Continuous Expansions of Yangtze River Islands After the Three Gorges Dam Tracked by Landsat Data Based on Google Earth Engine

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ABSTRACT Understanding the change of river islands is essential for water conservancy construction, channel navigation safety, and industrial/agricultural production. Yangtze River is the largest river in China; however, there are few long-term monitoring results on the changes of Yangtze River islands. To fill this gap, Landsat data available on the Google Earth Engine (GEE) were used to obtain the annual changes of the Yangtze River islands located from the lower reaches of the Three Gorges Dam (TGD) to the Yangtze River delta during 1986-2017. Moreover, we focused on the changes of those islands before and after the construction of the TGD. Annual areas of all river islands were calculated and spatial-temporal pattern of Yangtze River islands were analyzed. Our satellite observation results show continuous expansions of Yangtze River islands after the construction of the TGD in 2003. For the total 138 river islands, in three stages: before 2003, after 2003 and in the 32-year study period, 68, 118, and 124 river islands showed increasing trends, with the net increase of 286.47 km², 417.49 km², and 665.62 km². For the total 92 river island groups (138 islands), percentages of river island expansion are 41.30% (before 2003), 80.43% (after 2003) and 88.04% (1986-2017). Moreover, we found 10 newly developed river islands, with a net expansion of 87.42 km² and an expansion rate of 2.73 km²/year. The significant decrease (2-4 m) in water level before and after the TGD might be the main factor that results in the observed expansion of Yangtze islands downstream the TGD. We also highlighted the importance of using all available Landsat imagery for tracking the changes of river islands. Our satellite-derived dataset provide reference data for the land use planning and environmental protection in the Yangtze River drainage basin.

INDEX TERMS Google Earth engine, river islands, remote sensing, the Yangtze river, the three Gorges dam.

I. INTRODUCTION

At present, owing to the increasing energy demand induced by rapid growth of human populations and economic development, new sources of renewable energy are urgently required [1]. To fill the current energy gap, a large number of hydropower stations have been constructed along various rivers around the world over the past decades for the increasing electricity demand, and many dams and reservoirs were established for the impoundment [2]. Although those hydropower stations can produce many benefits, such as hydropower generation and flood control and navigation capacity increase, they can inevitably result in a series of potential environmental (e.g., river flow, water quality, sedimentation), ecological (e.g., ecosystem and biodiversity) and social (e.g., reservoir resettlement and water-related disease) problems from local to basin scale [3], [4]. Therefore, it is necessary to monitor and evaluate those environmental,
ecological and social changes induced by hydropower stations for better understanding their contributions, and further guiding related management, policy-making and future planning [5].

The Yangtze River is the largest river in China, ranking third worldwide, just after the Nile in Africa and the Amazon in South America [6]. It covers six provinces, playing an important role in the development of China’s national economy. There are a lot of industrial and agricultural activities in the Yangtze River Basin [7]. To provide more electricity and promote the social-economic development, Chinese government constructed Three Gorges Dam (TGD), which serves as the world’s largest hydroelectric project [8]. Apart from hydropower generation, TGD also aimed to develop and control the Yangtze River, reduce flooding in the Yangtze River basin, and decrease economic losses [9]. After the construction of TGD, significant changes in the middle and lower reaches of the Yangtze River have occurred in sediment discharge and hydrological conditions according to previous studies [10], [11]. Correspondingly, river islands located within the Yangtze River tend to experience potential changes, for example, caused shrinkage/expansion of river islands and enhanced the river islands’ stability. Changes of river islands can also affect the hydrological conditions of the Yangtze River in turn [12]. Actually, those river islands in the Yangtze River are of great value to many aspects, such as hydropower, flood control, shipping, and habitat provision [13], [14]. Hence, it is essential to monitor and understand changes of Yangtze River islands before and after the TGD. To date, several studies have been conducted to obtain changes of some river islands in the Yangtze River [15]–[17]. However, these studies focused on changes in river islands at a local scale, a large-scale results on the changes of Yangtze River islands after the TGD remains unclear. Over the past few decades, with multi-spectral 30 m resolution, free access, and global coverage, Landsat data have been used in studies related to long-term land and water monitoring [18].

Therefore, we used all Landsat data over 1986–2017 available on GEE platform to generate the annual maps of all Yangtze River islands (greater than 0.1 km$^2$) downstream of the TGD during the past 32 years, obtained temporal changes of Yangtze River islands, and discussed potential drivers. Specifically, our study pursued the following objectives: (1) to characterize the morphology of river islands in the middle and lower reaches of the Yangtze River; (2) to quantify the temporal changes of islands’ areas before and after the TGD; (3) to analyze the possible reasons that result in the continuous expansions of Yangtze River islands downstream the TGD after the TGD.

II. MATERIALS
A. STUDY AREA
The Yangtze River is the largest river in China and the third largest in the world, originates in the Qinghai Tibet Plateau and flows about 6300 km eastwards to the East China Sea. The Yangtze River Basin is about 1.8 × 10$^6$ km$^2$, across three regions of Southwest China, Central China and East China with importance of various aspects. The Yangtze river basin accounts for about 40% of China’s freshwater resources, more than 70% of the country’s rice production, 50% of its grain, more than 70% of fishery production, and 40% of the China’s GDP according to the World Wildlife Fund (http://wwf.panda.org). The Yangtze River developed many river islands, especially in the middle and lower reaches (Fig. 1).

River islands play an important role in the economic-social development of both sides of the Yangtze River, also make the flood control problem more complicated. With the rapid economic-social development in the Yangtze basin, the progress of industrialization and urbanization is accelerating [19]–[21]. The Three Gorges Dam (TGD) locates in Sandouping Town, Yichang City, Hubei Province, China. It is 38 kilometers away from the downstream Gezhouba Water Conservancy Project. The TGD has a total length of 3335m and a dam height of 185m. It is the main project of the Three Gorges Hydropower Station, the largest hydropower project in the world. The TGD project started on December 14, 1994, firstly conducted impoundment in June 2003, and reached a water level of 135m. It significantly changed the hydrological conditions in the middle and lower reaches of the Yangtze River, such as water level, runoff and sediment transport, and further altered a series of hydrodynamic processes [22]. These islands face increasing pressures on water resources and environmental protection. Thus, monitoring the changes of river islands is an essential work.

According to statistics [23], there are about 138 islands with the area larger than 0.1 km$^2$, downstream of the TGD in the Yangtze River. For the purpose of convenient description, the total 138 islands were divided into 92 island groups (Fig. 1). Note that some islands are close to each other, thus are grouped together. The islands that are uninhabited and with no official names, are named as unnamed islands (UI-) from upstream to downstream successively (Table 1).
TABLE 1. Detailed description on Yangtze River islands (Fig. 1).

| ID | NAME         | Number of islands | ID | NAME         | Number of Islands |
|----|--------------|-------------------|----|--------------|-------------------|
| 1  | Ge Zhou      | 2                 | 47 | Xuchang Island | 1                |
| 2  | UI-1 Island  | 1                 | 48 | Yaping Island  | 1                |
| 3  | UI-2 Island  | 1                 | 49 | Guan Island    | 1                |
| 4  | UI-3 Island  | 2                 | 59 | Enshi Island   | 1                |
| 5  | UI-4 Island  | 2                 | 51 | Yangzi Island  | 1                |
| 6  | Jiu Island   | 1                 | 52 | Tietong Island | 1                |
| 7  | Muyang Zhou  | 1                 | 53 | Fenghuang Island| 1               |
| 8  | UI-5 Island  | 1                 | 54 | Changhua Island| 2                |
| 9  | UI-6 Island  | 1                 | 55 | Xuzhou Island  | 1                |
| 10 | UI-7 Island  | 1                 | 56 | Heyuan Island  | 1                |
| 11 | Zuxing Zhou  | 1                 | 57 | Chenglei Island| 3                |
| 12 | UI-8 Island  | 1                 | 58 | Wenchu Island  | 1                |
| 13 | UI-9 Island  | 2                 | 59 | Ding Island    | 1                |
| 14 | UI-10 Island | 1                 | 60 | Tonglingzhou Island | 1         |
| 15 | Xiong Lake   | 1                 | 61 | Taihu Island   | 1                |
| 16 | Jiahuan Lake | 1                 | 62 | U2-1 Island    | 1                |
| 17 | Nanyang Zhou | 1                 | 63 | Husha and Tiemen Island | 1        |
| 18 | Nanmen and Xiang Zhou | 3 | 64 | Qian Zhou      | 1                |
| 19 | Zhang and Xin Zhou | 1 | 65 | Chongzhou Island | 1              |
| 20 | Huaian Zhou  | 1                 | 66 | Yangzi and Taixing Island | 4           |
| 21 | Fuxing Zhou  | 1                 | 67 | Hejiu Island   | 2                |
| 22 | UI-11 Island | 1                 | 68 | Xiushuang Island| 1               |
| 23 | Tsun Zhou    | 1                 | 69 | Xijiu and Xiusheng Island | 2         |
| 24 | UI-12 Island | 1                 | 70 | Ziliu Island   | 1                |
| 25 | UI-13 Island | 1                 | 71 | Zizhou Island  | 2                |
| 26 | Tiansheng Zhou| 1              | 72 | Yangzi Zhou    | 1                |
| 27 | Dongzhao Zhou| 1                 | 73 | U3-2 Island    | 1                |
| 28 | Yanzhong Zhou| 1                 | 74 | Bagou Island   | 1                |
| 29 | UI-14 Island | 1                 | 75 | U3-3 Island    | 1                |
| 30 | Dajia Zhou   | 1                 | 76 | Shiyue Island  | 2                |
| 31 | UI-15 Island | 1                 | 77 | Zhongruizhou Island | 2       |
| 32 | UI-16 Island | 1                 | 78 | Hechong Island | 1                |
| 33 | UI-17 Island | 1                 | 79 | U3-4 Island    | 1                |
| 34 | Xin Zhou     | 1                 | 80 | Lenggang Island| 1                |
| 35 | UI-18 Island | 2                 | 81 | Taiping Zhou   | 2                |
| 36 | Zhonggong Zhou| 3           | 82 | Xuhu Island    | 1                |
| 37 | Shengdai Island| 1           | 83 | Zhongda Island | 1                |
| 38 | UI-19 Island | 1                 | 84 | U3-25 Island   | 1                |
| 39 | Xiaoxi Zhou  | 1                 | 85 | Fengjiang Island| 1              |
| 40 | Minshan Island | 2           | 86 | Changning Island| 2               |
| 41 | Guanbo Zhou  | 1                 | 87 | Tongzhou Island| 5                |
| 42 | Tianzi Zhou  | 2                 | 88 | U3-26 Island   | 1                |
| 43 | Minhou and Yutai Zhou | 1 | 89 | Chongning Island| 7            |
| 44 | UI-20 Island | 2                 | 90 | Chengying Island| 6               |
| 45 | Fusheng Zhou | 1                 | 91 | Hengsha Island | 1                |
| 46 | Jingzhou Zhou| 1                 | 92 | U3-27 Island   | 6                |

B. DATA

1) LANDSAT IMAGERY

To quantify the temporal changes of Yangtze River islands, time series of Landsat TM (Thematic Mapper) and ETM+ (Enhanced Thematic Mapper) Top of Atmosphere (TOA) reflectance data from 1986 to 2017 was collected based on Google Earth Engine (GEE) platform. Landsat data provides a spatial resolution of 30 m and a temporal resolution of 16 days. According to the Worldwide Reference System, 20 TM scenes are required to cover the study area. A total of 9322 standard Level 1 Terrain-corrected (L1T) products were acquired for these scenes. Specifically, 7422 TM images during 1986 - 2011 and 1900 ETM+ images during 2012 - 2017 were used. The annual distribution of the Landsat imagery was presented in Fig. 2.

2) OTHER DATA

The Yangtze River boundary has been used to limit the spatial coverage of river islands, which can be downloaded from the Resource and Environment Data Cloud Platform (http://www.resdc.cn). The Yangtze River boundary was processed into shapefile format via the function “Raster to Polygon” provided by ArcGIS software, and projected to the Krasovsky_1940_Albers coordinates system. To perform the comparison with our produced river island maps, the global surface water dataset with 30 m resolution (GLC30-2010) was downloaded from the Global Change Research Data Publishing & Repository (http://www.geodoi.ac.cn) [23]. This dataset was processed into Geotiff format, and projected to the WGS_1984_UTM zone coordinates system.

III. METHOD

Fig. 3 shows the flowchart of the methodology used in the study. Our method consists of several steps. First, we generated annual Landsat images based on the GEE platform. Second, annual MNDWI (Modified Normalized Difference Water Index) images were generated. Island buffers were created using the Yangtze River boundary dataset. Then, optimal thresholds were calculated for 92 island groups. Finally, binarization on annual MNDWI images was performed. For each river island, the change rate of land areas was calculated using linear regression method and the land frequency map was produced by stacking all the river island maps together.
A. ANNUAL LANDSAT IMAGES GENERATION

Top of Atmosphere (TOA) calibrated Landsat 5 (TM) and 7 (ETM+) reflectance data is the main data source of this study. Based on the GEE platform [26], all annual Landsat images were generated. The GEE increases the utilization efficiency of satellite data, and enables pixel-based algorithms to process massive amounts of images. The GEE platform provides a good opportunity to obtain more insight into the long-term changes in the surfaces land of river islands. A simple cloud score function was applied to avoid the effect of clouds/shadows of Landsat data [27]. A reduction function provided by the GEE was used to generate the annual Landsat images over 1986–2017. For each pixel, the output is calculated by the median of all clear Landsat observations (without clouds and shadows) within each year, which can reduce the noise caused by outliers and poorly removed edges of clouds [28]. For islands mapping, the median compositing method can minimize the short-term waterline variability induced by water level variability, sedimentary seasonal variation and other noises [29].

B. ANNUAL MNDWI IMAGES GENERATION

Since Xu’ MNDWI [24] can effectively reduce the signal noise coming from the land cover features of built-up area, hence it has been widely used for water mapping [30], [31]. Here, this index was used to produce annual MNDWI images from annual Landsat images. The water body has a stronger absorptivity in the short-wave infrared (SWIR) band than that in the near-infrared (NIR) band. The expression of MNDWI is:

\[ MNDWI = \frac{\rho_{\text{Green}} - \rho_{\text{SWIR}}}{\rho_{\text{Green}} + \rho_{\text{SWIR}}}, \quad (1) \]

where \( \rho_{\text{Green}} \) is the TOA reflectance value of the Green band (band2 for Landsat TM/ETM+ data), \( \rho_{\text{SWIR}} \) is the TOA reflectance value of the SWIR band (band5 for Landsat TM/ETM+ data). The range of original MNDWI value is \([-1, 1]\). To facilitate subsequent processing, the MNDWI was converted to \([0, 255]\) from \([-1, 1]\).

The threshold can affect the segmentation results, and incorrect threshold values can lead to errors in estimating areas of river islands. The OTSU algorithm [25], a dynamic thresholding method, was performed to determine the optimal threshold for separate the land and water. The OTSU algorithm has been proven an effective method, has been widely used in previous studies [32].

C. ANNUAL RIVER ISLAND MAPPING

1) RIVER ISLAND BUFFER GENERATION

To limit the spatial coverage of river islands, the buffer of each river island was required. First, the buffer that centered along the channel of the Yangtze River with 2-km width was built. Second, threshold of MNDWI images within the first buffer from 1986 to 2017 can be calculated via the OTSU method. Third, those thresholds were used to classify MNDWI images into land and water (i.e., land = 1, water = 0). Forth, annual land-water maps were stacked together to produce the land frequency map ranging from 0 to 1. Then, the maximum coverage of the island was determined by the following criteria: (1) at least one year was above water between 1986 and 2017, (2) island pixels within the boundary of both sides of the main stream of the Yangtze River, and (3) the maximum island area is larger than 0.1 km\(^2\). Finally, river island buffers can be constructed by extending 500 meters with the island boundary as the center.

2) RIVER ISLAND MAP GENERATION

For each river island, a 32-year MNDWI median image was used to calculate the OTSU threshold for land-water classification (Fig. 4). Based on the annual MNDWI image, MNDWI median image is composed of the median value of all the annual MNDWI images from 1986 to 2017 at pixel level. This composite method can be viewed as constructing an average estimation of the most representative value at each pixel of the observations. The histogram bimodal method (HBM) is often used for threshold selection in image classification of land and water [33]. The frequency distribution of the annual MNDWI median image covered by the river island buffer was counted for each river island. The distribution formed two peaks, which represent the land and water around river islands. The optimal threshold for the OTSU method is determined as the valley between two peaks for the land-water classification.

Based on the annual MNDWI images and OTSU method, MNDWI images were binarized as land and water. The MATLAB function “imfill” was applied to infill inland water bodies of river islands in each primary land map of river islands (i.e., 1 represents land and 0 represents water). Finally, a 30-m resolution dataset of the multi-year river islands can be generated for further evaluations.

3) EVALUATION OF RIVER ISLAND TEMPORAL CHANGE

Annual maps of the river island groups from 1986 to 2017 were obtained using the above-mentioned method.
Then, all maps were processed into shapefile format with the Albers Equivalent Conical Projection using ArcGIS software. Then, the line generalization algorithm proposed by Wang and Müller was utilized to simplify the shapefile in ArcGIS [34].

The area of river islands was used to quantify the temporal changes. Specifically, annual areas for each river island group and the combined total of the river island groups were calculated. For each river island group and the total, a linear regression model was used to estimate the long-term change rates. $R^2$ and $p$-value for each linear regression were computed. Significance of linear regression was determined at a 95% confidence level.

Moreover, to reflect the spatial pattern of river island variations, the land frequency map for river islands can be generated by stacking all annual river island maps as follows.

\[
\text{Frequency}_j = \frac{1}{32} \sum_{i=1}^{32} \text{Land}_{ij},
\]

where $\text{Frequency}_j$ represents the land frequency map of the river island group $j$, $\text{Land}_{ij}$ is the river island map of the river island group $j$ in the $i$-th year.

**D. ACCURACY ASSESSMENT**

Accuracy assessment is the process of quantifying and checking the validity of maps of the river island group. Manual checking for each river island group was performed to ensure map accuracy by stacking the shapefile to corresponding NDWI maps via ArcGIS software. In addition, the classified result is also compared with the global dataset of 30m resolution surface water (GLC30-2010), according to the acquisition time of the satellite image used by GLC30-2010. Confusion matrix tables [35] were established to show the relationship between each river island group map and their reference data. The overall accuracy (OA), kappa coefficient (kappa), omission error (OE), and commission error (CE) were used to evaluate the accuracy of produced maps [36].

**IV. RESULTS**

**A. COMPARISON WITH THE GLC30-2010 DATA**

To show the performance of river island mapping results, we compared our results and the results from GLC30-2010 product (Fig. 5). Most of the Yangtze islands in the same year had similar areas from two datasets, exhibited a good agreement ($R^2 = 1.00$, $p < 0.05$). In addition, accuracies of those Yangtze islands were calculated using the GLC30-2010 data as the reference data set. The average of the overall accuracy (OA), kappa coefficient (kappa), omission error (OE) and commission error (CE) were 0.92, 0.80, 0.18 and 0.05, respectively.

To demonstrate river islands from our results and the GLC30-2010 data in detail, two cases were presented in Fig. 6. From the two sub images, the omission errors are mainly distributed in the island boundary region, and the commission errors are mainly distributed within the island. Overall accuracy, kappa coefficient, omission error and commission error of the Zhong and Xin Zhou were 0.85, 0.70, 0.27 and 0.02, respectively. Overall accuracy, kappa coefficient, omission error and commission error of the Emei Zhou were 0.97, 0.95, 0.03 and 0.02, respectively.

**B. RIVER ISLAND MAPPING**

Fig. 7 shows two examples of the extracted Yangtze island groups at an annual scale over 1986–2017. These two river island groups located in the middle and lower reaches of the Yangtze River, respectively. In this figure, the background is the areas observed as river area or land area on both sides of the river during 1986–2017. In Fig. 7, yellow and blue represent the yearly extent of river and island. The time series of annual river island area was also presented in the lower right of each sub image.

In addition, the spatial distribution of the frequency observed as land during the period 1986–2017 (Fig. 8(a), 8(c)) was used to reflect the spatio-temporal pattern of two island groups (Zhong and Xin Zhou, Emei Zhou). Areas with land frequency values close to 1 reflect the permanent land with a higher elevation. The closer the land frequency value of the area in the Yangtze islands is to 1, the higher the altitude of the area and the more permanent land coverage it has. Areas with major variations, which had land frequency values between 0 and 1, were found in the southwest region of Zhong and Xin Zhou and the northwest.
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FIGURE 7. Annual change of the land area of two example island groups during 1986–2017. In both (a) and (b), for each sub image, islands and water were marked with yellow and blue, respectively; and the time series of the island are were also presented in the lower right. In both (a) and (b), the lower right panel represents the location of example island groups (i.e., red color) in the Yangtze River (i.e., navy blue color).

(a) Zhong and Xin Zhou, centered at 29.95°N, 113.69°E, located in the middle reaches of the Yangtze River.

(b) Emei Zhou, centered at 30.51°N, 117.19°E, located in the lower reaches of the Yangtze River.

FIGURE 8. Spatial variation of the land area of two island groups during 1986-2017. The first column is the spatial distribution of the frequency observed as land for Zhong and Xin Zhou (a) and Emei Zhou (c) during the period 1986 – 2017 with 30-m resolution. The black line represents the Maximum boundary of the Yangtze islands (value > 0), while the white line represents the minimum boundary (value = 1). Background represents the river area or land area on both sides of the river. The second column shows the expansion and shrinkage in Zhong and Xin Zhou (b) and Emei Zhou (d) between 1986 and 2017. The expansion, shrinkage and unchanged area was marked with red, blue and yellow.

FIGURE 9. Annual change of the land area of the Yangtze River islands during 1986–2017. 88.04% of the Yangtze island downstream of the TGD were expansion (59.78% significantly) while 11.96% were shrinkage (5.43% significantly) during 1986–2017. 65.22% of the Yangtze island changes are statistically significant, while 34.78% are not. During the past 32 years, the greatest expansion was observed in Chongming Island, UI-27 Island, Changxing Island, Hengsha Island and Changxinsha Island, with a net land expansion of 533.82 km². In addition, the greatest shrinkage was observed in Fuxing Zhou, Jiangxin and Taixing Zhou, Nanmen and Xinyu Zhou, Emei Zhou, and Tuan Zhou, with a net land shrinkage of −10.74 km². Note that Chongming Island is the third largest island in China (1527.19 km² in 2017), second only to Taiwan Island and Hainan Island, respectively.

Fig. 9(a) shows the spatial distribution of the Yangtze River island change in the middle and lower reaches over 1986 – 2017. 88.04% of the Yangtze island downstream of the TGD were expansion (59.78% significantly) while 11.96% were shrinkage (5.43% significantly) during 1986–2017. 65.22% of the Yangtze island changes are statistically significant, while 34.78% are not. During the past 32 years, the greatest expansion was observed in Chongming Island, UI-27 Island, Changxing Island, Hengsha Island and Changxinsha Island, with a net land expansion of 533.82 km². In addition, the greatest shrinkage was observed in Fuxing Zhou, Jiangxin and Taixing Zhou, Nanmen and Xinyu Zhou, Emei Zhou, and Tuan Zhou, with a net land shrinkage of −10.74 km². Note that Chongming Island is the third largest island in China (1527.19 km² in 2017), second only to Taiwan Island and Hainan Island, respectively.

Fig. 9(b) shows the spatial distribution of the Yangtze River island change in the middle and lower reaches before the TGD operating. 41.30% of the Yangtze island downstream of the TGD were expansion (17.39% significantly)
While 58.7% were shrinkage (15.22% significantly) during 1986-2002, 32.61% of the Yangtze island changes are statistically significantly, while 67.39% are not. Before the TGD, five greatest expansions were observed in Changxing Island, UI-27 Island, Changxinsha Island, and Zhengrui Zhou, with a net land expansion of 247.60 km², and five greatest shrinkages were observed in Tianxin Zhou, Daijia Zhou, Emei Zhou and Guazihao Zhou, with a net land change of 101.81 km².

From Fig. 9(b) and (c), an obvious demarcation point of river island changes was observed in Zhenjiang, Jiangsu province. Two parts (i.e., coastal Yangtze islands and inland Yangtze islands) were divided for all Yangtze islands by Zhenjiang. Yangtze islands near the Yangtze River Estuary were grouped as the coastal Yangtze islands and other river islands were grouped as the inland Yangtze islands. Coastal Yangtze islands showed a continuous expansion before (14.07±2.45 km²/year) and after (24.13±2.04 km²/year) the TGD. Among 17 coastal Yangtze islands, 14 exhibited a continuous expansion before and after the TGD. However, most inland Yangtze islands showed a shrinkage before (−4.03±5.50 km²/year) the TGD while an expansion after (2.10±2.54 km²/year) the TGD. Among 75 inland Yangtze islands, 39 exhibited a shrink-then-expand before and after the TGD. Before and after the TGD, five greatest increases of island change rate were observed in Chongming Island, Changxinsha Island, Zihui Zhou and Zhongxinsha Island, with a net land change of 435.85 km², and five greatest decreases of island change rate was observed in Heyue Zhou, U-22 Island, U-24 Island, Changsha Zhou and Guazhao Zhou, with a net land change of 101.81 km². We also found 10 newly developed river islands, with a net expansion of 87.42 km².

C. RIVER ISLAND TEMPORAL CHANGE

The number of river islands was also counted and the total area of river islands was summarized for each year (Fig. 10(a)). The average, standard deviation, maximum, and minimum total area were 2822.52 km², 219.86 km², 3243.58 km² (in 2017), 2471.67 km² (in 1998), respectively. Fig. 10(b) demonstrated the annual variations in the number of the Yangtze islands from 1986 to 2017. The average, standard deviation, maximum, and minimum total number were, 86.56, 3.79, 92 (in 2011-2015), 81 (in 1987 and 1989), respectively. From 1987 to 2018, change rates in total area and number of Yangtze islands are 27.71±9.29 km²/year ($R^2 = 0.86$, $p < 0.05$) and 0.38±0.05 /year ($R^2 = 0.88$, $p < 0.05$), respectively.
The change rate in the total area of Yangtze islands before and after the TGD are $10.38 \pm 0.86$ km$^2$/year and $27.55 \pm 4.42$ km$^2$/year, which reflects an obvious increase of the trend in Yangtze islands expansion. Before and after the TGD, the average total areas of Yangtze islands are $2648.7 \pm 104.62$ km$^2$ and $3019.5 \pm 127.55$ km$^2$. Similar increase after the TGD can be observed in the number of Yangtze islands. The change rate in number of Yangtze islands before and after the TGD are $0.33 \pm 0.13$ /year and $0.38 \pm 0.19$ /year. From Fig. 8, we can see an obvious hiatus in the number of Yangtze islands after the year 2011. Before and after the TGD, the average numbers of Yangtze islands are $83.65 \pm 2.06$ and $89.87 \pm 2.23$.

Fig. 11(a) shows the annual variations in the total areas of the inland Yangtze islands from 1986 to 2017. The average, standard deviation, maximum, and minimum total area were, $1867.40 \pm 74.53$ km$^2$ and $1899.78 \pm 86.70$ km$^2$ (in 2017), $919.78 \pm 36.95$ km$^2$ (in 1987), $4.51 \pm 3.43$ km$^2$ (in 2011), and $3.83 \pm 2.04$ km$^2$ (in 1986). Fig. 12(b) demonstrated the annual variations in the number of the coastal Yangtze islands between 1986 and 2017. For each sub image, the black dash-dot line shows the original time series and the red dotted line shows responding linear fitting. Blue and green represent the linear fitting of time series before and after the TGD. Descriptions on linear fitting were given in different colors. The yellow dot line indicates the year of the TGD’s impounding.

V. DISCUSSION

A. EVALUATION OF ANNUAL RIVER ISLANDS OBTAINED FROM LANDSAT IMAGERY

To evaluate our produced annual river islands, an example was presented in Fig. 13. Fig. 13(b) shows the relationship between the in-situ water level and the location of river island’s boundary, which shows a strong and positive relationship. A quadratic function was used to estimate the relationship. Fig. 13(c) shows the time series of the Landsat-based location and the theoretical location of a transect from the annual island boundary. The correlation coefficient between the two time series can be obtained as $0.65$ ($P < 0.05$). Both time series exhibited a decreasing trend over 2008–2017. From Fig. 13(c), the theoretical location of annual river island’s boundary was estimated according to the relationship between water level and river island’s boundary (Fig. 13(b)). To demonstrate the necessary of using all Landsat data, the method of using one image per year (OIPY) was adopted.
the annual sediment discharges of the Datong station are
\( \times 4.92 \) the annual sediment discharges of the Yichang station are
upstream sediment discharge [42]. Before and after the TGD,
significant changes, while the sediment discharge has reduced
of the Yichang station and Datong station have no signif-
Since TGD began to operate in 2003, the runoff volume
Many previous studies have found that river islands can be
reduce the effect of river island mapping induced by water
An important advantage is that our method may significantly
highlight the importance of using all available Landsat data
theoretical location of annual river island’s boundary, and
and the method using theoretical location of annual river
island’s boundary are similar. Then, the theoretical location
of annual river island’s boundary can be calculated with the
annual averaged in-situ water level. Our calculations exhibit
a good consistency between the Landsat-based location and
the location of land-water boundary of the river island. (c) Time
series of the Landsat-based location (red) and the theoretical
location (blue) of a transect from the annual island boundary.

FIGURE 13. An example to evaluate the annual river islands obtained from Landsat imagery. (a) Location of a transect across a river island along the Yangtze River. (b) Relationship between the in-situ water level and the location of land-water boundary of the river island. (c) Time series of the Landsat-based location (red) and the theoretical location (blue) of a transect from the annual island boundary.

for the comparison. The OIPY method was repeated 10000
times using the Monte Carlo method. Specifically, during
each time, one Landsat image was selected randomly for each
year over 2008-2017 to calculate the change rate of river
island area using linear regression model. Based on change
rate results derived from 10000 repeated times, 95% uncer-
tainty can be obtained. The 95% uncertainty of river island
change rate of the presented one transect from the OIPY
method was 1.68 times greater than that from our method.
95% uncertainty of river island changes from our method
and the method using theoretical location of annual river
island’s boundary are similar. Then, the theoretical location
of annual river island’s boundary can be calculated with the
annual averaged in-situ water level. Our calculations exhibit
a good consistency between the Landsat-based location and
the theoretical location of annual river island’s boundary, and
highlight the importance of using all available Landsat data
for monitoring the annual change of river islands. In this
study, all Landsat data over the study period were used rather
than traditional studies of only using one image in each year.
An important advantage is that our method may significantly
reduce the effect of river island mapping induced by water
level dynamics.

B. INFLUENCING FACTORS ANALYSIS
Many previous studies have found that river islands can be
strongly affected by upstream sediment and runoff [37], [38].
Since TGD began to operate in 2003, the runoff volume of
the Yichang station and Datong station have no significa-
ent changes, while the sediment discharge has reduced
remarkably [39]–[41]. The reservoir intercepted 75% of
the upstream sediment discharge [42]. Before and after the TGD,
the annual sediment discharges of the Yichang station are
4.92 \times 10^8 \text{t} (1950-2002), 0.482 \times 10^8 \text{t} (2003-2012), and
the annual sediment discharges of the Datong station are
4.27 \times 10^8 \text{t} (1954-2002), 1.448 \times 10^8 \text{t} (2003-2012) [43].
TGD impoundment induced sharp decreases in SSC (sus-
pended sediment concentration) can lead to a small sed-
iment concentration along the reach downstream of the
dam, which could carry away sediments from the riverbed
or in the underwater portions of river islands [44]–[46].
Water level is another factor influencing river island changes
observed from Landsat data because the area of our observed
river island is determined by the local topography and
water level corresponding to the satellite pass. After the
TGD, water level in the middle and lower reaches of the
Yangtze River decreased [47]. Average water levels before
and after the impoundment of the Three Gorges Reser-
voir, Shashi, Chenglingji, Hankou, Huokou and Datong sta-
tion were reduced by 4.0 m, 2.3 m, 2.9 m, 2.8 m and
2.0 m, respectively [48]. Although the sediment declined
after the impoundment, a continuous and enhanced expa-
sion of Yangtze River islands can be observed from Landsat
data. We then inferred that the water level changes could
be a major factor contributing to the observed expansion of
Yangtze River islands before and after the construction of the
TGD. In addition, we can clearly observed a sharp decline
in 1998 from time series of Fig. 7, 10 and 11, which is caused
by the 1998 Yangtze flood [49].
Actually, some other factors can also influence the obser-
vation result of Yangtze River island changes [50]. Extensive
human activities such as reclamation and water conservation
projects, can alter morphologies of Yangtze islands, such as
Chongming Island and Changxing Island [27]. Although sea
level rise has been observed around the Yangtze River delta,
those coastal islands exhibited expansions owing to coastal
reclamations [27]–[31].

C. FURTHER CONSIDERATION
The Landsat data can provide a 30-m resolution and long-
term observation for river islands at an annual scale. The
width of many river bank collapses is smaller than 30 meters
according to related reports [51]. Those river bank collapses
always occur in a relatively short period. Timely actions
should be conducted to reinforce the embankment. In addi-
tion, the one-year temporal interval might omit the seasonal
changes induced by the seasonality of various natural factors
and some sharp changes induced by extreme events (such as
flooding and riverbank collapse) during one year. For exam-
ple, flooding can cause a large-scale inundation over a short
period. Therefore, more remote sensing data sources should
be considered to better characterize the change of river islands
at a higher spatial and temporal resolution in the future.
For example, Sentinel-2 imagery could realize high frequent
observations with a large spatial coverage from 2015 and
provide four spectral bands with a 10-m resolution [52].
Moreover, optical images often exhibit a limitation caused by
clouds and shadows. Synthetic aperture radar (SAR) sensors
[53], [54], such as Sentinel-1 [55] and Phased Array L-band
SAR (PALSAR) [56], enable to deal with the barrier and are
easy to detect islands using their cloud-penetrating capacity
day and night measurements, and thus provide cloud-free
and persistent monitoring. Hence, SAR images can be applied for obtaining more detailed temporal changes on river island changes. In the future, based on those multi source remote sensing data, we can monitor changes of river islands with a higher spatial-temporal resolution, which can accurately reflect more details in the river island evolution, such as seasonal fluctuation (dry season and flooding season) and riverbank collapse. Also, we should to pay more attention to quantify the contribution of human activities to the river island changes over the past decades.

VI. CONCLUSION
In this paper, from 1986 to 2017, satellite observation results of all river islands in the Yangtze River downstream of the TGD were obtained from all Landsat data provided by GEE platform within the study period. The MNDWI and threshold methods were used for the Yangtze islands mapping. We presented the spatial-temporal pattern of the Yangtze River islands observed by Landsat imagery to reflect the temporal change and spatial pattern. Several conclusions are as follows:

1) The Landsat data can be used to map the annual Yangtze islands. This method can be extended to some other similar studies (e.g., islands around the coastline, lakes, and rivers).

2) Results from Landsat data show an observed expansion of Yangtze River islands after the TGD construction in 2003. From 1987 to 2018, 124 river islands showed an increasing trend with a change rate of $27.71 \pm 2.92$ km$^2$/year. Before the TGD, 68 river islands showed an increasing trend with a change rate of $10.38 \pm 9.86$ km$^2$/year. After the TGD, 118 river islands showed an increasing trend with a change rate of $27.55 \pm 4.42$ km$^2$/year. For the total 92 river island groups, expansion percentages are $41.30\%$ (before 2003), $80.43\%$ (after 2003), $87.42\%$ (after 2003), and $88.04\%$ (1986–2017). We also observed expansions of Yangtze downstream the TGD and after the TGD might be the main factor that results in the increase of expansions of Yangtze islands downstream the TGD.

3) The significant decrease (2-4 m) in water levels before the TGD might be the main factor that results in the observed expansions of Yangtze islands downstream the TGD although the river discharge and sediment supply declined.

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