Morphological Characteristics of Tidal Creeks in the Central Coastal Region of Jiangsu, China, Using LiDAR

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Abstract: Tidal creeks are an important component of the intertidal zone and are essential for maintaining the balance between sedimentary processes and the hydrodynamic environment. A quantitative analysis of the morphological characteristics of tidal creeks is essential for understanding their processes of evolution and to evaluate the stability of tidal flats. This study describes the morphological characteristics of tidal creeks using a high-resolution airborne LiDAR DEM. The parameters include the number, order, length, width, depth, and width/depth ratio. The results show that the number and degree of development tidal creeks along the central coast of Jiangsu are higher than those in the radial sandbanks, and the mean width and length increase with the increasing tidal creek order. The number, length, and depth of tidal creeks in the salt marsh zone with well-developed vegetation are higher than those areas with little vegetation cover. The number of tidal creeks in the mid-upper intertidal zone is the largest, while the length and width of tidal creeks in the lower intertidal zone are the greatest. The differences in these characteristics are mainly related to the vegetation distribution, tidal flat width, and hydrodynamic conditions. Our findings potentially provide guidelines for coastal management and the evaluation of tidal flat stability.

Keywords: tidal creek; morphological characteristic; intertidal zone; thalweg; airborne LiDAR

1. Introduction

Tidal creeks are one of the most important geomorphological features of tidal flats, especially in the intertidal zone, and they are substantially affected by hydrodynamic forces and anthropogenic activities [1–3]. They are major conduits for the transport of water and sand to the upper part of tidal flats [4,5], and they are also the most active micro-geomorphological unit in the zone of the land-sea interaction [6]. The major tidal channels originate in the lower tidal zone and extend to the mid-upper part of the intertidal zone, comprising dendritic, pinnate, and parallel morphological structures [7]. The channels terminate in the salt marsh zone, at seawalls, or are linked with drainage channels inland. Tidal creeks have important functions for the docking of ships, as habitats for vegetation and wildlife, including juvenile fish, and in the transport of sediment and nutrients [8,9]. Tidal creeks are distributed in coastal zones worldwide, but are concentrated mainly in the coastal areas of the Netherlands, Germany and Denmark [10,11], the west coast of the United Kingdom [12,13], the east coast of the United States [14,15], Venice lagoon in Italy [4,16], and the east coast of China [17].
Unlike the unidirectional flow system of terrestrial river networks, tidal creeks are characterized by a bi-directional flow [18]. The morphological characteristics and dynamic evolution of tidal creeks are complex, sensitive, and variable under the combined influences of tidal and wave action, runoff, storm surges, sea-level rise, and anthropogenic activities [19]. Consequently, tidal creeks exhibit frequent channel migration, incision and erosion, sedimentation, and activation [20,21], which represent a substantial threat to tidal flat stability and coastal engineering [22], with effects on ports, navigable waterways, wind farms, and the construction of dikes. In addition, these processes affect tidal flat deposition, hydrology, and the overall coastal ecosystem [23,24].

A quantitative analysis of the morphological parameters of tidal creeks may contribute to the understanding of the spatial distribution of the tidal flat, and provide guidance for further research on the evolution of tidal creek systems using multi-source and time-series data. In addition, the morphological description of tidal creeks (i.e., order and width/depth ratio) can reflect the stability of tidal flats to a certain extent: The higher the order and the greater the width/depth ratio, the more unstable the tidal flat, which may render it unsuitable for coastal engineering construction. In addition, the analysis of tidal creek characteristics in the salt marsh zone and un-vegetation zones, may help in understanding the impact of vegetation on tidal creek development, and thus facilitate decision-making for the protection of tidal flat resources.

Numerous studies have measured some of the morphological parameters of tidal creeks using field investigations [25–27] and hydrological experiments [5,28–30]. However, these approaches are restricted by the large scale of observation required, and by the difficulty in simulating tidal creek characteristics under complex natural conditions. Remote sensing has major advantages for tidal flat observation [31–34], and light detection and ranging (LiDAR), in particular, can generate three-dimensional terrain data, and has been widely applied in intertidal zones [35–37]. Previous efforts using remote sensing have focused mainly on the extraction of tidal creeks [4,16,38,39], the analysis of morphological characteristics [40,41], and the process of evolution of tidal creeks [21,29,42,43]. These studies have tended to concentrate on planar morphological parameters, including the order [13,44,45], length [40,46], width [10,47], density [12,48], and curvature [15,49]. However, relatively little research has been conducted on the profile characteristics of tidal creeks, such as the depth and width/depth ratio, which directly impact the development, expansion, and drainage efficiency of tidal creeks. A few studies have selected a number of cross-sections to analyze the evolution of tidal creeks [50]. However, to the authors’ knowledge, no comprehensive observations have been made on the profile characteristics of large-scale tidal flats, tidal creek systems of varying scales, and on complex intertidal zonal tidal creek networks.

This study used an airborne LiDAR DEM to quantitatively analyze the morphological characteristics of tidal creeks in the central coast of Jiangsu, China. The specific objectives were (1) to comprehensively describe the morphological parameters of tidal creeks, including order, length, width, depth, and the width/depth ratio, using a LiDAR DEM; (2) to analyze, in detail, the morphological characteristics of tidal creeks on the overall, zonal and tidal basin scale; (3) to explore the major factors responsible for the differences in the morphological characteristics of different regions of the study area. Although the results pertain to a specific geographical area, the extraction method and analytical procedures are potentially applicable to other intertidal environments, and the results may provide insights and new metrics for the analysis of terrestrial river networks.

2. Materials and Methods

2.1. Study Area

The Jiangsu central coastal region is located to the west of the southern Yellow Sea (Figure 1a,b). The area contains the largest area of tidal flats in China (exceeding 5000 km²) and spans the largest area of Radial Sand Ridges (RSRs) in China (~2017 km², above the theoretical lowest tide). The study area consists of the coastal tidal flats from the port of Dafeng to Jueju Estuary and the offshore RSRs.
The length of the RSRs is ~200 km in the N-S (along the coastline) direction and the width is ~90 km in the E-W (perpendicular to the coastline) directions, and they have a fan-shaped distribution centered on the Jiang Harbor [51]. The purple dotted lines in Figure 1c represent a division of the N-S zonation, and the green, red and yellow areas represent the E-W zonation from land to sea. Under the influence of an amphidromic system in the southern Yellow Sea and a progressive Poincare wave system in the East China Sea [52,53], tidal flats in the central coastal region of Jiangsu are a major area of sediment supply, deposition and storage, and tidal creeks are well-developed and extensively distributed [54]. Therefore, the area is well suited for a study of their morphological characteristics.

![Figure 1. Location and zonation of the Jiangsu central coastal region. (a) Location of the study area. (b) Enlargement of the red dotted rectangle in (a). The orange area indicates the specific scope of the study area. (c) Spatial distribution and zonation of tidal creeks. (d-g) Different types of tidal creeks derived from high-resolution Google Earth images: (d) main tidal creek in the middle-upper intertidal zone, (e) tributary tidal creeks in the salt marsh zone, (f) tidal creeks close to a reclamation area, (g) tidal creeks developed in the lower intertidal zone.](image)

### 2.2. Datasets

Airborne LiDAR enables the rapid and accurate acquisition of large-scale and high-precision three-dimensional terrain data. It has been successfully applied to urban modeling and topographic monitoring [16,55–57], especially in the acquisition of high-precision DEMs in inaccessible areas such as coastal zones [37,58–60], open water surfaces [55], and gullies [61–63]. LiDAR surveys can describe the depth and cross-sectional area of tidal creeks, thus providing an effective means for analyzing their morphological characteristics. An airborne LiDAR survey of an area of ~1687 km² was conducted by the Jiangsu Provincial Bureau in April and May 2006. The main procedures involved in data processing were as follows. First, the errors and noise within the raw discrete point cloud were removed. Second, a DEM was generated using a bilinear interpolation method based on the point cloud data, and then resampled to a 5 × 5 m grid. Finally, a LiDAR DEM of the study was obtained by mask clipping. The vertical accuracy of the DEM is ~0.25 m. The LiDAR data were collected at low tide when most of tidal creeks were dry, enabling their relative depth to be obtained.
Landsat-5 TM images (Path/Row: 119/037) used were obtained from the United States Geological Survey (USGS) Earth Explorer. In order to assist the tidal flat zonation and to extract tidal creeks, TM images of the same period as the LiDAR data were chosen. The radiometric calibration, atmospheric and geometric correction were carried out on these images, and then a maximum likelihood classification method combined with a visual interpretation was conducted to extract tidal creeks. In addition, topographic maps (1:50,000) were collected for geometric registration of the LiDAR DEM and satellite images. More than 20 ground control points (GCPs) were selected in the terrestrial part of the coastal zone, and the root mean square error (RMSE) was controlled within one pixel.

In order to further understand the geomorphology of tidal flats and the development of tidal creeks, Jiang Harbor was also selected (Figure 1b). Jiang Harbor has a high degree of tidal creeks development for field investigations and observations. The section width and relative depth of typical tidal creeks in the nearshore area were measured using tape and the total station. In addition, a DJ M600 unmanned aerial vehicle (UAV) was used to photograph the salt marsh area, the laver (seaweed) cultivation zone, and the multi-scale tidal creeks on the tidal flat.

### 2.3. Zonation of Tidal Flats

In order to analyze the spatial distribution and morphological characteristics of tidal creeks in greater detail, this study zoned the tidal flat in both the N-S and E-W directions. In the N-S zonation, the coastal tidal flats were divided into five zones according to estuaries and radial sandbanks were divided into four zones depending on their location. In the E-W zonation, tidal flats were classified into supratidal, intertidal and subtidal zones. Of these zones, the intertidal zone was our research area. With the aid of satellite images for the same period, the boundary was manually delineated according to the spectral reflectance. The normalized vegetation index (NDVI) was determined from the TM image in order to distinguish the salt marsh zone and the un-vegetated areas. As a result, the intertidal zone was divided into the salt marsh zone, mid-upper intertidal zone, and lower intertidal zone (Figure 2), and the corresponding morphological characteristics of the tidal creek system were counted.

![Figure 2](image_url) (a) E-W zonation of tidal flats from land to sea. The two red dashed lines delineate the extent of the study area. (b–e) Coastal wind farm, salt marsh vegetation (Reeds, *Suaeda maritima*, and *Spartina alterniflora*), tidal creeks and laver cultivation zone respectively.

### 2.4. Extraction of Characteristics of Tidal Creeks

In order to analyze the morphological characteristics of tidal creeks, extraction is first required. On the basis of the LiDAR DEM, this study adopted the automated method for extracting tidal creeks proposed by Liu et al. [39], which includes the following steps: (1) A multi-window median neighborhood analysis (MNA) was used to calculate the relative depth of tidal creeks; (2) a multi-scale Gaussian-matched filtering (GMF) was used to enhance small tidal creeks; (3) a two-stage adaptive threshold (TAT) segmentation was performed separately to obtain the binarization of tidal creeks;
(4) the fusion of the multi-scale tidal creeks binarization results. Among them, the MNA was used to calculate the relative depth of tidal creeks, the multi-window median filtering was performed on the LiDAR DEM to obtain the maximum responses of depth (Figure 3b), and then the original DEM was subtracted from this result (Figure 3c). Thus, the continuous negative terrain becomes positive, and the non-tidal creeks become negative. For ease of calculation, the negative values were transformed to zero, so that the positive value of each pixel was the corresponding tidal creek depth (Figure 3d, Equation (1)).

\[
R_w = \text{median}\left(f(x, y) + w(m, n)ight) - f(x, y) \tag{1}
\]

where \( f \) is the elevation of original DEM, \( w \) is the median filter window template, \((x, y)\) and \((m, n)\) are respectively the coordinates of \( f \) and \( w \), and \( R_w \) is the residual between the median and the DEM, that is, the relative depth of tidal creeks.

**Figure 3.** Conceptual graph of MNA. (a) Elevation of the original DEM. (b) Median filtering (9 \( \times \) 9 window). (c) Residual topography \((c = b - a)\). (d) Positive value, namely relative depth.

Under the influence of strong hydrodynamic forces, the difference in the scale of tidal creeks is very obvious. They include, not only small tidal creeks of a few meters’ width, but also large tidal creeks of several hundred meters width. A complete tidal creek system usually consists of a main channel and a series of tributary channels, which are inter-connected in the form of a dendritic network. For the convenience of demonstrating the order and length characteristics, the planar tidal creeks with a complex structure was simplified to linear features. First, based on the binarization result of tidal creeks (Figure 4a), the mathematical morphology operation in Matlab R2017b was used to generate the centerline. The Horton–Strahler method was then used to manually define the order of the tidal creeks [44,45]. Specifically, the smallest tidal creek without branches is defined as the first order, and when two first-order tidal creeks converge, a second-order tidal creek is formed, and so forth. The main tidal creek with the largest fluxes of water and sediment is defined as the highest order. Notably, when the same order of tidal creeks converges, the order is increased by one, but when different orders of tidal creeks meet, the order is set to the creek with the higher order (Figure 4b).

Compared with terrestrial river systems, the tidal creek systems vary substantially, even in different sections of the same tidal creek. Although previous studies have analyzed the width characteristics of several segments [49], the limited number of sections cannot fully reflect the characteristics of the entire tidal creek system. In order to express the width of a tidal creek, the mean length of a transect is proposed. First, the centerline of a tidal creek was divided into equidistant segments with an interval of 5 m. Second, a number of lines perpendicular to the centerline were generated through these equally-spaced points, each vertical line being cut off by the tidal creek boundary. Finally, the mean length of the transects was taken as the width of the tidal creek (Figure 4b). Based on the transects of
the tidal creek, the points at 5-m intervals were generated and the depths of all points were obtained. The points of maximum depth on each transect were selected, and the mean value of these points was taken as the depth of the tidal creek.

Length is an important linear parameter of a tidal creek, which can directly reflect its dynamic status. Previous research on the evolution of tidal creeks usually used the centerline. However, this approach does not consider the influence of tidal flat topography on the local flow direction, and the spatial morphological characteristics of the tidal creek are not reflected accurately. Therefore, based on the centerline and the relative depth of the tidal creek, by connecting all of the points with maximum depths, the deepest line of the tidal creek was obtained, namely the thalweg. However, there were substantial variations in the thalweg due to several anomalous points, which caused the line of maximum depth to be inconsistent with the actual flow direction. Therefore, after connecting three consecutive points and determining whether the area of the triangle was larger than a specific threshold (20 m² was used in this study), a smoothing algorithm was used to remove the intermediate point. The remaining points were then connected to obtain a line linking the deepest points within the local section, which defined the thalweg (Figure 4c). The thalweg links the deepest points of a tidal creek, and it can reflect changes in the flow direction and be used to represent the evolution of tidal creeks.

The width/depth ratio largely depends on the erosional resistance of the tidal creek, which is determined by hydrodynamic conditions, vegetation cover, and sediment characteristics. During the formation of tidal creeks due to the consolidation of sediment and the velocity gradient, sediment movement on the channel floor is more stable than at the edges and the lateral velocity is much greater than at the bottom. As a result, sediment is more readily scoured at the edges than at the bottom, which results in the tendency of tidal creeks to widen laterally, rather than to incise vertically. Therefore, tidal creeks tend to have a wide and shallow cross-section and the width/depth ratio generally exceeds one.
3. Results

3.1. Extraction of Tidal Creeks

The automated algorithm for extracting tidal creeks proposed by Liu et al. [39] was used in the study area and the order of each tidal creek was displayed. The spatial distribution and ordering results of the tidal creek systems are shown in Figure 5.

![Figure 5. Results of tidal creek extraction and ordering. (a) Distribution of tidal creeks and N-S zonation of the tidal flats. (b–j) Delineation and ordering of typical tidal basins. (b–f) are coastal tidal creeks and (g–j) are offshore tidal creeks.](image)

3.2. Overall Characteristics of Tidal Creeks

As can be seen in Figure 5, tidal creeks are densely distributed in the central coastal region of Jiangsu, and the main channels and tributaries are inter-connected and exhibit a dendritic pattern. The complex tidal creek network can be characterized in terms of order. By comparing the number of tidal creeks in coastal areas and sandbanks, this study found that tidal creeks are mainly concentrated along the coast, with a total of 8867, representing 73.6% of the total coast (Figure 6). In addition, the degree of development in the coastal area is higher than that offshore, with the highest level of order 6, while the offshore tidal creeks are only developed up to order 5, and most of them are small tidal creeks of first-order and second-order. This is mainly due to the fact that tidal creeks in estuaries serve as channels for inland rivers to enter the sea and abundant water supply extends their length and provides appropriate conditions for the development of tidal creeks.

Once the order of a tidal creek has been defined, a quantitative description of its morphological characteristics can be obtained. The results indicate that, except for the highest-order, the number and...
mean length of tidal creeks increase with increasing order, and the relationship between order and the frequency of creeks tends towards an exponential function. A comparison of tidal creeks of a different order reveals that the minimum, maximum and standard deviation of most tidal creeks gradually increase with increasing order, and the increments of the high-order tidal creeks are much greater than the low-order creeks. In addition, the mean length of offshore low-order tidal creeks is greater than that for the coastal creeks. The main reason for these characteristics is that the wide tidal flats along the coast provide sufficient development space and the terminal creeks are relatively short because of the influence of vegetation. However, due to the instability of the radial sandbanks and the limitations of the tidal flat width, there are fewer higher-order tidal creeks and therefore, the mean length is smaller than on the coast.

The coastal and offshore tidal creeks are both characterized by an increase in the mean width with increasing order. Due to the limited number of high-order tidal creeks, only the first-order and second-order tidal creeks were fitted, and the frequency tended towards a normal distribution. For clarity, only tidal creeks with a width < 40 m are shown (Figure 7). Similar to the length characteristics, tidal creeks which are directly connected to the sea usually have a greater flow velocity and water volume and the rising tide and lateral erosion make the high-order tidal creeks vulnerable to transverse widening. However, as runoff velocity decreases, the hydrodynamic forces are weakened and the width of low-order tidal creeks decreases.

Compared with the length and width, the depth of tidal creeks varies only slightly, mainly within the range of 0.11–0.40 m, and the difference in the tidal creek depth between different orders is also small (Figure 8). The mean depths of tidal creeks can be ordered as follows: order 4 > order 3 > order 5 > order 6 > order 2 > order 1. This is mainly because of the combined effects of flood and ebb
tides: The flow rate increases rapidly at high tide, and tidal creeks are mainly eroded laterally, which increases their width rather than their depth, and therefore the depth of the highest-order tidal creeks is often not very large. On the ebb tide, the seawater recedes in the form of overflow, and when a specific depth is reached, the friction of the tidal beach hinders the water flow, and the slope becomes the main factor controlling the water flow. Therefore, in addition to receiving the receding water from the upper part, the middle and lower parts of tidal creeks also have to accommodate the returning water from the tidal beach. During the ebb tide phase, the water flow continuously scours the channel bottoms, resulting in the depth of the middle-order tidal creeks being the greatest. The low-order tidal creeks are far from the estuary, the hydrodynamic forces are weak, and the stabilizing effect of plant roots causes resistance to erosion, and therefore the depth is the shallowest.

During the formation of tidal creeks, the sediment flux on the floor is more stable than at the edges and the flow velocity at the margins is greater, resulting in greater susceptibility of the margins to erosion by the tide. This results in the lateral profile of tidal creeks being relatively wide and shallow. The width/depth ratio of tidal creeks varies in different areas, with ratios along the coast being concentrated within the range of 19–78. The offshore tidal creeks are wider and shallower and therefore the width/depth ratio is greater, concentrated within the range of 34–88 (Figure 9). The width/depth ratio varies substantially between different orders and the value of high-order creeks is larger. The frequency distributions of the first, second and third-order creeks are shown in Figure 9, and it is evident they are approximately normally distributed. For clarity, only the width/depth ratios < 150 are shown.

**Figure 8.** Frequency of the depth of (a) coastal and (b) offshore tidal creeks of different order.

**Figure 9.** Frequency distributions of the width/depth ratio of coastal (a) and offshore (b) tidal creeks of different order. The red, yellow and green curves are the regression results for first-order, second-order and third-order creeks, respectively.

### 3.3. Zonal Characteristics of Tidal Creeks

The coastal tidal creeks were divided into five zones according to the location of the estuary and the radial sandbanks were divided into four zones (Figure 1c). In addition, the intertidal zone was
divided into a salt marsh zone, mid-upper intertidal zone, and lower intertidal zone from land to sea (Figure 2), and the number of tidal creeks in each zonation were enumerated. As can be seen from Table 1, the number of coastal tidal creeks is greater than that offshore and the middle part of the coast has the largest number. However, except for Dongsha, there are a few tidal creeks in other areas in offshore sandbanks. In terms of E-W zonation, the number and length of tidal creeks in the salt marsh zone, with well-developed vegetation, are higher than those areas with little vegetation cover.

The statistics of the tidal creek length in different regions reveal that the mean tidal creek length of the salt marsh zone is the lowest and that of the lower intertidal zone is the largest. This is due to the fact that the salt marsh zone is close to the reclamation areas and it inhibits the extension of tidal creeks. Therefore, tidal creeks in the salt marsh zone are relatively short and narrow. The tidal flat in the lower intertidal zone is relatively wide and it also connected with the Western tidal channel and the Yellow Sand Ocean tidal channel, which is conducive to the development of tidal creeks and the abundant water supply promotes an increase in the length of the tidal creeks. Notably, although Dongsha has a large number and high-order tidal creeks, its W-E extension is limited due to the vertical orientation of sandbars and many small tidal creeks of the first-order reduce the overall length.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Salt Marsh Zone</th>
<th>Mid-Upper Intertidal</th>
<th>Lower Intertidal</th>
<th>Total Number</th>
<th>Overall Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>Mean Length</td>
<td>Number</td>
<td>Mean Length</td>
<td>Number</td>
<td>Mean Length</td>
</tr>
<tr>
<td>Region I</td>
<td>710</td>
<td>213</td>
<td>875</td>
<td>229</td>
<td>105</td>
</tr>
<tr>
<td>Region II</td>
<td>834</td>
<td>169</td>
<td>968</td>
<td>216</td>
<td>95</td>
</tr>
<tr>
<td>Region III</td>
<td>65</td>
<td>120</td>
<td>1572</td>
<td>209</td>
<td>479</td>
</tr>
<tr>
<td>Region IV</td>
<td>544</td>
<td>164</td>
<td>1273</td>
<td>200</td>
<td>197</td>
</tr>
<tr>
<td>Region V</td>
<td>—</td>
<td>—</td>
<td>434</td>
<td>278</td>
<td>716</td>
</tr>
<tr>
<td>Liangyue</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>155</td>
<td>452</td>
</tr>
<tr>
<td>Dongsha</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2052</td>
<td>347</td>
</tr>
<tr>
<td>Gaoni</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>655</td>
<td>324</td>
</tr>
<tr>
<td>Tiaozini</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>316</td>
<td>355</td>
</tr>
</tbody>
</table>

A comparison of the tidal creek widths in different regions reveals that the overall width of the offshore tidal creeks tends to be larger than in the coastal area, with the maximum in Tiaozini, followed by Liangyue, and Gaoni, which has the lowest value (Table 2). This is because the width of tidal creeks is related to the tidal volume and the tidal flat area. Tiaozini is connected to the Yellow Sand Ocean tidal channel and the tidal inflow is large. Liangyue is a small sandbar in the northernmost part of the RSRs and its periphery is an unstable zone. Under the scouring forces of the rising tide, the unstable tidal beach causes the high-order tidal creeks to widen laterally and the number is less in this sandbank, therefore the widths are relatively large. Gaoni is located between Dongsha and Tiaozini. The water flow is limited by the rising tide to some extent and therefore, the widths are relatively narrow. The maximum mean width of the coastal tidal creeks is in region V, which is largely related to the absence of vegetation cover since plant roots impede the lateral erosion of tidal creeks.

Based on the E-W zonation of the coastal tidal creeks, the reclamation line was taken as the baseline. The vertical lines perpendicular to the baseline were then drawn at 300-m intervals along the coastline (Figure 10a) and the widths of the tidal flat in different E-W zonation were counted (Figure 10b). The results show that the mean widths of the tidal flat decrease in the following order: lower intertidal zone, mid-upper intertidal zone, salt marsh zone. The lower intertidal zone is much greater than for the other two zones and there is little difference between the salt marsh zone and the mid-upper intertidal zone. The width of the tidal flat in different E-W zones is generally positively correlated with the number of tidal creeks and the greater the width of the tidal flat, the more tidal creeks are developed (Figure 10c). This is because the salt marsh zone is closest to the land, the volume of tidal inflow is small and vegetation growth largely inhibits lateral erosion of the tidal creeks, resulting in the occurrence of narrow first-order and several second-order tidal creeks in this area. The lower intertidal
zone is directly connected to the sea, the flow velocity is rapid and the water volume is large. As a result, lateral erosion of the tidal flat promotes the broadening of the main tidal creek and therefore, this zonation tends to have a large width.

Table 2. Summary statistics of the mean width and depth in different subzones (unit: m).

<table>
<thead>
<tr>
<th>Zone</th>
<th>Salt Marsh Zone</th>
<th>Mid-Upper Intertidal</th>
<th>Lower Intertidal</th>
<th>Overall Width</th>
<th>Overall Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Width</td>
<td>Mean Depth</td>
<td>Mean Width</td>
<td>Mean Depth</td>
<td></td>
</tr>
<tr>
<td>Region I</td>
<td>16.15</td>
<td>0.58</td>
<td>16.25</td>
<td>0.41</td>
<td>25.33</td>
</tr>
<tr>
<td>Region II</td>
<td>15.70</td>
<td>0.56</td>
<td>16.60</td>
<td>0.37</td>
<td>35.40</td>
</tr>
<tr>
<td>Region III</td>
<td>14.38</td>
<td>0.40</td>
<td>15.39</td>
<td>0.32</td>
<td>24.03</td>
</tr>
<tr>
<td>Region IV</td>
<td>15.61</td>
<td>0.39</td>
<td>16.44</td>
<td>0.38</td>
<td>21.97</td>
</tr>
<tr>
<td>Region V</td>
<td>—</td>
<td>—</td>
<td>16.58</td>
<td>0.29</td>
<td>26.04</td>
</tr>
<tr>
<td>Liangyue</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>37.90</td>
</tr>
<tr>
<td>Dongsha</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>24.82</td>
</tr>
<tr>
<td>Gaoni</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>22.10</td>
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Figure 10. Comparison of tidal flat width and tidal creek number in different zones. (a) The vertical lines perpendicular to the baseline are generated at 300-m intervals along the coastline. (b) Enlargement of the area of the red dashed rectangle in (a), and the width of the tidal flat in the E-W direction. (c) Relationship between the mean width of the tidal flat (black symbols lines) and the number of tidal creeks (red symbols lines) for each region in the coastal area.
The statistics of the tidal creek depth in the E-W zonation show that the mean depth is the greatest in the salt marsh zone and lowest in the lower intertidal zone. The main reasons for this are as follows: The stabilizing effect of vegetation reduces lateral erosion of the tidal creeks in order to discharge more water; the bottom of the tidal creek is scoured continuously, which results in an increase in depth. Therefore, the depth of the first-order, second-order and some of the third-order creeks developed in the salt marsh zone is greater than in the other zones. Compared with the coastal tidal creeks, the depth of the offshore tidal creeks is relatively small. This is mainly because of the absence of vegetation cover on the sandbanks and the fact that there is less seawater to be discharged during the ebb tide. Thus, the bottoms of tidal creeks are less scoured and the depths are relatively shallow.

The scatter plots of the tidal creek width versus the depth are shown in Figure 11. The width/depth ratio of tidal creeks is generally normally distributed in the E-W zonation. The distribution in the salt marsh zone is the most concentrated, followed by the mid-upper intertidal zone and the lower intertidal zone is the most dispersed. Relative to the coordinates of the central point, the width increases while the depth decreases and therefore, the lower intertidal zone is the largest (Figure 11) which is consistent with the results of previous research [2]. Vegetation has a stabilizing effect on the edge of a tidal flat, inhibiting the broadening of tidal creek channels and resulting in a minimum value in the salt marsh zone.

![Figure 11](image_url) Scatter plots of width versus depth of the tidal creeks in (a) the salt marsh zone, (b) the mid-upper intertidal zone, and (c) the lower intertidal zone.

### 3.4. Characteristics of Tidal Basins

Similar to terrestrial river basins, surface water in adjacent areas flows into the tidal creek systems defining a catchment area and the size and shape of catchments are influenced by tidal currents and topography. Clearly, the definition of the catchment is the first step in the analysis of the characteristics of a tidal creek system [17,64,65]. However, a fundamental difference between a tidal creek and a river is that the flows in the former are bidirectional and cannot be segmented solely by elevation [48,66]. Therefore, the boundary of a tidal creek catchment was defined as follows: The estuary and reclaimed area are the boundaries of sea and land respectively and the line equidistant between the adjacent tidal creeks is the lateral boundary. Based on this method, 56 representative tidal basins were selected from the study area, 28 from the coastal area and 28 from the offshore area. The distribution and order of tidal creeks in each tidal basin are shown in Figure 5. As can be seen in Figure 12a, most of the coastal tidal basins are developed up to order 5 and the tidal creeks connected to inland estuaries (such as tidal basins IE, IIIE, IVA, IVB, and IVC) are developed up to order 6. This is because tidal creeks in estuaries serve as channels for rivers entering the sea and their large runoff and the wide tidal beach provide favorable conditions for the development of high-order tidal creeks. In addition, the number of tidal creeks near the estuaries is larger (tidal basins IE, IIIE, and IVC), which is due to the development of numerous small tidal creeks in the nearby salt marsh zone. The number of tidal creeks in the middle part of a tidal basin is relatively small (tidal basins IC, ~IIB-IIC, ~IIIB-IIID), largely because the reclamation area reduces the width of tidal flats and thus inhibits the development of tidal creeks. A few tidal creeks extend to the reclamation area, but most tidal creeks terminate nearby. Compared with the coastal tidal basins, the tidal basins in RSRs are mainly developed to order...

...
The high-order tidal creeks are concentrated in the middle of Dongsha (tidal basins DA8, DB7), while the low-order tidal creeks are focused on Liangyuesha and the north of Dongsha (tidal basins LA1, DA2, DB2, DA3, DB3, DB5), due to the narrow tidal flat which cause the number of independent tidal basins to be much smaller than the number of coastal basins.

Figure 12. Numbers of coastal (a) and offshore (b) tidal creeks of different order in 56 tidal basins.

The mean length, width, and depth of tidal creeks in 56 typical tidal basins were analyzed with the following results: (1) In the coastal tidal basins (Figure 13a), the mean length and width of tidal creeks in coastal tidal basins are similar, with higher values in Regions III and V, mainly distributed in the mid-upper intertidal zone and in the lower intertidal zone (tidal basins IIIC-IIID, IVE, and Region V). The tidal flats south of the Jiang Harbor (Region III) are linked with the Yellow Sands Ocean tidal channel and the water level rises rapidly during high tide, causing lateral erosion of tidal creeks which greatly widens the channels. Therefore, the mean width of tidal creeks in Regions IV and V is larger than in the other regions. In addition, the mean depth of tidal basins in Regions I and II and tidal basin IVC are greater mainly due to their vegetation cover which impedes the lateral erosion of water. Thus, only the bottoms of tidal creeks are scoured continuously which increases their depth. (2) In the offshore tidal basins (Figure 13b), the maximum mean length and width of offshore tidal creeks is in Tiaozini (TA1), due to its abundant water sources and sufficient development space which promote the extension of tidal creeks. Moreover, tidal creeks in this tidal basin are subject to lateral and vertical erosion during high tide, causing them to be wider and deeper than in creeks elsewhere. The mean depth of offshore tidal creeks does not change substantially within each zone, which is related to the absence of vegetation cover on the sandbanks.
Figure 13. Mean length, width, and depth of the 56 tidal basins. (a,b) are coastal and offshore, respectively.

4. Discussion

4.1. Comparison with Previous Studies

The remote sensing data used to determine the morphological characteristic of tidal creeks mainly includes optical images (i.e., Landsat and Sentinel) [47], aerial photographs [12,40,67] and LiDAR DEM [13,21,41]. Among them, the acquisition of optical images is relatively easy and they have multi-band characteristics, which can be used to extract the features of tidal flats. The advantage of aerial photography is its high precision. LiDAR data have the highest acquisition cost, but it is possible generate three-dimensional terrain data which has major advantages for analyzing the profile characteristics of tidal creeks.

In terms of describing the morphological characteristics of tidal creeks, the methods proposed by Horton or Strahler were mostly used [40,41]. That is, the finger-tip tidal creek is the first-order, and the main tidal creek is the highest order. Chirol et al. reversed the Strahler method and defined the main tidal creek as the first-order [13]. For the expression of the length, most of the previous studies are based on the centerline, but this does not take into account the impact of local topography on the tidal flat. Therefore, the present study used the actual length of the tidal creek overflow, namely the thalweg, to denote the length of a tidal creek. In the cross-section analysis, the distance between two points on the edge of the section is taken as the width of the tidal creek and the average elevation of the two points on the edge is subtracted from the elevation of the deepest point to estimate the depth [21]. However, the topological structure is complex and even different sections of the same tidal creek may have different widths. Therefore, the method proposed by Davies [47] was used in which vertical lines of the centerline were generated according to a specific distance and the average length of multi-section lines was taken as the width of a tidal creek. Similarly, the depth of a tidal creek is calculated from the average of the points with the deepest value (greatest depths) in each section.

In the analysis of the morphological characteristics of tidal creeks, many studies describe the general relationships between parameters [21,40]. This study conducted a detailed division of the tidal flats and the characteristics of tidal creeks along the coast and sandbanks were compared. In addition, the characteristics of the salt marsh zone, the middle-upper intertidal zone, and the lower intertidal
zone were analyzed in detail. The results show that vegetation may promote the development of a tidal creek, which is consistent with the conclusion of Kearney [9].

4.2. Comparison with Satellite Images

Currently, optical images are primarily used in tidal flat research and they have provided a basis for extensive tidal creek research [47]. Landsat TM images are one of the commonly used data sources in optical images. However, LiDAR data has clear advantages for analyzing the profile characteristics of tidal creeks, enabling the depth and cross-sectional area to be estimated which cannot be extracted from optical images. In addition, it also has high-precision resolution and can analyze the planar characteristics of tidal creeks in more detail.

In order to illustrate their differences more clearly, a TM image of the same period as the LiDAR data was selected taking the well-developed Jiang Harbor as an example. The two data types are compared in Figure 14a,b. As can be seen from the figure, in terms of quantitative statistics, tidal creeks are more densely distributed in the LiDAR DEM and both large tidal creeks as well as the small tidal creeks near the reclamation area can be displayed. The number of tidal creeks recognized by the TM image is limited and only the larger tidal creeks in the intertidal zone can be extracted. In addition, in the definition of tidal creeks, the LiDAR DEM data exhibit six orders, while the TM image only shows three orders.

![Figure 14. Morphological characteristics of tidal creeks in the Jiang Harbor. Extraction and order definition of tidal creeks using (a) a LiDAR DEM and (b) TM images. The black line indicates the edge of the reclamation area.](image)

4.3. Limitation and Further Research

Airborne LiDAR can generate large-scale, high-precision terrain data with three-dimensional information. Inevitably, the cost of airborne LiDAR observation is high and the topography of tidal flats is complex and changeable, making it difficult to conduct periodic and continuous investigations which limits the application of this technology.

Future research will address the following: (1) With the help of high-precision LiDAR terrain data, the authors expect to produce an automated division algorithm for the tidal basins on the low-fluctuating tidal flat and the results can be compared with the watershed division method used for terrestrial river networks (i.e., D8). (2) Several typical tidal creeks were selected along the central coast of Jiangsu and UAVs were used to observe the topographic changes of tidal flats and the morphological characteristics of tidal creeks in order to determine the seasonal changes in tidal creeks.
5. Conclusions

Tidal creeks play an important role in maintaining tidal flat sediments and the hydrodynamic environment. A quantitative analysis of their morphological characteristics facilitates the understanding of the evolution of tidal creeks and the evaluation of tidal flat stability. An airborne LiDAR DEM in 2006 was used to extract tidal creeks in the central coastal of Jiangsu Province and an N-S and E-W zonation was applied to tidal flats. The number, order, length, width, depth and width/depth ratio of tidal creeks were quantitatively described in order to analyze their morphological characteristics in detail. The reasons for the differences are discussed in the context of the influence of natural factors, such as tidal dynamics and the tidal flat width, as well as the anthropogenic activities, such as the promotion of salt marshes and reclamation engineering.

The study demonstrated the advantages of using aerial LiDAR DEM data to quantitatively analyze the planar and profile characteristics of tidal creeks. The main conclusions are as follows: (1) Tidal creeks in the central coastal region of Jiangsu are well developed and the degree of development in the coastal area is higher than in the RSRs. With the increase of the tidal creek order, the mean width increases, as does the mean length (except for the highest order), while the depth differences are not obvious. Thus, the width/depth ratio also increases. (2) Vegetation may promote the development of tidal creeks. In the salt marsh zone along the coastal (Regions I–IV), the number, length and depth of tidal creeks in well-vegetated areas are greater than in the poorly-vegetated areas. (3) The width of the tidal flat is positively correlated with the number of tidal creeks. With respect to the zonation of the intertidal zone, the tidal flat of the mid-upper intertidal zone has the largest width, and therefore the number of tidal creeks is also the largest. The lower intertidal zone is directly connected with the tidal channel and the tidal creeks have the greatest length and width. These differences in morphological characteristics are mainly related to the vegetation development, tidal flat width and hydrodynamic conditions.

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