University of Dundee

Estimating muddy intertidal flat slopes under varied coastal morphology using sequential satellite data and spatial analysis

Zhou, Yong; Zhang, Dong; Cutler, Mark; Xu, Nan ; Wang, Xiao Hua; Sha, Hongjie

Published in:
Estuarine, Coastal and Shelf Science

DOI:
[10.1016/j.ecss.2021.107183](https://doi.org/10.1016/j.ecss.2021.107183)

Publication date:
2021

Licence:
CC BY-NC-ND

Document Version
Peer reviewed version

[Link to publication in Discovery Research Portal](#)

Citation for published version (APA):

Zhou, Y., Zhang, D., Cutler, M., Xu, N., Wang, X. H., Sha, H., & Shen, Y. (2021). Estimating muddy intertidal flat slopes under varied coastal morphology using sequential satellite data and spatial analysis. *Estuarine, Coastal and Shelf Science*, 251, [107183]. <https://doi.org/10.1016/j.ecss.2021.107183>

General rights

Copyright and moral rights for the publications made accessible in Discovery Research Portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from Discovery Research Portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain.
- You may freely distribute the URL identifying the publication in the public portal.

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Journal Pre-proof

Estimating muddy intertidal flat slopes under varied coastal morphology using sequential satellite data and spatial analysis

Yong Zhou, Dong Zhang, Mark E.J. Cutler, Nan Xu, Xiao Hua Wang, Hongjie Sha, Yongming Shen

PII: S0272-7714(21)00019-6

DOI: <https://doi.org/10.1016/j.ecss.2021.107183>

Reference: YECSS 107183

To appear in: *Estuarine, Coastal and Shelf Science*

Received Date: 10 August 2020

Revised Date: 28 November 2020

Accepted Date: 12 January 2021

Please cite this article as: Zhou, Y., Zhang, D., Cutler, M.E.J., Xu, N., Wang, X.H., Sha, H., Shen, Y., Estimating muddy intertidal flat slopes under varied coastal morphology using sequential satellite data and spatial analysis, *Estuarine, Coastal and Shelf Science* (2021), doi: <https://doi.org/10.1016/j.ecss.2021.107183>.

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2021 Published by Elsevier Ltd.

Author Agreement

All authors have read and approved to submit it to your journal. There is no conflict of interest of any authors in relation to the submission. This paper has not been submitted elsewhere for consideration of publication.

Authors:

Yong Zhou

Dong Zhang

Mark E. J. Cutler

Nan Xu

Xiao Hua Wang

Hongjie Sha

Yongming Shen

Estimating Muddy Intertidal Flat Slopes under Varied Coastal Morphology
Using Sequential Satellite Data and Spatial Analysis

**Yong Zhou¹, Dong Zhang^{1, 2*}, Mark E. J. Cutler³, Nan Xu¹, Xiao Hua Wang^{4, 5},
 Hongjie Sha¹, Yongming Shen¹**

*¹School of Marine Science and Engineering, Nanjing Normal University, Nanjing,
 210023, P.R. China*

*²Jiangsu Center for Collaborative Innovation in Geographical Information
 Resource Development and Application, Nanjing, Jiangsu province 210023, P.R.
 China*

*³School of Social Science, University of Dundee, Dundee, DD1 4HN United
 Kingdom*

*⁴School of Science, University of New South Wales, P.O. Box 7916, Canberra, BC
 2610, ACT, 2600, Australia*

*⁵The Sino-Australian Research Centre for Coastal Management, University of New
 South Wales, P.O. Box 7916, Canberra, BC 2610, ACT, 2600, Australia*

***Corresponding to:**

Dong Zhang (dongzhangnju@gmail.com)

School of Marine Science and Engineering, Nanjing Normal University, Nanjing,

23 *Jiangsu Province 210023, P.R. China*

24

25 Yong Zhou: njzhouyong_2018@hotmail.com

26 Dong Zhang: dongzhangnju@gmail.com

27 Mark E.J. Cutler: m.e.j.cutler@dundee.ac.uk

28 Nan Xu: hhuxunan@gmail.com

29 Xiao Hua Wang: x.h.wang@unsw.edu.au

30 Hongjie Sha: 470187688@qq.com

31 Yongming Shen: yongmsh@163.com

32

33 **Running head:** Estimation of Muddy Intertidal Flat Slopes

34

35 **Keywords:** Muddy intertidal flat, Slope, Remote sensing, Waterline, Tidal height,

36 DEM

37

38

39

40

41

42

43

44

Abstract:

Muddy intertidal flats are important resources for coastal development activities, such as coastal shoal reclamation and mudflat cultivation. Understanding changes in intertidal flat topography is essential for intertidal zone development, management, and protection. As an essential topographic factor, the slope of an intertidal flat can effectively express profile morphology in the cross-shore direction, reflect topographic undulation in the long-shore direction, and be indicative of intertidal flat erosion and deposition. Previously, intertidal flat slopes have been estimated by the two-temporal average gradient (TTAG) method using two spatially separated waterlines derived from satellite remote sensing data and their relevant water elevations. However, this method does not adequately reflect the profile morphology of different coastline types, especially sinuous coastlines, and is highly sensitive to the selected waterlines. This study proposes an effective strategy for estimating slope considering not only the characteristics of the vertical terrain undulation but also the horizontal plane-form shape of the coastline. Using waterlines extracted from sequential satellite images and their corresponding tidal height information, the slopes were estimated utilizing a profile morphology discriminant inferential (PMDI) method on straight coasts and a digital elevation model (DEM) method on sinuous coasts. We obtained the following results: (a) for straight coasts, by judging the various shapes of the coastal profiles and curve-fitting separately, the PMDI method

achieved significant improvements in accuracy and robustness of slope estimates compared to results obtained using the TTAG method; and (b) for sinuous coasts, the DEM-based method performed better for addressing the intersecting waterline issue and accurately retrieved the slope, although this accuracy is strongly dependent on the areal coverage of the DEM and the precision of the terrain inversion. Using this new paired methodology, we estimated that the average slope of the intertidal flats in the Mid-Jiangsu Province between the Sheyang Estuary, the Liangduo Estuary, and the Lianxing Port was 0.96‰. In general, the slopes from north to south in this coastal area exhibited a steep-gentle-steep pattern, which was consistent with in situ observed data. We conclude that stratifying the coastlines according to their plane-form shapes and applying different methods to straight and sinuous coastlines can result in a more robust estimation of coastal slope for muddy intertidal flats than previous TTAG methods. This work demonstrates the utility of satellite-based remote sensing for retrieving critical coastal geomorphological information in dynamic terrains where in situ data are difficult to obtain.

89

90

91 **1. Introduction**

92 Muddy tidal flats are low-gradient, tidally inundated coastal surfaces that are
 93 formed by the accumulation of fine-grained sediments in intertidal zones (Eisma,
 94 1998). They occur in a wide range of coastal climatic and oceanographic settings
 95 across the world (Wang et al., 2002b). As a land-sea interaction area, tidal flats play
 96 an important role in coastline stabilization (Murray et al., 2014) and are critical sites
 97 for intertidal land reclamation, biodiversity conservation, and coastal ecosystem
 98 protection (Sengupta et al., 2018; Ghosh et al., 2015).

99 China has abundant intertidal flat resources. As a country, it has the second
 100 greatest areal extent of tidal flats in the world (12,049 km²) (Murray et al., 2019). The
 101 length of the muddy tidal flat shoreline is over 4,000 km, occupying approximately
 102 one quarter of the country's total continental coastline (Wang and Zhu, 1994). Due to
 103 the abundance of intertidal land resources, this region has seen significant economic
 104 development over the past two decades, including agricultural production, aquaculture,
 105 port construction, etc. These anthropogenic activities have strongly affected the local
 106 wetland ecosystem, hydrodynamic environment, and tidal flat evolution (Murray et al.,
 107 2014; Wu et al., 2018; Chen et al., 2018). In recent years, researchers have developed
 108 numerous indices for describing the time-varying nature of muddy intertidal flats and
 109 monitoring their changes, particularly those related to topographic and
 110 geomorphological changes (Murray et al., 2014; Tseng et al., 2017; Ghosh et al.,

2015). As an essential topographic factor, the slope of an intertidal flat not only expresses profile morphology in the cross-shore direction but also reflects topographic undulation in the long-shore direction. Monitoring change in slope over time can indicate the erosional or depositional regime of the flat, as well as providing data to validate coastal geomorphological models (Chen et al., 2018) and determine the impact of coastal zone activities (Liu et al., 2013b). Thus, accurate slope estimation is important for understanding coastal changes and planning coastal zone development and utilization (Liu et al., 2013a).

To date, position and elevation data for tidal flat slope calculations have been mainly derived from either ground surveys and/or remotely sensed data (Salameh et al., 2019). For in situ ground surveys, sampling points along transect lines are measured using portable real-time kinematic (RTK) positioning systems or continuously operating reference stations (CORS). Although these conventional methods have advantages in terms of accuracy, the poor accessibility of mudflats and limited sampling time windows during fluctuating tidal conditions makes performing field surveys difficult, potentially hazardous, and expensive (Choi et al., 2010; Liu et al., 2013a). In comparison, remote sensing techniques provide a potentially cost-effective method for repeated large-scale tidal flat monitoring (Ryu et al., 2008; Chen et al., 2009). By calculating the tidal height and positional difference between two spatially separated waterlines extracted from satellite imagery, the two-temporal average gradient (TTAG) method has been used to calculate coastal slopes in muddy coastal areas (Mason et al., 1997; Ryu et al., 2008; Liu et al., 2013b; Sha et al., 2019).

However, the applicability, stability, and accuracy of this remote sensing-based slope estimation remain inadequate due, in part, to the issues identified below.

First, in open coast tidal flats, the shape of the tidal flat profiles vary considerably, such as lower concave, gentle, and upper convex profiles that indicate the erosional, stable, or accretional status of the beach, respectively (Zhang et al., 2018). The TTAG method only uses two elevation points along a transect and is unable to reproduce profile shapes outside of gentle linearly shaped profiles. Second, the resulting slope from the TTAG method is strongly dependent on the waterlines used in the calculation. If three or more waterlines are available for a single transect, then a decision is required to determine which two should be selected to derive the slope gradient. This not only excludes potentially important additional information about the shape of the profile but also introduces uncertainty into the reliability of the estimated slope. Third, waterlines derived on a relatively straight coast are generally smooth and roughly parallel to the coastline (where ‘coastline’ here refers to the highest tide level line). We can directly determine the unique intersection points between a transect line and its intersecting waterlines. However, in an estuary setting or along coastlines with large tidal creeks spread along flat surfaces, the waterline tends to be sinuous. In such cases, several intersecting points exist between one sinuous waterline and the transect line. As these points have the same elevation at different locations, selecting suitable intersection points from which to estimate the slope profile is subjective and will again lead to uncertainty in profile estimation.

Admittedly, these three deficiencies can be solved by deriving waterlines from

multiple digital elevation models (DEMs) derived from satellite remote sensing (Mason, et al., 1997; Kang et al., 2017; Wang et al., 2019). However, although a large number of geometrically and spectrally calibrated satellite images are available, the practical mass production of intertidal flat DEMs with different spatial scales is still in its early stage (Bishop-Taylor et al., 2019). For most muddy intertidal flats across the world, DEM data are rarely available to date and/or hampered by the significant temporal dynamics of tidal flats, meaning that they require frequent updating. On the sinuous coast, the local terrain is complex, and DEM is effective in describing the terrain undulation of the intertidal flat. However, on the straight coast, the height of the intertidal zone is distributed in strips, and variations in intertidal morphology are relatively simple. We can use a few approximately parallel waterlines to express variations in topography, which can mitigate the lack of DEM data to a certain extent.

The purpose of this paper is to propose a strategy for calculating the slope of muddy intertidal flats depending on the coastal morphology and provide a reliable result for expressing the change of terrain. The specific objectives are as follows: (1) determine the optimal slope estimation methods for muddy intertidal flats based on the consideration of morphological characteristics, (2) validate the accuracy of different slope estimation methods using in situ data and assess their applicability, and (3) present spatial trends in the slope of the muddy intertidal flat in the Mid-Jiangsu Province from the estimated slope values.

2. Study area

The Jiangsu Province is located on the eastern coast of mainland China. Owing to the abundant supply of fine-grained sediment and strong wave-current interaction, 94% of its 954 km total coastline is classified as muddy coast. In this study, the muddy intertidal flat on the Mid-Jiangsu coast ranging from the Sheyang Estuary to the Lianxing Port was selected for remote sensing-based slope estimation. Based upon the horizontal plane-form and vertical morphology of the coast, the study area is divided into two parts. As shown in Fig. 1, the northern part of the coast from the Sheyang Estuary to the Liangduo Estuary is relatively straight. Tidal creeks on the flat surface are narrow and slender, and their flow directions are mostly perpendicular to the coastline. The width of the intertidal flat varies from 1.5 km to 7 km with an average of approximately 4 km, while the slopes range from 3.7‰ to 1.1‰. Three main types of tidal flat profiles are observed here: erosional concave, gentle slope, and depositional convex. The southern part of the coast from the Liangduo Estuary to the Lianxing Port is sinuous, with large tidal channel systems spreading on tidal surfaces. Bidirectional tidal flow makes resulted in wide and winding tidal creeks. The width of the intertidal flat in the sinuous coast narrows from 7 km to 2.6 km, with a mean value of approximately 6.5 km, and the slopes range from 0.6‰ to 1.7‰ (Chen et al., 2018).

The study area is controlled by a semidiurnal tide with a tidal range of 1.7 - 4 m (Gong et al., 2012a). The significant tidal asymmetry indicates that flood tide is the dominant factor driving net sediment transport, which controls morphological changes

in the intertidal area. Waves in this region are very weak, as most of the wave energy is attenuated on the shallow water mudflats due to friction effects. The effective wave height in the study area is less than 1.0 m in winter and less than 0.5 m at other times (He et al., 2010).

Fig. 1. Location map of the study area showing the distribution of the tidal gauge stations and elevation measurement transects. The background image is a HJ-1B satellite CCD false-colour image acquired at Beijing Time (GMT+08:00) 09:28:37, March 30, 2014.

3 Materials and data

Satellite remote sensing imagery and sequential tide height data from controlling

tidal gauges were used for slope estimation. Independent ground-based bathymetric observations were simultaneously acquired and used to validate the accuracy of the slope estimates retrieved from satellite image data.

3.1 Satellite images

Owing to the hazardous ground survey conditions caused by dynamic tidal processes and muddy natural environments, ground observations of the intertidal terrain are rare. On the Jiangsu coast, the latest large-scale in situ survey was conducted from 2007 to 2008 (Chen et al., 2010). To match this time period, 14 Landsat-5 Thematic Mapper (TM) images acquired at different tidal height conditions were collected (Table 1). Among these images, 6 scenes imaged in 2007 covered the straight coast section from the Sheyang Estuary to the Liangduo Estuary, and 12 scenes from 2007-2008 covered the sinuous coast from the Liangduo Estuary to the Lianxing Port. All these images were atmospherically corrected using the Envi5.3 FLAASH module and registered to the UTM North 51 (WGS84) projection system by image-to-image registration, with a geo-rectification error less than 0.2 pixels.

3.2 Tidal height data

In this study, five tidal gauge stations along the Mid-Jiangsu coast were selected to determine the elevation of the waterlines extracted from the remote sensing images. From north to south, they were respectively the Sheyangzha (SYZ), Xinyanggang (XYG), Dafenggang (DFG), Liangduohezha (LDHZ), and Lvsigang (LSG) stations (Fig. 1). A month-long tidal height data observed with a half hour frequency at these

tidal gauge stations during 2007 and 2008 were acquired. They were used for tidal harmonic analysis to count the harmonic parameters at these stations (Munk et al., 1966).

3.3 Ground elevation data

In May 2007 and October 2008, profile elevation data from 29 transects were measured on-site under the 1985 National Height Datum (Fig. 1). Among them, 11 transects (labelled JD27 to JD37) are located on the straight coast section, and the other 18 transects (JD38 to JD56, excluding JD53) are located on the sinuous coast section.

The in situ elevation measurement covering the landward edge of the intertidal flat to the subtidal zone was divided into two parts (Chen et al., 2010). (1) The upper part of the transect in the intertidal zone, which was exposed during the mean spring low tide conditions, was investigated on foot using a Z-MAX GPS-RTK positioning system with real-time kinematic position accuracies of 0.010 m (horizontal) and 0.020 m (vertical) and a measuring interval along the transect line of 50 m. (2) The lower part of the transect, which was covered with shallow water during the mean spring high tide, was measured using a shipboard acoustic echo sounder and a GPS-RTK system for positioning. The measuring distance along the transect line was set to 10 m. After the tide level was corrected for water depth, the vertical accuracy for the shallow water terrain measurement was better than ± 0.01 m. The two surveys were combined to form the elevation profiles. As the elevation profile data were collected,

sections between the highest and lowest tidal levels were intercepted for in situ
intertidal flat slope calculation and estimated slope validation.

Table 1

Summary of images and the estimated tidal height at the time of satellite overpass.

Image acquisition date	Image acquisition time (GMT+08:00)	Plain-form shape of the coast covered	Tidal height at image acquisition time /m (Zero Point height datum of the abandoned Yellow River)				
			SYZ	XYG	DFG	LDHZ	LSG
2007/9/21	10:23:49	Straight	0.61	0.82	0.59	1.88	—
2007/8/20	10:24:05	Straight	0.08	-0.02	-0.76	1.15	—
2007/7/28	10:18:33	Sinuuous	—	—	—	2.07	1.68
2007/6/17	10:24:48	Straight & Sinuous	1.93	1.59	1.46	0.72	-0.17
2007/4/7	10:19:50	Sinuuous	—	—	—	0.98	-0.77
2007/3/29	10:25:40	Straight & Sinuous	0.36	0.55	0.79	1.97	2.03
2007/2/2	10:19:58	Sinuuous	—	—	—	1.03	1.49
2007/1/24	10:25:42	Straight & Sinuous	0.03	-0.31	-1.34	0.78	-1.43
2007/1/8	10:25:37	Straight & Sinuous	0.53	0.22	-0.42	0.84	-0.66
2008/12/5	10:08:55	Sinuuous	—	—	—	1.35	-0.22
2008/11/19	10:08:24	Sinuuous	—	—	—	1.29	-0.59
2008/10/18	10:09:00	Sinuuous	—	—	—	0.79	-0.53
2008/5/11	10:13:38	Sinuuous	—	—	—	1.06	-1.03
2008/4/25	10:14:03	Sinuuous	—	—	—	1.07	-0.79

4 Methods

4.1 Waterline extraction, discrete and tidal height assignment

The ‘waterline’ is defined as the boundary between a water body and an exposed tidal flat in a remotely sensed image (Ryu et al., 2008). Using the location and height information from a series of waterlines observed under different tidal stages, we can describe the surface undulation and slope variation characteristics of the intertidal flat. Prior to slope estimation, three basic processes are essential: (1) waterline extraction; (2) discrete waterlines to points; and (3) the association of tidal heights to discrete

points.

4.1.1 Waterline extraction

We used the combined processes of water index enhancement and Sobel edge detection to extract waterlines from the pre-processed Landsat-5 TM images. The normalized difference water index ($NDWI = (R_{Green} - R_{NIR}) / (R_{Green} + R_{NIR})$) (McFeeters, 1996) and the modified normalized difference water index ($MNDWI = (R_{Green} - R_{SWIR}) / (R_{Green} + R_{SWIR})$) (Xu, 2006), were chosen as a indice to increase the image greyscale contrast between the exposed intertidal flats and the water body, where R_{Green} , R_{NIR} , and R_{SWIR} are the spectral reflectance of the green, near-infrared, and shortwave infrared bands, respectively. On the muddy intertidal coast of the Mid-Jiangsu Province, tidal height conditions were the primary criteria for water index selection. In an image where the water was at high tide, we found that both indices were able to discriminate between water and non-water. However, due to the strong absorption of SWIR compared to VIR in turbid seawater, the MNDWI produced a stronger tonal contrast than NDWI and was more conducive to water body separation. While the water was at the middle to low tide, NDWI-based enhancement was more effective than MNDWI-based enhancement for waterline extraction. The reason was that the SWIR band was sensitive to the sediment moisture and remnant water on the exposed muddy flat surface, which led the water boundary on the enhanced MNDWI image more landward than the actual and had larger location errors (Ryu et al., 2002).

After the satellite images were enhanced by the selected water index, density slicing and edge detection were performed to extract the vector format waterlines. When an appropriate threshold was determined for the water index image, a binary file with pixel values for the water body of 1 and others of 0 could be generated. Then, a Sobel Edge Detector embedded in the Envi5.3 software package was used to detect the approximate absolute gradient magnitude at each pixel from the binary file to locate the edge of the water body. Since the Sobel operator is an isotropic 3×3 gradient operator, the resulting grid-format waterlines usually have a normal width of two pixels respectively representing land and sea pixels. A vector format waterline was then obtained by extracting its midline to avoid the dilemma of selecting land or sea boundary pixels as waterlines from grid-based waterline extraction methods. Finally, waterlines were visually inspected and corrected manually where breaks and unintentional small branches in the waterlines occurred.

4.1.2 Discrete waterlines to points

The slope of the muddy intertidal flat was estimated on a series of transect lines across the coast. As the waterlines and the transect line were all vector lines, it was easy to obtain the intersection points between them for further slope calculation. First, we drew a baseline positioned near the highest tidal level, which was at the landward side and roughly parallel to all the waterlines (Chen et al., 2018). Then, assuming that the intertidal flat slopes along the coast did not change dramatically, the transect lines were designed according to the plane-form shape of the coast. On the straight coast, a

transect line was drawn every 500 m approximately perpendicular to the baseline. In the sinuous coast, the transect lines were radially distributed and approximately vertical to the curved baseline. Then, by extracting the intersection between the waterlines and the transect lines, the waterlines were separated into a series of discrete points. In the direction along the transect lines, these discrete points were expected to have the largest height decline gradients, which could be used to describe the terrain variation characteristics ranging from the land to the sea.

4.1.3 Tidal height interpolation

Since the latitudinal span of the study area from the Sheyang Estuary to the Lianxing Port reaches 2.12 degrees, the tidal-wave deformation and Earth curvature change-induced spatial variation in water height over such a long distance could not be neglected (Wang et al., 2010), which meant that the discrete points from waterlines would have varied elevations. Classical tidal harmonic analysis is a point forecast model used to obtain the tidal height at any designated time and location. Critically, it does not depend on long-term and continuous on-site tidal height observation data (Munk et al., 1966). This makes it particularly suitable for the determination of tidal heights in muddy intertidal flats where there are generally few tide observation gauges or gauges with only short-term observation data.

According to the influence of the tidal component on the study area, the following eight major tidal harmonic constituents, namely, K_1 , O_1 , M_2 , S_2 , N_2 , K_2 , M_4 , and MS_4 , were selected for tidal height calculation (Sha et al., 2019). As we input the

tidal harmonic constituents, station latitude and satellite overpassing time into the T_TIDE MATLAB package (Pawlowicz et al., 2002), the tidal height at the image acquisition time could be simulated. The results are shown in Table 1. Validated by the observed tidal heights of the LSG tidal gauge station over July 12-21, 2008, the RMSE for the tidal height simulation was less than 15 cm, with a correlation coefficient r reaching 0.99. Since the tidal heights at the five gauge stations during the image acquisition period were obtained, the elevation of those discrete points from vector format waterlines could be assigned by latitudinal linear interpolation along the coast (Chen et al., 2018).

4.2 Slope estimation method

We suggest that the plane-form shape of the coast is the key criterion in selecting the method for determining the slopes in intertidal flats. Dividing the coast into straight and sinuous coasts by the shape of the delineated waterlines, slope retrieval was performed using either the profile morphology discriminant inferential (PMDI) method or DEM-based method (Fig. 2).

Fig. 2. Flow diagram of the slope estimation strategy in muddy intertidal flats based on the plane-form of the coastline.

4.2.1 Two-Temporal Average Gradient (TTAG) method

The traditional TTAG method was applied for estimating the slope on the straight coast to compare its efficiency with that of the PMDI method. For a broad and flat muddy coast, terrain variations from land to seaward will be approximately uniform. Based on the equiangular triangle theory, the TTAG method simulates the slope of the coast using spatially separated waterlines extracted from two-temporal satellite images with relatively large tidal height intervals (Liu et al., 2013b). The corresponding formula is as follows:

$$S = \frac{\Delta H}{\Delta L} \quad (1)$$

where S is the slope of the coast and ΔH and ΔL are the height difference and positional difference of these two waterlines, respectively.

4.2.2 Profile Morphology Discriminant Inferential (PMDI) method

In straight coast sections, the PMDI method is suitable for slope calculations owing to its consideration and fitting of varied profile shapes. This method included two steps: (1) mudflat profile shape discrimination and (2) profile curve fitting and slope calculation.

To determine the approximate profile shape for a coastal transect, three discrete points intersecting between the transect line and three evenly distributed waterlines of the intertidal flat are initially selected, which are referred to as the landward, intermediate, and seaward points (Fig. 3). Their positions and heights are defined as (L_1, H_1) , (L_0, H_0) , and (L_2, H_2) , where L represents the horizontal distance between these discrete points and the origin point, and H is their corresponding tidal elevations. The origin point is the intersection of the transect line and the baseline (Chen et al., 2018). A linear discriminant equation, $H = a \cdot L + b$, is then established to calculate linear relationship coefficients a and b by the point values of (L_1, H_1) and (L_2, H_2) on the land and sea sides. This is used to calculate the estimated tidal height H^* at the position of the intermediate point with the horizontal distance L_0 as the input. Taking the average error Δ as the judging criterion, when $|H^* - H_0| \leq \Delta/2$, the profile is considered to be of a gentle slope type. When $H^* - H_0 > \Delta/2$, the profile is of the erosional concave type. When $H^* - H_0 < -\Delta/2$, the profile is of the deposited

convex type. In general, the average error Δ is set as 15 to 20 cm, which is 1 to 1.33 times the RMSE of the tidal height harmonic simulation in the study area.

Fig. 3. Profile discrimination diagram for muddy intertidal flats.

For different types of tidal flat profiles, five evenly distributed discrete points along the transect line are sufficient to retrieve the profile. No significant improvement in the estimated slope is achieved by increasing the number of intersecting points. Sha et al. (2019) found that the single exponential decay function is most suitable for erosional concave type profiles, the linear fitting function for gentle slope types, and the second-order polynomial function for depositional convex type profiles. After the approximate shape of each transect is determined, these functions are then used to fit the actual profiles of tidal flat surfaces. The positions and elevations are recorded for the discrete points extracted from the profile fitting curve along the direction of the transect line with equal distance intervals of 50 m.

The profile slope can be calculated using the following formula:

$$S = \frac{(\frac{h_0-h_1}{l_1} \cdot s_1 + \frac{h_1-h_2}{l_2} \cdot s_2 + \dots + \frac{h_{n-1}-h_n}{l_n} \cdot s_n)}{(s_1 + s_2 + \dots + s_n)} \quad (2)$$

where n is the number of discrete points; $h_0, h_1, h_2, \dots, h_n$ are the corresponding elevation values of these points, and $l_1, l_2, \dots, l_n$ and $s_1, s_2, \dots, s_n$ are their horizontal projection distances and actual surface distances, respectively.

4.2.3 DEM-based slope calculation method

On a sinuous coast, a DEM-based approach is suggested for slope estimation. The vector format waterlines are spatially separated into discrete points at an interval of 50 m. Tidal heights at the time of image acquisition are linearly interpolated from their neighbouring tidal gauge stations and assigned to each of them. They are used to create a triangulated irregular network (TIN) implemented within the ArcGIS 3D Analyst toolbox (Sagar et al., 2017). The TIN model is further converted to a raster format DEM with a 30 m spatial resolution to represent the undulation of the intertidal flat surface. Since the DEM is constructed from the vector waterlines and converted to a regular cell-based raster grid, there is no requirement to include the original intersection points in the dataset as they have been submerged and smoothed during the generalization process of the DEM terrain surface. By overlapping the preset transect lines on the generated DEM, the corresponding sets of (x, y, z) point data with an equal interval of 50 m are easily extracted. The slopes for sinuous coast sections at different locations can be estimated using formula (2).

5 Results

Four indices were used for the comparison of slope estimation results between

the remote sensing-based methods and in situ observed data: root mean square error (RMSE), mean absolute error (MAE), mean relative error (MRE), and correlation coefficient (r).

5.1 Slope in Mid-Jiangsu intertidal coast

Using the data described in section 3, intertidal flat slopes for the Mid-Jiangsu coast were estimated by the PMDI method on the straight coast and the DEM-based method on the sinuous coast. They were compared to the in situ measured slope data (Fig. 4(a)). Since the transects used for slope estimations did not coincide with the surveyed profiles, the slopes of those transect lines that were closest to both sides of the measured transects were averaged to evaluate the accuracy of the estimated slope.

Fig. 4. Comparison of the estimated and measured slopes along the Mid-Jiangsu coast.

(a) shows the slopes estimated by the PMDI method on the straight coast and the DEM-based method on the sinuous coast, and (b) and (c) show the correlations between the estimated and measured slopes on the straight coast and sinuous coast, respectively.

5.2 Slope estimation accuracy in straight coast

In this section, the in situ measured slopes, together with the estimated results by

the TTAG method, were used to assess the slope estimation accuracy of the PMDI method.

5.2.1 Accuracy assessment of the PMDI method

On the straight coast from the Sheyang Estuary to the Liangduo Estuary, the slope estimated by the PMDI method ranged from 2.22‰ in the north to 0.24‰ in the south, showing steeper slopes in the north and flatter slopes in the south, which was consistent with the variations in the in situ measurements (see the upper part of Fig. 4(a)). There was a good linear correlation between the estimated results and in situ observed results ($r=0.71$, Fig. 4(b)). The MAE, RMSE, and MRE of the slopes estimated by the PMDI method were 0.34‰, 0.44‰, and 30.42%, respectively. The estimated average slope (0.94‰) was slightly smaller than the in situ measured slope (1.11‰). Benefitting from curve fitting processing, there was generally good agreement between the measured profiles and the profiles estimated using the PMDI method (Fig. 5(a)). Among the 11 transects on the straight coast, JD27 and JD28 were located in the erosional-depositional transition zone near the Sheyang Estuary. The strong tidal wave deformation caused by the estuarine topography introduced relatively larger errors in the tidal prediction. So the estimated tidal heights at the discrete waterline points for these transects were higher than the in situ elevation, especially at the upper intertidal flat. However, as a commonly used index, the slope showed the height difference of the terrain under a certain horizontal distance. The overestimation of tide heights for all discrete points will maintain a similar height difference and have a slight impact on slope estimation. Transects JD29 to JD32 were

467 located between the Xinyang Port and the Dafeng Port. This area belongs to the core
468 area of a nature reserve, which has been designated for protecting red-crowned cranes.
469 Without human activities in this intertidal zone, it is in a state of continuous silting,
470 and the profile shape belongs to a depositional convex type. There is a good level of
471 agreement between the measured and estimated profiles here with a MRE of less than
472 10% in comparison with the in situ measured slopes. This contrasts with transects
473 JD34 to JD37 between the Dafeng Port and the Dongtai Estuary, where the tidal flat
474 surface is characterized by many slender tidal creeks. The terrain of the measured
475 profiles shows considerable undulation, and the winding shape of the waterlines has a
476 significant influence on the accuracy of slope estimations, with larger MRE values (>
477 60%) found here.

Fig. 5. Comparison between measured (black curves) and simulated profiles. (a) Profiles simulated by the PMDI method (red dotted curves) for transects JD27 to JD37 along the straight coast. (b) Profiles obtained from the DEM-based method (red curves) for transects JD 38 to JD56 along the sinuous coast. (c) Distribution of the

waterlines and the measured transects along the straight coast. (d) The DEM and the location of measured transects along the sinuous coast.

5.2.2 Accuracy comparison with the TTAG method

To compare the slope estimation accuracy on the intertidal flat and validate the broad applicability of the PMDI method, among the five evenly distributed waterlines used for profile curve fitting, two of them located at the landward and seaward sides were selected for calculating average slope using the TTAG method. Compared to the in situ measured slope, the TTAG results also showed a strong linear correlation ($r=0.7$), which was very close to that of the PMDI method. The MAE, RMSE, and MRE values were 0.37‰, 0.54‰, and 39.28%, respectively. Comparing the TTAG method, slopes estimated by the PMDI method increased in accuracy, with decreases of 0.03‰, 0.10‰, and 8.86% for the MAE, RMSE, and MRE, respectively. The improved accuracy was caused by the use of profile shape judgement and curve fitting. Owing to the discriminative treatment for different profile shapes, the PMDI method shows good potential for slope estimation and slope-change monitoring in muddy intertidal areas along straight coastlines.

5.3 Slope estimation accuracy in sinuous coast

On the sinuous coast, from the Liangduo Estuary to Lianxing Port, good agreement between the measured and estimated slope values was found, with a linear correlation value r reaching 0.94 (Fig. 4(c)). The estimated slopes ranged from 0.24‰

to 5.94‰, which were slightly larger than the measured slopes, which varied from 0.36‰ to 4.95‰. Compared with the measured slope values, the MAE, RMSE, and MRE of the slopes by the DEM-based method were 0.74‰, 0.56‰, and 39.09%, respectively. They were slightly larger than the estimates calculated using the PMDI method in the straight coast section due to the more complex terrain present in this region. Transects with larger errors (i.e., MRE greater than 60%) were concentrated within the region ranging from JD40 to JD44.

Fig. 5(b) shows the comparison of the profiles obtained by the DEM-based method with the in situ measured profiles along the sinuous coast. The slope exhibited an increasing trend from north to south, owing to the gradual reduction in shore silting capacity and the narrowed shore width. Transects JD38 to JD47 were located between the Liangduo Estuary and the Yaowang Port. Tidal flats here are generally wide with many large meandering tidal creeks distributed on a flat surface. Owing to the lack of satellite imagery at dates/times with high tidal elevations, the selected waterlines did not cover the entire intertidal flat. Consequently, the upper region of the constructed DEM near these two transect areas could only adequately cover the middle of the intertidal flat. As a result, the estimated slopes only represented the middle to lower portions of the transects. These profiles are mostly of the lower concave type, and the upper parts of the coastal profiles were always steeper. Thus, the estimated slopes in this wide intertidal flat were approximately 56% smaller than the measured slopes (Fig. 4(a)). Based on the long-term series of satellite remote sensing image data analysis, it was found that sun-synchronous satellites, such as Landsat, only observe a

limited portion of the true tidal range at any given location and exhibit strong biases in this spatial range (Bishop-Taylor et al., 2019; Sagar et al., 2017). Therefore, finding an effective method to construct a DEM that covers the entire intertidal flat is important to further improve the accuracy of intertidal flat slope estimations.

In the area south of the Xiaomiaohong water channel, the construction of artificial seawalls has stabilized tidal flat growth. Here, the intertidal flats became narrower, and the slopes became steeper. At transects JD49 to JD56, the DEM constructed from sequential images covered all intertidal flats. The estimated and measured profiles were in good agreement. The estimated slopes were 17.6% larger than the measured slopes, indicating that the accuracy of the estimated slopes was significantly better than that of their northern neighbouring transects.

6. Discussion

6.1 Point set selection for slope estimation

In the straight coast section, although in most cases the waterlines were relatively straight and parallel, there were still some sinuous waterlines around the estuaries and wide tidal creeks. These factors strongly influenced the slope estimation by the PMDI method. Taking transect JD37 located near the Dongtai Estuary as an example, the local intertidal flat is broad and gentle, and tidal channels are well developed. Here, the delineated waterlines are obviously sinuous and concave to the landward side (Fig. 6). Thus, intersection points between a single waterline and the transect line may not be unique. Although the actual tidal height differences between these intersection

points are small enough to be ignored, their position differences are relatively large. When different discrete points are chosen for slope calculation, different slope results are obtained, which will cause unpredictable errors in the profile slope estimations.

Fig. 6. Sinuous waterlines distributed near the Dongtai Estuary. (a) Five sinuous waterlines labelled A to E from land to sea and (b) an enlarged map indicating measured transect JD37 and the distribution of the intersecting points on transect lines 639 to 642. The number sequence of these points on each waterline is from north to south. If there is more than one intersecting point between the transect line and the waterline, their number sequences are from sea to land.

In the measured profile JD37 (Fig. 6), intersection points on the three transect lines from 640 to 642 were chosen to estimate the slope difference derived from different point selection scenarios. There are 7, 15, and 7 intersection points between

the sinuous waterlines and the transect lines of 640 to 642, respectively. These points are distinguished as landward point, middle points, and seaward point depending on the distance between the point and the land. According to their locations, the point selection is grouped into three scenarios: all points are selected from the landward side (S1), all are selected from the seaward side (S2), and all are selected from the middle (S3). Thus, for discrete points selected from land to sea, there are many permutations to calculate the slope for each transect line. Table 2 lists the 9 permutations of the point set for transect lines 640 to 642 and their corresponding slope results. Comparing the three scenarios, the slope results from scenarios S1 and S2 have better estimation accuracy than scenario S3. For scenarios S1 and S2, they all have a permutation of point set along different transect lines with an estimated slope of 0.45‰, which is close to the measured slope of 0.55‰. Further comparing scenarios S1 and S2, the slope estimated by scenario S1 is better than that estimated by scenario S2, as it is closer to the measured slope value.

Table 2

Slope results by different point permutations under three-point selection scenarios.

Point selection scenario	ID of the transect line	Point permutation (from land to sea)	Estimated slope of each transect line (‰)	Average slope at JD37 (‰)
<u>S1: all points selected from the landward side</u>	640	A4-B2-C2-D2-E2	0.05	0.22
	641	A7-B5-C5-D5-E5	0.19	
	642	B8-A8-C6-D6-E6	0.45	
<u>S2: all points selected from the seaward side</u>	640	B2-A2-C2-D2-E2	0.45	0.19
	641	A5-B3-C3-D3-E3	0.03	
	642	A8-B6-C6-D6-E6	0.10	
<u>S3: all points</u>	640	A3-B2-C2-D2-E2	0.04	0.10

selected from the	641	A6-B4-C4-E4-D4	0.15
middle	642	A8-B7-C6-D6-E6	0.11

580

581 Therefore, considering the morphological characteristics of the shore, three
582 principles for selecting discrete points along a transect line are proposed as follows: (1)
583 for one waterline with several alternative points with similar tidal heights, the point
584 closest to the landward side is better; (2) the relationship between the tidal height and
585 the position of the candidate points should be considered, that is, the point of high tide
586 level should be close to the landward side, and the point of low tide level should be
587 close to the seaward side; and (3) if the above conditions are not satisfied, the discrete
588 points to which the tidal height and location are coordinated should be spaced as
589 evenly and far apart as possible.

590

591 **6.2 Robustness of the PMDI method**

592 **6.2.1 Waterline data sensitivity for the TTAG method**

593 For the TTAG method, the slope estimation results are sensitive to the two
594 selected waterlines if more waterlines are available. In this test, for the five spatially
595 distributed waterlines in the straight coast analysis, the seaward waterline was set as
596 the base waterline, and another waterline was chosen among the other four landward
597 waterlines orderly from land to sea to examine the stability of the TTAG method in
598 the mudflat near the Doulong Port. The results show that the more smaller the
599 distance between two discrete points is, the larger the variation in the estimated slope
600 (Fig. 7), The RMSE, MAE, and MRE increase rapidly from 0.5‰ to 17‰, 0.4‰ to

5%, and 40% to 700%, respectively. The correlation coefficient also decreases quickly from $r=0.7$ to $r=-0.23$. Therefore, the TTAG method exhibits low robustness and requires two waterlines with large tide height differences and long distances to better estimate the slope.

Fig. 7. Slope estimation accuracy changing trends for the TTAG method with the replacement of one of the two waterlines. Taking the seaside waterline on January 24, 2007 as the base waterline, (a), (b), (c), and (d) show the status that the second waterline is orderly closer to the base waterline. (e) is the variation trends of r and RMSE. (f) is the variation trends of MRE and MAE.

6.2.2 Waterline data sensitivity for PMDI method

Since five waterlines are needed for profile curve fitting in the PMDI method, we chose an additional waterline with a middle tidal height for a waterline replacement

test to examine the slope's sensitivity to using different waterlines. A waterline derived from an image acquired on September 21, 2007 was replaced by a waterline imaged on March 29, 2007. Curve fitting and slope estimations were performed again for each transect by the PMDI method (Fig. 8). After the replacement of a middle waterline, the MAE, RMSE, and MRE of the slope for transects JD27 to JD37 were 0.28‰, 0.42‰ and 27.15%, respectively. These values were similar to those seen before replacement (section 5.2.1). In addition, the correlation coefficient between the two slope results before and after the replacement of the waterline ($r = 0.92$) still shows good agreement. Spatially, only JD27 and JD28 showed a large difference in the resulting slope (Fig. 8), which was caused by the narrower width of the intertidal flat in these two transects. The other transects were not significantly influenced by the replacement of the waterline. Thus, the PMDI method exhibited a higher degree of robustness and relative insensitivity to the choice of waterlines than the TTAG method.

Fig. 8. Slope results of the PMDI method at transects JD27 to JD37 before and after a middle waterline is replaced. (a) The original distribution of five waterlines. (b) Distribution of waterlines in which the pink waterline is replaced by a green waterline.

6.3 Strategy for slope estimation methods selection

Due to varied hydrodynamics and sediment depositional movements, muddy tidal flats exhibit different plane-form shapes in the along-shore direction and apparent morphological undulation in the cross-shore direction. Therefore, to obtain more accurate profile slope results, different methods are required according to the morphological characteristics of the tidal flat. As summarized in Table 3, if waterlines along the coast are relatively straight and smooth, the PMDI method performs well

due to its high robustness and good profile shape adaptability. When the distance between the two selected waterlines is large and the tidal flat surface is gentle, the TTAG method can be used. However, although this method is simpler than the PMDI method in terms of the calculation and data requirements, we have demonstrated that its sensitivity to waterline selection cannot be ignored. In more sinuous coastal regions, the DEM-based method can better estimate tidal flat slopes and simulate profile shapes. However, this method requires more waterlines.

Table 3

Comparison of methodological advantages and disadvantages of different methods for tidal flat slope calculation.

Slope estimation method	Assessment indicator				Suitable coastal type
	Number of waterlines	Operational complexity	Calculation effectiveness	Robustness	
TTAG method	2	Simple	Fast	Low	Straight and gentle
PMDI method	5	Simple	Fast	High	Straight
DEM Method	More	Complicated	Slow	High	Sinuous

7. Summary and conclusion

Based on waterlines taken from sequential satellite images and their tidal height information, the slopes of the intertidal zone of the Mid-Jiangsu coast with different profile morphologies were calculated using the PMDI method and the DEM-based method. In summary, the following conclusions can be drawn:

- (1) The accuracy of slope calculation in the straight coast by the PMDI method is

higher than that of the traditional TTAG method. The robustness of the PMDI method is definitively improved, without any obvious increase in inconvenience, by tidal flat profile discrimination and curve fitting. Therefore, the PMDI method is suitable for slope estimation in muddy coasts for relatively smooth and straight waterlines. Comparatively, the TTAG method is only appropriate to simulate slope change in intertidal flats that are broad and gentle.

(2) The DEM-based method was suitable for calculating tidal flat slopes in sinuous coastal sections. However, there are a few disadvantages to using this method, such as the requirement of more waterlines to express the details of tidal flat surface terrain undulation and cover the whole area of the intertidal flat, which increases the complexity of the analysis.

(3) An average slope of 0.96‰ is derived for the intertidal flat on the muddy mid-Jiangsu coast by satellite remotely sensed data. From the Sheyang Estuary to the Lianxing Port, the slopes exhibit a steep-slight-steep spatial pattern from north to south. This trend estimated by remote sensing data is in agreement with the in situ observed results.

Overall, this work highlights the potential of deriving robust estimates of muddy intertidal flat slopes and topography from satellite remotely sensed data and suggests an appropriate strategy for selecting a slope estimation method according to the morphology of the coast, which may be applicable to other settings and coasts around the world.

Acknowledgement

This work was supported by the National Natural Science Foundation of China [grant numbers NO.41771447; U1609203], and the sponsorship of 2019 Jiangsu Overseas Visiting Scholar Program for University Prominent Young & Middle-aged Teachers and Presidents. The author would like to thank the USGS for providing the Landsat series images freely.

Conflict of Interest

None declared.

Reference

- Bishop-Taylor, R., Sagar, S., Lymburner, L., Beaman, R.J., 2019. Between the tides: Modelling the elevation of Australia's exposed intertidal zone at continental scale. Estuar Coast Shelf Sci, 223, 115-128. <https://doi.org/10.1016/j.ecss.2019.03.006>
- Chen, J., Wang, Y., Cai, H., 2010. Profile characteristics study of the Jiangsu coast. *The Ocean Engineering*, 28(4), 90-96. <https://doi.org/10.16483/j.issn.1005-9865.2010.04.009>
- Chen, W., Chang, H., 2009. Estimation of shoreline position and change from satellite images considering tidal variation. *Estuar Coast Shelf Sci*, 84(1), 54-60. <https://doi.org/10.1016/j.ecss.2009.06.002>
- Chen, W., Zhang, D., Cui, D., Lv, L., Xie, W., Shi, S., Hou, Z., 2018. Monitoring spatial and temporal changes in the continental coastline and the intertidal zone

- 706 in Jiangsu province, China. *Acta Geogr Sin*, 73(7), 1365-1380.
 707 <https://doi.org/10.11821/dlxb201807014>
- 708 Choi, J.K., Ryu, J.H., Lee, Y.K., Yoo, H.R., Woo, H.J., Kim, C.H., 2010. Quantitative
 709 estimation of intertidal sediment characteristics using remote sensing and GIS.
 710 *Estuar Coast Shelf Sci*, 88(1), 125-134.
 711 <https://doi.org/10.1016/j.ecss.2010.03.019>
- 712 Eisma, D., 1998. Intertidal deposits: river mouths, tidal flats, and coastal lagoons (Vol.
 713 16). CRC Press. <https://doi.org/10.1201/9780138750308>
- 714 Ghosh, M. K., Kumar, L., Roy, C., 2015. Monitoring the coastline change of Hatiya
 715 Island in Bangladesh using remote sensing techniques. *ISPRS J Photogramm*
 716 *Remote Sens*, 101, 137-144. <https://doi.org/10.1016/j.isprsjprs.2014.12.009>
- 717 Gong, Z., Wang, Z., Stive, M. J. F., Zhang, C., & Chu, A., 2012. Process-based
 718 morphodynamic modeling of a schematized mudflat dominated by a long-shore
 719 tidal current at the central jiangsu coast, china. *J Coast Res*, 28(6), 1381-1392.
 720 <https://doi.org/10.2112/JCOASTRES-D-12-00001.1>
- 721 He, X.; Hu, T., Wang, Y., Zou, X., Shi, X., 2010. Seasonal distributions of
 722 hydrometeor parameters in the off-shore sea of Jiangsu. *Marine Science*, 34(9),
 723 44-54 (in Chinese with English abstract).
- 724 Kang, Y., Ding, X., Xu, F., Zhang, C., Ge, X., 2017. Topographic mapping on
 725 large-scale tidal flats with an iterative approach on the waterline method. *Estuar.*
 726 *Coast. Shelf Sci*. 190, 11-22. <https://doi.org/10.1016/j.ecss.2017.03.024>
- 727 Li, C., Zhang, J., Deng, B., 2001. Holocene regression and the tidal radial sand ridge

- 728 system formation in the Jiangsu coastal zone, east China. *Mar. Geol.*, 173(1-4),
 729 97-120. [https://doi.org/10.1016/S0025-3227\(00\)00169-9](https://doi.org/10.1016/S0025-3227(00)00169-9)
- 730 Liu, Y., Li, M., Mao, L., Cheng, L., Chen, K., 2013a. Seasonal pattern of tidal-flat
 731 topography along the Jiangsu middle coast, China, using HJ-1 optical images.
 732 *Wetlands*, 33(5), 871-886. <https://doi.org/10.1007/s13157-013-0445-6>
- 733 Liu, Y., Huang, H., Qiu, Z., Fan, J., 2013b. Detecting coastline change from satellite
 734 images based on beach slope estimation in a tidal flat. *Int J Appl Earth Obs*
 735 *Geoinf*, 23, 165-176. <https://doi.org/10.1016/j.jag.2012.12.005>
- 736 Mason, D. C., Davenport, I. J., Robinson, G. J., Flather, R. A., McCartney, B. S., 1995.
 737 Construction of an inter-tidal digital elevation model by the 'Water-Line' Method.
 738 *Geophys Res Lett*, 22(23), 3187-3190. <https://doi.org/10.1029/95GL03168>
- 739 Mason, D. C., Davenport, I. J., Flather, R. A., 1997. Interpolation of an Intertidal
 740 Digital Elevation Model from Heighted Shorelines: a Case Study in the Western
 741 Wash. Estuar Coast Shelf Sci, 45, 599-612.
 742 [https://doi.org/10.1016/S0272-7714\(97\)90001-9](https://doi.org/10.1016/S0272-7714(97)90001-9)
- 743 Mason, D. C., Davenport, I. J., Flather, R. A., Gurney, C., Robinson, G. J., Smith, J.
 744 A., 2001. A sensitivity analysis of the waterline method of constructing a digital
 745 elevation model for intertidal areas in ERS SAR scene of Eastern England.
 746 *Estuar Coast Shelf Sci*, 53(6), 759-778. <https://doi.org/10.1006/ecss.2000.0789>
- 747 McFeeters, S. K., 1996. The use of the Normalized Difference Water Index (NDWI)
 748 in the delineation of open water features. *Int J Remote Sens*, 17(7), 1425-1432.
 749 <https://doi.org/10.1080/01431169608948714>

- 750 Munk, W. H., Cartwright, D. E., 1966. Tidal spectroscopy and prediction. Philos
 751 Trans R Soc Lond A, 259(1105), 533-581. <https://doi.org/10.1098/rsta.1966.0024>
- 752 Murray, N. J., Clemens, R. S., Phinn, S. R., Possingham, H. P., Fuller, R. A., 2014.
 753 Tracking the rapid loss of tidal wetlands in the Yellow Sea. Front Ecol Environ,
 754 12(5), 267-272. <https://doi.org/10.1890/130260>
- 755 Murray, N.J., Phinn, S.R., DeWitt, M. et al., 2019. The global distribution and
 756 trajectory of tidal flats. Nature, 565, 222–225.
 757 <https://doi.org/10.1038/s41586-018-0805-8>
- 758 Pawlowicz, R., Beardsley, B., Lentz, S., 2002. Classical tidal harmonic analysis
 759 including error estimates in MATLAB using T_TIDE. Comput Geosci, 28,
 760 929-937. [https://doi.org/10.1016/S0098-3004\(02\)00013-4](https://doi.org/10.1016/S0098-3004(02)00013-4)
- 761 Ryu, J.H., Won, J.S., Min, K.D., 2002. Waterline extraction from Landsat TM data in
 762 a tidal flat: A case study in Gomso Bay, Korea. Remote Sens Environ, 83,
 763 442-456. [https://doi.org/10.1016/S0034-4257\(02\)00059-7](https://doi.org/10.1016/S0034-4257(02)00059-7)
- 764 Ryu, J.H., Kim, C.H., Lee, Y.K., Won, J.S., Chun, S.S., Lee, S. 2008. Detecting the
 765 intertidal morphologic change using satellite data. Estuar Coast Shelf Sci, 78(4),
 766 623-632. <https://doi.org/10.1016/j.ecss.2008.01.020>
- 767 Sagar, S., Roberts, D., Bala, B., Lymburner, L., 2017. Extracting the intertidal extent
 768 and topography of the Australian coastline from a 28 year time series of Landsat
 769 observations. Remote Sens Environ, 195, 153-169.
 770 <https://doi.org/10.1016/j.rse.2017.04.009>
- 771 Salameh, E., Frappart, F., Almar, R., Baptista, P., Heygster, G., Lubac, B., De Michele,

- 772 M., 2019. Monitoring Beach Topography and Nearshore Bathymetry Using
 773 Spaceborne Remote Sensing: A Review. *Remote Sens*, 11(19), 2212.
 774 <https://doi.org/10.3390/rs11192212>
- 775 Sengupta, D., Chen, R., & Meadows, M. E., 2018. Building beyond land: An
 776 overview of coastal land reclamation in 16 global megacities. *Appl Geogr*, 90,
 777 229-238. <https://doi.org/10.1016/j.apgeog.2017.12.015>
- 778 Sha, H., Zhang, D., Cui, D., Lyu, L., Ni, P., 2019. Remote sensing prediction method
 779 of coastline based on self-adaptive profile morphology. *J Oceanogr*, 41(9), 170–
 780 180. <https://doi.org/10.3969/j.issn.0253-4193.2019.09.016>
- 781 Stutz, M. L., & Pilkey, O. H., 2002. Global distribution and morphology of deltaic
 782 barrier island systems. *J Coast Res*, 36(sp1), 694-708.
 783 <https://doi.org/10.2112/1551-5036-36.sp1.694>
- 784 Tseng, K.H., Kuo, C.Y., Lin, T.H., Huang, Z.C., Lin, Y.C., Liao, W.H., Chen, C. F.,
 785 2017. Reconstruction of time-varying tidal flat topography using optical remote
 786 sensing imageries. *ISPRS J Photogramm Remote Sens*, 131, 92-103.
 787 <https://doi.org/10.1016/j.isprsjprs.2017.07.008>
- 788 Warner, J. C., Sherwood, C. R., Signell, R. P., Harris, C. K., Arango, H. G., 2008.
 789 Development of a three-dimensional, regional, coupled wave, current, and
 790 sediment-transport model. *Computer & Geosciences*, 34, 1284-1306.
 791 <https://doi.org/10.1016/j.cageo.2008.02.012>
- 792 Wang, Y., Healy, T., and Members of SCOR Working Group 106, 2002. Definitions,
 793 properties and classification of muddy coasts. In Healy, T.R., Wang, Y., and

- 794 Healy, J.A. (eds.), *Muddy Coasts of the World: Processes, Deposits and Function*.
 795 Amsterdam: Elsevier, 9-18. [https://doi.org/10.1016/S1568-2692\(02\)80076-6](https://doi.org/10.1016/S1568-2692(02)80076-6)
- 796 Wang, Y., Zhu, D., 1994. Tidal flats in China. *Oceanology of China Seas*, Springer,
 797 Dordrecht, 445-456. https://doi.org/10.1007/978-94-011-0886-7_9
- 798 Wang Y., Liu Y., Jing S., Sun, C., Wei, X., 2019. Evolution of the topography of tidal
 799 flats and sandbanks along the Jiangsu coast from 1973 to 2016 observed from
 800 satellites, *ISPRS J Photogramm Remote Sens*, 150, 27-43.
 801 <https://doi.org/10.1016/j.isprsjprs.2019.02.001>
- 802 Wang, Z., Gao, S., Huang, H., 2010. Spatial variations of tidal water level and their
 803 impact on the exposure patterns of tidal land on the central Jiangsu coast. *ACTA*
 804 *OCEANOL SIN*, 29(1), 79-87. <https://doi.org/10.1007/s13131-010-0010-6>
- 805 Wu, W., Yang, Z., Tian, B., Huang, Y., Zhou, Y., Zhang, T., 2018. Impacts of coastal
 806 reclamation on wetlands: Loss, resilience, and sustainable management. *Estuar*
 807 *Coast Shelf Sci*, 210, 153-161. <https://doi.org/10.1016/j.ecss.2018.06.013>
- 808 Xu, H., 2006. Modification of normalized difference water index (NDWI) to enhance
 809 open water features in remotely sensed imagery. *Int J Remote Sens*, 27(14),
 810 3025-3033. <https://doi.org/10.1080/01431160600589179>

Highlights

- Proposed a strategy for slope estimation considering the intertidal flat morphology
- Slope estimated by the TTAG method is sensitive to the selection of waterlines
- The PMDI method is robust for slope estimation in straight coast with good accuracy
- The DEM-based method performs better in simulating slope changes in sinuous coast
- The estimated average slope of intertidal flats in Mid-Jiangsu Province was 0.96‰

Conflict of interest

The authors declared that they have no conflicts of interest in this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Authors:

Yong Zhou

Dong Zhang

Mark E. J. Cutler

Nan Xu

Xiao Hua Wang

Hongjie Sha

Yongming Shen