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Impacts of Land-Use Changes on the Lakes across the Yangtze Floodplain in China

Cong Xie,[‡] Xin Huang,[*,†,‡] Hongqiang Mu,[§] and Wei Yin[∥]

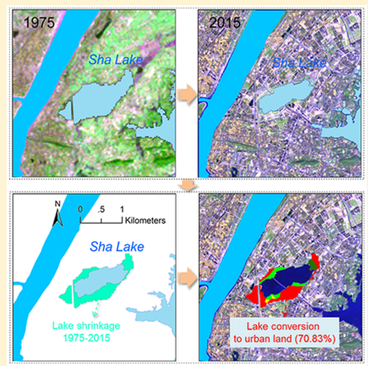
[†]School of Remote Sensing and Information Engineering and [‡]State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan 430079, People's Republic of China

[§]Yangtze Valley Water Resources Protection Bureau, Changjiang Water Resources Commission, Wuhan 430010, People's Republic of China

[∥]Yangtze River Water Resources Protection Science Institute, Wuhan 430051, People's Republic of China

Supporting Information

ABSTRACT: The middle and lower Yangtze (MLY) floodplain has one of the most densely distributed lake clusters in China but suffered from long-term lake reclamation and wetland degradation due to intensive cultivation, fish rearing, and urban expansion over the past several decades. As a land-use alternation to support human life, the conversion of lakes to cropland, aquaculture ponds, and human settlements provides essential ecosystem goods at the expense of the deterioration of wetland environment. To quantify the driving factors of lake changes, we investigated the land-use transitions from lakes (≥1 km^2) between 1975 and 2015 using Landsat remote sensing data. We found that the dramatic decline in lake area (a net decrease of 13.8 ± 1.4%) over the four decades was largely attributed to human-induced transformation from lakes to cropland, fish ponds, and built-up areas, accounting for 34.6%, 24.2%, and 2.5% of the total area reduction, respectively. The remaining loss, associated with vegetation (37.3%) and bare land (1.4%) and coming mainly from China's two largest freshwater lakes (Poyang and Dongting), can be explained by climate variation, sediment deposition, and hydrological regulation. These findings shed new light on the quantitative impacts of human activities and climate variation on lake changes and provide a scientific foundation for wetland management decision-making.



INTRODUCTION

Lakes, acting as a regulator of the carbon cycle and global climate in the terrestrial system, constitute a significant component of global water resources, providing an irreplaceable environment for aquatic fauna and flora as well as for human survival.[1] However, due to intensive human activities and climate change, lakes all over the world have undergone drastic changes,[2−7] drawing considerable attention to climate change,[8,9] water resources,[10,11] and environmental pollution.[12] Lake shrinkage and wetland degradation at the global scale have caused extensive concern about how to accurately track lake changes and driving factors, as well as to ease their impact on ecological systems.

The middle and lower Yangtze (MLY) floodplain is covered with the largest freshwater lake cluster in East Asia, which plays a critical role in flood control, runoff regulation, human consumption, and social development. As an important commodity grain base, accounting for 24% of China's agricultural production, the MLY floodplain is one of the most densely populated regions, sustaining 25% of the total population (338 million) of China.[13] Due to intensive cultivation, fish rearing, and urban expansion over the past half century, the region is now considered to be one of the most fragile ecological systems in the world[14] and has experienced rapid shrinkage of the lake area,[15−18] severe degradation of the wetland ecosystem,[19] deterioration of water quality,[20] and decreased biodiversity.[21]

Although a few studies have focused on either individual lake regions (e.g., Poyang, Dongting, Tai, and Chao),[22−25] or lake groups in the MLY floodplain,[15−17,26] the quantitative impacts of climatic and anthropogenic factors on the lake changes across the entire floodplain still remain unclear. For example, the freshwater lakes in the Central Yangtze area of China have undergone dramatic changes over the past several decades, mainly due to intensive land reclamation, resulting in serious negative ecological consequences.[17,18] Some studies have also reported that the changes of lakes in the MLY floodplain were more attributed to human activities (e.g., impoldering practices, enclosures, and urban expansion) than natural factors (e.g., climate change and sediment accumulation).[5,15,27] The previous understanding of the various potential driving forces behind lake changes is mainly based on qualitative description or correlation analysis, yet quantifying such drivers of lake degradation is of great importance to the lake regions suffering from both climate change and anthropogenic activities.

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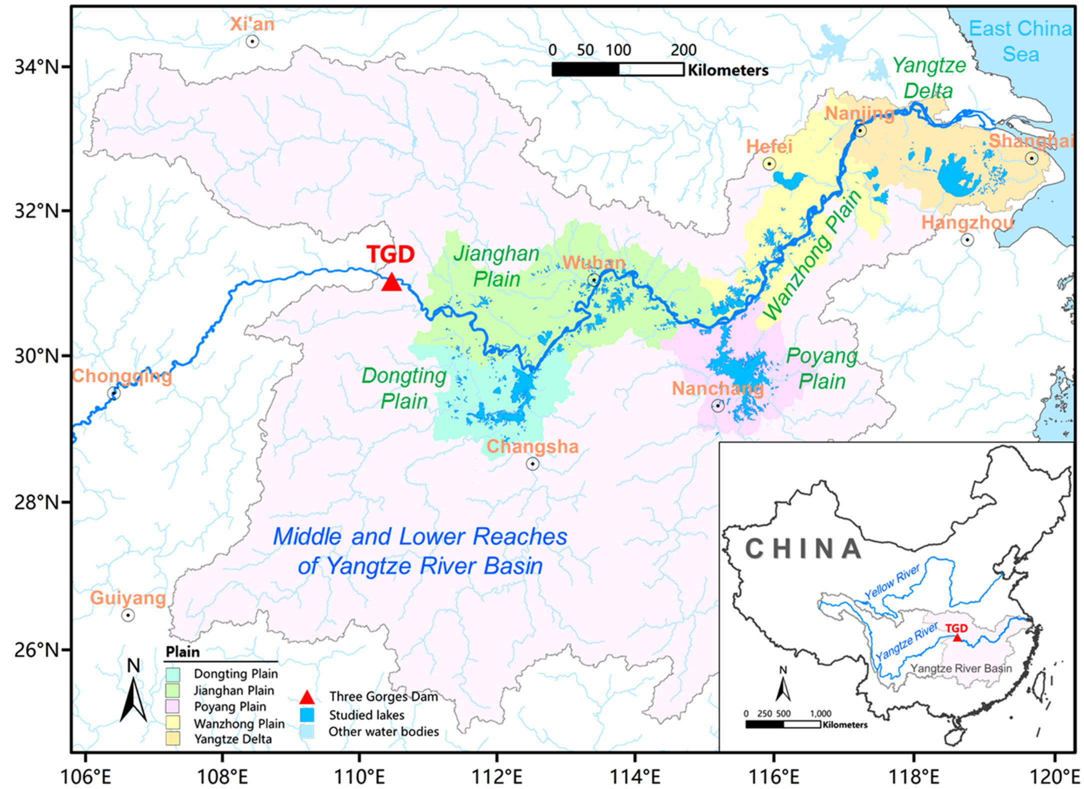

Figure 1. Distribution of lake groups in the middle and lower reaches of the Yangtze River. The MLY floodplain consists of the most alluvial regions in the middle reach (e.g., Dongting, Jianghan, and Poyang plains), and the lower reach (e.g., Wanzhong and Yangtze Delta plains) of the Yangtze Basin. The inset shows the location of the study area in China.

Therefore, the objective of this study is to quantify the lake changes and associated driving forces across the MLY floodplain by exploiting four decades of Landsat remote-sensing images. Furthermore, we also discussed the negative ecological impacts (e.g., flood disasters, biodiversity loss, and water quality) of lake degradation caused by excessive human exploitation. The long-term quantitative results provide a scientific basis for balancing the inherent trade-offs between human consumption and lake protection and help inform future decision-making for wetland management and ecosystem restoration.

■ MATERIALS AND METHODS

Study Area. The middle and lower Yangtze (MLY) basin, situated in eastern China, refers to the section extending from Three Gorges Dam (TGD) to the mouth of the Yangtze River, with an area of 7.8×10^5 km^2 (106°7′−121°47′ E, 24°30′−33°54′ N) and an elevation of less than 50 m (Figure 1). Influenced by the subtropical monsoon climate, this region is characterized by abundant rainfall, with an annual mean precipitation (AMP) of 1000−1400 mm and an annual mean temperature (AMT) of 14−18 °C. The MLY basin is well-known for the most dense group of freshwater lakes in East Asia, representing 38.17% of the total freshwater area in China.[15] Containing over 75% of the total surface area of the lakes in the MLY basin, the MLY floodplain consists of a series of alluvial plains, which can be divided into five lake subregions (i.e., Dongting, Jianghan, Poyang, Wanzhong, and the Yangtze Delta; Figure 1) according to the spatial distribution of lakes and geographical differences.[26] A total of four of the five largest freshwater lakes in China, i.e., Poyang, Dongting, Tai, and Chao, constitute vitally important components of the lake systems in the MLY floodplain, providing an indispensable ecological environment for aquatic fauna and flora. Many wetlands in the floodplain serve as internationally important habitats for endangered species and migratory waterfowl, and nine sites have been designated as Ramsar sites[28] (Table S1). However, the lake resources of the floodplain have suffered from long-term extensive exploitation to support rapid population growth and economic development, leading to the increasingly irreconcilable conflict between human consumption and lake conservation. Consequently, the regional ecosystem has experienced a serious degradation over the past few decades, with a significant vulnerability to human activities and climate change. For example, the surface area of Dongting Lake decreased by 49.2% between the 1930s and 1998, mainly due to intensive impoldering practices.[18]

Data. In this study, remotely sensed data were obtained from the United States Geological Survey (USGS; http://www.usgs.gov/), including Landsat Multispectral Scanner (MSS) images taken around 1975, Thematic Mapper (TM), and Enhanced Thematic Mapper Plus (ETM+) images taken around 1990, 2000, and 2010, and Operational Land Imager (OLI) images taken around 2015 (Table S2). Cloud-free images were acquired in the wet season to avoid the influence of seasonal variation on the estimation of the lake surface area. By the comparison of multitemporal images acquired over at least two years for each study period, the suitable images (excluding anomalous rainfall or drought conditions) were chosen so that the impacts of particularly wet and dry years did not skew the results (e.g., lakes area as well as land use changes). Additionally, the monthly air temperature and precipitation data from 1975 to 2015 from 24 meteorological

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stations over the MLY floodplain were acquired from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/). Agricultural data, aquaculture area, human population, and urban area were documented from the local statistical year book[29−33] and were used to provide auxiliary materials to analyze the effects of human activities on lake changes.

Methods. All the remote sensing images were well georeferenced based on topographical maps, and the MSS images were resampled to the resolution of TM images (30 m). Normalized difference water index (NDWI[34] and MNDWI,[35] Table 1) was calculated to delineate the water surface area of lakes (≥1 km^2) for each selected image. Note that in this study, we only focused on natural lakes, and hence, rivers, reservoirs, and artificial ponds were removed. To strictly control the accuracy of lake area extraction, we manually delineated the water boundary of each lake by visual interpretation of images. The software ArcGIS 10.3 was used to calculate the water surface area of each lake. Following the careful delineation of lake surface area, the lake database of the MLY floodplain was established.

Table 1. Information Indexes Derived from Band Operation of Landsat Images[a]

information indexes	abbreviation	formula
normalized difference water index	NDWI[b]	$\text{NDWI} = \frac{\text{green} - \text{NIR}}{\text{green} + \text{NIR}}$
modified normalized difference water index	MNDWI[c]	$\text{MNDWI} = \frac{\text{green} - \text{SWIR}}{\text{green} + \text{SWIR}}$
normalized difference vegetation index	NDVI	$\text{NDVI} = \frac{\text{NIR} - \text{red}}{\text{NIR} + \text{red}}$
normalized difference built-up index	NDBI	$\text{NDBI} = \frac{\text{SWIR} - \text{NIR}}{\text{SWIR} + \text{NIR}}$
bare soil index	BSI	$\text{BSI} = \frac{(\text{SWIR} + \text{red}) - (\text{NIR} + \text{blue})}{(\text{SWIR} + \text{red}) + (\text{NIR} + \text{blue})}$

[a]Spectral bands: near-infrared (NIR) and short-wave infrared (SWIR) bands. [b]NDWI is calculated for Landsat MSS images. [c]MNDWI is calculated for Landsat TM/ETM+/OLI images.

Changes in lake area (i.e., shrinkage, expansion, and no change) were further detected by overlapping the lake maps from different periods of 1975−2015 in the software ArcGIS 10.3. The change rate in surface water area was calculated as the ratio of the difference of the lake area between two periods (A_{t1} and A_{t2}) to the lake area in the earlier period, i.e., $(A_{t2} - A_{t1})/A_{t1} \times 100\%$, and thus, a change rate of −100% suggests that the lakes had vanished. Furthermore, an elaborate classification scheme combining several information indexes (i.e., modified normalized difference water index (MNDWI),[35] normalized difference vegetation index (NDVI),[36] normalized difference built-up index (NDBI),[37] and bare soil index (BSI),[38] Table 1) was employed to quantitatively identify the land-use transitions from lakes to others, including aquaculture ponds, vegetation, built-up areas, bare land, and agricultural land. The empirical threshold values for the information indexes were manually selected for image classification based on the ENVI 5.1 software. Because cropland and vegetation are spectrally similar in summer images, we collected spring images to distinguish cropland from vegetation.[39] An example of Sha Lake (a typical lake suffering from serious land reclamation in Wuhan) is shown in the Abstract graphic. To ensure the reliability of the quantitative results, we validated carefully the detected land-use changes of each lake by visual examination referring to high-resolution images from Google Earth.[40] In this study, the uncertainties were mainly associated with the 40 year remote sensing data, the image-processing methods, and the census data from local statistical yearbooks, which were presented in Text S1.

■ RESULTS AND DISCUSSION

Changes in Lake Surface Area between 1975 and 2015. The area and number of all the lakes across the MLY floodplain (Table S3) were derived from Landsat images from 1975 to 2015. To facilitate an analysis of different-sized lakes, the lakes were categorized into four groups: 1−10, 10−50, 50−100, and >100 km^2.[41] A total of 389 lakes (≥1 km^2) were extracted for 1975, of which the four groups accounted for 78.1%, 13.6%, 4.2% and 4.1%, respectively. Over the past four decades, the total area of lakes has decreased by 2132.3 ± 219.6 km^2 (13.8 ± 1.4%), and the number of lakes experienced a net reduction of 26 (from 389 to 363), including 37 vanished lakes and 11 newly formed lakes (Table S3). The lakes in Dongting Plain experienced the most-serious decline (855.1 ± 131.8 km^2) in surface area while, relatively, the slightest decrease of lake area (153.7 ± 27.8 km^2) occurred in the Yangtze Delta. An increase in the area and number of lakes can be observed in the size group 10−50 km^2 (Table S3), on account of the degradation of the lakes from the size group 50−100 km^2. The water surface area of most lakes (61.6%) experienced a significant reduction between 1975 and 2015, the majority of which showed a change rate of −50−0% (Figure 2).

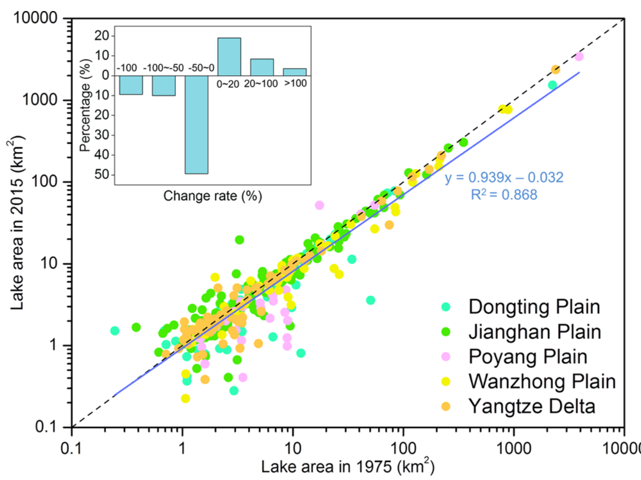

Figure 2. Comparison of lake area between 1975 and 2015 for each subregion. The inset shows the frequency distributions of change rate in lake area, suggesting that most lakes shrunk with a change rate of −50−0% and a few lakes vanished (change rate of −100%). The solid and dashed lines represent the fitted and 1:1 lines, respectively.

To investigate the temporal changes of lakes, 85 medium and large lakes (≥10 km^2) were further studied over the five nominal periods: 1975, 1990, 2000, 2010, and 2015. The total surface area of the lakes across the entire floodplain showed a rapid reduction during 1975−2000, with a slight increase after 2000 (Figure 3). To describe the change trend of the lake area on a statistical basis, the paired samples *t*-test was employed using the Statistical Package for the Social Sciences (SPSS) software to compare the area of each individual lake between different periods (e.g., 1975 versus 1990 and 1990 versus 2000)

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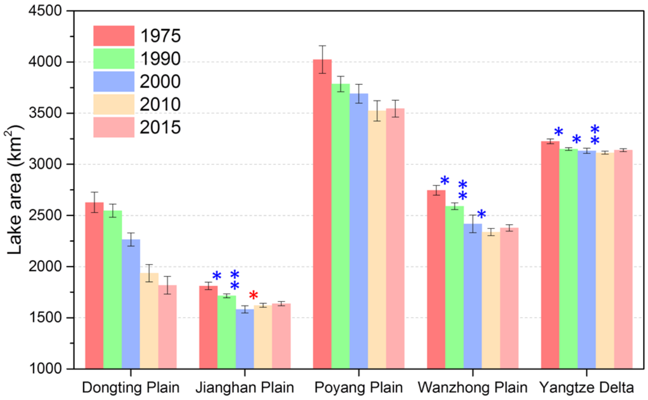

Figure 3. Changes of lake area in each subregion during the five periods: 1975, 1990, 2000, 2010, and 2015. The error bars are taken as the uncertainties of lake surface areas. The paired samples *t*-test was employed to compare the lake area between different time periods. The single asterisk (*) in blue suggests significant decrease in lake area at 80% confidence level, double asterisks in blue indicate decrease at 95% confidence level, and the red asterisk denotes increase in lake area at 80% confidence level.

in all subregions (Figure 3). Statistical significance was determined at the 80% or 95% confidence level. The lakes in Jianghan Plain shrunk notably ($p < 0.2$) during 1975−2000, whereas the water surface area showed a significant increase ($p < 0.2$) in this region from 2000 to 2010. Wanzhong Plain and the Yangtze Delta witnessed a remarkable reduction ($p < 0.05$ or $p < 0.2$) of lake area in the period of 1975−2010, while a statistically insignificant decrease ($p > 0.2$) occurred in Dongting Plain and Poyang Plain.

Quantitative Analysis of Driving Forces of Lake Changes. To identify the quantitative impacts of natural and anthropogenic factors, lake changes (transition to aquaculture ponds, vegetation, developed areas, bare land, and cropland) across the whole floodplain were obtained by accurate interpretation of Landsat data over the past four decades (Figure 4a). The results revealed that the significant shrinkage of lakes was predominately driven by human activities, i.e., lakes were directly converted into cropland, aquaculture ponds, and built-up areas (see examples in Figure S1a−c), accounting for 34.6% (898.3 km^2), 24.2% (627.7 km^2), and 2.5% (64.5 km^2) of the total loss in lake area, respectively. Furthermore, the conversion of lakes into vegetation (Figure S1d) and bare land can explain the remaining reduction in surface area (i.e., 967.0 and 35.5 km^2 with 37.3% and 1.4% in proportion, respectively), as a result of local climate variation, sediment siltation, and hydrological regulation. Furthermore, we identified the major land-use type for each lake in terms of the area of change, hereafter referred to as the "major conversion type". In this way, the lakes were categorized into five groups according to the "major conversion type", and the number of lakes in each group was derived for all the subregions (Figure 4b). Aquaculture pond or cropland was the "major conversion type" for most lakes, 50.1% and 37.3% in number, respectively. The percentage of vegetation as the "major conversion type" (7.5%) showed a significant difference compared to that of vegetation in area (37.3%, as shown in Figure 4a), which suggested a large change to vegetation occurred in a few lakes.

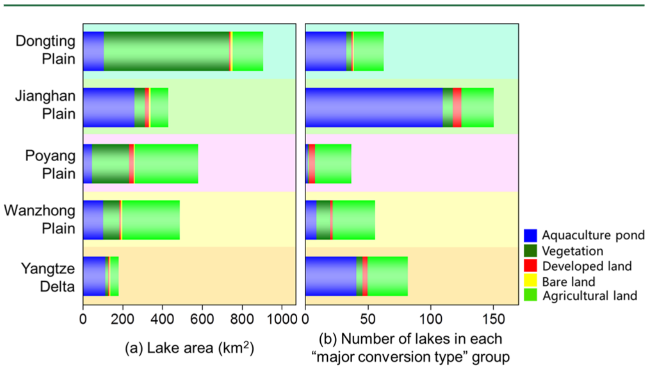

Figure 4. Land-use changes from lakes (≥1 km^2) to other land-use types (including aquaculture ponds, vegetation, built-up areas, bare land, and agricultural land) in the MLY floodplain during 1975−2015. (a) Stacked charts represent the area of each land-use type to which the lakes were converted. (b) Stacked charts indicate the number of lakes in each "major conversion type" group.

Human-Induced Land-use Changes of Lakes. Lake changes exhibited different spatial patterns from west to east along the Yangtze River, depending on the regional ecological environment and economic conditions. The lakes in Jianghan Plain and the Yangtze Delta were primarily converted into aquaculture ponds, while Wanzhong Plain was dominated by the transition to cropland. The abundant freshwater resources in Jianghan Plain facilitated the rapid expansion of aquaculture ponds in Hubei province (Figure 5c) but at the cost of 60.3% (260.4 km^2 in area) loss in lakes devoted to aquatic breeding. For example, Hong Lake, the largest lake in Jianghan Plain, had a decrease of 30.4 km^2 (98.7% of the aggregate reduction) as a result of enclosure practices for fish farming. As an important economic activity in the floodplain, fish rearing has provided locals with a plentiful aquatic resource, which has gradually encroached on the natural lakes through the construction of barriers for growing aquaculture area (Figure 5c).[27] Along with the rapid development of fishery industry, the overexploitation of fish resources has posed a serious threat to the survival of native fauna and flora, resulting in severe decline of biodiversity.[21] The lakes in the Yangtze Delta showed a similar pattern, i.e., a large amount of lakes were turned into fish ponds, leading to a reduction of 112.6 km^2, induced by the increasing market demands for aquatic products. For instance, Tai Lake, China's third-largest freshwater lake, supporting one of the most important fisheries for crabs, carp, and eels, suffered from the over-exploitation of freshwater resources and the deterioration of water quality.[25] In Wanzhong Plain, extensive impoldering for food production to support a growing population in Anhui Province (Figure 5e) was the leading driving force, inducing 59.5% (291.2 km^2 in area) of the total loss in lakes. Due to intensive land reclamation and overuse of chemical fertilizers, Shengjin Lake national nature reserve (Table S1) experienced wetland degradation and environmental pollution from 1986 to 2002.[42] Overall, human-induced land-use transitions from lakes to cropland, fish ponds, and urban areas represent the major drivers of lake shrinkage in the above three plains (i.e., Jianghan, Wanzhong, and Yangtze Delta), accounting for 84.6% of the total loss in lake area. However, natural factors such as meteorological variation, soil erosion, and sediment accumulation, inducing lake changes to vegetation and bare land, can explain the additional 15.4% of area reduction. Over the past 40 years, a consistent increase ($p < 0.001$) has been observed in interannual temperature (Figure 5a), whereas no significant trend ($p > 0.1$) can be seen in interannual precipitation change (Figure 5b). Therefore, it was

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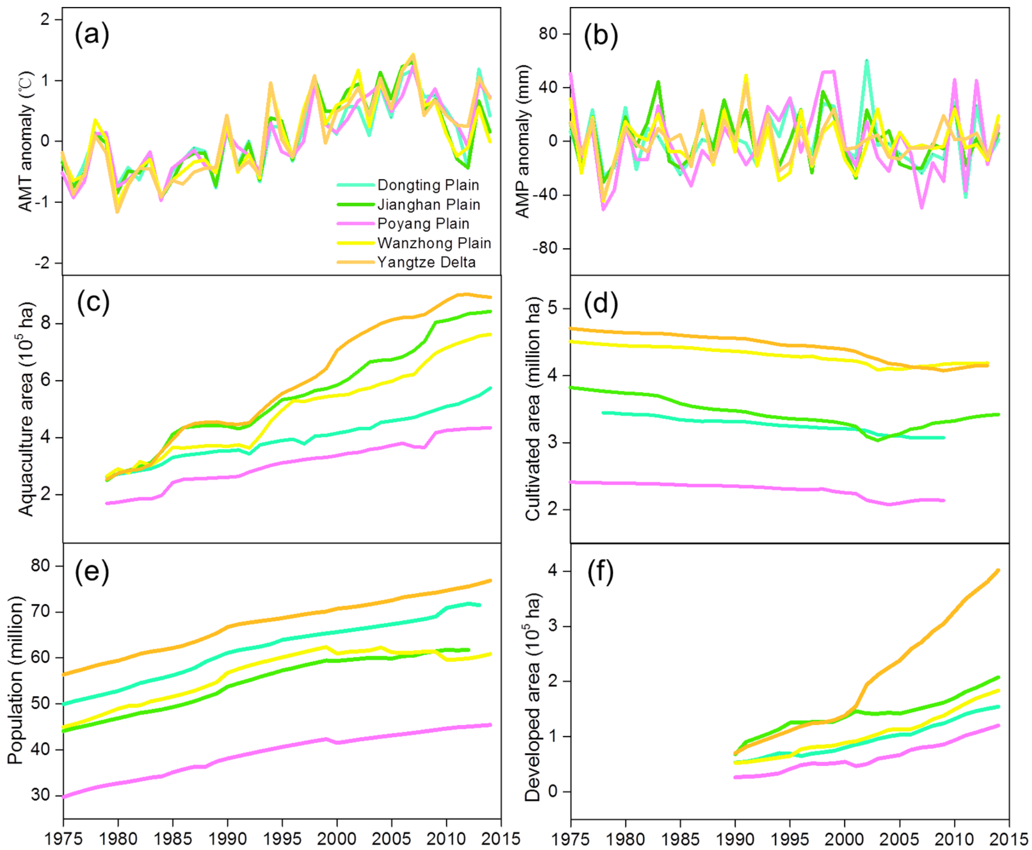

Figure 5. Changes in climate and human activities in the MLY floodplain over the past few decades. (a, b) The annual mean temperature (AMT) anomaly and annual mean precipitation (AMP) anomaly in each subregion, respectively. (c−f) The aquaculture area, cultivated area, human population, and developed area in each subregion, respectively.

believed that the climate change may not be considered as a major driving factor for lake shrinkage in the MLY floodplain.[15,18] Compared to climate change, soil erosion has a more significant impact on lake changes, which can increase the influx of sediment into lakes and raise the lake bed levels.[15,27] Although the free connection between the Yangtze River and most lakes in the MLY floodplain has been blocked as a result of local floodgate control or channel diversion,[17,26] these lakes have experienced accelerated sediment accumulation due to soil erosion from nearby cultivated lands.[27] For example, Hong Lake suffered from severe soil erosion and sedimentation from 1976 to 1983, inducing a rapid expansion of hydrophytes at an annual average speed of 7.41 km^2.[43]

Lake Degradation in Poyang and Dongting Plains. Poyang and Dongting plains witnessed the largest degradation from lakes to vegetation, accounting for 32.4% (188.4 km^2) and 69.4% (631.0 km^2) of the reduction of lake area in the respective regions (Figure 4a), mainly from China's two largest freshwater lakes (Poyang and Dongting). Connected freely to the Yangtze River, the two lakes experienced a dramatic reduction in surface area over the past few decades, leading to widespread exposure of wetland vegetation (187.2 and 620.1 km^2 in area, respectively).[23,44−46] Long-term sediment siltation due to a large amount of water-soil exchange with the Yangtze River was an important factor, resulting in the loss of the water storage capacity of lakes.[15] For instance, Dongting Lake had an annual sediment input of 1.9×10^8 t, mainly from the Yangtze River, leading to a high sedimentation rate of 10−30 mm/year.[27] Furthermore, TGD, the world's largest hydroelectric dam, with a reservoir storage capacity of >39 km^3,[47] aggravated the water-level decline of the Yangtze downstream lake systems (e.g., Poyang and Dongting), accelerating the emergence of wetland vegetation.[44]

In addition to the transition to wetland vegetation, Poyang and Dong plains have also suffered from excessive human utilization (i.e., transformation from lakes into cropland, fish ponds, and built-up areas), representing 66.8% and 29.6% of the area reduction in the respective regions. For example, extensive land reclamation has been another dominant driver for the shrinkage of Poyang Lake, resulting in a decrease of 249.8 km^2 in surface area for agricultural use. Dongting Lake has also undergone a sharp shrinkage from 4955 km^2 in the 1930s to ∼2266 km^2 in the early 1990s as a result of the practice of intensive impoldering.[18] Generally, the quantitative results have demonstrated that in Central Yangtze (including Dongting, Poyang, and Jianghan plains), human-induced lake conversions were the major driving factors (53.5%) for the decline in the lake surface area, while natural factors (e.g., climate change and sediment siltation) and hydrological regulation (e.g., TGD) should be responsible for the remaining loss (46.5%), which triggered the transformation from lakes to vegetation and bare land. For the entire MLY floodplain, when Dongting and Poyang Lakes are excluded, the direct land-use transitions from lakes to fish ponds, cropland, and urban areas can explain 86.1% of the lake area loss, indicating local anthropogenic activities were the dominant driver of lake shrinkage in the entire study area.

Relative Contributions of Anthropogenic and Natural Drivers. To further identify the relative contributions of human activities and natural factors on the lake changes, we

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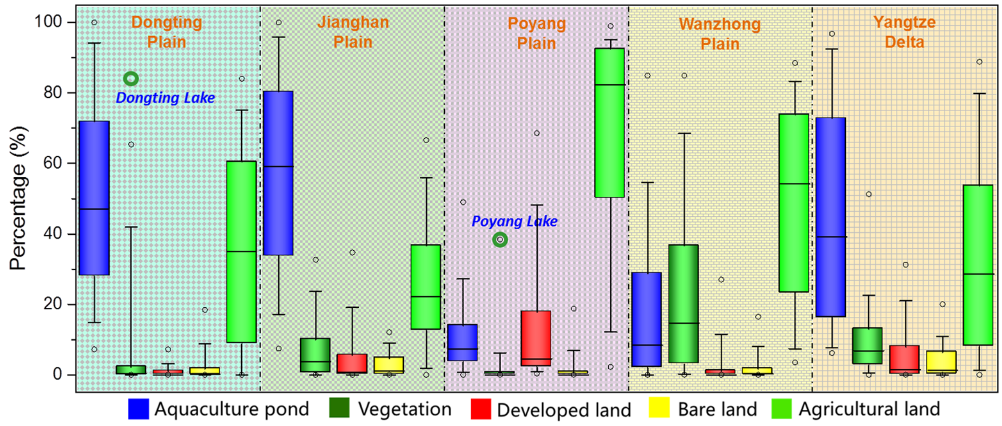

Figure 6. Boxplots show the percentage distributions of land use (including aquaculture pond, vegetation, developed land, bare land, and agricultural land) in area, to which all lakes (≥1 km^2) were converted in each subregion during the period of 1975−2015. The percentages of vegetation from Dongting and Poyang Lakes are highlighted in green circles. The horizontal lines (boxes and whiskers) in each boxplot are the 10th, 25th, 50th, 75th, and 90th percentiles, and the circles indicate the fifth and 95th percentiles.

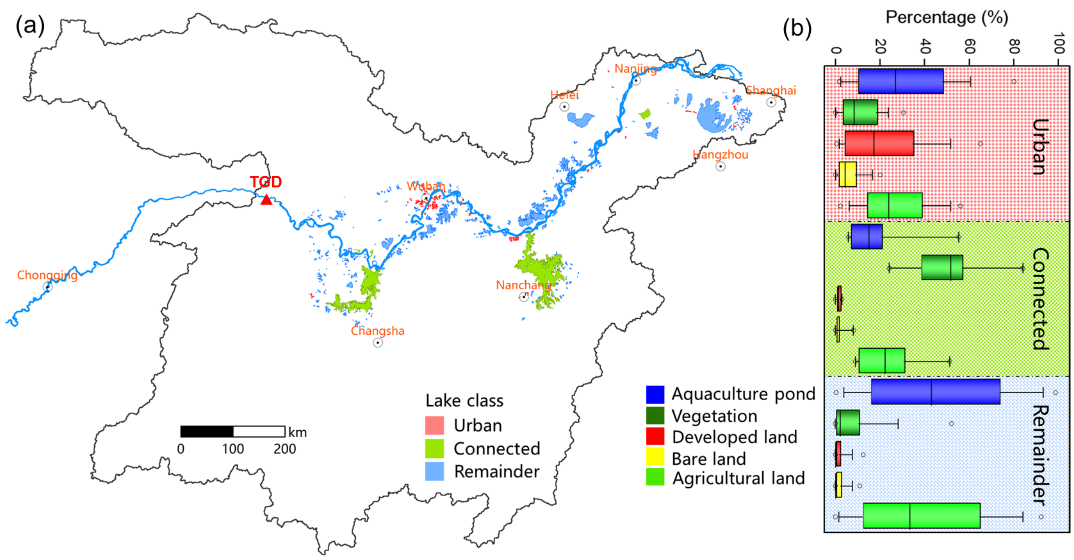

Figure 7. (a) Distributions of lake classes in the MLY floodplain, i.e., Class I ("Urban"), Class II ("Connected"), and Class III ("Remainder"). (b) Boxplots show percentage distributions of land use, including the conversion of lakes in each class to aquaculture ponds, vegetation, developed areas, bare land, and cropland.

investigated the percentages of the land-use conversions of each lake in surface area (i.e., aquaculture ponds, vegetation, built-up areas, bare land, and cropland). The percentage distributions in each subregion are illustrated in Figure 6. For the whole floodplain, the transition from lakes to aquaculture ponds accounted for the highest proportion, on average (43.2%), followed by agricultural land (38.4%), vegetation (7.9%), built-up area (7.4%), and bare land (3.1%). The results demonstrate that local land reclamation and exploitation of lake resources were the leading factors driving the lake shrinkage in the MLY floodplain. Moreover, despite the dramatic exposure of wetland vegetation occurring in Dongting and Poyang Lakes (highlighted in green circles in Figure 6), Dongting Plain witnessed the largest transformation from lakes into aquaculture ponds and agricultural land (in terms of average proportion, 50.2% and 36.5%, respectively), and Poyang Plain had the highest percentage (68.4% on average) of conversion into cropland. In the other three subregions (i.e., Jianghan, Wanzhong, and the Yangtze Delta), the leading land-use transformations from lakes (in terms of average proportion) are consistent with the results presented in Figure 4a. Additionally, under the accelerated process of urbanization, an increasing demand for land use in urban areas triggered the serious transformation from lakes into developed land, accounting for 7.4% of lake conversion, on average.

Driving Mechanisms among Different Lake Classes. In general, the lakes close to urban areas were vulnerable to the expansion of lakeside construction, e.g., real estate, traffic infrastructure, and tourist facility.[15] These lakes are referred to as urban lakes in this study (Figure 7a), which are categorized as Class I ("Urban"), consisting of 16.2% (63 in number) of the total lakes in the floodplain. The lakes freely connected to the Yangtze River are categorized as Class II ("Connected"), including five lakes, i.e., Poyang, Dongting, Shijiu, and two oxbow lakes (Heiwa and Yangtze Ancient Channels).[26] The remaining 82.5% of lakes (321 in number) in the floodplain are categorized as Class III ("Remainder"), as their free connections with the Yangtze River were blocked by artificial channel diversion and local floodgate controls. As an important component of urban ecological environment, urban lakes have

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been suffering from the severe influence of rapid urbanization, which is one of the most pervasive anthropogenic land conversions, leading to an area decrease of 22.2 km^2 (23.0% on average) in Class I lakes devoted to human settlements in the past few decades (Figure 7b). For example, Wuhan, the largest mega-city with an estimated population of 10.6 million in Central China,[48] has undergone an accelerated urbanization and significant shrinkage in urban lakes, such as Dong Lake, Nan Lake, and Sha Lake, which were converted into built-up areas occupying 32.4%, 59.4%, and 70.8% of loss in the respective surface areas (Figure S2a,b). The lakes in Class II (e.g., Poyang and Dongting) experienced a considerable exposure of wetland vegetation with a total area of 816.0 km^2 (51.0% on average), induced by the Yangtze flows. The pattern of change in Class III lakes was dominantly driven by extensive human activities for cropland and fish ponds, accounting for 45.7% and 39.0% of the decline in surface area, respectively. For instance, the shrinkage of the representative lakes, e.g., Tai Lake, Chao Lake, Hong Lake, and Liangzi Lake, was largely attributed to land reclamation for agricultural use or the enclosure practice for aquaculture (Figure S2a,b).

Ecological Impacts of Lake Degradation. Under the context of China's reform and opening-up policy since 1978, which has accelerated the process of industrialization and urbanization, excessive exploitation caused significant shrinkage of lakes during the period of 1975−2000. The Yangtze floodplain, one of the most fragile ecological systems in the world, has suffered from severe ecological consequences, e.g., increasing flood disasters, decreasing biodiversity, and environmental pollution. The human-induced rapid reduction in lake area across the MLY floodplain has a significant impact on the hydrological and ecological services.[17]

Flood Disasters. Numerous lakes across the MLY floodplain have played a critical role in accommodating the Yangtze floods. However, rapid shrinkage of the lake water area and their reduced connection with the Yangtze River has led to a significant decrease of the flood storage and drainage capacity.[49] For example, extensive reclamation has greatly reduced the water storage capacity of Dongting Lake from 2.68×10^{10} m^3 in 1954 to 1.74×10^{10} m^3 in 1983 (decreased by 35.1%),[50] which has increased the risk of flood hazard in the Yangtze River. From the 1950s to the 1990s, the recurrence frequencies of flood disasters on the Yangtze River have increased rapidly (Figure S3a).[49] In the 1950s, the recurrence interval of floods was as long as 10 years on average, but the average interval declined to 3−5 years between the 1960s and the 1980s and to only 2.5 years during the 1990s. In particularly, the 1998 flood, one of the most serious natural disasters on the Yangtze, was due not only to an extreme climatic catastrophe but also to the human-induced reclamation, deforestation, and soil erosion, causing enormous loss of economy amounted to 166 billion yuans or 20 billion U.S. dollars.[51]

To investigate the trend in the magnitude of Yangtze floods, water level data from the 1950s to the 1990s were collected from Duchang hydrological gauging station in the middle Yangtze.[52] From the 1950s to the 1990s, the magnitude of the annual peak water level recorded at the Duchang station has gradually increased (Figure S3b). The annual maximum water level increased from 18.51 m in the 1950s to 20.44 m in the 1990s. In addition, there has been a significant increase in the frequency of the peak water level, suggesting increasing risks of severe floods.[53] During the 1950s, water level exceeded 19 m in only two years, while in the 1990s, water level exceeded 19 m almost every year and exceeded 20 m in five years. The data analyzed in this study have all shown a notable increase in the frequency and magnitude of floods after the 1950s, in parallel with the rapid decline of lake water area.

Aquatic Plants and Fish. The lakes in the Yangtze Basin, as well as the Yangtze and its tributaries, provide important habitats for aquatic animals and plants. Nevertheless, severe degradation of lakes and wetlands over the past several decades has resulted in rapid loss of habitats, inducing a decline of biodiversity and extinction of endemic species. For example, the species richness of aquatic plants has shown a significant decrease during the past 50 years in Futou, Hong, and Dong lakes of middle Yangtze. The number of plant species in Futou Lake decreased from 70 to 61 between the early 1980s and the 2000s, i.e., nine plant species disappeared from the lake.[54] At Hong Lake, the aquatic plant richness has declined from 102 to 94 during the past few decades, as a result of the excessive development of fisheries. Since the 1970s, the dominant plant species in Dong Lake, such as sago pondweeds, duck lettuce, and ivy-leaf duckweed, have mostly disappeared, mainly due to the overexploitation of lake resources.[55]

Moreover, the loss of fish species was also increasing at an alarming rate. The species richness of fishes in Tai, Liangzi, and Dong lakes has dropped rapidly in the recent decades, consistent with the decline of lake water area. Before the 1980s, there were over 107 species of fish in Tai Lake, but only 60 species of fish could be collected in the 2000s.[56] The number of fish species in Liangzi Lake declined from 75 to 54 during the 1970s and 1980s. Similarly, Dong Lake experienced a rapid loss of the fish species (from 67 to 38) between the 1960s and 1990s, including some rare species such as the Yangtze grenadier anchovy and Reeve's shad.[21,55] The Baiji dolphin, a well-known endemic species of the Yangtze River, decreased dramatically from 6000 in the 1950s to 60 in 1998, and now this species may become extinct in this study area.[21]

Water Quality. Excessive exploitation of lake resources for agricultural, aquaculture, or urban purposes has also caused the severe deterioration of water quality of the lakes across the MLY floodplain.[57] For example, the water surface of East Tai Lake was occupied rapidly by high-intensity enclosure culture since the 1990s, leading to significant increases in nutrient loading to the lake, such as nitrogen and phosphorus. From 1960 to 1981, total nitrogen (TN) increased dramatically from 0.05 to 0.9 mg/L, chemical oxygen demand (COD_{Mn}) increased by 49% (from 1.9 to 2.83 mg/L), and total phosphorus (TP) remained stable.[57] Since the 1990s, Tai Lake has reached the eutrophic state, with TN, TP, and COD_{Mn} increased from 2.349, 0.058, and 3.9 mg/L in 1990 to 2.7, 0.133, and 6.33 mg/L in 2000, respectively.[57]

In addition, rapid urbanization and industrialization has resulted in land-use alterations in the watershed area of urban lakes, increasing the rate of urban contaminant inputs to the lakes.[58,59] The conversions of agricultural land in the watershed area to urban areas may induce even greater levels of water pollution.[60] For example, in the watershed of Tangxun Lake, TN and TP loads have showed an increasing tendency since 1991, and the high-value areas of pollutant loads have expanded from north to south with the increase of developed areas.[61] In Dong Lake, TN and COD_{Mn} increased from 1.92 and 4.7 mg/L in 1986 to 2.46 and 7.6 mg/L in 2000, respectively.[57] Water pollution caused by rapid urbanization has profound effects on the function of the lake as a drinking water supply, and thus exacerbated the lack of accessible drinking water in the cities.[62]

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To mitigate these negative impacts, local governments have implemented a series of wetland restoration projects, such as establishing national wetland reserves, prohibiting impoldering and returning cropland to lakes, which contributed to the slight increase in surface area of lakes after the year 2000.[15,63] For instance, Liangzi Lake, with the largest water storage capacity in Hubei Province, experienced an area shrinkage from 350.0 km^2 in 1975 to 286.2 km^2 in 2000 (a decrease of 18.2%), mainly due to the excessive lakeside enclosure for fish rearing. The implementation of lake conservation and restoration policies, e.g., prohibiting the enclosure practice and removing barriers in fish ponds, was conducive to an increase of 2.8% in lake area (from 286.2 to 304.8 km^2) during 2000−2015. However, the lake areas of each subregion are forecast to decrease until the year 2020 (Figure S4) except for the Jianghan Plain (with a slight increase). For the whole MLY floodplain, the total area of lakes ($\geq$10 km^2) is expected to experience a reduction of 2.58% from 2015 to 2020. Under the accelerated urbanization and population growth, the numerous valuable lakes across the Yangtze floodplain will continue to suffer from land-use alternations for agriculture, aquaculture, and human settlements, with the ongoing vulnerability to both human activities and climate change.[5,15,26] More effective action is urgently required to balance the trade-offs between human consumption and ecological conservation, and the further reconstruction of natural wetland ecosystems will be a tremendous challenge for policymakers.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b04260.

Tables showing descriptions of Ramsar sites, acquisition dates of the Landsat images, changes in the surface area of lakes, validation results of Landsat water areas, and accuracy assessments for land-use changes. Figures showing examples of lake conversions in the MLY floodplain, charts indicating area and proportion of land-use types, frequency and magnitude of floods on the Yangtze River, a regression forecast, examples of the interpretation of Landsat images, the geographic distribution of validation sample points and error, and comparisons of Landsat mapped lake areas and reference datasets. Additional details on uncertainty analysis(PDF)

■ AUTHOR INFORMATION

Corresponding Author

*Phone: +86-02768771318; fax: +86-02768778086; e-mail: xhuang@whu.edu.cn.

ORCID

Xin Huang: 0000-0002-5625-0338

Notes

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