Long-term evolution analysis of coastal geomorphology in Jiangsu based on Google Earth Engine

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Abstract: In the past few decades, the tidal flats along the Jiangsu coast have been extensively modified, which has affected the function of a tidal flat ecosystem. In this paper, 4556 Landsat remote sensing images were processed based on the Google Earth Engine to classify features in the region from 1989 to 2019, and the overall and local geomorphology of the Jiangsu coastal area in the past three decades were analyzed and discussed. The trend of tidal flats in the study area has decreased 345.61 km², with an average loss of 11.52 km² per year. The expansion of human activities has led to the migration of the Jiangsu coast to the sea, the reduction of natural coastline fragmentation, and the expansion of artificial coastline to the sea.

1. Introduction

With the economic development in the past decades, human activities have had a great impact on the coastal landforms of Jiangsu Province, and many problems have arisen while gaining economic benefits. As an important coastal landform, tidal flats are an important indicator of the geomorphological evolution. As a reserve land resource [1], tidal flats have a high development value and are also the habitat of many organisms [2], and they also play a great role in storm prevention, stabilization of coastlines, and protection of coastal ecology [3]. However, tidal flats are also one of the most fragile ecosystems, not only winds and waves erode tidal flats, but also human activities can cause massive loss of tidal flats [4]. Therefore, in this paper, we choose tidal flats as the key point to analyze the geomorphological evolution of coastal areas in Jiangsu Province in the past three decades based on the changes of tidal flats' morphology, distribution, and area by classifying remote sensing satellite images.

GEE (Google Earth Engine) cloud platform launched by Google, using gfs-like file system and spanner mass storage [5], relying on the powerful data storage and data processing capabilities of Google cloud platform itself, integrates massive shared remote sensing images and geographic data, providing users with extremely fast access to and processing of geographic data. Nicholas J. Murray et al. studied the distribution and evolution of global mudflats based on GEE and found that the global loss of tidal flats may exceed 20,000 km² since 1984 [3]. Based on a similar approach, Zhang et al. extracted the spatial and temporal distributions of the three aforementioned landforms and estimated their areas, using the coastal area from Hangzhou Bay to Yalu River in eastern China as the study area [6]. Cao Wenting et al., on the other hand, focused on the evolution of tidal flats in Zhoushan Islands, Zhejiang Province, based on GEE, and found that the area of both water and tidal flats decreased by 6% [7].

In this paper, GEE was applied to extract the geomorphology from Jiangsu coastal Landsat image
collection during 1989-2019 and analyze the evolution trend of coastal geomorphology in Jiangsu Province to discuss the changes of coastal geomorphology under human activities.

2. Materials and methods

2.1. Study area
The study area of this paper is the buffer zone extending 5 km landward and 35 km seaward from the coastlines of Jiangsu Province (Fig. 1). The coastal areas of Jiangsu Province have a subtropical and warm temperate monsoon climate with abundant rainfall and are covered by clouds for a considerable part of the year. The coastline of Jiangsu Province starts from the mouth of Xiuzhen River at Lianyungang in the north and ends at the north mouth of the Yangtze River in the south, with a total length of 954 km. And It is densely populated, rich in various production activities, and frequent human activities.

![Fig.1 Study area: the buffer zone of Jiangsu Province](image)

2.2. Satellite images
GEE platform was used to construct the Landsat image collections including (Landsat 4, 5, 7, and 8). The Landsat 4 and 5 satellites stopped working in 1993 and 2013, respectively, while the Landsat 7 and 8 satellites were still in orbit when the experiment was completed. They have more complete uptake and inclusion of global surface observation data for all years, and the time range completely covers the study area of this paper, which is sufficient to construct the time-series image collections of coastal areas in Jiangsu Province. A total of 4556 satellite images from 1989-2019 were selected for processing and analysis by integrating the data collected by the satellites and obtaining and using high-quality images as much as possible to improve the accuracy of the experimental results.

2.3. Methods

2.3.1 Spectral feature analysis
In this paper, the coastal features of Jiangsu Province were classified into four categories: tidal flats, water bodies, vegetations, and others, so a preliminary classification was made concerning to four indices including Normalized Difference Vegetation Index(NDVI), Enhanced Vegetation Index(EVI), modified Normalized Difference Water Index(mNDWI), and Land Surface Water Index(LSWI). The formulas are as follows.

\[ NDVI = \frac{\rho_{NIR} \cdot \rho_{RED}}{\rho_{NIR} + \rho_{RED}} \]  

\[ EVI = \frac{\rho_{NIR} \cdot \rho_{RED}}{\rho_{NIR} + 6 \times \rho_{RED} - 7.5 \times \rho_{BLUE}} + 1 \times 2.50 \]
Where $\rho_{\text{NIR}}$ is the reflectance in the near-infrared band, $\rho_{\text{RED}}$ is the reflectance in the red band, and $\rho_{\text{BLUE}}$ is the reflectance in the blue band.

$$m\text{NDWI} = \frac{\rho_{\text{GREEN}} - \rho_{\text{MIR}}}{\rho_{\text{GREEN}} + \rho_{\text{MIR}}}$$  \hspace{1cm} (3)$$

Where $\rho_{\text{GREEN}}$ is the reflectance in the green band, $\rho_{\text{MIR}}$ is the reflectance in the mid-infrared band.

$$\text{LSWI} = \frac{\rho_{\text{NIR}} - \rho_{\text{SWIR}}}{\rho_{\text{NIR}} + \rho_{\text{SWIR}}}$$  \hspace{1cm} (4)$$

Where $\rho_{\text{NIR}}$ the reflectance in the near-infrared band, $\rho_{\text{SWIR}}$ is the reflectance in the short-wave infrared band.

Using one index alone can cause large errors, and it was found that combining these four spectral indices above can lead to better classification\cite{4}. In this paper, the image elements with EVI less than 0.1 and at the same time EVI less than $m\text{NDWI}$ or NDVI less than $m\text{NDWI}$ were initially classified as water bodies, and similarly, for vegetation, there were related properties, and the image elements that also satisfy EVI greater than or equal to 0.1, NDVI greater than or equal to 0.2, and LSWI greater than 0 were initially classified as vegetation, so the decision tree in Figure 2a was obtained.

![Fig.2 classification decision tree(a for spectral index feature classification, b for frequency classification)](image)

2.3.2 Extraction of tidal flats using image element water frequency

In this paper, we analyzed the classification of coastal features in Jiangsu Province by year. The temporal resolution of Landsat images is 16 days, and there are about 23 images in a year, each location (image element) corresponds to 23 different classification cases, resulting in a frequency of being classified as different features. This paper calculated the frequency of the image element being classified as water bodies and vegetation, which were noted as $F_{\text{Water}}$ and $F_{\text{Vegetation}}$, and their values were the ratio of the number of times the same image element is classified as water body (vegetation) to the total number of times the same image element is observed in the de-clouded data set, respectively.

Combined with the tidal data, the water frequency and plant frequency can be used as a basis for delineating the tidal flats\cite{4}. In the experiment of this thesis, the image element with $F_{\text{Water}}$ between 0.05 and 0.95 was classified as tidal flats, and the image element larger than 0.95 was classified as water body, which can be considered as the actual feature location corresponding to this image element is water for most of the year, and its specific decision tree is shown in Figure 2b.
2.3.3 Accurate evaluation

The classification results of 2018 were chosen to assess the accuracy based on dummy color composite images. Sample points from local map and field photo were selected and compared to discriminate. 150 points were selected on the images for each feature, and then the overall accuracy, user accuracy, producer accuracy, and Kappa coefficient of the classification were obtained separately. The user accuracy was 81%、88%、88%、91% for tidal flats, water bodies, vegetation, and other features, and the producer accuracy was 89%、82%、86%、78%, respectively. kappa coefficient was 0.75, and the discriminated results had high consistency, indicating that the classification results were good.

3. Discussion

3.1 Changes in tidal flats area

Tidal flats are the most important geomorphology in the coastal area in Jiangsu Province, and this paper focuses on the analysis of the changes of tidal flats area, and Figure 3 shows the distribution of tidal flats in the coastal area of Jiangsu Province in 1989, 1999, 2009, and 2019. The change of the total tidal flats area in the study area over the past three decades can be obtained by measuring the tidal flats area through GEE, which is shown in Figure 4.

![Fig. 3 Tidal flats of different year](image)

![Fig. 4 Changes in Tidal flats area](image)

From 1989 to 2019, about 345.61 km² of tidal flats were lost in the study area, with an average loss of 11.52 km² per year, among which, more tidal flats were lost between 1999 and 2004, with an average loss of 38.2 km² per year.

In the radical sand ridges, which is near Qianggang, the tidal flats near the land, have been continuously lost, with 532.19 km² of tidal flats being converted into salt fields, farmland, harbor, etc. The rate of decline accelerated significantly from 1994 to 2004, with 303.92 km² lost over the decade, and the rate of decline of tidal flats declined after 2004. Near the coast, the sediment was deposited continuously, and the human activity range was expanding with the siltation of the tidal flats to the ocean, and the artificial coastline was increasing. The area was steadily silting up to 7 km² to 15 km² per year towards the sea.

The total area of some of the tidal flats in Nantong remains relatively stable, and the development rate is basically consistent with its siltation rate.

3.2 Impact of human activities

3.2.1 Reclamation

Over the past three decades, reclamation has been one of the most frequently human activities in this area. Some of the tidal flats have been transformed farmland, salt farms, and aquaculture, others have
been further developed into harbor, construction, and industrial land. The natural coastline along the coast of Jiangsu Province, which was originally intact and coherent, has gradually become fragmented over the past three decades, and reclamation have led to an increase in the number of man-made shorelines and their migration to the sea (Fig. 5).

A large number of mudflats have been converted into salt fields, or used for aquaculture and crop cultivation, and the tidal flats have been lost due to unreasonable and single-directional occupancy, and the expansion rate of tidal flats has not been able to catch up with the loss rate, while the artificial land area has been increasing, which is the main reason why the total area of tidal flats in the study area has been decreasing since 1994.

![Fig. 5 Comparison of feature classification in Qianggang (red: tidal flats, blue: water bodies, green: vegetation, black: others)](image)

3.2.2 Salt farm
There are lots of salt farms along Jiangsu coast from north to south, many of them were transferred from tidal flats. Compare the classification map between 1989 and 2019 in Dafeng salt farm (Fig. 6), it can be seen that most of the tidal flats have become salt fields, while the land has advanced some distance towards the coast. Another example is the Qidong salt field, where the tidal flats did not change significantly before 2000, and from 2000 to 2019, the scale of the salt field expanded, and people kept expanding the salt field on the newly silted tidal flats, and as of 2019, the tidal flats in coastal areas such as Jinhai town and Donghai town were almost reclaimed. However, there is no large-scale land creation activity in the area except for the salt farm.
3.2.3 Port construction

The tidal flats in Nantong area were reclaimed and used mostly for agriculture and fisheries, and the tidal flats in some areas of Nantong expanded significantly outward between 1989 and 2019, as shown in Figure 7, where the original tidal flats were artificially transformed into land, the extent of crops (vegetation) increased, and a large migration of the artificial shoreline toward the coast occurred. At the same time, the tidal flats continued to produce siltation outside the artificial shoreline. From 1989 to 2019, the original tidal flats were almost reclaimed, and the shoreline in 2019 almost completely extended to where the tidal flats bordered the sea in 1989, and new tidal flats of similar size to the original tidal flats were deposited outside the artificial shoreline in 2019, which also illustrates the rapid deposition of tidal flats in the region. In addition, many ports have been built in the area where the
original tidal flats were located, such as the port of Bingfang in the Tongzhou Bay port area and the port of Huanben, etc. These areas have changed tremendously over the past 30 years, and the ports have replaced the tidal flats and are clearly advancing towards the sea, bringing huge economic benefits to the area.

4. Conclusion
The coastal geomorphology of Jiangsu has changed significantly in the past three decades. In this paper, the trend of tidal flats evolution along the Jiangsu coast during 1989-2019 was analyzed by spectral features using the Google Earth Engine with respect to a synthetic time series of Landsat images collections.

(1) The study area has lost 345.61 km$^2$ of tidal flats in the past three decades, accounting for about 17% of the total area in 1989, with an average annual loss of 11.52 km$^2$. With a series of tidal flats development and protection policies, this unique natural feature has been effectively protected in last ten years. A combination of strategies is needed to maximize the value of Tidal beach and sustainable development.

(2) The expanding scope of human activities, salt farm, reclamation and port construction have all encroached the original tidal flats, causing the overall migration of Jiangsu's coast to the sea, fragmenting the natural coastline, and increasing the artificial coastline.

(3) The GEE platform plays an important role in tidal flats extraction and geomorphological classification, providing very important technical support for data acquisition and analysis, and is an essential tool for remote sensing image time series analysis.

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