Analysis of the Use of Geomorphic Elements Mapping to Characterize Subaqueous Bedforms Using Multibeam Bathymetric Data in River System

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Received: 2 September 2020; Accepted: 26 October 2020; Published: 30 October 2020

Featured Application: This work has application in separating subaqueous dune areas from the flat bed and assessing the scouring risk associated with the pit distribution. It verifies the feasibility of applying landscape analysis methods to characterize subaqueous micro-topography.

Abstract: Riverbed micro-topographical features, such as crest and trough, flat bed, and scour pit, indicate the evolution of fluvial geomorphology, and have an influence on the stability of underwater structures and overall scour pits. Previous studies on bedform feature extraction have focused mainly on the rhythmic bed surface morphology and have extracted crest and trough, while flat bed and scour pit have been ignored. In this study, to extend the feature description of riverbeds, geomorphic elements mapping was used by employing three geomorphic element classification methods: Wood’s criteria, a self-organization map (SOM) technique, and geomorphons. The results showed that geomorphic element mapping can be controlled by adjusting the slope tolerance and curvature tolerance of Wood’s criteria, using the map unit number and combination of the SOM technique and the flatness of geomorphons. Relatively flat bed can be presented using “plane”, “flat planar”, and “flat” elements, while scour pit can be presented using a “pit” element. A comparison of the difference between parameter settings for landforms and bedforms showed that SOM using 8 or 10 map units is applicable for land and underwater surface and is thus preferentially recommended for use. Furthermore, the use of geomorphons is recommended as the optimal method for characterizing bedform features because it provides a simple element map in the absence of area loss.

Keywords: multibeam; flat bed; scour pit; Wood’s criteria; self-organization map; geomorphons

1. Introduction

Bedforms in river flows have an effect on bed roughness, flow conditions, and sediment transportation [1]. From an engineering perspective, they often present major navigation problems as they can reduce the local water depth. A large number of navigation channel regulations have been implemented and associated work has been conducted, which has changed the morphology and hydrodynamic behavior of rivers such as the Yangtze River. As bedforms are not static, it is also important to analyze them prior to laying pipelines and cables. In this respect, a multibeam
echosounding system provides high-resolution bathymetric data that show the terrain of bedforms, and extracting the features of bedforms from bathymetric data has thus been the focus of intensive research in recent years.

Many studies have focused on extracting the crest and trough of bedforms because height, wavelength, and asymmetry of bedforms provide an indication of the flow velocity and direction [2,3]. In this respect, a bedform tracking tool was developed to automatically detect the locations of crests and troughs from the curves of profiles [4–6]. In addition, Van Dijk et al. [7] used a geostatistical filter to generate crest and trough lines as a set of points from the filtered bathymetric surface, and Debese et al. [8] used geodesic morphology to extract the salient crest and trough lines of sand structures in three dimensions. However, for a flow with an increasing strength, many typical bedforms can be formed, such as ripples, dunes, anti-dunes, lower flat beds, and upper flat beds [9–11]. Flat beds are also identified as plane beds in some studies [12–14]. A flat bed is a widely spreading bedform in a river’s subaqueous environment, and it may not contain many crest and trough features. The complicated development and spatial distribution of the bedform cannot be comprehensively identified using only crest and trough. In addition, scour pits can be contained in troughs with varying elevations with manual inspection, as indicated in many studies [15–18]. Therefore, a greater detailed geomorphic element layer is required to describe the texture or roughness information of features such as flat and plane beds, and scour pits. Particularly, scour pits have an influence on the stability of underwater structures.

Studies that previous classified terrestrial landform elements were used as a reference in this study, as the elements of flat, plane, and pit can be detected via variations in the terrain using these classification methods or techniques. Wood [19] developed criteria for dividing the land’s surface into six elements (plane, pit, peak, ridge, valley, and pass) based on four morphometric parameters (slope, cross-sectional curvature, maximum curvature, and minimum curvature). Ehsani and Quiel considered the aforementioned four factors as the input vectors for the self-organization map (SOM) to classify terrain surface by training [20]. In the SOM technique, 10 elements are defined (including flat planar, gentle slope ridge, and gentle slope channel). Jasiewicz et al. used geomorphons instead of geomorphometric variables to divide the surface into flat, pit, valley, ridge, peak, shoulder, footslope, hollow, and spur elements based on the visual angle [21]. A fuzzy method [22] and an object-based method [23] have also been used to classify elements; however, they are relatively complicated to use. A few attempts have been made to apply Wood’s criteria and geomorphons in the sea environment. For example, Stefano and Mayer [24] found that the use of geomorphons was superior to Wood’s criteria for describing submarine sand waves, and Cui et al. [25] modified geomorphons to detect seafloor hill, depression, ridge, valley, shoulder, and foot-slope. However, these methods have not been used in the subaqueous environment of rivers, and the approach and features with respect to using these methods to characterize river bedforms are currently unclear.

This study aimed to conduct an experiment on extending the extraction of the following bedform features: the crest and trough of dunes, flat beds, and scour pits. Three methods, including Wood’s criteria, the SOM technique, and geomorphons, were selected to map the geomorphic elements and to describe the bedforms of the river system, as it is relatively simple to implement all these methods. Although there is no pit-related element, the SOM technique was used to characterize bedforms as it contains the description of flat, ridge, and valley.

2. Materials and Methods

2.1. Study Area and Data

The geomorphic system from the lower reaches of the Yangtze River to the estuarine delta has undergone varying degrees of adaptive adjustment in recent years. The lower reaches of Datong (located in Chizhou City) are affected by the tide of the East China Sea, and they thus belong to the tidal reach area [26]. Numerous engineering construction projects have been implemented in the
Yangtze River Estuary, and these have caused extension of the fluctuating section of the tidal zone [27]. The rise in relative sea level will ultimately lead to a rise in the tide level and changes in the dynamic conditions of the Yangtze River Estuary area. In addition, aggravation of river channel erosion in the mouth of the Yangtze River has seriously impacted the evolution of the river channel in the middle and lower reaches of the Yangtze River [28,29]. Therefore, in the past decade, many underwater micro geomorphology surveys and researches using multi-beam sounding systems have been conducted in the tidal reach area [16–18,30,31]. With respect to the importance of studying this area, the tidal reach region is also the focus of this study (see Figure 1a).

Figure 1. (a) Location of the two bathymetric survey areas in Yangtze River, (b) geomorphologic environment surrounding Chizhou Reach, and (c) that of the Yangtze Estuary. (d) Sample data for Chizhou Reach and (e) Yangtze Estuary. Six cross-sections were set in the sample zones and used to compare the water depth profiles with the distribution of mapped geomorphic elements.
Two bathymetric datasets were collected from the end and start of the tidal reach respectively, and were used as study cases (Figure 1a). The measurements of the first set were collected in Chizhou Reach within the Yangtze River (Figure 1b) where two flows converge in one direction, and the channel width ranges from 1 to 2 km (approximately), and those for the second set were collected in the North Port Channel of the Yangtze Estuary (Figure 1c) where the flow diverges in two directions and the channel width ranges from 4 to 10 km (approximately). Bathymetric point cloud data were acquired using a SeaBat 7125 multibeam system operating at a frequency of 400/200 kHz and DGPS (Differential Global Position System) -positioned. Data were input into PDS2000 software (Version 4.2.16, Teledyne RESON, Rotterdam, The Netherlands) to generate a grid model with a resolution of 1 × 1 m. Two sample zones (Figure 1d,e), both with an area of 450 × 360 m^2, were cut from the grid model and used to compare the feasibility of the three geomorphic element mapping methods. The two aforementioned zones were representative of dune and relatively flat areas. Interpretation by manual inspection separated dune areas and relatively flat areas, as shown in Figure 1d,e.

The water depth for the sample data of Chizhou Reach ranges from 6.155 to 15.761 m (Figure 1d), and the depth of the Yangtze Estuary ranges from 8.607 to 19.007 m (Figure 1e). Both sample zones contained blank areas with NODATA value that is always represented by –9999 in files in ASCII format. The actual areas excluding NODATA value were 131,041 and 138,623 m^2, respectively.

### 2.2. Wood’s Criteria

Wood [19] used morphometric parameters, including slope and three curvatures, to classify geomorphic features relating to plane, pit, ridge, channel, peak, and pass. The aforementioned four parameters were calculated based on the study of Evans [32]. Wood [19] defined a set of criteria for defining geomorphic elements by comparing the aforementioned four parameters with slope tolerance and curvature tolerance (Table 1). Slope tolerance separates flat surfaces from slopes, and curvature tolerance separates planar surfaces from ridges and channels.

| Slope              | Cross-Sectional Curvature | Maximum Curvature | Minimum Curvature | Class Output |
|--------------------|---------------------------|-------------------|-------------------|--------------|
| Slope tolerance    |                           |                   |                   |              |
| (Sloping surface)  | >Curvature tolerance      |                   |                   | Ridge        |
|                   | < – Curvature tolerance   |                   |                   | Channel      |
|                   | <Curvature tolerance      |                   |                   | Plane        |
|                   | > – Curvature tolerance   |                   |                   |              |
| <Slope tolerance   |                           |                   |                   |              |
| (Horizontal surface)| >Curvature tolerance      |                   |                   | Peak         |
|                   | < – Curvature tolerance   |                   |                   | Pass         |
|                   | <Curvature tolerance      |                   |                   | Channel      |
|                   | > – Curvature tolerance   |                   |                   | Plane        |
|                   | <Curvature tolerance      |                   |                   |              |
|                   | >Curvature tolerance      |                   |                   |              |

The GRASS GIS version 7.6.1 (GRASS Development Team, Beaverton, OR, USA) provides a tool, r.param.scale, that directly implements Wood’s criteria by adjusting the value of slope tolerance and curvature tolerance. The use of different slope and curvature tolerance settings enables the drawing of distinct geomorphic elements maps. This study aimed to determine suitable tolerance settings to be applied in extracting bedforms’ features.

### 2.3. SOM Technique

The SOM technique also calculates the four parameters referred to in Wood’s criteria; however, it combines the four parameters into an input vector to train the SOM. The SOM is a realistic model based on the function of the biological brain [33]. Formally, the SOM commonly arranges output map units in the form of one, two, or three dimensions and connects them to input vectors via weights. Close input vectors within the space are clustered into units that are also close [34,35]. This means that...
surface points can be considered to be the same geomorphic element if their input vectors are very close compared to others.

In this study, the SOM technique was used in MATLAB 2019b (The MathWorks, Natick, MA, USA) via the command “newsom.” Prior to learning, four input parameters were normalized to the range of 0–1, as indicated in previous researches [20,36]. The number of iterations affects the amount of computation required; therefore, to reduce the mapping time, it is necessary to control the iterations. The iteration values of rough tuning and fine tuning were thus set as 100 and 100, respectively. The number and combination of output map units was preset, as it is impossible to determine which number will provide a meaningful classification. Following the learning phase, the trained SOM was used to classify the geomorphic elements based on the input vectors for each cell, and the optimal number and the corresponding output were selected after analysis. One of the aims of this study was to determine a suitable map unit combination that enabled the identification of bedforms’ features.

2.4. Geomorphons

Jasiewicz and Stepinski [21] identified local geomorphic elements using local ternary patterns [37]. In this respect, a ternary pattern depicts the terrain type in the adjacent domain of the central cell through quantifying the local surface using the line-of-sight principle [38].

Using this principle, eight elevation profiles beginning in the central cell and extending to the “lookup distance” along eight principal compass directions can be drawn from the digital elevation model (DEM) to calculate the zenith and nadir angles in the central cell. Using a comparison between zenith ($\phi_{DL}^D$) and nadir angles ($\psi_{DL}^D$), Equation (1) can thus be employed to calculate a slot denoted by the symbol, $\Delta_{DL}^D$, where $D$ is the direction and $L$ is the lookup distance,

$$
\Delta_{DL}^D = \begin{cases} 
1 & \text{if } \phi_{DL}^D - \psi_{DL}^D < -t \\
0 & \text{if } |\phi_{DL}^D - \psi_{DL}^D| \leq t \\
-1 & \text{if } \phi_{DL}^D - \psi_{DL}^D > t
\end{cases}
$$

As each elevation profile has one slot, 8 slots can be calculated for a ternary pattern. Based on the numbers of (−1) and (+1) in the slots, a lookup table established by Jasiewicz and Stepinski [21] can then be used to define 10 geomorphic elements: flat, pit, ridge, valley, peak, shoulder, spur, slope, hollow, and foot-slope.

The GRASS GIS version 7.6.1 provides a tool “r.geomorphon” for implementing geomorphons. The author wrote that the geomorphons in MATLAB 2019b extend the flatness to $0^\circ$, which cannot be used as a flatness value in GRASS GIS. The flatness threshold, $t$, is a kernel parameter which influences the mapping results. Therefore, another aim of this study was to find the suitable flatness setting for bedforms’ features.

3. Results

3.1. Wood’s Criteria-Based Geomorphic Elements Mapping for Describing Subaqueous Bedforms

The local range of the surface used to calculate the morphologic parameters is limited to the size of the window. If the size is too small, such as $3 \times 3$ m, the output will be substantially influenced by meaningless roughness relating to errors; however, if the size is too large, NODATA values will be attributed to more cells near the boundary. Therefore, a reasonable size of traversing window was set as $7 \times 7$ m in this study. Slope tolerance and curvature tolerance are two key parameters controlling classification. As shown in Figure 2, a larger area is regrouped into plane when the curvature tolerance is larger, while more ridge, pit, and pass can be defined when the slope tolerance is larger. Curvature tolerance should be set within 0.005–0.05, as this can provide an output that is close to eye-based recognition of the relatively flat area.
Figure 2. Wood's criteria-based distribution of geomorphic elements with different slope tolerance in rows and curvature tolerances in columns for the sample data of (a) Chizhou Reach of the Yangtze River and (b) the Yangtze Estuary.

Six cross-sections were set (as shown in Figure 1) to draw the depth profile, and these were overlaid with identified elements, as shown in Figure 3. Cross-section 1 in the figure shows a longitudinal profile of large dunes (with a length of 19 m and height of 2 m) according to the classification of bedforms in Reference [39]. Cross-section 4 also shows the longitudinal profile of dunes on a similar scale. Cross-sections 2 and 5 show transverse profiles along the trough of dunes, respectively. Cross-section 3 shows a longitudinal profile of relatively flat bedforms (with a length of approximately 20 m and a height between 0.1 and 0.3 m), and Cross-section 6 shows a longitudinal profile of bedforms: it is basically flat and is considered to be a flat bed in this study.

Figure 3. Cont.
were considered for arranging the output map units (Figure 4). The mean slope and cross-section curvature for each map unit were calculated as coordinates to plot the units within the feature space. According to a previous study [20], the units should be concentrated in three lines that correspond to three main groups (channel, planar, and ridge) to ensure that the units are well-defined as geomorphic elements. The units can then be sub-defined by slope (such as flat, gentle slope, moderate slope, steep slope, and very steep slope).

Trough and crest are the main features in dune areas [15–18]. Using Wood’s criteria, the crest and trough were mainly represented by ridge and valley elements, as shown in Figure 3a. The widths of the ridges and valleys were determined by the curvature tolerance set: large values induced narrow ridges and valley, as shown in Figure 2. Many studies have ascertained that scour pits can be contained in the troughs of bedforms with varying elevations [15–18], and bedforms contain scour pits with diverse sizes. In the case of Wood’s criteria, the size of the pit element was determined by the curvature and slope tolerance set, as indicated in Table 1. Large slope tolerance with smaller curvature caused larger areas to be defined as scour pits, as shown in Figure 3a, where the scale of pit element was enlarged in both the longitudinal and transverse profiles with a decrease in curvature tolerance. Many studies have identified flat bed as being a typical bedform [9–11]. With Wood’s criteria, the element plane was used to indicate a relatively flat, smooth, inclined area, as shown in Figure 3b, and the value of the curvature tolerance determined the distribution of the plane elements. Using Wood’s criteria, a curvature tolerance of 0.01 can be used to filter relatively flat bedforms using plane elements. As evident from Figure 3b, a relatively smaller curvature tolerance should be used to define plane elements on a flat bed.

3.2. SOM Technique-Based Geomorphic Elements Mapping for Describing Subaqueous Bedforms

The morphometric parameters calculated under a window size of 7 × 7 m when employing Wood’s criteria were also combined into the input vector to train the SOM. When using the SOM technique, the number of output map units corresponds to the number of geomorphic elements, and the spatial arrangement form of the units can be one-, two-, or three-dimensional. Although the most reasonable number of map units is unknown, Yan et al. [36] found that two and three dimensions offer a more meaningful classification. As a result, arrangement forms including (3 2), (4 2), (2 2 2), (3 3), and (5 2) were considered for arranging the output map units (Figure 4). The mean slope and cross-section curvature for each map unit were calculated as coordinates to plot the units within the feature space. According to a previous study [20], the units should be concentrated in three lines that correspond to three main groups (channel, planar, and ridge) to ensure that the units are well-defined as geomorphic elements. The units can then be sub-defined by slope (such as flat, gentle slope, moderate slope, steep slope, and very steep slope).
Figure 4. Distribution of map units in the feature space with different numbers and arrangement map units using the self-organization map (SOM) technique for the sample data of (a) Chizhou Reach and (b) the Yangtze Estuary.

For Chizhou Reach, the suitable number of output map units was found to be 8, and the units were arranged in the form of (2 2 2), as shown in Figure 4a. Table 2 lists the suitable definitions and areas associated with each map unit. Map units 3 and 6 were given the same definition (moderate slopes, planar) because they host relatively smaller areas and are situated very close within the feature space. For the Yangtze Estuary, (5 2) was selected as the suitable arrangement of map units (Figure 4b), and map units 7 and 8 were given the same definition (moderate slopes, planar).

Table 2. Statistical results for geomorphic elements under Wood’s criteria, the SOM technique, and geomorphons.

| Method            | The Sample Data of Chizhou Reach | The Sample Data of Yangtze Estuary |
|-------------------|----------------------------------|----------------------------------|
|                   | (Map Unit)                       | Element                          | Area (m²) | Percentage (%) | Area (m²) | Percentage (%) |
| Wood’s criteria   | Plane                            | 36,586                           | 32.05     | 35,455         | 29.54     |                |
|                   | Pit                              | 3668                             | 3.21      | 4089           | 3.41      |                |
|                   | Valley                           | 30,124                           | 26.39     | 29,972         | 24.97     |                |
|                   | Pass                             | 12,188                           | 10.67     | 12,754         | 10.62     |                |
|                   | Ridge                            | 28,573                           | 25.03     | 33,267         | 27.71     |                |
|                   | Peak                             | 3029                             | 2.65      | 4496           | 3.75      |                |
|                   | Total                            | 114,168                          | 100.00    | 120,033        | 100.00    |                |
| SOM technique     | (1) Flat, planar                 | 28,645                           | 25.09     | 21,239         | 17.69     |                |
|                   | (2) Gentle slopes, channel       | 16,624                           | 14.56     | 13,209         | 11.00     |                |
|                   | (3) Moderate slopes, planar      | 8960                             | 7.85      | 14,528         | 12.10     |                |
|                   | (4) Moderate slopes, channel     | 12,308                           | 10.78     | 9517           | 7.93      |                |
|                   | (5) Gentle slopes, ridge         | 17,859                           | 15.64     | 7255           | 6.04      |                |
|                   | (6) Moderate slopes, planar      | 3232                             | 2.83      | 12,141         | 10.11     |                |
|                   | (7) Steep slopes, ridge          | 13,414                           | 11.75     | 8927           | 7.44      |                |
|                   | (8) Steep slopes, channel        | 13,126                           | 11.50     | 11,827         | 9.85      |                |
|                   | Total                            | 114,168                          | 100.00    | 120,033        | 100.00    |                |
whereas the steep slope channels are located on the lateral side of the gentle slope channel (Figure 6b). Therefore, gentle slope ridges and channels tend to be linear along crests and troughs. However, a pit element could not be identified using this technique, as shown in Figure 5 and Table 2. The SOM technique not only divided the surface into channel and ridge but also further divided these two features based on their slopes, as shown in Figure 5. Gentle slope ridges are narrow and are located on the crest of dunes, and steep slope ridges are located on the lateral side of gentle slope ridges (Figure 6a). In addition, the gentle slope channel is narrow and located on the trough of dunes, whereas the steep slope channels are located on the lateral side of the gentle slope channel (Figure 6b). Therefore, gentle slope ridges and channels tend to be linear along crests and troughs. However, a pit element could not be identified using this technique, as shown in Figure 5 and Table 2. The SOM technique indicates relatively flat bedforms with flat, planar elements that correspond to the middle curvature and lowest slope while the middle curvature and relatively large slope are related to the relatively steep planar. However, it is difficult to precisely distinguish flat beds using this technique. Moreover, when the crest and trough are very wide, the lower slope planar can be generated in the crest and trough of bedforms.

### Table 2. Cont.

| Method | The Sample Data of Chizhou Reach | The Sample Data of Yangtze Estuary |
|--------|----------------------------------|-----------------------------------|
| Element | (Map Unit) | Area (m²) | Percentage (%) | Area (m²) | Percentage (%) |
| Ridge  | 16,184 | 12.35 | Ridge  | 24,891 | 17.96 |
| Shoulder | 17,360 | 13.25 | Shoulder | 15,918 | 11.48 |
| Spur | 7361 | 5.62 | Spur | 11,827 | 8.53 |
| Slope | 28,809 | 21.98 | Slope | 29,986 | 21.63 |
| Hollow | 7238 | 5.52 | Hollow | 10,283 | 7.42 |
| Foot-slope | 17,119 | 13.06 | Foot-slope | 7054 | 5.09 |
| Valley | 11,779 | 8.99 | Valley | 13,816 | 9.97 |
| Pit | 2029 | 1.55 | Pit | 2843 | 2.05 |
| Flat | 21,858 | 16.68 | Flat | 20,679 | 14.92 |
| Peak | 1304 | 1.00 | Peak | 1326 | 0.96 |
| Total | 131,041 | 100.00 | Total | 138,623 | 100.00 |

The SOM technique not only divided the surface into channel and ridge but also further divided these two features based on their slopes, as shown in Figure 5. Gentle slope ridges are narrow and are located on the crest of dunes, and steep slope ridges are located on the lateral side of gentle slope ridges (Figure 6a). In addition, the gentle slope channel is narrow and located on the trough of dunes, whereas the steep slope channels are located on the lateral side of the gentle slope channel (Figure 6b). Therefore, gentle slope ridges and channels tend to be linear along crests and troughs. However, a pit element could not be identified using this technique, as shown in Figure 5 and Table 2. The SOM technique indicates relatively flat bedforms with flat, planar elements that correspond to the middle curvature and lowest slope while the middle curvature and relatively large slope are related to the relatively steep planar. However, it is difficult to precisely distinguish flat beds using this technique. Moreover, when the crest and trough are very wide, the lower slope planar can be generated in the crest and trough of bedforms.

![Figure 5. SOM technique-based distribution of geomorphic elements for the sample data of (a) Chizhou Reach and (b) the Yangtze Estuary.](image1)

![Figure 6. Water depth profile overlaid by SOM technique-based elements for (a) Cross-section 1 and (b) Cross-section 4.](image2)
3.3. Geomorphons-Based Geomorphic Elements Mapping for Describing Subaqueous Bedforms

Geomorphons requires that the lookup distance has a relatively large size. Jasiewicz and Stepinski [21] suggested using 50 cells, as a larger distance provided no added benefits in their study. We also used a lookup distance containing 50 cells (equal to 50 m) in this study. The function of flatness is more important, and the slot is denoted by 0 for basically horizontal surface with the difference between the nadir and zenith angle smaller than flatness. When the area of flatness is large, a greater number of slots are denoted by 0, which means that a larger area is then defined as being a flat element, as shown in Figure 7. The figures show that the flat element area is too large when flatness is greater than 4°.

![Figure 7](image)

**Figure 7.** Geomorphons-based distribution of geomorphic elements with different flatness degrees for the sample data of (a) Chizhou Reach of the Yangtze River and (b) the Yangtze Estuary.

In the case of geomorphons, ridge and valley elements were also used to represent crest and trough bedforms: their scales were determined by flatness, and they increased in accordance with decrements in flatness (Figure 8). Similarly, the size of the pit element was determined by flatness, and smaller degrees of flatness created a greater surface with low roughness into a pit element within troughs of bedforms, as indicated in Figure 8, where the scale of the pit element is enlarged in both the longitudinal and transverse profiles and the decrements in flatness relate to those in cross-sections 1, 2, 4, and 5. Geomorphons use flat element to indicate relatively flat areas under suitable flatness degrees, and a flatness degree of 2° can be used to filter relatively flat bedforms using flat elements. Cross-section 6 in Figure 8 shows that when flatness was 0°, the flat bed could be redefined as a slope element without a ridge and a valley, and Cross-section 3 shows that relatively flat bedforms were redefined as slope elements coupled with a ridge and a valley (Figure 8). It thus seems feasible to use geomorphons to distinguish flat beds from relatively flat bedforms by combining geomorphons-based element maps when flatness is equal to zero and relatively smaller.
Figure 8. Water depth profile overlaid by geomorphons-based elements for Cross-sections 1–6 under various flatness degrees.

3.4. Comparison of the Three Methods

The number and combination of map units control the mapping result when using the SOM technique, while thresholds determine the results when using Wood’s criteria and geomorphons. Table 2 lists the statistical results of elements for the three methods under suitable parameter settings. In this respect, a curvature tolerance of 0.01 and a slope tolerance of 5° is considered to be a suitable combination for separating relatively flat areas from subaqueous dunes areas when using the plane element in Wood’s criteria. In this study, 2° was set as the optimal flatness to match flat elements with relatively flat areas. For Chizhou Reach, the total area of all the geomorphic elements defined by Wood’s criteria and the SOM technique was 114,168 m², and an area of 16,873 m² provided a NODATA value or caused data loss. For the Yangtze Estuary, the total area was 120,033 m² and an area of 18,590 m² provided a NODATA value or caused data loss (Table 2). These morphometric parameters were calculated in a window of 7 × 7 m. A geomorphic element was defined as NODATA when the window contained a NODATA value (a cell of blank area). In contrast, geomorphons provided a superior result, and the area between output and input was equal.

For the description of flat bed, Wood’s criteria uses the plane element to indicate relatively flat areas, and curvature tolerance determines the distribution of the plane element, which can host a
relatively larger slope angle. The SOM technique indicates a relatively flat area with flat, planar element corresponding to middle curvature and lowest slope. Middle curvature and relatively large slope relate to relatively steep, planar areas. Geomorphons uses flat elements to indicate relatively flat areas, and the definition of flat is related to a basically horizontal surface. As a result, the percentage of flat elements (in geomorphons) is the lowest, while that of plane (in Wood’s criteria) is the largest (Table 2). For the description of scour pit, the size of the pit element is determined by the set of curvature and slope tolerance in Wood’s criteria, and by the assignment of the flatness value in geomorphons; however, it cannot be defined using the SOM technique. To describe trough and crest, the SOM technique not only divides surface into channel and ridge but also further divides them based on their slope. Gentle-sloping ridge and channel tend to be the linear crest and trough of bedforms. For Wood’s criteria and geomorphons, the crest and trough are present in an areal form, and their sizes change in accordance with slope tolerance and flatness. In comparison to the SOM technique, Wood’s criteria and geomorphons provide a relatively simple element map matching with bedforms’ features.

4. Discussion

4.1. Comparison with Terrestrial Landform Element Mapping

These three methods have different critical values for subaqueous bedforms in river systems and terrestrial landforms. Using Wood’s criteria, the DEM (Digital Elevation Model) size employed in a geomorphologically diverse region of Central Mexico was $90 \times 90$ m, and the suitable tolerances of slope and curvature were set as $6^\circ$ and 0.0001, respectively [40]. In addition, a $90 \times 90$ m DEM was used for morphologic element mapping and $1^\circ$ and 0.0005 were employed as the suitable tolerances of slope and curvature respectively, at the border of Poland, Slovakia, and Ukraine [20]. Furthermore, a DEM of $50 \times 50$ m was utilized for landform delineation in South Tyrol with slope and curvature set as $14^\circ$ and 0.002, respectively [41]. In this article, these critical values were set as $5^\circ$ and 0.01 when data in the resolution of $1 \times 1$ m were obtained via measurements in two areas of the Yangtze River. Although the slope tolerance is similar to that of other studies, the curvature tolerance is considerably larger than that used for terrestrial landforms. For geomorphons, the reported flatness in the literature varies with the area of focus; however, it essentially ranges from $0^\circ$ to $3^\circ$ [21,42–45], which is close to the $2^\circ$ used in this study.

For the SOM technique, the optimal classification was obtained when a suitable number and combination of map units were set. The optimal number of map units changed with the four input morphometric parameters, which was also mentioned in a previous study [36]. All studies have analyzed different terrain, which means that a variety of vectors have been input to the SOM. In a previous study, a suitable number of 10 map units was determined at the boundary between Poland, Slovakia, and the Ukraine [20], and 8 was suggested for use in a loess area [36]. In this research, 8 and 10 map units were used for the two samples, respectively. It thus appears that the common number of map units used is 8 or 10, although the optimal number of map units changes.

A digital terrain model obtained via remote sensing basically contains no missing data for entire regions. However, bathymetric data always contain blank areas in a general situation. The SOM technique and Wood’s criteria do not operate effectively in the presence of blank data, because their use is based on the calculation of slope, cross-sectional curvature, maximum curvature, and minimum curvature.

4.2. Limitations and Prospects

Figure 9 presents a strategy for using geomorphic elements to characterize river bedform features. In this respect, the crest, trough, flat bed, and scour pit are considered. Many of the geomorphic elements shown in Figure 9 are indicative of special geographic units in other subaqueous environments; for example, peak and pit can be used to map seafloor hills and depressions [25]. Further studies are required to determine the indicative functions of the geomorphic elements for subaqueous objects;
for example, for erosional holes, erosional flutes, sand mining holes, and sinking boats, which relate to the anthropogenic drivers of subaqueous topographical changes [18], and for bank scarps, toes, and failure, which relate to bank slope stability.

Figure 9. Strategy for describing subaqueous bedforms features using geomorphic elements in a river system.

The spatial scales of ripples in a bedform generally have lengths in the order of 0.05–0.50 m [46] and cannot be detected when using a cell size of 1 m. The bathymetric data used in this study were at a resolution of 1 × 1 m, which means that the ripples between subaqueous dunes and the flat bed were inevitably ignored. Geomorphic elements mapping using higher resolution bathymetric data are required in further studies to ameliorate this limitation. In addition, dunes often show superimposed relationships under various bedform scales [3,47], because of the effect of complex flow dynamics on different temporal and spatial scales. The bathymetric data cell size may thus need to be adjusted to identify superimposed regions on different scales.

Height, length, and direction of bedforms are important parameters relating to the dynamic features of flow [2]. Although the geomorphic elements map is not suitable for use in calculating these parameters, it provides the potential to narrow the analysis range by separating the dunes area from the relatively flat bedforms. Previous studies have inferred that subaqueous geomorphic elements have statistical relationships with the category of landforms [40,42]. Some studies have found that the spatial distribution of geomorphic elements presents a certain pattern that represents the type of landform [48,49]. As in the relationship between landform elements and landscape, all of the geomorphic elements listed in Figure 9 are meaningful for comprehensively depicting the pattern of elements and regionalizing the bedform areas; however, the development of a more detailed method remains the subject of further research. In addition, the generation of a geomorphic elements map has the great potential to be used in auto-tracking the movement of bedforms, which is significant for assessing bedform instability [50,51].

5. Conclusions

This study analyzed the use of geomorphic element mapping methods for depicting subaqueous bedforms in the Yangtze River. The main conclusions are presented as follows.

The plane element in Wood’s criteria, the flat, planar element in the SOM technique, and the flat element in geomorphons can be used to indicate the existence of relatively flat bedforms. A curvature tolerance of 0.01 in Wood’s criteria, and flatness of 2° in geomorphons, are considered to be optimal thresholds for automatically filtering relatively flat bedforms from subaqueous dunes. In addition, for the description of scour pit, the value of slope tolerance and flatness can be used to adjust the size of a pit element, which increases with a decrease in the threshold, while the SOM technique cannot extract pit. We recommend geomorphons as the optimal method for characterizing bedforms’ features, because it provides a simple element map without any loss of area.
Slope tolerance and flatness are close to the landform element classification, while curvature tolerance is far larger. The optimal number and combination of map units appears to change for different areas but is generally 8 or 10, irrespective of the bedform or landform analyzed. Therefore, with the SOM, 8 and 10 map units should be recommended in future studies.

Using the three methods, many other elements (such as spur, hollow, peak, and pass) can be extracted to reflect the detailed roughness of bedforms or other subaqueous objects (bank scarp, erosional hole, and sinking boat), and this remains the subject of future studies. The spatial distribution of geomorphic elements presents a certain pattern of elements that represents the type of bedform, and it can be used to narrow the range of morphology and dynamic analysis of bedforms.

**Author Contributions:** Conceptualization, G.Y. (Ge Yan) and H.C.; methodology, G.Y. (Ge Yan); validation, G.Y. (Ge Yan), H.C. and L.T.; formal analysis, G.Y. (Ge Yan); investigation, G.Y. (Ge Yan); resources, H.C., Y.J., G.Y. (Guoqiang Yang) and Q.Z.; data curation, L.T. and W.X.; writing—original draft preparation, G.Y. (Ge Yan); writing—review and editing, H.C.; supervision, H.C.; project administration, H.C. and Y.J. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the China Geological Survey, grant number DD20190260, NSFC-NWO-EPSRC, grant number 51761135023, and the Natural Science Foundation of China, grant number 41476075.

**Acknowledgments:** We acknowledge Shuwei Zheng, Jiahao Zhang, and Kai Hua for their assistance with conducting field survey work.

**Conflicts of Interest:** The authors declare no conflict of interest.

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