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Hundred-year spatial trajectory of lake coverage changes in response to human activities over Wuhan

Jialin Wang, Xiaobin Cai, Fang Chen, Zhan Zhang, Yufang Zhang, Kun Sun, Tianhao Zhang and Xiaoling Chen

1 State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan 430079, People’s Republic of China
2 Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan 430077, People’s Republic of China
3 Division of Geodetic Science, School of Earth Sciences, Ohio State University, Columbus 43210, OH, United States of America
4 School of Remote Sensing and Information Engineering, Wuhan University, Wuhan 430079, People’s Republic of China
5 School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, People’s Republic of China
6 Joint Institute for Regional Earth System Science & Engineering, University of California, Los Angeles, CA, United States of America

E-mail: xiaoling.chen@whu.edu.cn

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Abstract

Environmental changes induced by ongoing anthropogenic activities have caused severe lake degradation. Because of the lack of long-term records, few studies have investigated the change in Wuhan lakes, and the effect of human activities on regional lake changes prior to 1973 has not been systematically studied yet. Therefore, in this study, historical maps and Landsat images were combined to track these changes from the 1920s to 2015. Three phases could be identified over the nearly 100-year study period. The most dramatic lake reduction (21.53 km² yr⁻¹) occurred during Phase II (1950s–1980s) rather than Phase III (after the 1980s), as indicated by previous studies; the decreased lake area in Phase II was almost double that in Phase III. This reduction could be attributed to major hydraulic engineering projects during Phase II based on the watershed-scale analysis. In addition, land-use conversion over the past 45 years was used to quantify the impact of human exploitation on lakes. The shrinkage of lakes was predominately driven by agricultural activities, such as reclamation (39.2%) and aquaculture development (29.0%), and urbanization was a secondary driving force (19.8%), despite the rapid economic development of Wuhan. This study therefore provides a practical guide for lake protection in other areas similar to Wuhan.

1. Introduction

As valuable natural ecosystems and resources, lakes are not only crucial habitats for wildlife [1, 2], but also play essential roles in global carbon cycling and climate change mitigation [3]. Lake ecosystems thus provide critical ecosystem services from which human beings benefit [4]. However, lakes have globally undergone dramatic and irreversible changes due to intensive human activities and climate change over the past decades [5–8]. These changes include severe water quality deterioration as well as shrinking and even vanishing [9, 10]. Hence, an in-depth understanding of lake coverage change is crucial to conserving lake ecosystems.

Remote sensing data with synoptic and frequent observations, especially Landsat time series data, have been widely used to study changes in lakes (such as lake area, number, and morphology) [9, 11–14]. Several pioneering studies have used remote sensing data to monitor the lake changes in Wuhan, China, a city with numerous lakes. Some studies suggested that the dramatic decline in Wuhan lakes was primarily caused by urban expansion [15–17], whereas others with more extensive research areas indicated that the reduction in lakes was predominately driven by fishery activities [10]. Such contrasting findings might be attributed to the limited satellite observations (5–42 years) used in these studies, which created difficulties in revealing long-term lake
changes in Wuhan, especially since the city has undergone nearly a century’s history of intensive urban development [15, 16]. In this context, historical maps can provide useful complementary data to Landsat images for studying long-term changes in regional lakes and revealing how the main driving factors act [18–20].

Analyses of temporal changes of lakes usually use the administrative boundaries as the statistical analysis unit [16, 21, 22], and urban planning and management are also based on it, which cannot reflect the real characteristics of hydrological changes within the Wuhan city. However, the urban water cycle and surface runoff do not follow political boundaries. Therefore, the statistical unit of lake changes in urban planning should be based on the watershed as the catchment unit.

Major hydraulic engineering projects (e.g. the Three Gorges Dam) were proved to play important roles in the reduction of river-connected lakes [23, 24]. Multiple large hydraulic engineering projects have been constructed in Wuhan over the past century, but the impacts of these projects on lake changes remain unclear. Improved understanding of these impacts is therefore critical to effectively balance the trade-offs of lakes and to realize the sustainable development of lakes. Therefore, the trajectory of lake changes in Wuhan over longer timespans needs to be investigated by using more detailed historical maps and satellite observations.

To bridge the abovementioned gaps, this study aims to investigate the lake changes over nearly 100 years in Wuhan, and to evaluate the associated driving forces by combining the historical maps and Landsat time-series images. We had the following four specific objectives:

1. To obtain accurate results of lake changes over nearly 100 years.
2. To explore the driving forces behind the long-term lake changes and determine the intensity of these changes in different phases.
3. To determine the impact of hydraulic engineering projects on lake changes by using watershed-scale analyses [25].
4. To study the response of lakes to natural and anthropogenic factors according to quantitative results of related land-use and land-cover data analyses.

2. Materials and methods

2.1. Study area

Known as the ‘city of a hundred lakes,’ Wuhan is one of the cities with the highest number of lakes in China [26–28]. It is located in the eastern Jianghan Plain on the confluence of the Yangtze and Han River, with an area of 8494.41 km² (29°58’–31°22’N and 113°41’–115°05’E, figure 1). The annual temperature and precipitation in Wuhan are 16.3 °C and 1205 mm, respectively, and the maximum precipitation regularly occurs in June and July [15]. Meanwhile, the topography of Wuhan is dominated by relatively flat land less than 50 m above sea level [29, 30], and dense rivers join together to form numerous lakes [31]. Due to the water balance impact of the surrounding rivers on it [32], the spatial distribution of lakes would be greatly affected by the river realignment over long periods [33]. Therefore, the distribution pattern of lakes in Wuhan heavily depends on the evolution of the Yangtze and Han Rivers as well as that of other smaller rivers.

Over the past century, the high frequency of flood disasters in Wuhan has severely threatened the safety of residents’ lives and properties [34–36]. With socio-economic development, the growing needs of municipal, industrial, and agricultural sectors for water have increased the demand for the construction of hydraulic engineering projects to manage water resources better. The launch of such projects has modulated the water flow to and from the lakes and changed lake hydrological processes, which further affected the lake evolution [37].

Wuhan currently contains 166 lakes, which are all shallow and vulnerable to disturbances by anthropogenic activities and climate change [30]. The population of Wuhan rose from 0.79 million in 1920 to 10.6 million in 2015. The significantly increased population has been accompanied by the rapid development of agriculture, aquaculture, and real estate over the past century. As a result, the lakes in this region have suffered tremendous impacts from intensive human activities [17, 38], resulting in substantial negative consequences, including dramatic shrinkage [21, 39, 40], severe deterioration of water quality [15, 26], and reduced indigenous biodiversity [41, 42].

2.2. Data

To analyse long-term lake changes in Wuhan, we used historical maps from the 1920s–1988 to fill the blank before the development of satellite-based remote sensing, which constitutes a study period of nearly 100 years. Two series of historical maps were used in this study. The maps of the 1920s were developed by the Army of Hubei Mapping Agency Ordnance Survey from 1916–1921, and the entire city of Wuhan was covered by 11 maps (scale 1:100 000, table 1). Lake area data in two phases (the 1950s and 1988) were extracted from the historical maps of Atlas of Lakes in Hubei Province (1950s–1988), which were compiled by the Hubei Provincial Department of Water Resources (scale of 1:50 000–1:100 000). Lake coverage during the 1970s–2015 was derived from Landsat satellite images, including Multispectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+),
High-quality (cloud-free) Landsat images (table 1) were downloaded from the United States Geological Survey (http://glovis.usgs.gov/) and the Chinese Geospatial Data Cloud (http://www.gscloud.cn/). The trajectory of lake changes was derived from the combination of historical maps and remote sensing images between the 1920s and 2015. The maps provided a novel view on historical lake changes. For example, the evolution of Wu Lake (red mark in figure 1) is shown in figure 2 and was derived from two historical maps (the 1920s and 1950s) and satellite images from two phases (1970s and 2015). Wu Lake was found to have suffered fragmentation and dramatic decline over the past century.

SRTM-DEM (Shuttle Radar Topography Mission Digital Elevation Model) data, with a ground resolution of 90 m from the Geospatial Data Cloud (www.gscloud.cn/), were used to divide the small watersheds of Wuhan to better analyse the characteristics of lake changes.

2.3. Methods
First, all of the historical maps (in the 1920s, 1950s, and 1988) were converted into digital images via scanning at 600 dots per inch. Then, geographically registered based on the large-scale topographic map of Wuhan (scale of 1:10 000 in 2013). The lake coverage on historical maps was extracted via digitization. Landsat time series images were processed through radiometric calibration and FLAASH atmosphere correction using ENVI 5.2 software. All the MSS images were resampled to a resolution of 30 m for consistency with TM, ETM+, and OLI images. The Landsat data were interpreted to provide accurate lake boundaries (each lake area $\geq 0.05 \text{ km}^2$) [43]. The lake area was readily affected by short-term precipitation and may have fluctuated within a single year [11]. Therefore, to eliminate the uncertainty of lake boundaries caused by seasonal rainfall fluctuation, we calculated the average lake area extracted every five years (1970, 1975, 1980, 1985, 1990, 1995, 2000, 2005, 2010, and 2015, respectively). To verify the consistency between the two types of data, the lakes on historical maps in 1988 were compared with remote sensing results in 1990 (see accuracy assessment in table A1 (see supplementary material available online at (stacks.iop.org/ERL/15/094022/mmedia))). Furthermore, the land-use transformation maps around the lakes between the two phases were interpreted. Nine periods of land-use transformation with five-year gaps, namely 1970–1975, 1975–1980, 1980–1985, 1985–1990, 1990–1995, 1995–2000, 2000–2005, 2005–2010, and 2010–2015, respectively).
Table 1. Historical maps and Landsat MSS, TM, ETM+ and OLI series images used in this study.

| Historical maps | Scale | |
|-----------------|-------|---|
| Year            | 1:50 000 | 1:75 000 | 1:80 000 | 1:90 000 | 1:100 000 | Total |
| 1920s           | 0      | 0      | 0        | 0        | 11        | 11    |
| 1950s & 1988    | 1      | 4      | 4        | 1        | 4         | 14    |
| Total           | 1      | 4      | 4        | 1        | 15        | 25    |

| Satellite Images | Resolution | Period | |
|-----------------|------------|--------|---|
| MSS (1973–1984) | Band 1–4: 78 m | 1970–1979 | 26 | 28 | 54 |
| TM (1987–2011)  | Band 1–5: 30 m | 1980–1989 | 0 | 12 | 51 | 162 | 225 |
| ETM+ (1999–2015)| Band 1–5: 30 m | 1990–1999 | 0 | 0 | 5 | 243 | 248 |
| OLI (2013–2015) | Band 1–7: 30 m | 2000–2015 | 0 | 0 | 91 | 91 |
| Total           | 26        | 40     | 56     | 496     | 618 |

Figure 2. The historical maps (a–1920s b–1950s) and remote sensing images (c–1970s d–2015) of Wu Lake.

1995–2000, 2000–2005, 2005–2010, and 2010–2015, were obtained to identify land-use transition types and explore the different land demand impact on lake reduction. The lake-related land-use changes were detected by overlapping the lake maps of different phases during 1970–2015. The changing area related to lakes in each phase was interpreted into six categories lakes (not including artificial ponds), cropland, natural vegetation area, bare land, aquaculture area, and developed land, through visual interpretation from the remote sensing images.

Watershed analyses were used to provide the physical and ecological value in revealing the real characteristics of lake changes, and also to better...
establish cause-and-effect relations between anthropogenic activities and lake changes [44]. Based on SRTM-DEM data, a GIS tool (Arc-Hydro; ESRI) was employed to divide the study area into 12 watersheds (figure A1): Dao River (WS-1), She River (WS-2), Tongji-Hou Lake (WS-3), Fuhuan River (WS-4), Liangzi Lake (WS-5), Northlake (WS-6), Dongsha Lake (WS-7), Tangxun Lake (WS-8), Moshui-Longyang-Nanbeitaizi Lake (WS-9), West Lake (WS-10), Jin River (WS-11), and Dongjin River (WS-12) watersheds [45].

3. Results and discussion

Wuhan has numerous lakes surrounding the city core whilst experiencing rapid urban expansion. It can therefore be considered an ideal place to study the conflicts between lake ecosystem conservation and urban development and may produce useful land use management guides for other similar cities worldwide. Furthermore, given that land use change is a long-term process shaped by both natural and anthropologic factors, we highlight the need for the long-term study that incorporates both remote sensing images (after 1973) and historical maps (before 1973) to capture such long-term changes. Therefore, the generality of this study is that such long-term change monitoring methods can be applied to any other region, as long as they have early historical records.

In this study, we analysed the changes in the size and number of lakes using a combination of historical maps and remote sensing data. The results indicated varying trends over the study period of nearly 100 years. These two types of data were consistent for the period during which both historical maps and remote sensing images were available. The accuracy of the lake areas derived from both datasets in the same period was higher than 94%, and the consistent ratio of lake coverage between imagery and maps was higher than 85%. This suggested that lake data derived from historical maps for periods without satellite imagery were accurate.

3.1. Lake change trajectory in Wuhan over nearly 100 years

The trends in the size and number of lakes in Wuhan over the century-long study period are presented in figure 3. The lake area decreased from 1789.0 km$^2$ in the 1920s to 695.3 km$^2$ in 2015. The disappeared lake area accounted for 61.1% of the total area, indicating drastic shrinkages in Wuhan.

Based on the trends in the lake area, the history of lake changes could be divided into three phases: Phase I (the 1920s–1950s), Phase II (the 1950s–1980s), and Phase III (the 1980s–2015). The annual change rates in lake area were calculated as $-2.86$ km$^2$ yr$^{-1}$ in Phase I and $-10.34$ km$^2$ yr$^{-1}$ in Phase III, which were both obviously lower than that in Phase II ($-21.53$ km$^2$ yr$^{-1}$). This suggested that the lakes underwent the sharpest decrease in Phase II, during which Wuhan experienced a decline in lake area, from 1703.3 to 1057.3 km$^2$. This shrinkage accounted for 59.06% of the total decrease in lake area throughout the study period. The smallest decrease in lake area occurred in Phase I, from 1789.0 to 1703.3 km$^2$, and accounted for 7.84% of the total decrease in lake area. Moreover, the number of lakes in Wuhan fluctuated over the past century. There were 116 lakes in the 1920s, and then the number reached a peak, 176 lakes in the 1950s. In this period, the net increase of lake number was mainly due to the larger lakes split into smaller lakes, which made the lakes more fragmented. In Phase II, the number of lakes experienced a net reduction of 18 (from 176 to 158), leading to the decline of the ecosystem. And then 8 new lakes appeared to the current 166 lakes in 2015.
3.2. Lake changes at watershed scale

Using watershed-scale divisions provide the scientific significance to illustrate lake changes within Wuhan city and analyse how the anthropogenic factors act. The number and area of lakes were calculated based on the 12 watersheds as the 12 complete water systems (figure 4). The spatial distribution of these watersheds is plotted in figure A1. Except for the Dongjin River watershed (WS-12), all watersheds had a decreasing tendency during the study period. This indicated that the reduction in lake area occurred in almost all the watersheds of Wuhan over the past 100 years.

In Phase I, lake area in WS-1, WS-2, WS-8, and WS-12 showed an increasing trend, whereas in the remaining watersheds decreased. The maximum reduction of the lake area was observed in WS-5, which reached 96.3 km². On the other hand, WS-2 experienced the largest increase (62.3 km²), with a newly formed lake in this region, which might have been caused by the river flooding near the Yangtze River. With 17 new lakes, WS-12 had the most significant increases in lake number. In Phase II, the lake area reduction was larger than 100 km² in three watersheds (260.4 km² in WS-4, 208.2 km² in WS-2, and 154.6 km² in WS-1). Seven watersheds showed a slight decline in lake area of <35 km². Only two watersheds experienced an increase in lake area: WS-12 had the largest increase of 77.6 km², and WS-5 had an increase of 17.3 km². During this phase, lake number increased sharply in WS-4 and WS-2 because of the formation of new lakes. In Phase III, all the watersheds showed a decreasing trend in lake area, with a total loss of 362 km². A remarkable reduction of 102 km² (accounting for nearly one-third of the total loss in area) occurred in WS-12. The most dramatic changes in lake number occurred in WS-4 because of the division of large lakes into numerous smaller ones, leading to an increase of ten lakes over the past 35 years.
3.3. Total lake area change of Wuhan in recent 100 years

The severe decline of lakes in Wuhan has garnered widespread attention because of the rapid economic development in the region [16, 46, 47]. Previous studies have shown that Wuhan experienced dramatic lake shrinkage over the last decades. Our results indicated that the loss rate had been underestimated, and the actual peak of lake shrinkage occurred prior to the study periods of these studies. For example, Ma et al. and Deng et al. showed that the change rate of Wuhan’s lake area might range from −7.49 to −4.11 km² yr⁻¹ [46, 47], whereas our results suggest that the lakes experienced an area reduction of 388.08 km² over the same period, with a change rate of −9.24 km² yr⁻¹. Such underestimations might be due to the extent and lake extraction procedures of these studies. Rural areas experienced a more severe reduction in lakes than did the urban areas in the Jianghan Plain, including Wuhan [10, 48]. This has contributed to the significant underestimation of lake reduction because most previous studies focused on the central urban area of Wuhan. Moreover, lake area might be impacted by random rainfall events. However, previous studies only used single-date images to represent the lake area over specific periods, which might introduce errors. Classification accuracy could also affect the results, as these studies depended on automatic classification procedures. Our results with multitemporal images and visual interpretation yielded more robust results. Consequently, lake reduction in Wuhan might be significantly underestimated in recent decades.

Based on our long-term lake trends, the most serious decline (646.01 km²) occurred in Phase II (the 1950s–1980s) with a rate of −21.53 km² yr⁻¹. Phase II can be considered as the peak of lake shrinkage over the 100-year study period. The high lake shrinkage rate might be caused by hydraulic engineering projects, with most of them initiated in this period. In addition, the extensive impoldering activities were largely driven by the increasing demand for food imposed by the rising population from the 1950s to 1978 and exacerbated by the low annual output per square kilometer [38]. Accelerated agricultural reclamation played an important role in the decreasing lake area during this period. In general, lakes in the 12 studied watersheds were subject to severe agricultural reclamation during Phase II, with 72.6% of the lake area turned into croplands to support the rapid population growth and economic development.

3.4. Impact of hydraulic engineering projects

After 1949, a series of hydraulic engineering projects were initiated to benefit the growing population of Wuhan in terms of flood control, electricity generation, irrigation, and shipping, for example. The hydraulic engineering projects of Wuhan mainly operated during the 1950s to 1980s, which coincided with the most dramatic lake changes, as indicated in this study. The hydraulic engineering projects included channel realignment projects, dam construction, and flood storage projects, which alleviated flooding but limited the development of lakes [49, 50].

At the same time (the 1950s–1980s), more than 75 lakes (>839.4 km², accounting for 49.3% of total lake area) experienced the most abrupt lake change in Wuhan. To investigate the spatial heterogeneity of lake changes, the percentages of unchanged, increased, and decreased lake area during this period were compared based on watershed units. The unchanged area percentage (U_P), increased area percentage (I_P), and decreased area percentage (D_P) of lakes in different watersheds between the 1950s and 1980s were calculated (table A2). Then, the 12 watersheds were categorized into three groups based on the largest corresponding percentage of lake change: Type A, dramatically decreased watersheds (when DP = max(U_P, I_P, D_P)); Type B, insignificantly changed watersheds (when UP = max(U_P, I_P, D_P)); Type C, dramatically increased watersheds (when IP = max(U_P, I_P, D_P)). The percentage of lake area changes in the 12 studied watersheds ranged from −88.73% to 108.70%. Three watersheds were categorized as Type A (WS-1, WS-2, and WS-4), only one (WS-12) as Type C, and the remaining eight as Type B. The average change ratio (−81.13%) in Type A watershed was more than six times larger than that in Type B watersheds (−11.63%). Only WS-12 experienced a sharp increase in lake area. Notably, the main hydraulic engineering projects were mostly in operation when the abrupt changes in the watersheds occurred (including Types A and C).

Generally speaking, there were two kinds of hydraulic engineering projects in Wuhan: channel realignment projects and flood diversion projects. Three large-scale channel realignment projects were constructed in Type A watersheds and one in Type C watersheds, whereas none were built in Type B [51]. Figure 5 shows the four key hydraulic engineering projects: Fu Huan River Diversion Project (FHRDP built in 1959, located in WS-4); Dong Jin River Downstream Diversion Project (DJRRDP built in 1966, located in WS-12); She River Downstream Treatment Project (SRDTP built in 1977, located in WS-2), and Da Rong River Downstream Diversion Project (DRRDPP built in 1970, located in WS-1). In addition, Duijiatai Flood Diversion Sluice (DFDS, located in WS-12) was completed in 1956. To alleviate flood disasters, FHRDP, SRDTP, and DRDDP were built to modulate the water flow to and from the lakes. The natural connection between rivers and lakes were separated by the construction of these projects, which triggered the transformation of lakes into other land-use types. The maximum reduction in lake area of 266.92 km² (90.7%) occurred in
WS-4, and the lake area in this watershed remained only 33.41 km$^2$ in the 1980s. Lake area in WS-2 also experienced a dramatic reduction (210.97 km$^2$), leading to widespread exposure of wetland vegetation. In Phase II, the DRDDP blocked 1793 km$^3$ of inflow water from the river basin, inducing a steep decrease of 159.8 km$^2$ in lake area (74.67% of the aggregate reduction) in WS-1. For example, the water level of Zhangdu Lake (the largest lake in WS-1) reduced by 1.6 m because of this project [51]. Compared with the other 11 watersheds, the lake area in WS-12 (Type C watershed) tended to increase by 62.35% (a net increase of 78.91 km$^2$) in Phase II. The DFDS was designed to employ lakes and low-lying land along the Yangtze River to store excess water from flooding. The DFDS operations were carried out 16 times in Phase II (table A3), and large areas of land were inundated, forming new lakes and causing lake expansion in WS-12. In addition, some lakes were reduced in the watershed because of the regulated flow pattern of DJRDDP. The lakes in WS-12 were also affected by the five operations of DFDS in Phase III (figure 4, table A3).

It should be noticed that it is difficult to directly quantify the impact of hydraulic engineering projects on lakes. However, we have attempted to quantitatively compare the average lake area changes of Type A (with channel realignment projects), Type B (no hydraulic engineering projects), and Type C watersheds (with flood diversion projects and channel realignment projects). Lake changes in Type B watersheds could be used as a reference for Phase II. The shrinkage rate of lake area in Type B watersheds was approximately 11.3%, while that of Type A watersheds was 81.1%. Thus, the 69.8% reduction of lake area in Type A watersheds could be attributed to the river treatment projects. Similarly, the 123.8% increase of lake area in Type C watersheds might be caused by the joint action of the two kinds of hydraulic engineering projects (i.e. one flood diversion project, and one channel realignment project).

3.5. Lake changes during rapid development period

Rapid economic development in Wuhan has intensified the use and exploitation of lakes [52–54]. To investigate the impact of land use on lake changes between 1970 and 2015, land-use data were employed to identify the quantitative impacts of natural and anthropogenic factors. The interconversion between lake coverage and five different land-use and land-cover types, including cropland, natural vegetation, bare land, aquaculture ponds, and developed areas, has occurred frequently over the past 45 years [10]. Land-use conversions to meet the demands for human development, namely farmland, aquaculture ponds, and developed areas, has occurred frequently over the past 45 years [10]. Land-use conversions to meet the demands for human development, namely farmland, aquaculture ponds, and developed areas, were mainly influenced by anthropogenic factors (figure 6(a)), which is similar to Xie
et al [10]. The remaining reduction of lake converting to bare land and vegetation can be attributed to climate change, leading to widespread exposure of wetland vegetation. The five different land-use types might also be converted into lakes because of natural factors and lake protection policies (figure 6(b)), such as concentrated precipitation and returning farmland to lake [11, 55]. A large proportion of the lake area loss was predominately driven by anthropogenic activities (figure 6(c)), i.e. lakes were directly converted into farmland, aquaculture ponds, and developed land, accounting for 39.2% (151.64 km$^2$), 29.0% (112.12 km$^2$), 19.8% (76.49 km$^2$) of the total net loss in lake area, respectively. Additionally, the remaining reduction of lakes was converted to vegetation, and bare land, accounting for 9.1% (35.0 km$^2$), and 3.1% (11.8 km$^2$) of the total net loss in lake area, respectively, as a result of natural factors. Besides, the details of land-use transitions from lakes in each watershed were also analysed (figure A2).

Figure 6(c) shows that the shrinkage of lakes after 1970 in Wuhan was mostly due to the conversion of lake area to farmland, which accounted for 39.2% (151.64 km$^2$) of the total net loss in lake area. This suggests that extensive impoldering for food production remains a major driving factor of lake-area loss. Several previous studies have further suggested that the shrinkage of lakes in Wuhan is mainly attributable to urban expansion (accounting for 54%–60% of the total reduction in lake area) [15–17], whereas urbanization only caused a loss of 19.8% (76.49 km$^2$) in our study. The higher proportion of urban expansion in the previous studies was because their study areas mainly comprised central Wuhan city, ignoring the surrounding suburbs. In contrast, the conversion of lakes into developed land comprised less than 10% of lake loss across the entire Jianghan Plain [10]. A higher ratio of urban expansion in our findings may be attributed to the rapid urbanization of Wuhan city relative to the surrounding areas [15, 53]. The area converted from lakes to farmland had a decreasing trend since 1980, which was related to the implementation of lake conservation and restoration policies [55]. However, a net increase in lake area of 32.28 km$^2$ occurred during 1975–1980 because of the conversion of vegetation and cropland to lakes, which could be explained by natural factors, such as rain. A large amount of precipitation occurred in 1980 with a high annual mean precipitation (AMP) of 1623.6 mm. The AMP in 1980 was 303.4 mm higher than that in 1975, leading to an increase in lake level. After 2000, some cropland was converted to lakes mainly because of the ‘returning cropland to lakes’ policy, establishing wetland restoration projects (such as Chenhu Wetlands Nature Reserve, a Ramsar wetland) [56], and regulating hydraulic engineering projects (such as DFDS) in WS-12. Additionally, as shown in figure 6(c), aquaculture ponds initially
had an increasing tendency, further reducing lake area, and then decreased after 2000 due to the specific regulations enforced by the Chinese government to remove enclosures from lakes, which corroborated the findings of Dai et al. The remaining reduction of lakes due to conversion to bare land (3.1% loss in lake area) and vegetation (9.1% loss in lake area) may result from climate change, which has led to widespread exposure of wetland vegetation.

4. Conclusions

To summarise, we used historical maps and remote sensing images to investigate the evolution of lakes and the associated driving factors in Wuhan over nearly 100 years. We highlight that the lake loss rate has been largely underestimated, and the actual peak of lake shrinkage occurred much earlier than that suggested by previous studies. We also investigated the divergent responses of lakes to hydraulic engineering projects at the watershed scale. Finally, we found that conversion to agricultural land-use types, rather than urban encroachment, was the most significant driver in lake shrinkage, even during rapid urbanization periods.

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Notes

The authors declare no competing financial interest.

Data Availability Statement

The data that support the findings of this study are available upon request from the authors.

ORCID iD

Tianhao Zhang https://orcid.org/0000-0003-3456-8262

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