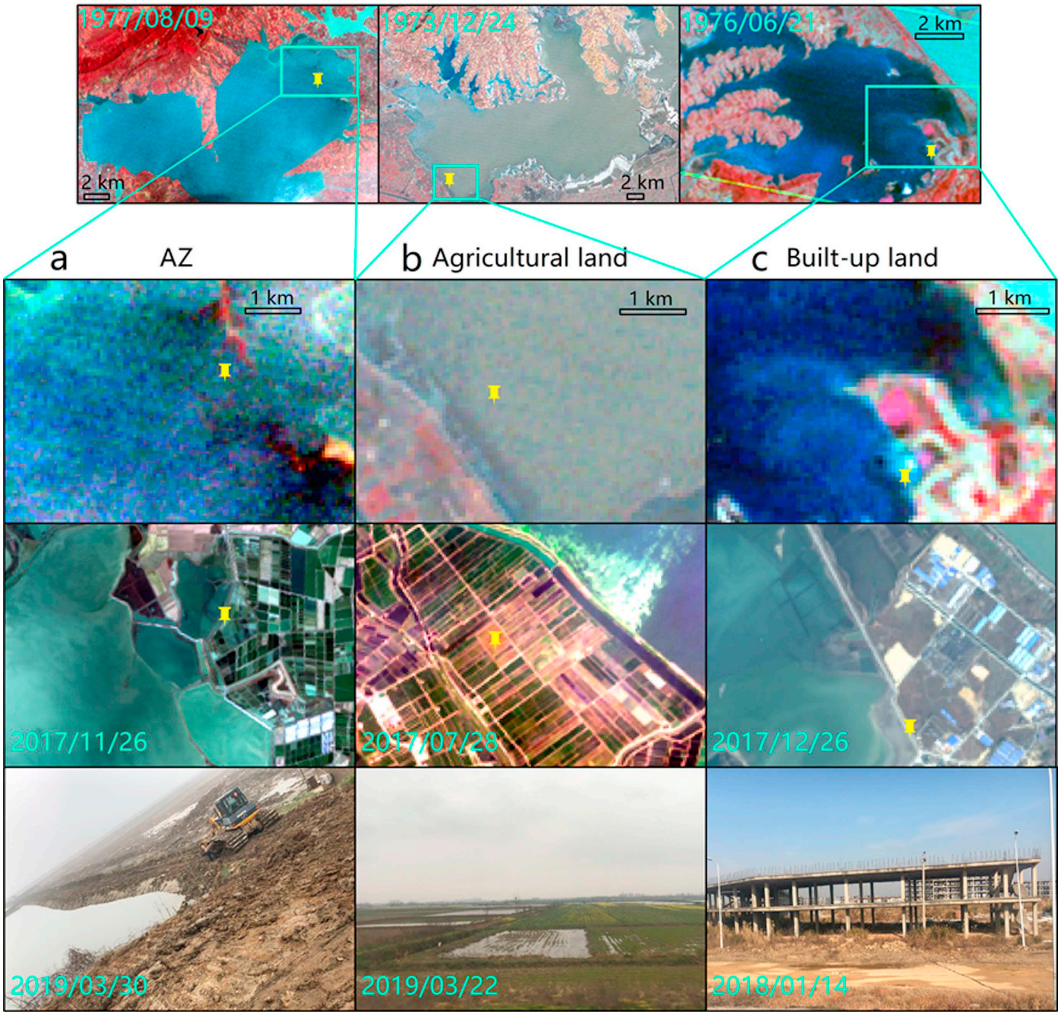

Fig. 2. Examples of pre- and post-reclamation changes for different lake reclamation types, as observed in Landsat images and digital photos. (a) Aquaculture zones (AZs) in Nanyi Lake, (b) agricultural land in Longgan Lake, and (c) built-up land in Chihu Lake. The lower panels show digital photos taken of these reclamation types, with the photographic locations (yellow marks) annotated in the Landsat images. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

patterns over the whole Yangtze Plain over a long time series have been lacking. We fill this knowledge gap using five decades of Landsat observations to examine the reclamation histories of 112 large lakes (area > 7 km^2) (see Fig. 1). The total inundation area of the examined lakes accounted for 97.8% of the lake area in the Yangtze Plain in the 1970s (Cui et al., 2013).

2.2. Data collection

The Landsat remote sensing data used to study the lake reclamation changes were obtained from the United States Geological Survey (USGS) (https://glovis.usgs.gov/), including data from the Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+) and Operational Land Imager (OLI). The MSS images data has an original spatial resolution of 68 × 83 m, which were resampled to 30 m resolution to match data that were collected by the other Landsat instruments. The lower spatial resolution of MSS has a minimal impact on the delineation of reclaimed areas, since the artificial dikes on lakes are clearly evident in these images. In total, 3963 high quality images with minimal cloud cover and sun-glint contamination (visual inspection with the USGS Global Visualization Viewer, also available at https://glovis.usgs.gov/) were downloaded, spanning the years 1973 to 2018 and covering 10 different Landsat paths/rows (see Fig. S1a). The temporal distribution of the remote sensing images is demonstrated in Fig. S1 (b-d). Note that the Landsat 7 ETM+ data collected after 2003 have a slatted appearance due to the missing scan-line corrector strips (Andrefouet et al., 2003) which affected the reclaimed areas delineated and hence, were excluded from this study given its continued data collection and distribution.

Water samples from the reclaimed Aquaculture zones and nearest Natural water areas were collected in 2019 (see sampled lakes in Fig. 1), and the temporal gap of sample collections between Aquaculture zone and the corresponding Natural water were < 30 min. Water quality parameters were quantified via laboratory analysis including chlorophyll-a (Chl-a, in mg m^{-3}) and various nutrient concentrations. Specifically, the Chl-a concentration was measured with the spectrophotometric method (HJ-897-2017) recommended by the State Environmental Protection Administration of China. The total phosphorus (TP, in mg L^{-1}) concentration was measured with the ammonium molybdate spectrophotometric method (GB 11893–1989). The concentration of nitrate nitrogen (NO_3^--N, in mg L^{-1}) was determined with the cadmium column reduction method (GB 17378.4–2007). The concentration of nitrite nitrogen (NO_2^--N, in mg L^{-1}) was determined with the cadmium column reduction method (GB 7493–87). The ammonia nitrogen (NH_4^+-N, in mg L^{-1}) was measured with the salicylic acid spectrophotometry method (GB536–2009), and the total dissolved nitrogen (TDN, in mg L^{-1}) was measured using a total organic carbon (TOC)-L CSH/CSN analyzer and an ASI-L autosampler (Shimadzu, Japan).

To examine the linkages between lake reclamation and human activities, socioeconomic datasets, including data on the population census, grain production, and annual yearly fishery production, were obtained from local annual statistical yearbooks. Data on the areas of built-up land in the counties surrounding the studied lakes were also obtained from the China City Statistical Yearbooks from 1985 to 2017. Lake drainage basin boundaries were delineated using SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS) (Lehner and Grill, 2013). Flood frequency data (i.e., the number of floods occurring each decade) in the Yangtze River Basin were compiled from a previous study (Yin and Li, 2001) and the annual flood disaster report released by the China Flood Control and Drought Relief Headquarters Office. Precipitation data (from 1951 to 2018) from 20 gauge stations in the Yangtze River Basin were downloaded from the China Meteorological Data Sharing Service System (http://data.cma.cn/), and the decadal mean precipitation values from the 1950s to 2010s were estimated to examine whether the increased flood frequency was due to changes in local precipitation.

2.3. Delineation and validation of the lake reclamation areas

Lake boundaries were defined as the maximum water extent in the 1970s (i.e., the intersection of the extracted water areas between 1973 and 1979). The water areas were extracted with a thresholding method employing the commonly used normalized difference water index NDWI = $(R_{green} - R_{nir})/(R_{green} + R_{nir})$, where R_{green} and R_{nir} are the radiometrically calibrated reflectance values of the green and NIR bands, respectively (Wang et al., 2014). A simple NDWI threshold was able to accurately separate water and land in the study region since the Yangtze Plain lakes are of low elevation (< 30 m above sea level) and far from urban areas. Therefore, NDWI should be relatively free from the impacts of terrain shadow, urban shadow from high buildings, and other effects. Semiautomatic software developed by Hou et al. (2017) was used to select the optimal NDWI threshold for lake delineation in every single image. Delineation of reclamation areas was restricted within the boundary of each lake.

While the water/land interface could be determined with the NDWI method, it was challenging to classify Natural waters and Aquaculture zones due to their similarities in the spectral domain. Instead, the different spatial patterns between Natural waters and aquaculture regions were used to separate the two surface features. As shown in Fig. 2, dikes were constructed to separate the aquaculture fishery regions from the main lakes. Dikes appeared as regular straight lines in the remote sensing images and were clearly distinguishable compared to the boundaries of Natural waters which were irregular in shape. As these spatial features were not recognizable by conventional image classification methods (e.g., supervised/unsupervised approaches), Aquaculture zone boundaries were visually interpreted and manually delineated using ArcGIS software (version 10.1). Whenever a regular edge was found in a water body, the delineated polygon was considered an Aquaculture zone.

For lakes with small seasonal changes in inundation (109 of the 112 lakes examined in this study), Agricultural/built-up land reclamation was identified as the NDWI-classified non-water regions within the lake boundaries. However, additional effort was required for the Yangtze River-connected Poyang, Dongting and Shijiu lakes due to their dynamic seasonal inundation regimes. The exposed floodplains of these lakes during the dry season could be misclassified as Agricultural/built-up land if the NDWI-based method alone was used. Hence, the discrimination between natural floodplains and Agricultural/built-up land was also based on visual interpretation. The reclaimed Agricultural/built-up lands had regular-shaped boundaries when used for agricultural cultivation, and the contrast in spectral characteristics between reclaimed built-up land and natural land surfaces was remarkable (see Fig. 2). Therefore, the boundaries of Agricultural/built-up lands were drawn manually based on differences with the floodplain in both the spectral (built-up) and spatial (farmland) domains. When performing the manual delineation, the images acquired before and after the current image were referenced to avoid the impacts of floods on the reclamation areas. For example, although an area could be inundated in the current image due to floods, the area would be delineated as Agricultural/built-up land if it appeared as Agricultural/built-up land in the former and latter images. Although this process was less effective in the 1970–1980 when Landsat observations were more limited, we were fortunate that most of the satellite data were acquired in dry seasons when floods are less likely to occur.

The areas of Natural water and reclaimed regions (i.e., Aquaculture zones and Agricultural/built-up land) were then estimated as the size of the delineated polygons using statistical tools in ArcGIS. These procedures were time and labor intensive considering the large scale of the Yangtze Plain (10 Landsat paths/rows), the number of lakes and reclaimed regions (112 lakes, with the possibility of multiple reclamation regions occurring in one lake), and the long time period (1973–2018). Note that areas of Natural water for three Yangtze-connected lakes were excluded from further analysis since the limited Landsat observations (particularly in the early periods) were not able to accurately characterize the lakes' rapid inundation seasonality.

To validate the accuracy of the 30-m resolution Landsat-delineated reclamation areas, the same delineations over high-resolution Google Earth images were used as references. 60 Google Earth images concurrent with the Landsat images (without flood occurrences) were obtained, including 52 lakes and spanning the period from 2006 to 2018 (high-resolution images earlier than 2006 were not available). The differences in acquisition time between the Landsat and Google Earth images were < 10 days, and changes in the hydrological conditions were negligible. The Aquaculture zone and Agricultural/built-up land reclaimed regions were manually determined using ArcGIS following the same methods used for the Landsat images. Validation of reclamation types was conducted at both the pixel and areal levels. At the pixel level, the Google Earth-delineated results were resampled to the same resolution as the Landsat imagery, and error matrices (user's accuracy, producer's accuracy, and Kappa coefficients (Congalton, 1991)) were estimated (Table S3). The Landsat-delineated reclamation showed mean accuracy levels of > 80% for the two reclamation types, and the mean Kappa coefficient was 0.78 (represents "very good" or "substantial" performance as determined by Czaplewski (1994)). Areal comparisons between the Landsat and Google Earth-derived reclamations found that the two independent observations showed high consistencies for both reclamation types, with R^2 = 0.94 and RMSE = 18.0% for Agricultural/built-up land and R^2 = 0.99 and RMSE = 5.7% for Aquaculture zones. Therefore, the accuracy of manually delineated reclamation regions over the Landsat images was sufficient for further analyses in this study.

2.4. Analysis of long-term reclamation changes

Lake sizes and reclaimed areas varied markedly, making it difficult to compare the extent of exploitation between lakes using absolute changing values. Therefore, the delineated reclamation areas were normalized over the lake sizes (i.e., the maximum water extents in the 1970s) to calculate the areal percentages of the different lake cover types.

Due to the limited number of high quality Landsat images in the 1970s–1980s (see Fig. S1), it was not possible to conduct annual reclamation mapping for each lake, and the seasonal inundation area change for some lakes could also influence the average area if only dry season data were available. As a compromise, the maximal areas of Natural waters and reclaimed regions (i.e., Aquaculture zones and Agricultural/built-up land) were selected over a three-year period to examine the long-term reclamation changes. The total number of 3-years period between 1973 and 2018 was 16, with the last period only

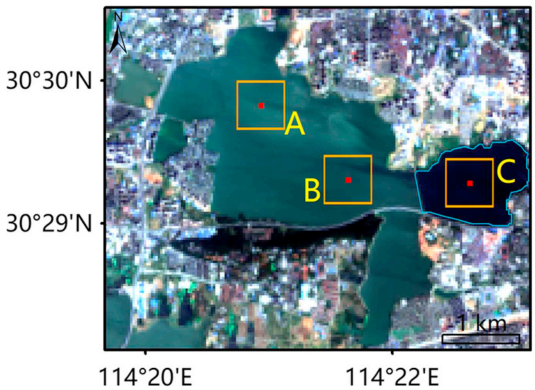

Fig. 3. Schematic map of the method of estimating the water color (FUI) differences between Aquaculture zones and Natural waters. "A" and "B" are nature waters, and "C" and is an Aquaculture zone.

included a single year (2018). Almost all 112 lakes had at least one observation for each three-year period over the past five decades. As Landsat data was not available in the first period (i.e., 1973–1975) for 14 lakes in the eastern Yangtze Plain (see Fig. S1d), values for the second period were used. To examine the extent of the reclamation for each lake, we estimated the ratios (in percentage terms) between different lake cover types in 2018 and the lake area in 1973. Linear regressions were performed over the 16 periods for each lake cover type to assess statistically significant changes (i.e., $p < .05$) over the past half century.

A normalization process was conducted to determine whether there were any common change patterns in the reclamation processes among different lakes: $NA_{i,j,k} = A_{i,j,k}/A_{max,j,k}$, where $NA_{i,j,k}$, $A_{i,j,k}$ and $A_{max,j,k}$ are the normalized area, three-year maximum area, and the maximum area from 1973 to 2018, respectively. The subscript i is the lake cover type ($i \in$[Natural water, agricultural or built − up land, Aquaculture zone]), j indicates the three-year period ($j \in$[1973 − 1975, 1976 − 1978, ……., 2015 − 2017, and 2018]) and k represents the lake number ($k \in$[1, 2, …, and 112]), respectively. For example, the period with the maximum reclaimed area of Aquaculture zones will have a normalized Aquaculture zone area of 100%. Normalization helped reveal the similarities of the reclamation histories among the different lakes and identified the turning points for the different reclamation types.

2.5. Clustering of the historical reclamation patterns

Cluster analysis was performed based on the normalized area data of Aquaculture zones and Agricultural/built-up lands for all 112 lakes from 1973 to 2018 to find common reclamation patterns among the different lakes over the past half century. Cluster analysis was performed using k-means clustering in SPSS (version 19.0) (Alfiani and Wulandari, 2015), and the 112 lakes were classified into 4 classes.

2.6. Calculation of the area transitions between the different lake cover types

Four years of data denoting the areas of three lake cover types for all 112 lakes were selected, including 1973 (the data from some lakes were from later years since Landsat images were unavailable from 1973 for these lakes, see Fig. S1), 1985, 2000 and 2018. These years represent the times separating the three clustered change phases. The lake cover transitions between the different periods (i.e., 1973–1985, 1985–2000, 2000–2018, and 1973–2018) were determined. For each lake cover type, the change percentage of the lakes was estimated as the relative difference in area between 1973 and 2018.

2.7. Assessment of hydrological impacts

Regional and global studies have demonstrated that the water storage capacity in lakes and reservoirs (S) has a power function relationship with the inundation area (A) which can be expressed as $S = a \times A^b$, where the constants a and b were calibrated specifically for the lakes in the Yangtze River Basin ($a = 0.0015$, $b = 1.0841$) by (Cai et al., 2016). This formula was used to estimate lake water storage capacities and to assess the associated changes due to reclamation. Note that the inundation area used here was the summation of Natural

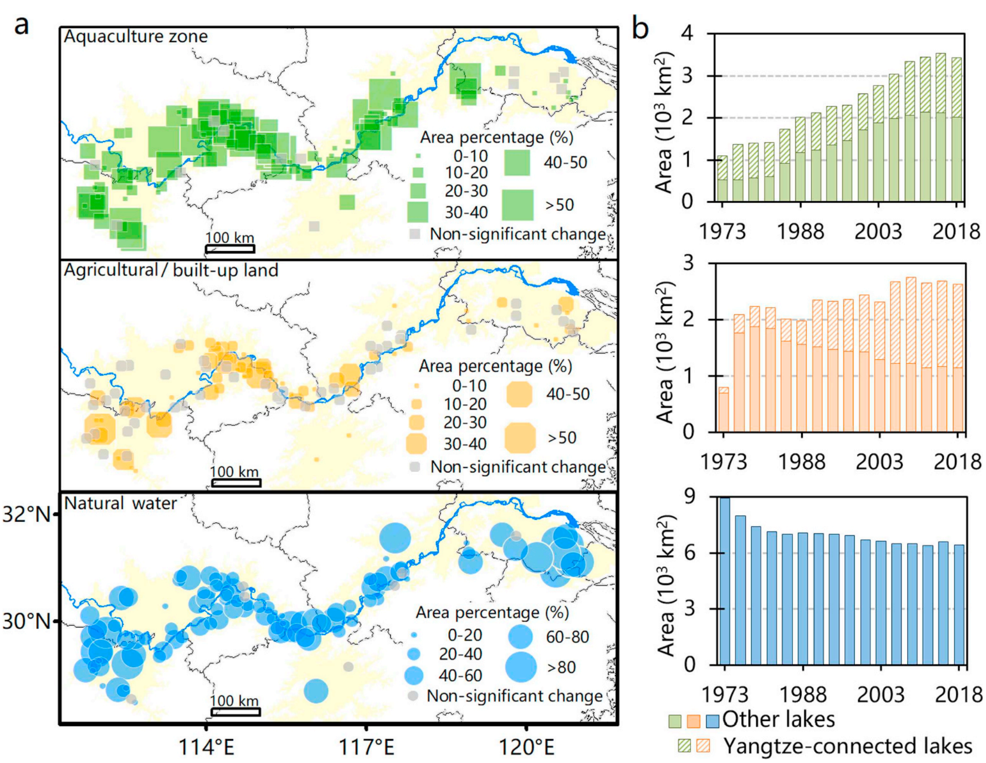

Fig. 4. Patterns and long-term changes in lake reclamation in the Yangtze Plain. (a) Fraction of Aquaculture zones, Agricultural/built-up lands and Natural waters in each lake during the last observational period (i.e., 2018). Lakes with significant changes between 1973 and 2018 were color shaded within each panel, and lakes with non-significant changes are marked with gray color. (b) The total areas of the three lake cover types between 1973 and 2018. Three Yangtze-connected lakes were excluded from the total area of the Natural waters, due to their regulated inundation seasonality see details in Section 2.3).

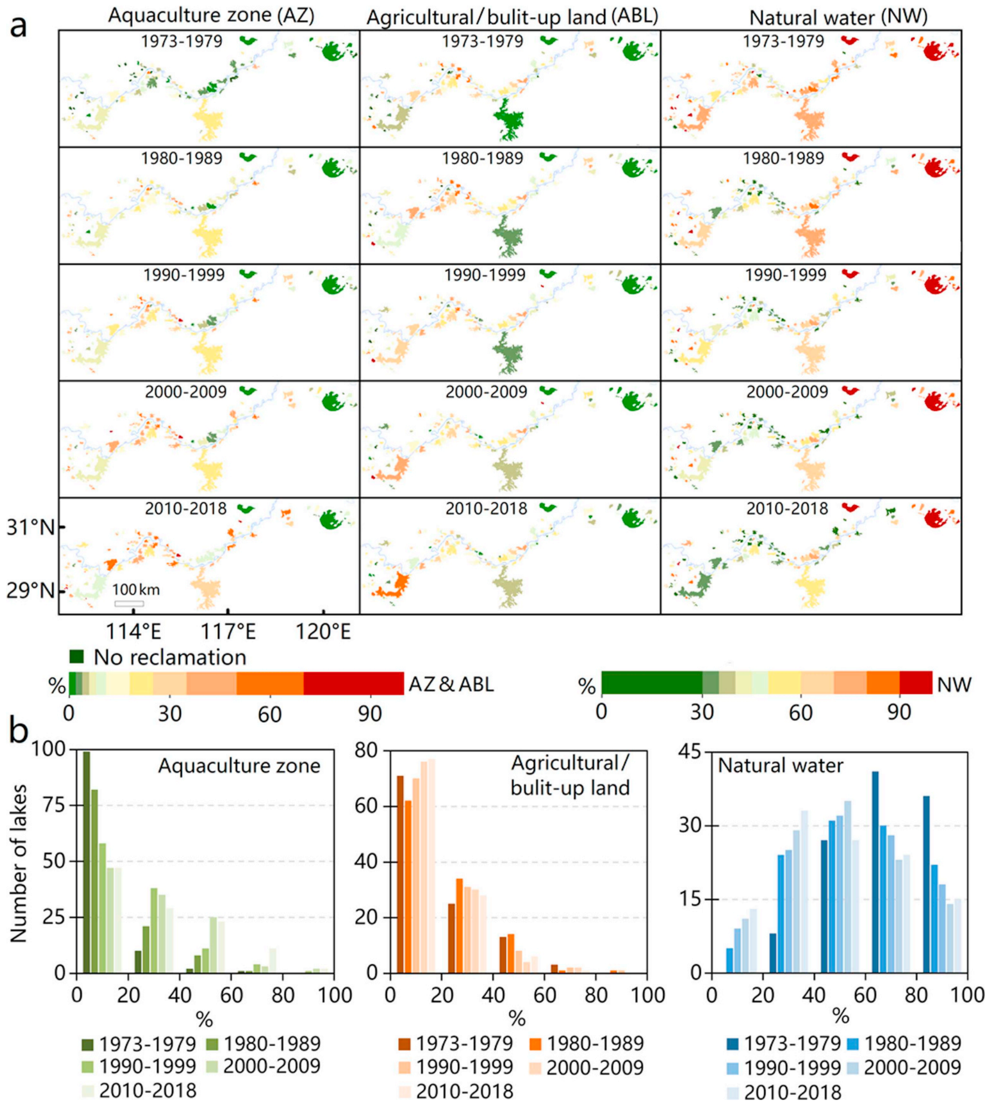

Fig. 5. Multi-decadal changes in lake reclamation in the Yangtze Plain. (a) The decadal mean areal percentages of different lake cover types in the Yangtze Plain from 1973 to 2018. (b) Histograms of the decade areal percentage (i.e., ratio between the current area and the maximum lake extent in the 1970s) of different lake cover types.

waters and Aquaculture zones as both are capable of storing water.

To demonstrate the potential impacts of reclamation on hydrology, differences in water storage (denoted as ΔS) between the beginning and end of the observational period were estimated for each lake. The ΔS of the lakes within the same drainage basin was then summarized and normalized against the basin area to calculate the basin-scale water depth equivalent (BWDE). Positive ΔS values were found for 94.6% of the examined lakes due to land explorations, indicating increased land exploration and reduced water storage in lakes and meantime, leading to positive BWDEs for all the lake basins.

2.8. Satellite-derived water color

The Landsat-derived Forel-Ule index (FUI) was used to examine the impacts of reclamation on water color changes. The FUI has been used as a comparative color scale for more than 100 years to quantify the water colors of oceans, lakes and rivers (Wernand and Woerd, 2010). The FUI classifies waters into 21 color types that range from indigo-blue to cola brown (the values of the FUI range from 1 to 21), representing different trophic states (Wang et al., 2018; Wernand and Woerd, 2010). The Landsat images were first processed with ACOLITE software (version 20,170,718.0 (Vanhellemont and Ruddick, 2015) to remove the atmospheric path radiance, and the images were then used to estimate the FUI values using the three visible bands as follows (Li et al., 2016; Wang et al., 2018):

$$X = 2.7689R + 1.7517G + 1.1302B$$
$$Y = 1.0000R + 4.5707G + 0.0601B$$
$$Z = 0.0000R + 0.0565G + 5.5934B \tag{1}$$

Where R, G and B represent the red, green, and blue bands in Landsat surface reflectance images. Then, the angle α within a chromaticity coordinates (x', y') was calculated as:

$$x' = Y/(X + Y + Z) - \frac{1}{3}$$
$$y' = X/(X + Y + Z) - \frac{1}{3}$$
$$\alpha = \left(\mathrm{ARCTAN2}\frac{x'}{y'}\right) \times 180/\pi \tag{2}$$

Using the angle α and a 21-class of FUI color type lookup table, the corresponding FUI value could be obtained.

For each Aquaculture zone, the maximum inscribed rectangle on the Landsat image (annotated as C in Fig. 3) was determined, and two additional windows that were the same size as C in Natural waters were

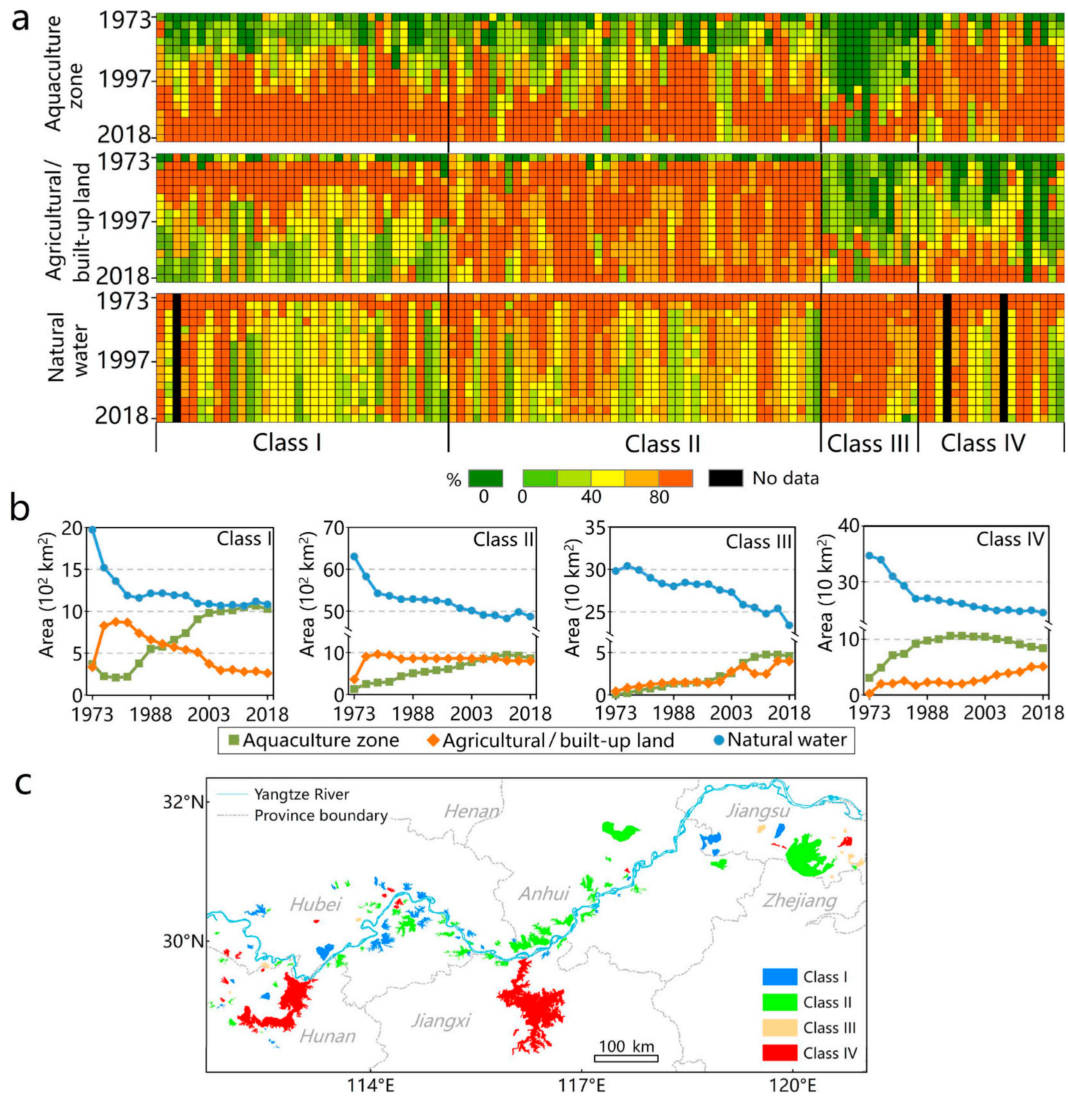

Fig. 6. Trends and interannual variability in lake reclamation patterns by four lake classes. The four classes were identified based on their similarity in temporal dynamics using a cluster analysis over the normalized areas of Aquaculture zones and Agricultural/built-up land. (a) Long-term changes in the normalized areas of Aquaculture zones, Agricultural/built-up land, and Natural waters from 1973 to 2018 for lakes. Each column represents a lake. Natural waters of the three Yangtze-connected lakes were excluded. (b) Trends of the total area for the three lake cover types, separated by each lake class. (c) The spatial distributions of the four lake classes.

also selected. One was closest in distance to the Aquaculture zone (annotated as B in Fig. 3), while the other was far from C (annotated as A in Fig. 3), and the distance between A and B was equal to the distance between B and C. The edges of these windows were at least five pixels away from lake boundaries to eliminate the potential influence of land adjacency effects (Feng and Hu, 2017; Masek et al., 2006). Small and narrow Aquaculture zones were thus excluded, resulting in a total number of 354 ABC pairs covering 62 studied lakes. The mean FUI values of these windows were calculated, and the differences between B vs C and A vs B were then estimated. The differences between B and C can be considered the result of lake reclamation. Differences between A and B were calculated as a reference to capture the impacts of other factors that could cause water color changes. Differences between A and B as well as B and C for the 354 pairs were estimated.

3. Results

All 112 lakes experienced some degrees of reclamation from 1973 to 2018. The total reclaimed area of the Yangtze Plain was 6056.9 km^2 in 2018, representing 41.6% of the total lake area in 1973 (see Fig. 4). Prominent aquaculture expansion has occurred since the mid-1980s, with the total area of Aquaculture zones increasing from 1101.9 km^2 in 1973 to 3429.2 km^2 in 2018. In parallel, the area of reclaimed Agricultural/built-up lands increased from 802.3 km^2 to 2627.7 km^2, with different trends observed in the three Yangtze-connected lakes compared to the other lakes (Fig. 4). Agricultural/built-up land reclamation was more prominent in the lakes upstream of Poyang Lake than downstream, and the exploited areas represented small fractions in lakes located in Jiangsu Province throughout the past decades.

The areal percentages of Natural waters, Agricultural/built-up land, and Aquaculture zones in different decades are shown in Fig. 5. Numerically, the Aquaculture zones of 99 lakes accounted for < 20% of their entire lake areas in the 1970s. Remarkable expansions of Aquaculture zones occurred from the 1970s to the 1990s, with moderate changes thereafter. The Agricultural/built-up land changes were different from the changes in Aquaculture zone, with the reclaimed area even decreasing in certain periods rather than steadily increasing. For example, the reclaimed Agricultural/built-up land areas increased from the 1970s to the 1980s, but decreased in the latter two decades of the 1990s and 2000s (see Fig. 5). Nevertheless, the two largest lakes

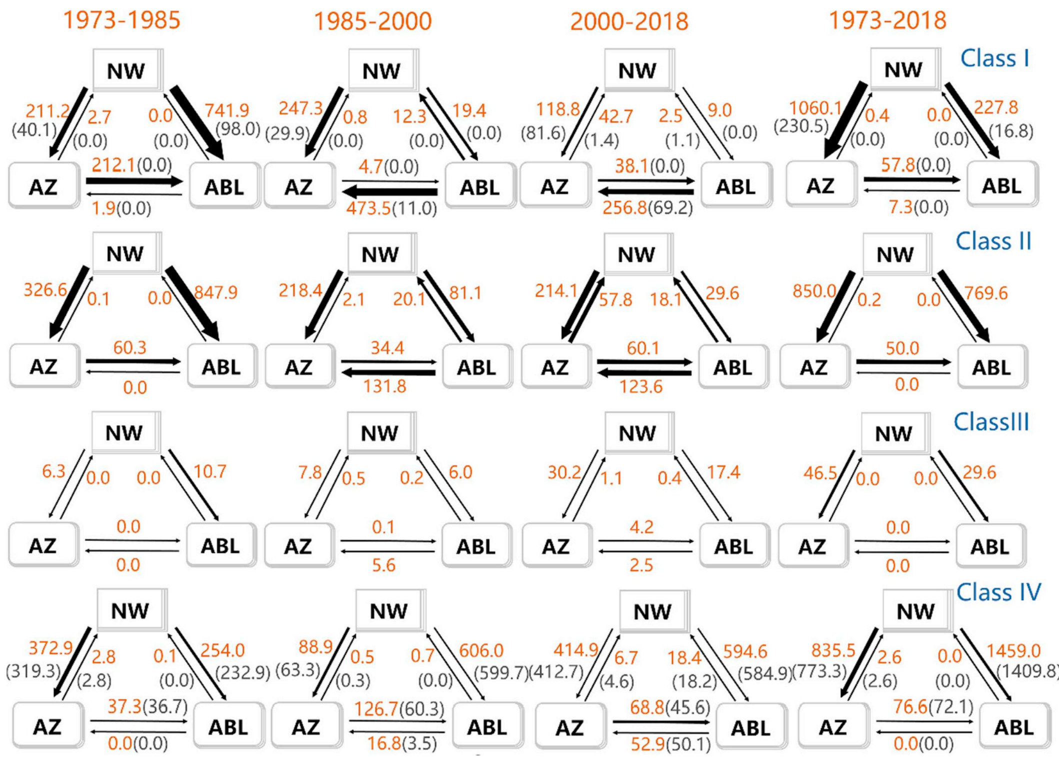

Fig. 7. The changed areas (in km^2) between the three lake cover types (i.e., Aquaculture zone or AZ, Agricultural/built-up land or ABL, and Natural water or NW) for different periods and classes. The numbers inside and outside of the parentheses represent areas (in km^2) for all 112 lakes and the three Yangtze-connected lakes, respectively, and the width of the arrow represents the numbers outside of the parentheses.

(Poyang and Dongting Lake) exhibited pronounced increases in Agricultural/built-up land during the past decades, even reaching 57.1% of the original lake areas in the 2010s. The illustrated areal changes in Natural water were the combined changes from the two reclaimed lake covers, showing the rapid decreases for these two periods: 1970s - 1990s and 2000s - 2010s.

The cluster analysis identified four classes of major lake reclamation patterns (Fig. 6). Class I lakes, mostly located in Hubei Province, saw an early increase in Agriculture/built-up land, followed by increases of aquaculture since the mid-1980s (Figs. 6 & 7), and the aquaculture maxima for most lakes was reached in around the year 2000. Class II lakes, mostly located in Anhui Province, were also subject to early reclamation for Agriculture/built-up lands, which stabilized in the 1980s, followed by further reclamation for Agriculture/built-up. Despite some recent reclamation for Agriculture/built-up and Aquaculture. Class III lakes, with half of these located in Jiangsu Province, escaped large scale reclamation and retained a high proportion of Natural water. Class IV lakes, distributed in different provinces, experienced early reclamation for aquaculture and which stabilized, and the increase of Agricultural/built-up lands mainly occurred in the last two decades.

We identified three distinct phases of lake cover changes based on the above cluster analysis: 1973–1985; 1985–2000; and 2000–2018 (Figs. 6a & 8). During each phase, the change percentages for the three lake covers (i.e., Natural water, Agricultural/built-up land, and Aquaculture zones) are color coded in Fig. 8(a-b) to show the reclamation transitions that occurred. The first phase included the most extensive reclamation activities, with 92.9% of lakes showing Agriculture/built-up gains and 76.8% showing aquaculture gains. In the second phase, reclamation was mainly characterized by aquaculture expansion, which increased by 1186.7 km^2. The aquaculture gain was due to transitions from both Natural waters (562.5 km^2) and Agricultural/built-up lands (624.2 km^2). In the third phase, most lake surface changes occurred between the two reclaimed types, with transformations from Agricultural/built-up lands to Aquaculture zones (435.9 km^2) greatly exceeding changes in the opposite direction (171.2 km^2). During the last phase the area of Natural waters recovered via conversion from Agricultural/built-up lands and Aquaculture zones, while such transitions rarely occurred in the first phase and took place at much lower magnitudes during the second period. Conversions from Natural waters to Agricultural/built-up lands were found in Yangtze-connected lakes (i.e., lakes with considerable inundation seasonality) during all three phases.

4. Discussion

Previous studies have also presented reclamation associated lake dynamics on the Yangtze Plain. For example, Du et al. (2011) indicated that lake reclamation in the middle reaches of the Yangtze River basin has caused lake surface area decreases by 1592 km^2 from 1970s to 2000 in Jianhan Plain and Dongting Lake area. The study by Cui et al. (2013) also showed that 3177.9 km^2 of lake area loss was occurred during 1970–2008 in the middle and lower reaches of the Yangtze River basin, and they also argued that lake reclamation was responsible for these changes. A recent study by Xie et al. (2017) displayed the land-use changes on the lakes in the Yangtze Plain from 1975 to 2015, and quantified the area transformations between lakes and cropland, fish ponds, and built-up lands. Although these are more or less aligned with our finding, our study represents the first comprehensive attempt to use continuous satellite observations to examine the lake area change in Yangtze Plain from 1973 to 2018. Indeed, such an extensive monitoring effort not only makes it possible to reveal the multi-decadal patterns (see Fig. 6a) of change in the Yangtze Plain lakes, but also to unveil their potential linkages with the governmental policies.

4.1. Linkages between lake reclamation and policy drivers

The three distinct phases of lake reclamation coincided with key government policies and major socio-economic events (see Fig. 8c and

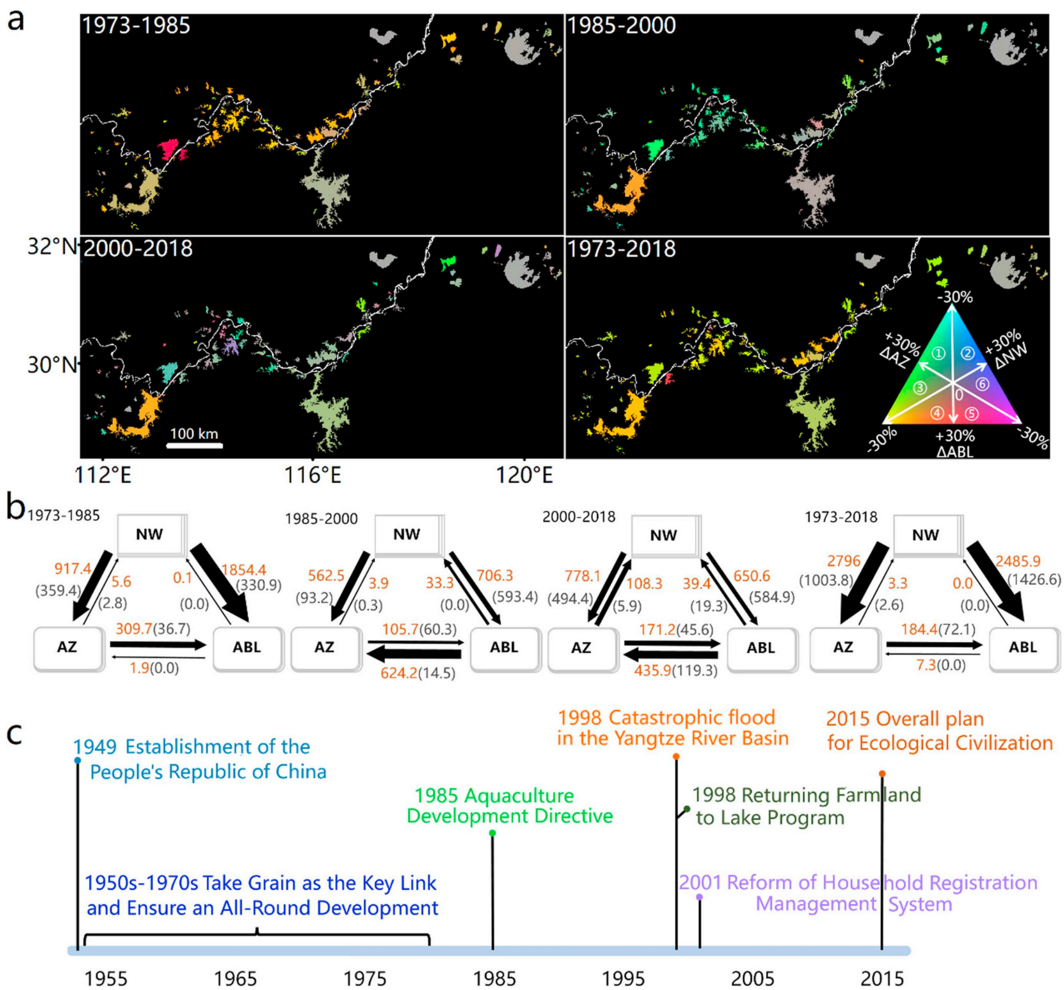

Fig. 8. Areal changes in reclamation types during three development phases and potential socioeconomic drivers. (a) The transition maps for three phases (1973–1985, 1985–2000 and 2000–2018) and the entire period (1973–2018). The triangle legend contains six quadrants (circled numbers), which represent the following change directions: ① Aquaculture zone (AZ) gain with Agricultural/built-up land (ABL) loss; ② Natural water (NW) gain with ABL loss; ③ AZ gain with NW loss; ④ ABL gain with NW loss; ⑤ ABL gain with AZ loss; and ⑥ NW gain with AZ loss. The magnitude of the transitions (in percentages, with a maximum of 30% in the legend) were estimated as the areal differences between the start and end years divided by the total lake areas. (b) Areal changes of three lake cover types during different phases. The numbers outside and inside of the parentheses represent data for all 112 lakes and the three Yangtze-connected lakes, respectively, and the widths of the arrows represent the numbers outside of the parentheses. (c) Chronology of major socioeconomic events and policies that impacted the reclamation patterns.

Table 1). The dramatic increases in Agricultural/built-up lands between 1973 and 1985 followed large-scale farmland reclamation from lakes between the 1950s–1970s in the pursuit of food security following government-supported rapid increases in population (2–3% p.a.) (Fig. 9a & b) (Cui et al., 2013; Fang et al., 2005). The influence of population growth was corroborated by the significant correlation ($R^2 > 0.57, p < .05$) found between the population size and the total reclamation area for the five provinces in the Yangtze Plain (Fig. 9c).

The large-scale increase in fishery developments in the second phase during 1985–2000 occurred following the release of *Aquaculture Development Directive* in 1985 (Tang and Zou, 2010). This Directive aimed to enhance fishery production throughout China, boosting livelihoods and meeting the protein demands of the increasing population (Cui et al., 2013; Fang et al., 2005). The retreat from Agricultural/built-up lands to aquaculture during the last phase of 2000–2018 may have also been associated with the *Returning Farmland to Lake Program*, which was implemented after the catastrophic Yangtze flood in 1998 (Fang et al., 2005; Jiang et al., 2005). This program was specifically designed to recover flood storage capacity by promoting the return of reclaimed agricultural land to water bodies (Jiang et al., 2005).

Continued expansion of Agricultural/built-up lands occurred in more than 50 lakes despite tightened government policies since 1998. Such an increase may have been due to the scarcity of land available for urbanization in the Yangtze Plain since the 2000s (Xie et al., 2017) (see Fig. 9d). Urbanization has accelerated throughout China in the past two decades after the *Reform of the Household Registration Management System* in 2001 (Ren, 2015). Rapid increases in Agricultural/built-up lands in Dongting Lake between 1985 and 2018 went against central government directives. The reclaimed floodplains were planted with reeds (*Phragmites communis*), poplar (*Populus*), and canola (*Brassica campestris L.*) for papermaking and crop production to increase the incomes of underdeveloped local regions (see Fig. 10). Although the 2015 policy has strictly banned these activities, the complete removal of these commercial vegetation types has not yet occurred.

Aquaculture area has declined since 2015 after four decades of steady growth (1970s–2010s) (see Fig. 4b). This reversal pattern seemed to follow the policy released in 2015 about the *Overall Plan for Ecological Civilization* (Gao et al., 2018), which requires lacustrine/riverine fishery reclamation projects to be dismantled gradually to restore the ecosystem services of natural wetlands.

Table 1
Description of the major policies and socioeconomic events in China during the past half century.

Time/period	Policy/event	Agency	Description
1949	Establishment of the People's Republic of China	–	–
1950s–1970s	Take Grain as the Key Link and Ensure an All-Round Development	The Central Government of China	To pursue food sufficiency for a rapid increase in population, the central government of China proposed the slogan "Take grain as the key link and ensure an all-round development". Massive reclamations of lakes and wetlands occurred afterwards to increase cropland area and food production.
1985	Aquaculture Development Directive	The Central Government and the State Council of China	A series of policies were released to develop the fishery industry in China, aiming to promote people's income and meet the protein demands of an increasing population.
1998	Catastrophic flood in the Yangtze River Basin	–	The flood affected 21.2 million hectares of land and 223 million people, resulted in the death of 3004 people and caused a direct economic loss of ~23 billion US dollars.
1998	Returning Farmland to Lake Program	The Central Government and the State Council of China	After the catastrophic flood in 1998, the Returning Farmland to Lake Program was enacted to recover the lake flood storage capacity by promoting the conversion of farmland to natural lakes. Large-scale returning-farmland activities were reported in the lakes in Hunan, Hubei, Jiangxi and Anhui provinces from the winter of 1998 to 2003.
2001	Reform of Household Registration Management System	The Ministry of Public Security	By reforming the household registration management system in small cities and towns, this policy was used to orderly transfer the rural population to cities and to accelerate the process of urbanization in China.
2015	Overall Plan for Ecological Civilization	The Central Government and the State Council of China	To promote the progress of ecological civilization in China and to achieve the United Nation's sustainable development goals (SDGs), the protection of ecological environments of the Yangtze River system has been listed as one of the most important components of the national major development strategies

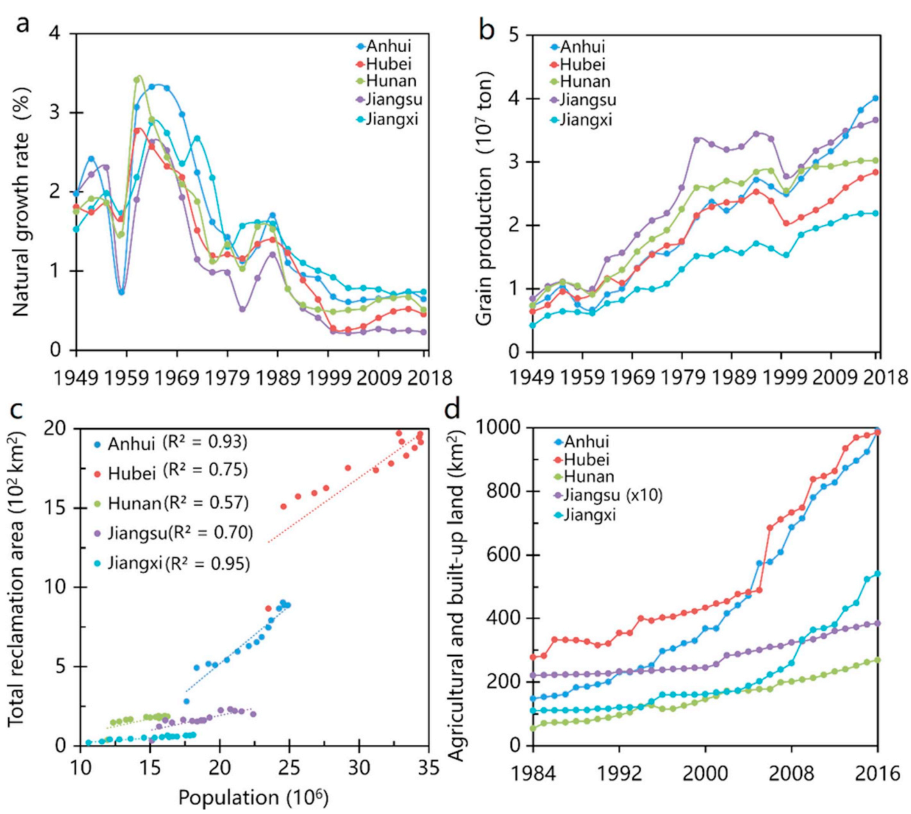

Fig. 9. Impacts of increases in population and built-up area on lake reclamation. (a) Changes in the natural population growth rates of different provinces since 1949. (b) Long-term changes in the total grain production values of different provinces since 1949. (c) The correlations between the provincial populations and the total satellite-delineated reclaimed areas in the 5 provinces in the Yangtze Plain. (d) Long-term changes in the built-up area in the 5 provinces in the Yangtze Plain.

4.2. Environmental impacts

Lake reclamation in the Yangtze Plain was important for enhancing food security in the early years since the 1970s, as indicated by the synchronous growth in grain production and population before 2000 (Fig. 9b). The growth of Aquaculture zone also contributed to food security in this region, indicated by the high correlations ($R^2 > 0.8$, $p < .01$) between provincial fishery production and the area of aquaculture for all provinces (Fig. S2).

Despite these socio-economic benefits, the impacts of lake exploitation on natural ecosystems were apparent. Flood risk increased due to substantial reduction in water storage capacity of almost all lakes (Fig. 11a & b). The total decrease in lake storage was 12.7 km^3 for the 112 lakes, representing 29.8% of the lake storage in the 1970s. Consequently, runoff that could otherwise have been stored in these lakes contributed to flooding. An extreme case was the capital city of Hubei Province (Wuhan, with a population of > 8 million). Reclaimed Agricultural/built-up lands reduced two large urban lakes within the city (Nanhu Lake and Tangxun Lake) to 2/3 of their original area in the 1970s. The decreased lake storage capacity is equivalent to a water

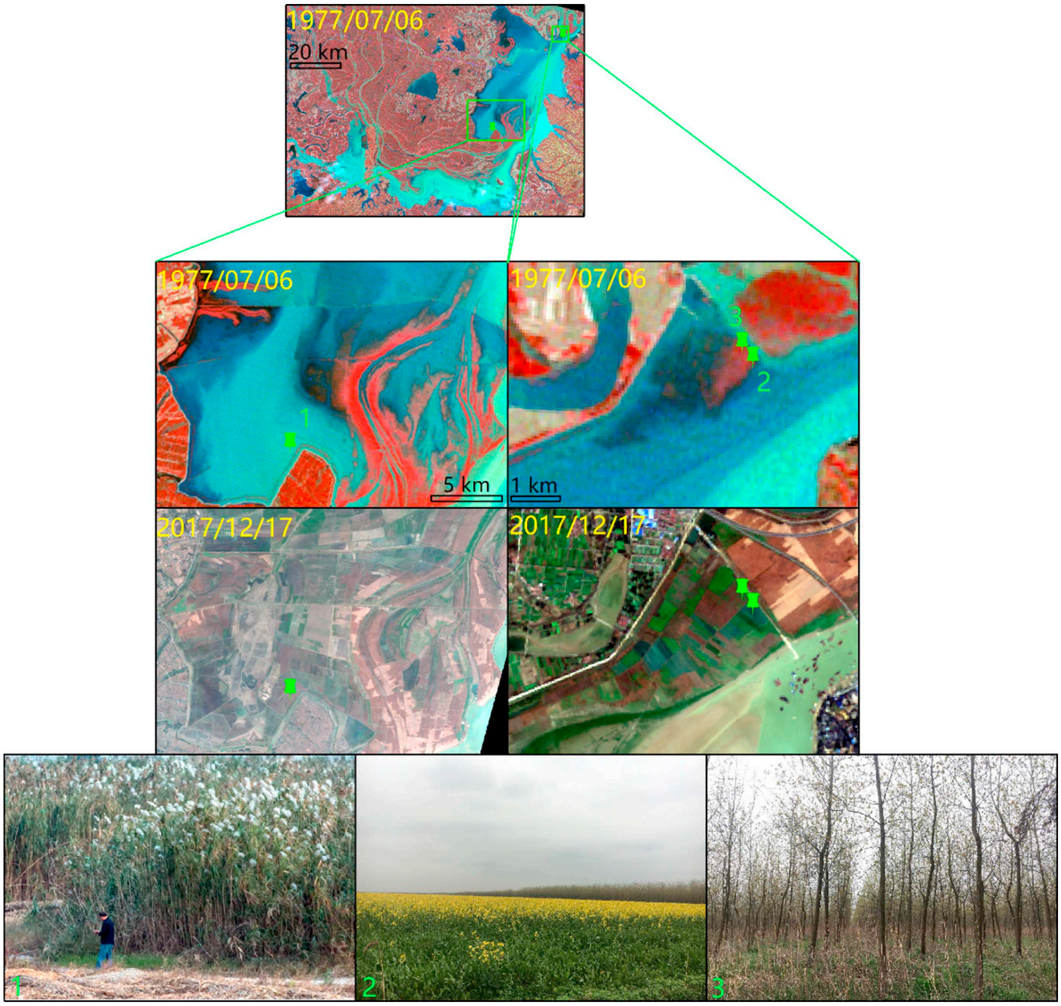

Fig. 10. Comparison of pre- and post-reclamation conditions in the Landsat images of Dongting Lake. The lower panels show the digital photos of reclaimed Agricultural/built-up land for different cultivation purposes (1. Reed (*Phragmites communis*), 2. Canola (*Brassica campestris L.*) and 3. Poplar (*Populus*)), and the photographic locations are annotated (green marks) in the Landsat images. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

depth of > 100 mm when the water is evenly distributed over the entire drainage basin (Fig. 12). Reclamation of lakes and increases in impervious surfaces in Wuhan have resulted in frequent waterlogging problems within the city in recent years, leading to the loss of human life and damage to property (Wu et al., 2019). Despite fairly stable precipitation in this region, more frequent and extreme floods have been recorded in the Yangtze River in recent decades, which may have been exacerbated by the massive Agricultural/built-up land development since the 1970s (Fig. 11b).

We further examined the potential impacts of reclamation on water quality. The amount of pollutants entering the Yangtze Plain lakes has increased considerably in recent decades due to increased point/non-point source pollution (Zhu et al., 2019), and water quality issues have been exacerbated via lake reclamation activities. For example, reclaimed Aquaculture zones could substantially reduce water exchange and thus the dilution effects of pollutants in the main part of the lake (Zhang et al., 2015). Worse still, the extensive utilization of nutrient-rich baits for fishery cultivation in Aquaculture zones further adds nutrient loads into lakes, leading to eutrophication and cyanobacteria blooms (Guan et al., 2020; Guo, 2007; Li et al., 2013). Indeed, satellite-based observations demonstrated statistically significant changes (a test of the null hypothesis of significant difference between two groups of datasets resulted in a significance level of $p < .05$) in water color (represented by the Forel-Ule index, or FUI, in dimensionless (Wang et al., 2018)) caused by aquaculture (Fig. 11c), and in situ measurements further revealed higher concentrations of chlorophyll-a (Chl-a) and nutrient loads (i.e., more eutrophic waters) in Aquaculture zones than in adjacent Natural waters (Fig. 11d).

Severe biodiversity losses have been reported in the Yangtze Plain lake wetlands in recent decades (such as reductions in fish species, migrating birds, aquatic insects, etc.) (Hu et al., 2005; Jiang et al., 2007; Xia et al., 2017), and some studies have also partially attributed such changes to lake reclamation and associated agricultural or fishery activities. However, a more rigorous analysis of the direct and indirect impacts of reclamation on the regional biodiversity requires a more comprehensive field survey.

5. Conclusion

Using five decades of satellite observations, we have provided the first compressive assessments of the patterns, policy drivers, and environmental impacts of lake reclamation in the Yangtze Plain of China. With 41.6% of the total lake area reclaimed over the past half century, the lakes have been subject to very significant anthropogenic alteration. The types of reclamation activities changed over time following government policy priorities. Satellite and in situ observations revealed the dramatic impacts of lake reclamation on the local hydrology (reduced 29.8% of the total lake storage) and water quality (enhanced nutrient

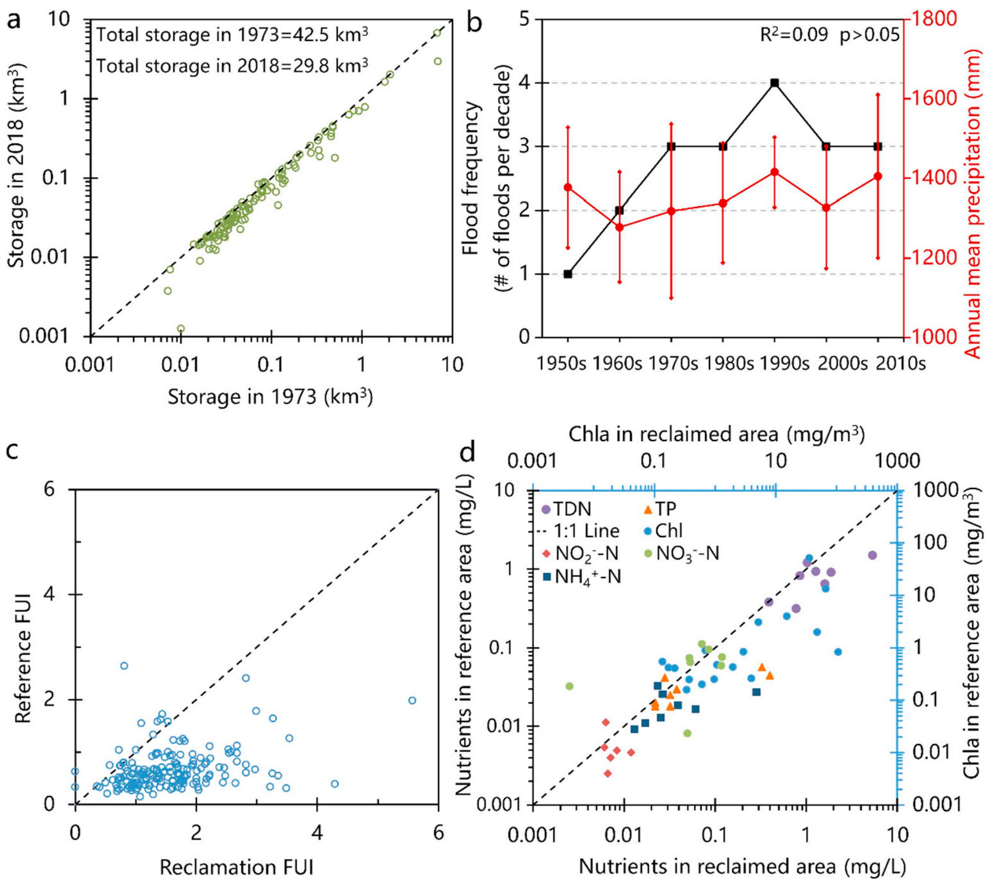

Fig. 11. Impacts of lake reclamation on hydrology and water quality. (a) Comparison of the water storage capacities between the start and end years of the study period, with each point representing one lake. (b) Long term variability of the flood frequency and decadal mean precipitation in the Yangtze River Basin, also annotated is the correlation between these two parameters. Red bars represent one standard deviation. (c) Landsat-derived water color (FUI, dimensionless) to show the difference between Aquaculture zones (Reclamation) and Natural waters (Reference). (d) Comparison of the in situ-measured water quality parameters in Aquaculture zones and the adjacent Natural waters. TDN, total dissolved nitrogen; TP, total phosphorus; Chla, chlorophyll-a. The points in c and d represent paired datasets from the reclamation and reference regions, where the X-axes indicate the values in reclaimed area and Y-axes represent values in the corresponding reference area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

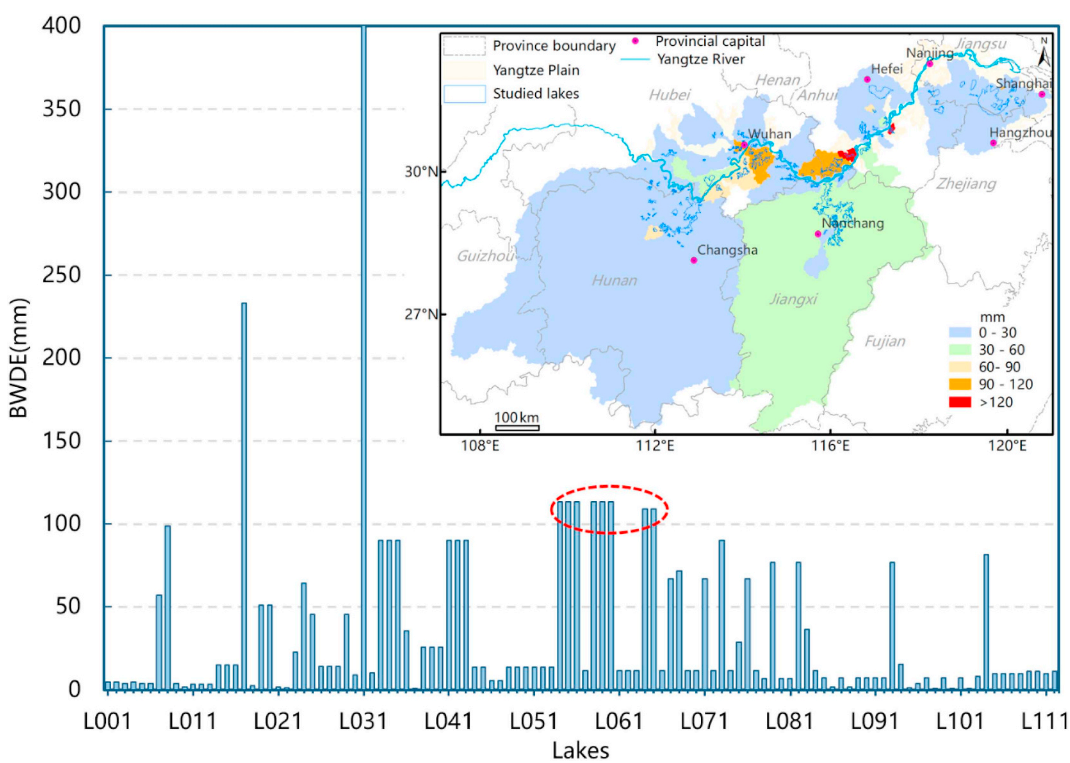

Fig. 12. The basin-scale water depth equivalent (BWDE) for the drainage basins of 112 lakes. (a) The magnitude of BWDE for 112 lake basins, the lake basins in the red ellipse are located in Wuhan City. The lakes are arranged by their longitudes, and from the left (L01) to the right (L112) are consistent with their geographic locations in the Yangtze Plain (refer to Table S1 to match the name and code for each lake. (b)The spatial distribution of BWDE for different lake basins in the Yangtze Plain, where shaded colors represent different BWDE levels (note that some lakes could share one basin). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

loads). The results demonstrate the impact of anthropogenic activities in changing the landscape of a significant region of the Earth, making the Yangtze Plain a paragon of the Anthropocene. However, reducing or returning the lake reclamation area to their natural state will remain a significant challenge due to the trade-off between socioeconomic development and ecological security.

Declaration of Competing Interest

None.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (NOs: 41971304, 41671338, 41890852 and 41890851), the Key Program of the Chinese Academy of Sciences (ZDRW-ZS-2017-3-4) and the High-level Special Funding of the Southern University of Science and Technology (Grant No. G02296302, G02296402). We also thank three anonymous reviewers for their help in commenting and improving the original manuscript.

Data availability

The Landsat data can be obtained from the U.S. Geological Survey at https://glovis.usg.gov. Metrological data were downloaded from the China Meteorological Data Sharing Service System (http://data.cma.cn/). Socioeconomic datasets including the population census, grain production and annual yearly fishery production data are available in the annual statistic books from local governments and agencies. The Landsat delineated datasets in this paper are avaliable at https://figshare.com/articles/dataset/Reclamation_shapefile_rar/12687230.

Author contributions

L.F. initiated the project, X. H. wrote an initial draft of the manuscript, and X.H., L.F., J.T., X.S., J.L., Y.Z., Y.D., J.W., Y.X., Y.Z., C.Z., and B.B., performed the data processing and analysis. All authors participated in interpreting the results and refining the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rse.2020.111998.

References

Alfiani, A.P., Wulandari, F.A., 2015. Mapping student's performance based on data mining approach (a case study). Agric. Agric. Sci. Proc. 3, 173–177.
Andrefouet, S., Bindschadler, R., Brown de Colstoun, E., Choate, M., Chomentowski, W., Christopherson, J., Doorn, B., Hall, D., Holifield, C., Howard, S., 2003. Preliminary Assessment of the Value of Landsat-7 ETM+ Data Following Scan Line Corrector Malfunction. US Geological Survey, EROS Data Center, Sioux Falls, SD, USA.
Cai, X., Feng, L., Hou, X., Chen, X., 2016. Remote sensing of the water storage dynamics of large lakes and reservoirs in the Yangtze River basin from 2000 to 2014. Sci. Rep. 6, 1–9.
Congalton, R.G., 1991. A review of assessing the accuracy of classifications of remotely sensed data. Remote Sens. Environ. 37, 35–46.
Cui, L., Gao, C., Zhao, X., Ma, Q., Zhang, M., Li, W., Song, H., Wang, Y., Li, S., Zhang, Y., 2013. Dynamics of the lakes in the middle and lower reaches of the Yangtze River basin, China, since late nineteenth century. Environ. Monit. Assess. 185, 4005–4018.
Czaplewski, R.L., 1994. Variance Approximations for Assessments of Classification Accuracy. Res. Pap. RM-316. US Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO (29 p., 316).
Davidson, N.C., 2014. How much wetland has the world lost? Long-term and recent trends in global wetland area. Mar. Freshw. Res. 65, 934–941.
Donchyts, G., Baart, F., Winsemius, H., Gorelick, N., Kwadijk, J., Giesen, N.v.d., 2016. Earth's surface water change over the past 30 years. Nat. Clim. Chang. 6, 810–813.
Du, Y., Xue, H.-p., Wu, S.-j., Ling, F., Xiao, F., Wei, X.-h., 2011. Lake area changes in the middle Yangtze region of China over the 20th century. J. Environ. Manag. 92, 1248–1255.
Fang, J., Rao, S., Zhao, S., 2005. Human-induced long-term changes in the lakes of the Jianghan plain, Central Yangtze. Front. Ecol. Environ. 3, 186–192.
Fang, J., Wang, Z., Zhao, S., Li, Y., Tang, Z., Yu, D., Ni, L., Liu, H., Xie, P., Da, L., Li, Z., Zheng, C., 2006. Biodiversity changes in the lakes of the Central Yangtze. Front. Ecol. Environ. 4, 369–377.
Feng, L., Hu, C., 2017. Land adjacency effects on MODIS aqua top-of-atmosphere radiance in the shortwave infrared: statistical assessment and correction. J. Geophys. Res. Oceans 122, 4802–4818.
Gao, S., Wang, H., Li, W., 2018. Course and orientation of ecological civilization system reform over 40 years of reform and opening-up. Reform 294, 49–63.
Ge, D., Jin, Z., 2009. Impacts of climate change and its variability on rice production in middle and lower valley of the Yangtze River,China. Chin. J. Rice Sci. 23, 57–64.
Guan, Q., Feng, L., Hou, X., Schurgers, G., Zheng, Y., Tang, J., 2020. Eutrophication changes in fifty large lakes on the Yangtze plain of China derived from MERIS and OLCI observations. Remote Sens. Environ. 246, 111890.
Guo, L., 2007. Doing Battle with the green monster of Taihu Lake. Science 317, 1166.
Hou, X., Feng, L., Duan, H., Chen, X., Sun, D., Shi, K., 2017. Fifteen-year monitoring of the turbidity dynamics in large lakes and reservoirs in the middle and lower basin of the Yangtze River, China. Remote Sens. Environ. 190, 107–121.
Hu, H., Kang, H., Gong, G., Zhu, M., Zheng, W., Wu, F., He, D., Li, Z., Geng, D., 2005. Biodiversity of winter waterbirds in Hubei, China. Resour. Environ. Yangtze Basin 14, 421–428.
Jia, Q., Wang, X., Zhang, Y., Cao, L., Fox, A.D., 2018. Drivers of waterbird communities and their declines on Yangtze River floodplain lakes. Biol. Conserv. 218, 240–246.
Jiang, H., Xu, W., Qian, F., Chu, G., 2007. Impact of habitat evolvement and human disturbance on winter water birds in Shengjin Lake of Anhui Province, China. Chin. J. Appl. Ecol. 18, 1832–1836.
Jiang, J., Huang, Q., Sun, Z., 2005. Countermeasures for protection and management of lakes in middle and lower reaches of the Yangtze River. Resour. Environ. Yangtze Basin 14, 40–43.
Lehner, B., Grill, G., 2013. Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. Hydrol. Process. 27, 2171–2186.
Lewis, T.L., Lindberg, M.S., Schmutz, J.A., Heglund, P.J., Rover, J., Koch, J.C., Bertram, M.R., 2015. Pronounced chemical response of subarctic lakes to climate–driven losses in surface area. Glob. Chang. Biol. 21, 1140–1152.
Li, J., Wang, S., Wu, Y., Zhang, B., Chen, X., Zhang, F., Shen, Q., Peng, D., Tian, L., 2016. MODIS observations of water color of the largest 10 lakes in China between 2000 and 2012. Int. J. Digital Earth 9, 788–805.
Li, M., Zhang, W., Xia, Y., Gao, Y., 2013. Study on removal efficiencies of pollutant from constructed wetland in aquiculture waste water around Poyang Lake. Procedia Environ. Sci. 10, 2444–2448.
Ma, R., Duan, H., Hu, C., Feng, X., Li, A., Ju, W., Jiang, J., Yang, G., 2010a. A half-century of changes in China's lakes: global warming or human influence? Geophys. Res. Lett. 37, 1–6.
Ma, R., Yang, G., Duan, H., Jiang, J., Wang, S., Feng, X., Li, A., Kong, F., Xue, B., Wu, J., Li, S., 2010b. China's lakes at present: number, area and spatial distribution. Sci. China Earth Sci. 54, 283–289.
Masek, J.G., Vermote, E.F., Saleous, N.E., Wolfe, R., Hall, F.G., Huemmrich, K.F., Gao, F., Kutler, J., Lim, T.-K., 2006. A Landsat surface reflectance dataset for North America, 1990–2000. IEEE Geosci. Remote Sens. Lett. 3, 68–72.
Pekel, J.-F., Cottam, A., Gorelick, N., Belward, A.S., 2016. High-resolution mapping of global surface water and its long-term changes. Nature 540, 418–422.
Prigent, C., Papa, F., Aires, F., Jimenez, C., Rossow, W., Matthews, E., 2012. Changes in land surface water dynamics since the 1990s and relation to population pressure. Geophys. Res. Lett. 39, 1–5.
Ren, J., 2015. Since the founding of our country household register system reform and the urbanization process of periodic analysis. J. Sanmenxia Polytech. 14, 113–117.
Roach, J., Griffith, B., Verbyla, D., Jones, J., 2011. Mechanisms influencing changes in lake area in Alaskan boreal forest. Glob. Chang. Biol. 17, 2567–2583.
Tang, Y., Zou, W., 2010. Review on the legal system of fisheries resources conservation and management in China. Resour. Sci. 32, 28–34.
Tao, S., Fang, J., Ma, S., Cai, Q., Xiong, X., Tian, D., Zhao, X., Fang, L., Zhang, H., Zhu, J., Zhao, S., 2020. Changes in China's lakes: climate and human impacts. Natl. Sci. Rev. 7, 132–140.
Vanhellemont, Q., Ruddick, K., 2015. Advantages of high quality SWIR bands for ocean colour processing:examples from Landsat-8. Remote Sens. Environ. 161, 89–106.
Wang, J., Sheng, Y., Tong, D., 2014. Monitoring decadal lake dynamics across the Yangtze Basin downstream of Three Gorges Dam. Remote Sens. Environ. 152, 251–269.
Wang, S., Li, J., Zhang, B., Spyrakos, E., Tyler, A.N., Shen, Q., Zhang, F., Kuster, T., Lehmann, M.K., Wu, Y., 2018. Trophic state assessment of global inland waters using a MODIS-derived Forel-Ule index. Remote Sens. Environ. 217, 444–460.
Wernand, M.R., Woerd, H.J.v.d., 2010. Spectral analysis of the Forel-Ule ocean colour comparator scale. J. Eur. Opt. Soc. Rapid Publ. 5.
Wu, H.-L., Cheng, W.-C., Shen, S.-L., Lin, M.-Y., Arulrajah, A., 2019. Variation of hydro-environment during past four decades with underground sponge city planning to control flash floods in Wuhan, China: An overview. In: Undergroud Space.
Xia, S., Wang, Y., Lei, G., Liu, Y., Lei, J., Yu, Xiubo, Wen, L., Zhou, Y., 2017. Restriction of herbivorous waterbird distributions in the middle and lower Yangtze River floodplain in view of hydrological isolation. Wetlands 37, 79–88.
Xie, C., Huang, X., Mu, H., Yin, W., 2017. Impacts of land-use changes on the lakes across the Yangtze floodplain in China. Environ. Sci. Technol. 51, 3669–3677.
Xie, P., 2017. Biodiversity crisis in the Yangtze River:the culprit was dams, followed by overfishing. J. Lake Sci. 29, 1279–1299.
Yang, D., 1986. The paleoenvironment of the mid-lower regions of Changjiang in the full-glacial period of lake pleistocene. Acta Geograph. Sin. 41, 302–310.
Yang, X., Anderson, N.J., Dong, X., Shen, J., 2008. Surface sediment diatom assemblages

and epilimnetic total phosphorus in large, shallow lakes of the Yangtze floodplain: their relationships and implications for assessing long–term eutrophication. Freshw. Biol. 53, 1273–1290.

Yin, H., Li, C., 2001. Human impact on floods and flood disasters on the Yangtze River. Geomorphology 41, 105–109.

Zeng, Q., Gu, X., Chen, X., Mao, Z., 2013. The impact of Chinese mitten crab culture on water quality, sediment and the pelagic and macrobenthic community in the reclamation area of Guchenghu Lake. Fish. Sci. 79, 689–697.

Zhang, Y., Bleeker, A., Liu, J., 2015. Nutrient discharge from China's aquaculture industry and associated environmental impacts. Environ. Res. Lett. 10, 045002.

Zhang, Y., Jeppesen, E., Liu, X., Qin, B., Shi, K., Zhou, Y., Thomaz, S.M., Deng, J., 2017. Global loss of aquatic vegetation in lakes. Earth Sci. Rev. 173, 259–265.

Zhou, B., Yin, J., Jin, B., Zhu, L., 2014. Degradation of Wuchang Lake wetland and its causes during 1980-2010. Acta Geograph. Sin. 69, 1697–1706.

Zhu, G., Xu, H., Zhu, M., Zou, W., Guo, C., Ji, P., Da, W., Zhou, Y., Zhang, Y., Qin, B., 2019. Changes of trophic state and driving factors in lakes at the middle and lower reaches of Yangtze River in the past 30 years. J. Lake Sci. 31.

Zhu, Z., 1995. Aquiculture-based production belts and their prospect for development in China. J. Nat. Resour. 1, 23–29.