LETTER

A cascading reaction by hydrological spatial dynamics alternation may be neglected

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Abstract

Water regime changes play a critical role in the structure and function of watershed ecosystems. However, most previous studies focused only on static fixed-point quantitative change at a given time, ignoring the hydrological spatial distribution states of wetting and drying and lacking dynamic indicators for characterization. Here, we constructed a new dynamic index to characterize water alternation of wetting and drying of Poyang Lake, the largest freshwater lake in China, using all available Landsat images and Google Earth Engine from 1987 to 2020. In addition, we analyzed the relative contribution of the dam to water regime changes according to geographical characteristics, and a neglected cascading reaction was found between the upstream and downstream of the basin. The results showed that the alternation of Poyang Lake significantly intensified, and varied with different years. Although the apparent regulation of the Three Gorges Dam (TGD) has no significant impact on the maximum storage of the downstream Poyang Lake and the runoff of the further Yangtze Estuary, the TGD has changed the water spatial alternation of Poyang Lake, resulting in a cascading reaction to the runoff of the Yangtze Estuary.

1. Introduction

Hydrological processes are the most basic and important ecological processes of a watershed ecosystem (Riis and Hawes 2002), involving the growth, reproduction, and succession of organisms and maintaining the stability of the structure and function of the watershed ecosystem. Water flow acts as a bond and messenger, connecting various components of the watershed ecosystem in series with the geographical characteristics of the upper and lower reaches to carry out energy exchange and material transfer. Therefore, the movement state of water flow is crucial to the watershed ecosystem. Due to the limitation of watershed natural scale and management strategy, watershed monitoring and management are more difficult (Sabatier et al 2005, Kerr 2007). It is common for large accumulations of static hydrological data to be continuous and quantitative records from hydrological stations in different branches and administrative jurisdictions (Deegan et al 2007, Longuevergne et al 2013). However, it is still challenging to describe the spatial distribution states of water regime changes.

Dam construction has always been a popular research topic in watershed hydrology. According to the International Commission on DAMS, more than 58 000 large DAMS (height > 15 m) have been built worldwide, and the number of DAMS is still increasing year by year, especially in developing countries (Gleick 2012, Linnerooth-Bayer and Mechler 2006). Globally, 60% of 227 large rivers have been diverted and segmented and at least one of the 106 major basins has been transformed by large dams (WCD 2000). The impact of dams on the watershed ecosystem has been confirmed, with positive examples such as providing stable water levels and water supplies, improving the lifestyles of residents, promoting vegetation growth and agricultural development (Cogels et al 1997), regulating water abundance and drought (Zhang et al 2012), preventing flood disasters (Zhao et al 2020), etc; there are also more negative ones, such as reducing freshwater outflows, resulting in a decrease in fish stocks (Chen 2002), hindering the spread of plant seeds and reducing vegetation diversity on downstream banks (Brown and Chenoweth 2008). However, most of the indicators
of water regime in these previous studies are static fixed-point quantitative data at a given time, such as the amount of water body area (water storage) or the change in water level, and how the spatial distribution state of the water regime is characterized has not been examined.

The change of water regime in the basin is more complex and the spatial-temporal scale is larger. Therefore, there are higher requirements and limitations for data accuracy and scale in watershed research. The Google Earth Engine (GEE) platform can quickly process massive data, so that the image data of long time series can be applied to the analysis, which greatly improves the utilization efficiency of data (Casu et al 2017, Gorelick et al 2017), and enables us to understand more long-term changes in water regime, as confirmed and published in our previous studies (Wang et al 2019, Zong et al 2019, Liu et al 2020).

Poyang Lake, which is the largest freshwater lake downstream of the Three Gorges Dam (TGD) on the Yangtze River in China, was selected as the study area. The TGD is the world’s largest water conservation project. Since operating, some ecological environmental changes downstream have been incorporated, such as frequently low and dry water levels in Poyang Lake (Hao 2019) and changes in estuarine sediment and brackish waterfronts (Xie and Yang 2011, Qiu and Zhu 2015). However, it has been argued that the change in the water regime of the Yangtze River is a natural cycle process, and the TGD cannot be the dominant factor (Li et al 2016, Ye et al 2018, Jiang et al 2019). Considering the above, our study aimed to investigate the spatial dynamic changes of water in Poyang Lake from 1987 to 2020 using time-series Landsat TM/ETM+/OLI images and the GEE cloud computing platform. The specific objectives of this study are to (a) construct an intelligible dynamic indicator to characterize the water spatial distribution states of wetting and drying and analyze its inter-annual variations and (b) analyze the relative contribution of the TGD to determine whether dam operation can be a dominant cause and its impact.

2. Materials and methods

2.1. Study area

Poyang Lake, located downstream of the TGD on the Yangtze River, is one of the world’s most important ecological regions according to the World Wildlife Fund (Zhao et al 2007). It typically has throughput lake characteristics, and its seasonal water level varies greatly throughout the year (Ma et al 2007). It is a large catchment area (Xu and Duan 2013) which connected with the Yangtze River directly (figure 1). It not only receives water from surrounding rivers but also accepts back irrigation of the Yangtze River water. As the last barrier in the lower reaches of the Yangtze River, it controls the water intake balance in the middle and lower reaches and is of great significance to maintain biodiversity and flood defense.

The Datong Hydrological Station (figure 1) is an important downstream hydrological station for detecting runoff in the Yangtze River Basin. It is located at the boundary of the tidal zone (Xia et al 2016), receiving 97% of the total runoff from the Yangtze River. So it can represent the runoff of the Yangtze River into the sea, which is a direct embodiment of the amount of water coming from the upstream. The flow of the station is usually used as basic data for the governance and development of the lower reaches of the Yangtze River and the Yangtze Estuary.

2.2. Landsat data and pre-processing

We used all available Landsat images between 1 January 1987, and 31 December 2020, which have been archived in the GEE, and counted the total number of observations (figure 2). Bad-quality observations, including clouds, snow/ice, and scan-line corrector-off gaps, were identified using a specific threshold of the quality assessment band (Zhu and Woodcock 2012, Zhu et al 2015) and were not included in data analyses.

Three widely used vegetation indices (VIs) and one water-related spectral index were calculated. Specifically, Normalized Difference Vegetation Index (NDVI) (Tucker 1979) and Enhanced Vegetation Index (EVI) (Huete et al 1997, 2002) are widely used to evaluate the greenness of vegetation. Land Surface Water Index (LSWI) is used to evaluate vegetation, and soil water content (Gao 1996, Xiao et al 2004). The modified Normalized Difference Water Index (mNDWI) (Xu 2006) has high sensitivity in identifying open water bodies. These indices are used to identify vegetation (Huete et al 2002, Xiao et al 2006) and water bodies (Xu 2006, Chen et al 2017, Zou et al 2017, 2018):

\[
\text{NDVI} = \frac{\rho_{\text{nir}} - \rho_{\text{red}}}{\rho_{\text{nir}} + \rho_{\text{red}}} \tag{1}
\]

\[
\text{EVI} = 2.5 \times \frac{\rho_{\text{nir}} - \rho_{\text{red}}}{\rho_{\text{nir}} + 6 \times \rho_{\text{red}} - 7.5 \times \rho_{\text{blue}} + 1} \tag{2}
\]

\[
\text{LSWI} = \frac{\rho_{\text{nir}} - \rho_{\text{swir}}}{\rho_{\text{nir}} + \rho_{\text{swir}}} \tag{3}
\]

\[
\text{mNDWI} = \frac{\rho_{\text{green}} - \rho_{\text{swir}}}{\rho_{\text{green}} + \rho_{\text{swir}}} \tag{4}
\]

where \(\rho_{\text{blue}}, \rho_{\text{green}}, \rho_{\text{red}}, \rho_{\text{nir}}\) and \(\rho_{\text{swir}}\) are blue (450–520 nm), green (520–600 nm), red (630–690 nm), near-infrared (NIR: 760–900 nm), and shortwave infrared (SWIR: 1550–1750 nm) bands of Landsat TM/ETM+/OLI imagery, respectively.

2.3. Data of river runoff

Long-term runoff data of the Yangtze Estuary were obtained from the Bulletin of China River Sediment
from 1987 to 2020, mainly the annual runoff data (www.cjh.com.cn) (Wei et al 2015).

2.4. Datasets of various drivers
2.4.1. Climate data
The precipitation data were mainly from the National Oceanic and Atmospheric Administration PERSIANN Climate Data Record on GEE, and we extracted all pixels overlapping the boundary of Poyang Lake and used the average value as the precipitation condition.

On the one hand, the temperature data came from the China Meteorological Forcing Dataset, which is based on an internationally available product and integrates the conventional meteorological observation data of the China Meteorological Administration.
(He et al. 2020), in which the near-surface annual mean temperature was used for driving force analysis. Temperature data were obtained from the China Meteorological Data Sharing Service System (http://data.cma.gov). We collected data from all available weather stations in the Poyang Lake and interpolated them with the Shuttle Radar Topography Mission digital elevation model data to obtain a usable data format.

2.4.2. Socio-economic data
Population and gross domestic product (GDP) were obtained from online local statistical yearbooks (http://tongji.cnki.net). The population data is obtained by interpolating the boundary of the administrative region where the whole lake is located and the vector boundary of Poyang Lake. Due to the lack of GDP data and the high overlap (96.6%) between the scope of the Poyang Lake water system and the administrative regions of Jiangxi Province (Tang 2019). The GDP of Jiangxi Province is used to represent the relevant data of Poyang Lake, and some of the missing values of the years by interpolation.

2.5. Algorithm of dynamic indicator
Before obtaining the alternation, we must identify the intermediate parts that are not alternating. The ’mNDVI + VI’ method, which is used to detect mixed cells of vegetation and water bodies, is an index and pixel-based identification algorithm. It combines EVI, NDVI, and mNDWI to determine mixed cells with high accuracy. This algorithm was originally developed and applied in the United States to extract water bodies, achieving better results and higher accuracy (96.91%) (Zou et al. 2017). Furthermore, it was compared with other water detection algorithms, including TCW, AWEI, and mNDWI (Zhou et al. 2017). The results showed high accuracy (98.1%) between Landsat 7 ETM+, Landsat 8 OLI, and Sentinel-2 MSI (Wang et al. 2018). Specifically, the pixel will be recognized as an actual water pixel (equation (5)) when water signals were stronger than vegetation signals (mNDWI > EVI or mNDWI > NDVI) and the vegetation was excluded (EVI < 0.1). For each pixel, we counted the number of observations within a year as water body and then divided it by the total number of good observations in that year. We termed the resultant ratio as water body frequency (equation (6)). According to this algorithm, the water body frequency indicates the duration for which the water body appears at a certain pixel location at a certain time:

\[
\text{Water} = \begin{cases} 
1, & \text{EVI} < 0.1 \text{ and (mNDWI} > \text{EVI or mNDWI} > \text{NDVI)} \\
0, & \text{Other values}
\end{cases}
\] (5)

\[
\text{WaterFreq} = \frac{\text{SUM}_{\text{water}}}{\text{SUM}_{\text{total}} - \text{SUM}_{\text{bad}}} \tag{6}
\]

where WaterFreq is the frequency of water body scaled to 0 and 1 among all the good-quality observations, SUM_{water} is the number of water bodies observations extracted by equation (5), SUM_{total} is the total number of observations in a year, SUM_{bad} is the number of bad-quality observations in a year.

The waterbody frequency map (figure 3(a)) was composed of 99 thresholds with an interval of 0.01 every year. There will be low-frequency noise of poor quality that cannot be filtered out. Specifically, peaks were obvious at a threshold of 0.16, and these peaks gradually disappear as the threshold increased. In 1999, there was still a peak at the threshold of 0.33. When it reached 0.34, the noise was eliminated, and the trend tended to be stable. When a pixel had an annual water body frequency greater than or equal to 0.34, it was classified as an effective water pixel. In a year, all the effective water pixels formed the maximum water body extent. The water area map shows a decrease in noise as the threshold increased in 1999 (figure 3(b)).

Then, we determined the ranges of EVI, NDVI, and LSWI based on the vegetation types of Poyang Lake combined with previous studies (Xiao et al. 2009) and obtained a more suitable threshold range for inland lakes: EVI $\geq$ 0.1, NDVI $\geq$ 0.2, and LSWI < 0.19 to identify the Poyang Lake vegetation (equation (7)). Similar to WaterFreq, a vegetation frequency map was constructed (figure 4). The trend eventually stabilizes at a value, whether it is water or vegetation, with the frequency threshold increasing, representing the stable part of different features in a year named permanent water and permanent vegetation, respectively:

\[
\text{Vegetation} = \begin{cases} 
1, & \text{EVI} \geq 0.1 \text{ and NDVI} \geq 0.2 \\
0, & \text{LSWI} < 0.19 \\
\text{Other values}
\end{cases}
\] (7)

After identifying vegetation and water bodies, other features and alternating parts were filtered using a spatial overlay on GEE. Other features refer to neither water bodies nor vegetation but are more complex and mixed. These may be impervious areas, bare land, buildings, or other uncertain parts. It is difficult to directly identify and filter through the threshold besides the limitation of image resolution. Therefore, we implemented spatial overlay analysis on GEE by constructing arithmetic rules (figure 5). Specifically, three pixel states: water, vegetation, and other features are exposed at a certain time. The pixel state may convert into four types during a period with alternating pixels appearing...
Figure 3. Selection of water body frequency thresholds. (a) Maximum water body area using 99 different water body frequency thresholds. (b) Noise at different water body frequency thresholds (0.04, 0.14, 0.24, 0.34) in the maximum water body map in 1999.

Figure 4. Frequency threshold trend. (a) Water frequency threshold. (b) Vegetation frequency threshold.

at different frequencies. Permanent other features are filtered by equation (8), which is negated from the intersection of the total range with the largest occurrence of water and vegetation, which is a union of water body frequencies and vegetation frequencies with a threshold of 0.01. Alteration is negation after
The arithmetic rules and process of spatial overlay analysis on GEE.

**Figure 5.** The arithmetic rules and process of spatial overlay analysis on GEE.

intersecting between the total range and the union of permanent features (equation (9)):

\[
\text{Permanent Other Feature} = N \cap (WF_1 \cup VF_1) \tag{8}
\]

\[
\text{Alteration} = N \cap (PW \cup PV \cup PO). \tag{9}
\]

The definition of permanent other features is the same as the permanent water and permanent vegetation, which refers to the pixels that are not occupied and transformed by water and vegetation and exist stably. \(N\) is the total range of the study area, \(WF\) and \(VF\) are the abbreviations for water frequency and vegetation frequency, subscript 1 represents the percentage of the frequency threshold value, and \(PW\), \(PV\), and \(PO\) are the abbreviations for permanent features, respectively.

The ratio of alternation was calculated using equation (10), which represents the ratio of pixels in a non-fixed state (not occupied by water bodies, nor covered by vegetation and other ground features year-round) in a period:

\[
\text{AlterRatio} = \frac{N - \sum_{i=1}^{k} (PW_i + PV_i + PO_i)}{N} \tag{10}
\]

where AlterRatio is the abbreviation of the ratio of alternation, \(N\) is the total range of the study area, \(PW\), \(PV\), and \(PO\) are the abbreviations for permanent features, \(i \leq k\), \(PW_i\) is the area of the permanent water in the \(i\)th year, and similar to \(PV_i\) and \(PO_i\), respectively.

### 2.6. Accuracy assessment

We used the stratified random sampling approach and very high resolution images from Google Earth to assess the accuracy. Specifically, the classified images can be generated into random points and buffers in ArcGIS, which are stored in keyhole markup language, zipped (KMZ) file format, and then loaded into Google Earth for comparison with high-resolution images. Finally, a confusion matrix was calculated to evaluate the accuracy (Chen et al. 2017).

Field data are usually the best way to verify the accuracy, we not only based on previous field experience but also consulted residents. Besides, comparison with concurrent higher-resolution observations is also a good way to assess accuracy (Bierman et al. 2011). The spatial texture of water bodies and vegetation is easy to recognize at 30 m high-resolution (Hu et al. 2010), and Sentinel-2 L1C images have higher resolution (10 m). Therefore, atmospheric-corrected Sentinel-2 Multispectral Instrument, Level-1C data were obtained from GEE and used to validate the results.

### 2.7. Spatial-temporal dynamics analysis

The spatio-temporal dynamics of the water regime in Poyang Lake and Yangtze Estuary were analyzed using the robust linear trend regression method and Theil-Sen (Kendall–Theil, TS) regression. The sequential \(t\)-test algorithm was also applied to detect their differences in different dam periods.

### 2.8. Driving forces analysis

Five factors were selected as potential driving factors to explore their relationship with the water regime through multiple linear regression analysis, and the regression variable was the AlterRatio of Poyang Lake from 1987 to 2020. There are two environmental factors: annual average precipitation (denoted as Precipitation) and annual average temperature (\(Y_{\text{mean}}\))
and three human activity factors including population, GDP, and the TGD operation node (Period) as dummy variables.

3. Results

3.1. Accuracy assessment of features

According to the field situation of Poyang Lake, there has always been an un raced water body and un surged vegetation northeast of Dahuchi Lake (figures 6(a1) and (b1)), regardless of the rise and fall of water during the year. Thus, we compared the AlterRatio image with the Sentinel-2 image at any time of the year and found that we did not confuse the water body with vegetation. The recognized permanent water and permanent vegetation were within the visually recognizable range of the Sentinel-2 image, which is also in line with our definition. The enlarged area (figures 6(a2) and (b2)) named Sanjiangkou is a famous Ming Dynasty water warfare site in history (Zhang 1987), which is used to detect the coverage of permanent water precisely because the river channel had to water year-round, and the comparison results after overlapping are factual. The confusion matrix was calculated and the result shows high consistency between the classification maps and ground reference data (table 1). The user accuracies of water and vegetation are 95.23% and 94.1% and the producer accuracies are 96.17% and 94.32% respectively, the overall accuracies are 94.96% and Kappa coefficients are 0.91.

3.2. Spatio-temporal dynamics of water regime in 1987–2020

The annual maximum water area of Poyang Lake exhibited a linear decline, this was not significant
Table 1. Accuracy assessment of classification.

| Class     | User accuracy/commission error (%) | Producer accuracy/omission error (%) | Overall accuracy (%)/Kappa coefficient |
|-----------|------------------------------------|--------------------------------------|----------------------------------------|
| Water     | 95.23/4.77                         | 96.17/3.83                           | 94.96/0.91                             |
| Vegetation| 94.10/5.9                          | 94.32/5.68                           |                                        |

Figure 7. The inter-annual dynamics of the maximum water area and the AlterRatio of Poyang Lake.

\( p > 0.05 \) between 1987 and 2020 (figure 7(a)). It fluctuated over different years with an average of 2703 km\(^2\). Meanwhile, the AlterRatio changed significantly (figure 7(a)) with an average of 66.8%. After operating the TGD, the average value was as high as 73.5%, reaching a maximum of 79.3% in 2009. The AlterRatio showed a statistically significant increasing trend \( p < 0.01 \). The mapping (figure 7(c)) reflected the alteration changes.

Then, we \( t \)-test both in two periods: pre-TGD stands for the period before the TGD runs, and post-TGD stands for after. Results showed that the annual maximum water area did not demonstrate a significant difference between the pre-TGD and post-TGD periods \( p > 0.05 \), whereas AlterRatio was more elevated in the post-TGD period than in the pre-TGD \( p < 0.01 \).

3.3. Driving factors for spatio-temporal dynamics of AlterRatio

To further investigate the relative contribution of the TGD to the AlterRatio, a multiple stepwise regression model with the five aforementioned driving factors was analyzed. The forest plot (figure 8) shows that \( Y_{\text{mean}} \), and GDP were not statistically significant \( p > 0.05 \), and Precipitation, Population, and Period of the TGD had significant effects on AlterRatio \( p < 0.05 \). The regression results showed that among the three significant variables, Population and Period had positive and significant effects on the AlterRatio, while Precipitation had negative and significant effects. The absolute value of the standardization coefficient (table 2) showed that the Population was the most important factor affecting AlterRatio, followed by Precipitation and Period. This result reflects that in the past 30 years, the dynamics of water regimes have not only been dominated by natural climate but also by a combination of climate and human activities. Thus, the influence of human factors on water regimes cannot be underestimated. The operation of the TGD is one of the factors that significantly affect the AlterRatio of Poyang Lake.

3.4. The neglected cascading reaction by hydrological spatial dynamics alternation

We established a robust linear trend regression model for the runoff of the Yangtze Estuary, and there was no significant change between pre-TGD and post-TGD \( p > 0.05 \) (figure 9(a)), showing that the TGD had no significant effect on runoff. However, we constructed a generalized linear model for the AlterRatio and runoff through Poisson regression analysis, and the results effectively reflected the linear response trend of the decrease in runoff with an increase in the AlterRatio (figure 9(b)), indicating that the AlterRatio had a significant effect on runoff \( R^2 = 0.41, p < 0.05 \).

Overall, the operation of the TGD has no direct or significant impact on runoff into the sea, but it is one of the main drivers of AlterRatio in Poyang Lake. Combined with the geographical location of the TGD and the Poyang Lake, a neglected cascading reaction is found in water changes, which also reveals that focusing only on the two ends of the problem may ignore the internal cascading reaction.
Table 2. Multiple regression coefficients between five variables and AlterRatio.

| Variable      | $Y_{\text{mean}}$ | Precipitation | GDP   | Population | Period |
|---------------|-------------------|---------------|-------|------------|--------|
| Coefficient   | $-0.17$           | $-0.48^{**}$  | 0.09  | $0.62^{*}$ | 0.3$^*$|

$^*$Where $^{**}$ represents p-value < 0.01, $^{*}$ represents p-value < 0.05.

4. Discussion

4.1. Classification accuracy

In landscape classification, although water bodies and vegetation are clearly distinguished, the species are relatively single. This is mainly because some classifications are intermediate variables in the study, so we did not pay too much attention to them. If the research focuses on this part, it can be handled by adjusting the algorithm rules.

In the process, we only distinguish permanent features and alternating parts, and the internal reaction of alternation has not been clear. It is determined by the complexity of the ecosystem. Many substances interact in the ecosystem, and more clear mechanisms need to be filled by more field experiments.

4.2. The relationship between population and water regime

The reason that the population had the highest contribution may be the strong correlation between population and other anthropogenic factors, especially land use. We used a comprehensive index of land use...
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Table 3. The classification values of land use degree.

| Type         | Unutilized land | Natural land          | Agricultural land                | Urban land                                      |
|--------------|-----------------|-----------------------|----------------------------------|------------------------------------------------|
| Category     | Unused or difficult to use | Forest, grass, and water | Cultivated land, garden, and artificial grassland | Towns, residential areas, industrial land, and transportation land |
| Grade indices| 1               | 2                     | 3                                | 4                                              |

Figure 10. Map of land use degree of Poyang Lake.

degree (La) to characterize the land use degree of Poyang Lake. The La reflects the extent of human development and utilization of land and is an important indicator for measuring the depth and breadth of land use (Zhuang and Liu 1997). The formula used is as follows:

\[
La = 100 \times \sum_{i=1}^{n} Ai \times Ci. \tag{11}
\]

\(Ai\) is the graded index of land use degree of the \(i\)th grade; \(Ci\) is the percentage of the graded area of the \(i\)th grade of land use degree. Based on proven experience (Zhuang and Liu 1997), grading indices for the degree of land use were obtained by assigning the ideal state of land use to four land use grades and assigning their category values to the four land-use grades (table 3).

According to La and data on land use in Jiangxi, China 2020 (www.resdc.cn/), we drew a land-use degree map of Poyang Lake in ArcGIS (figure 10). This shows that 87% of Poyang Lake is at a medium strength of land use, which confirms the impact of population. Although population occupies a larger explanatory weight, the various behaviors and phenomena connected by human beings may be more essential and detailed reasons. It is necessary to further explore the influence of human activities on the specific impact mechanisms of the Poyang Lake water regime.
4.3. Watershed cascading reaction based on meta-ecosystem theory

It is easy to neglect the cascading reaction caused by the TGD to alternation of Poyang Lake directly, and it is also rational with the cognitive and statistical results that there were no significant effects on the maximum storage of Poyang Lake and the runoff of the Yangtze Estuary by the dam’s superficial regulation, which is exclusive to the basin and watershed ecology characteristics. On one side, because of the difficulty of monitoring large spatial scaled basins, static quantitative data in small areas are more readily available (Soininen et al. 2015); on another side, it is not comprehensive enough to consider the problem of watershed ecosystems, only focusing on a certain area, but ignoring the relationship between different ecosystems in the basin, which is concerned with meta-ecosystem theory. Meta-ecosystem was defined as a set of ecosystems connected by spatial flows of energy, materials, and organisms across ecosystem boundaries (Loreau et al. 2003). In contrast to the meta-community concept, which only considers connections among systems via the dispersal of organisms, the meta-ecosystem more broadly embraces all types of spatial flows among systems, as well as constraints and feedback from abiotic factors (Gravel et al. 2010).

Abiotic factors such as water flow enable different ecosystems within the basin to be connected, which act as transmitters of materials and energy, from the perspective of the watershed meta-ecosystem. This coincides with our study object and results. In our study, the Poyang Lake ecosystem and Yangtze estuary ecosystem are connected by the flowing water in the basin. The water regime changes of the two ecosystems are synchronous but have their characteristics. Because of the closeness and throughput, the lake ecosystem presents different spatial landscape distribution, while the downstream estuarine ecosystem is not only affected by the water from the upstream, but also by the ocean. How to quantitatively describe the relationship between two different ecosystems is also the concern of the meta-ecosystem theory. Our study can also be used as supplementary proof that if the water spatial alteration of Poyang Lake between the TGD and the Yangtze Estuary is not considered, it will be blinded by the static data on the surface, considering that the TGD has no impact on the runoff into the sea and ignores the ecosystem cascading reaction between. Quantitative empirical research on the spatial flows between ecosystems is still lacking, and we hope that our study will shed some light.

5. Conclusion

The construction and operation of water conservation projects are unavoidable in certain social development processes. In the pre-construction assessment, only static quantitative data such as water level, water area, and water storage capacity are often considered, ignoring the hydrological spatial distribution states of wetting and drying, lacking dynamic indicators for characterization, and unwittingly impacts ecosystems. Therefore, in this study, we built a dynamic indicator that can reflect the water spatial distribution states—AlterRatio through the GEE platform, based on pixels and frequencies. All available Landsat data from 1987 to 2020 were used to focus on the Poyang Lake’s alternation, the last lake connected to the Yangtze River directly in China, and its spatio-temporal dynamics and the driving force were analyzed. The results show that the alternation of Poyang Lake has increased significantly over the past 30 years and the driving force analysis also shows that the dynamics of the water regime are no longer dominated by the natural climate alone, but by the combined effects of climate and human activities. The effects of human factors cannot be underestimated. The operation of the TGD is one of the factors that significantly affect the wetting and drying of water in Poyang Lake. Through the analysis of the runoff into the sea, we found that although the apparent regulation of the TGD had no significant impact on the maximum storage of the downstream Poyang Lake and the runoff of the further Yangtze Estuary, it indirectly affected the runoff of the Yangtze Estuary by affecting the dynamic alternation of Poyang Lake. Finally, our study provides suggestions and references for the assessment of water conservancy projects in the future, not only focusing on static data at a given time but also considering the water spatial distribution states in the basin and internal cascading reaction.

Data availability statement

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

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Conflict of interest

Authors declare no conflicts of interests.

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