

MULTISCALE SPATIAL RELATION EXTRACTION OF A REMOTELY SENSED WATERLINE IN A MUDDY COASTAL ZONE WITH CHONGMING DONGTAN AS AN EXAMPLE

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ABSTRACT:

To address the difficulty of waterline extraction in areas with gentle slopes in the muddy coastal zone, Chongming Dongtan in the Yangtze River estuary is selected as the research object. This paper analyzes the spatial relationship of the waterline in Landsat images at three spatial scales, gives a method for numerically calculating the spatial relationship characteristics at different spatial scales and the application means in waterline extraction, and constructs a model for waterline extraction from Landsat images using the multiscale spatial relationship. Finally, the execution efficiency and positioning accuracy of the multiscale spatial relationship waterline extraction model are quantitatively evaluated. The results show that the spatial relationship is effectively used to solve the problem of discontinuous extraction of a weak waterline in the muddy coastal zone, and the waterline recognition ability for remote sensing images is significantly improved. The position accuracy of waterlines obtained by the improved method can reach 12.4 meters. Compared with other methods, this method shows great advantages in terms of automation, waterline continuity, and positioning accuracy and provides technical support for the use of remote sensing technology to study the dynamic changes in coastal zones.

1. INTRODUCTION

The waterline is the instantaneous crossover line between the undulating sea and the land under tidal fluctuations (Yi et al., 2016). It is of great significance that the information on the temporal and spatial changes of the waterline is obtained quickly and accurately. Currently, extracting waterline from remote sensing images is the main method.

The essence of obtaining the waterline from remote sensing images is edge detection, and the key technology is to realize the separation of land and sea (Mason et al., 2016). How to obtain water boundaries rapidly and accurately from remote sensing images has been actively explored by domestic and foreign professionals in different directions. Reference (Aedla et al., 2015) proposes a threshold segmentation method to extract the waterlines from remote sensing images. The threshold segmentation method is a more efficient method, and the extracted waterline is continuous and complete. However, it has higher requirements on the contrast between sea and land, and the accuracy of the extracted waterline is low. Reference (Liu et al., 2019) uses the spectral and geometric features of ground objects to extract remotely sensed waterlines by using supervised classification methods such as neural networks, support vector machines and object-oriented methods. These methods are difficult to select the classification sample in the coastal zone against a complex background, and it is prone to misclassification and missing classification. Reference (Liu et al., 2004) applies edge detection methods such as the Canny operator and wavelet transform in remote sensing to extract waterline. However, this edge detection method is easily affected by noise, the waterline often breaks, and the latter requires much editing work. References (Zhu et al., 2019; Guo et al., 2016) introduce the active contour model into the

extraction of waterlines from remote sensing images. The active contour model is complicated, and the amount of calculation is large. In places where the waterline is seriously sunken or where the contrast between sea and land is poor, the method has difficulty converging to the correct position. In addition, some experts have tried the ant colony algorithm, random walk algorithm and flood inundation algorithm in remote sensing waterline extraction (Xing et al., 2017). These methods have a high degree of automation, but they do not consider the continuity and positioning accuracy of the waterline under the conditions of a complex coastal background. In summary, the number of technologies and methods for obtaining waterlines by remote sensing images is very large, and they are still being developed and improved.

The remote sensing extraction of waterlines is always a research point in the coastal zone application of remote sensing technology (Viana et al., 2019). In particular, a silty coast with a gentle slope is affected by the high water content of the tidal flat on the side of the tidal flat and the high sand content of the nearshore water. The above-mentioned remote sensing waterline extraction methods have not been satisfactory thus far. In the current waterline extraction methods, from the perspective of image processing, people focus on the use of various algorithms to efficiently extract the waterline from the suddenly changing information of the image and rarely consider the spatial relation and geometric characteristics of the ground features in the image. The waterline is a geographical phenomenon. It has its own laws in terms of the geometric form, spatial distribution and interrelationship. To obtain the waterline more accurately, scientifically and quickly, spectral features, geometric features, spatial relation features and other geographical factors should be taken into consideration when extracting the waterline.

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This paper analyzes the spatial relation of waterlines at different spatial scales, introduces it to the key links of waterline remote sensing extraction, such as waterline detection, recognition and connection, and proposes a method for extracting waterlines along muddy coasts using multiscale spatial relationship features. This method is a comprehensive method that integrates threshold segmentation, edge detection and classification through multiscale spatial relations under the framework of object-oriented technology. It solves the problem of poor continuity, poor positioning accuracy, and poor levels of automation in the current remote sensing methods of extracting waterlines. The main contribution of this paper is to provide the calculation and application method of the spatial relation feature of the waterline in a remote sensing image. Experiments show that the application of multiscale spatial relations can improve the quality and efficiency of waterline detection.

2. RESEARCH MATERIALS AND METHODS

The fast-developing Chongming Dongtan was selected as the research area, Landsat-5 satellite images were used to study the spatial relation characteristics and calculation methods of waterlines at different spatial scales, and an implementation plan for extracting remotely sensed waterlines using multiscale spatial relations was given.

2.1 Study area and data set

2.1.1 Overview of the study area: Chongming Dongtan is located in the estuary of the Yangtze River, the easternmost area on Chongming Island. It is a typical muddy flat (the red rectangular box in Figure 1). Chongming Dongtan is formed by the gradual deposition of sediment carried by the runoff of the two waterways of the south branch and the north branch of the Yangtze River, as well as the silt carried by the fluctuating tidal currents. It is narrow from north to south and wide from east to west, distributed in a semielliptical shape outside the seawall. The Yangtze River estuary is a medium-strength tidal estuary, with an average tidal range from 2.43 m to 3.80 m, a maximum rising tide speed of approximately 0.72 m/s, a maximum falling tide speed of approximately 0.74 m/s, and a sand content above 1.0 kg/m³. Due to the relatively stable flow and sediment conditions, Chongming Dongtan extends to the sea with an annual siltation speed of 100–350 m/year. Chongming Dongtan is mostly composed of sand, with a wide beach surface and gentle slope (approximately 0.24%). A large amount of water remains on the slope, hence, it is often used as a research object for extracting a weak waterline.

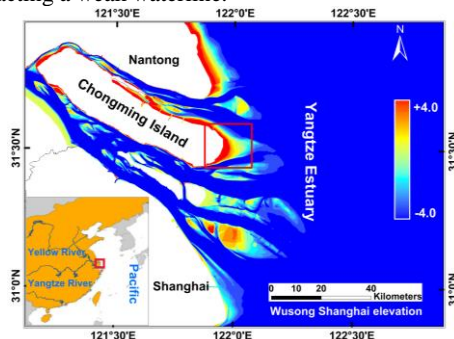


Figure 1. The location of the study area

2.1.2 Data set: The Landsat series of satellite images has a time span of nearly 50 years, with a wide map size and moderate

spatial and spectral resolutions. They can also be downloaded for free. Due to these characteristics, Landsat images are often used as data sources for researching the long-term changes in large-scale coastlines. Therefore, based on Landsat-5 images, it is of great significance to carry out an analysis and application research on the spatial relation of remote sensing image waterlines at medium scales. The satellite images were acquired on March 3 and April 20 in 2007, and the imaging moments were the low tide period of spring tide. The former is the state of flood tide, the latter is the state of ebb tide. Under these two tidal conditions, the technical methods for extracting tidal flat waterlines using spatial relation features are studied.

2.2 Spatial relationship characteristics of edges at different scales

Edges at two different spatial scales can be extracted from Landsat images and put into the real scene to analyze their geometric characteristics and spatial relation with other features. In addition, we found that certain attributes of edge pixels also have significant spatial distribution regularity. Therefore, this paper analyzes the spatial relationship characteristics of a waterline on three spatial scales.

2.2.1 Characteristics of edge spatial relationships with low spatial resolution:

Low-spatial-resolution edges refer to those edges extracted from Band6 by the threshold segmentation method. They are the dividing line between water and nonwater. In terms of the waterline, these edges specifically refer to the boundary line between sea and land, which is the target of remote sensing extraction. Figure 2 shows the result of overlaying low-spatial-resolution edges on false-color remote sensing images (R=B5, G=B4, B=B2). Band6 extracts the edges of large-scale geographic targets such as Approximate waterlines (white lines), fishponds and island boundaries (red lines). The edges of these large-scale geographic targets show the following spatial relationship characteristics:

(1)The boundary lines of fishponds and isolated islands are located inside mature land and inside sea water, respectively, and the waterline is located in the area between land and sea. The three types of edges have obvious differences in spatial position.(2)The edges of fish ponds and islands are relatively short and are generally closed polygons. The waterlines are unclosed curves, the length of which is much longer than that of other edges.

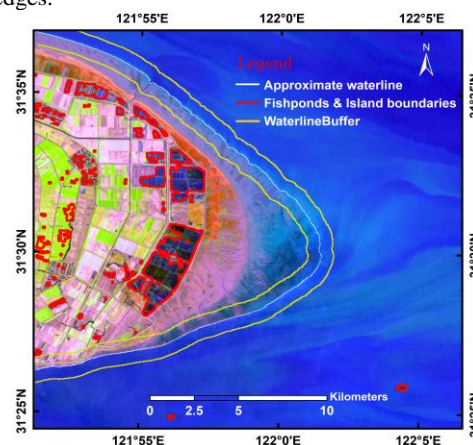


Figure 2. On the remote sensing image of 20 April 2007, the spatial relationship of the low-spatial resolution waterline.

The low-spatial-resolution edge positioning accuracy is poor,

but it is continuous and complete, approximately describing the position and shape of the edge. We refer to the low-spatial-resolution waterline as the approximate waterline. The special pattern of approximate waterlines in spatial distribution and geometric characteristics provide a theoretical basis for automatic computer identification.

2.2.2 Characteristics of edge spatial relationships with high spatial resolution: High-spatial-resolution edges refer to those edges from Landsat-5 satellite images except for those from Band6. Figure 3 shows the result of overlaying high- and low-spatial-resolution edges on false-color remote sensing images (R =B5, G =B4, B =B2). The high-spatial-resolution edges include waterline, tidal channels, farmland, fishponds, roads, and artificial dams. These medium-scale geographic targets have a large number and rich types of edges and show the following spatial relation characteristics:

(1)The edges of roads, farmland, dams, vegetation, and fish ponds are mainly located inside relatively mature land, and these edges are far away from the waterline.(2)The edge of the water located in the tidal channel and the tidal flat is relatively close to the waterline in terms of the spatial distance, but there are obvious differences between them in terms of geometric form and spatial relation. For example, the edge of a tidal channel generally has a large angle with the waterline. The edge of water on the tidal flat is generally a small-scale and closed polygon, and the geometrical form of the large-scale waterline is quite different from the edge of water on the tidal flat.(3)The high- and low-spatial-resolution waterlines are close in space and similar in shape.

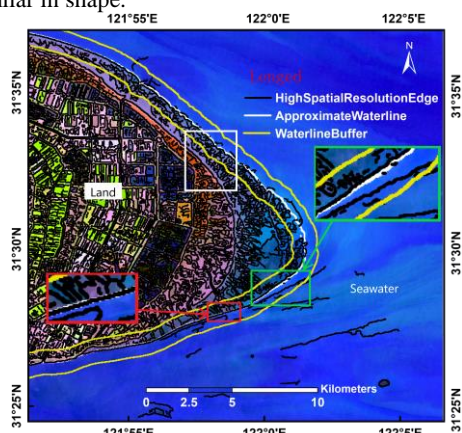


Figure 3. On the remote sensing image of 20 April 2007, the features of the edge spatial relationship with high resolution.

The high-spatial-resolution waterline is obviously different from other edges in terms of the spatial distribution, geometry and interrelation, but it has a significant correlation with the approximate waterline.

2.2.3 Spatial relation characteristics of the edge pixel gradient amplitude and direction: Figure 4 shows the results of non-maximum suppression of images in the white rectangular frame of Figure 3. Figure 4.a shows the position of the edge points, with good continuity on the waterline (red line). Figure 4.b shows the gradient amplitude of edge points, and the gradient amplitude of adjacent edge points is similar. Different types of edges have different edge gradient amplitude and have significant spatial distribution characteristics. The edge of the dam is the strongest, followed by the edge between the waterline and the dam, and the edge in the sea is the weakest. Figure 5 shows the calculation result of the gradient direction of

the edge. The gradient direction presents the position of the edge, as shown by the black arrow. Combining Figure 4 and Figure 5, we find that the same edge has consistency in the gradient amplitude and direction. This phenomenon should occur because the DN value of remote sensing images reflects the spectral characteristics of ground objects. According to the first law of geography, edge pixels should have spatial characteristics such as aggregation and a regular distribution. This paper uses the spatial relation characteristics of pixels to identify edge pixels and improves the ability of waterline detection using the traditional Canny operator.

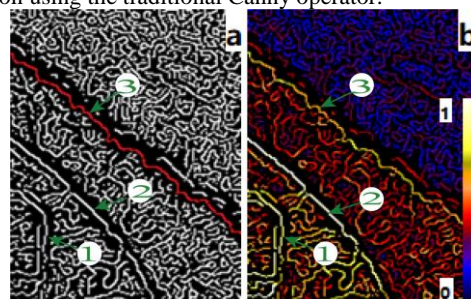


Figure. 4a shows the position of the edge pixels. Figure. 4b shows the gradient magnitude of the edge pixels. Arrows 1,2 and 3 point to the artificial dams, vegetation boundary and waterline respectively.

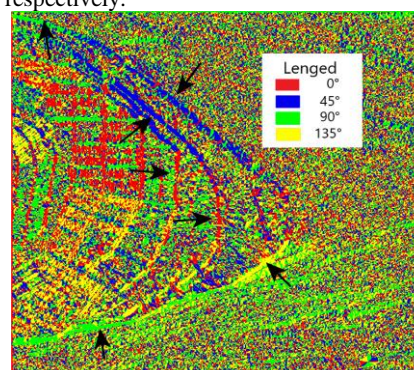


Figure. 5 At the point of the arrow, the gradient direction of the edge pixel represents the edge significantly. These edges include farmland boundaries, roads, artificial dams, vegetation boundaries and waterlines.

2.3 Calculation and application methods of multiscale edge spatial relation features

2.3.1 Calculation method of edge spatial relation features with low spatial resolution:

The low-spatial-resolution edges mainly include the boundary lines of large-scale geographic targets such as waterlines, fish ponds and isolated islands. The spatial relation features mainly include the length (N) and shape (S). The length (N) here is expressed by the number of pixels, and the shape (S) is divided into two types: closed and unclosed.

2.3.2 Calculation method of edge spatial relationship features with high spatial resolution:

The high-spatial-resolution edge mainly includes spatial relation features such as the length (N), shape (S), position (D), direction (A) and geometric topological relationship. In this paper, an approximate method for calculating high-spatial-resolution edge spatial relationship features is given based on the approximate waterline. Next, a simple explanation of the principle and a calculation formula are given.

The length of the edge (N) is represented by the number of pixels. The shape (S) of the edge is described by the degree of similarity between the high-spatial-resolution edge and the approximate waterline, and the calculation formula is shown in (1).

$$S = \frac{\sum_{i=1}^N (d_i - \bar{d})^2}{N} \quad (1)$$

In the formula, N represents the number of edge pixels, which is the length of the edge, and d_i represents the shortest distance from the i -th pixel on the edge to the approximate waterline. The essence of formula (1) is the distance variance from the edge of high spatial resolution to the approximate waterline. The larger the variance is, the greater the difference in the shape of the two curves. Otherwise, the smaller the difference in shape will be. The edge position (\bar{d}) is represented by the average value of (d_i), which can be positive or negative. Among them, a positive value indicates that the edge is close to land, and a negative value indicates that the edge is close to the sea. The direction of the edge is expressed by the angle between the edge and the approximate waterline, and this angle is calculated using formula (2).

$$\theta = \arcsin\left(\frac{d_{\max} - d_{\min}}{N}\right) \quad (2)$$

In this formula, d_{\max} , d_{\min} and N refer to the maximum and minimum distances from the high-spatial-resolution edge to the approximate waterline and its own length, respectively.

2.3.3 Improved Canny method based on pixel spatial relation features: The traditional Canny operator judges whether a pixel is an edge pixel through high and low thresholds and the neighborhood relationship, and the edge is prone to break. The improved Canny operator cancels the high and low thresholds, takes the edge as an object, and judges whether it is the same edge pixel by the correlation of the edge pixel gradient and direction. The improved Canny operator has strong edge continuity.

2.3.4 Multiscale waterline fusion method: The approximate waterline with low spatial resolution is not accurate, but it approximately describes the shape of the waterline. The high-spatial-resolution waterline has rich details and accurate positions, but it is prone to discontinuities. The advantages of the two types of waterline fusion methods can be combined to obtain an accurate and continuous waterline with full details. The basic idea is to take the high-spatial-resolution waterline as the basis and take the local approximate waterline corresponding to the fracture as an object. After rotating and translating, we can cause the local approximation to overlap the high-spatial-resolution waterline optimally and then intercept the local approximate waterline to complete the connection of the waterline. The calculation formula is shown in (3).

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix} + \begin{bmatrix} \Delta X \\ \Delta Y \end{bmatrix} \quad (3)$$

In the formula, (x, y) is the position of the high-spatial-resolution waterline, (X, Y) is the approximate waterline position, $(\Delta X, \Delta Y)$ is the approximate waterline translation, and θ is the approximate waterline rotation angle.

2.4 Waterline extraction model of a multiscale spatial relationship

Spatial relationship features of different scales are used to achieve the rapid, accurate and complete extraction of waterlines. The model is divided into the following three main steps:

Step 1: The large-scale spatial relationship features can be used to automatically extract the approximate waterline. The full threshold segmentation method classifies Band6 into water and nonwater. Using large-scale spatial relationship features, the computer completes the automatic extraction of the approximate waterline. Full threshold segmentation involves using the Otsu method to calculate the segmentation threshold. The output of this step is the approximate waterline and the buffer mask of the waterline constructed based on the approximate waterline.

Step 2: The improved Canny operator is used to detect edges in high-spatial-resolution remote sensing images, considering these edges as line element objects, and to calculate the spatial relationship features of the edges according to the method in section 2.3.2. Finally, the requirements of high-spatial-resolution waterlines are used to identify the waterline automatically. To reduce the amount of calculation, mask processing is performed before edge detection and spatial relation feature calculation. The output of this step is the high-spatial-resolution waterline.

Step 3: High-spatial-resolution waterline is merged with the approximate waterline. The multiscale waterline fusion method is used to connect the high-spatial-resolution breaking waterline with an approximate waterline.

For the sake of clarity, the flow chart of the method for extracting the waterline of Landsat images by using multiscale spatial relations is shown in Figure 6.

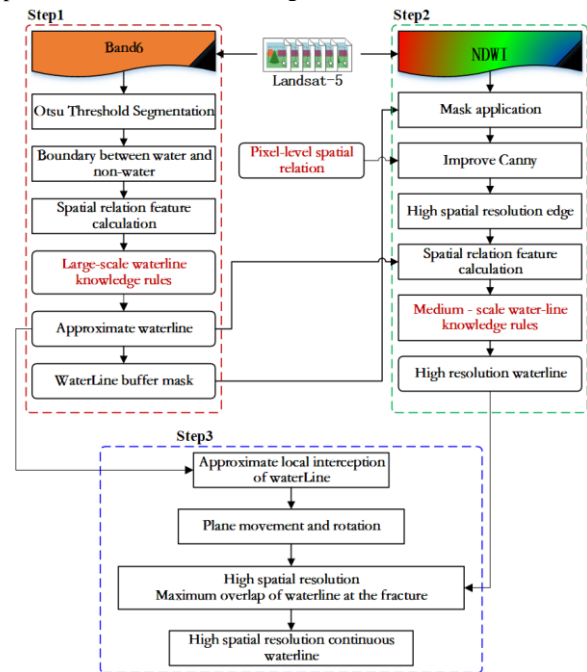


Figure 6. Flow chart of the waterline extraction method

2.5 Method for evaluating the waterline positioning accuracy

On the false-color remote sensing image ($R=B5$, $G=B4$, $B=B2$), the screen digitization method is used to extract the high-spatial-resolution waterline and use it as the reference waterline L' . Taking the shortest distance between the waterline extracted

by the spatial relationship and the reference waterline as the true value, formula (4) is used to evaluate the positioning accuracy of the former. In the formula, $L_i - L'_i$ represents the shortest distance from point i on L to L' , and N is the number of sample points.

$$m = \sqrt{\sum_{i=1}^N (L_i - L'_i)^2 / N} \quad (4)$$

3. EXPERIMENTAL PROCESS AND ANALYSIS

The Canny operator is improved based on the spatial relation features of edge pixels, the spatial relation features at different scales are applied to the key technical links of extracting waterlines from remote sensing images, such as waterline extraction, recognition and connection, yielding good experimental results.

3.1 Automatic extraction of approximate waterline results for large-scale spatial relationship features

The full threshold segmentation method extracts the edges of Band6. The result is shown in Figure 2. Band6 is very sensitive to temperature. There is a very large difference in coldness and warmth between water and land, and the waterline is very easy to extract. Figure 7 shows the thermal infrared Band histogram of Landsat-5 satellite image, which has obvious bimodal nature. Reference(Mason, et al.,2016) also points out that the waterline extracted by using Band6 has good continuity but poor positioning accuracy. According to the large-scale spatial relationship features, the length threshold is greater than 400 pixels, and the edge of the unclosed state is a knowledge rule of the approximate waterline. The method can accurately delete edges such as fish ponds and islands (indicated by the red line in Figure 2) while keeping the approximate waterline.

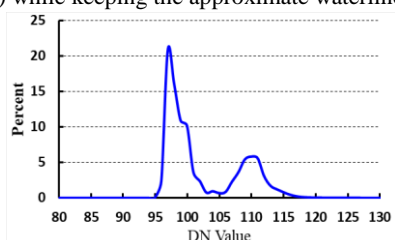


Figure.7 Histogram of DN value in thermal infrared band of Landsat-5 satellite image.

Fifty sample points were collected at equal intervals from north to south along the approximate waterline. Equation (4) was used to evaluate the positioning accuracy of the approximate waterline. The error (m) is 40.35 m, the maximum error is 224 m, and the minimum error is 12 m. The distribution of error is shown in Figure 8. In the figure, the horizontal axis is the sample sequence number, and the vertical axis is the positioning error of the approximate waterline.

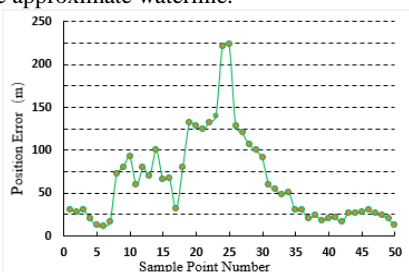


Figure 8. Positioning accuracy of the approximate waterline.

Figure 8 shows that the error of the waterline mainly occurs at sample points 20–30. These sample points are located at the easternmost end of the study area, with the gentlest beach slope. The mixed pixels result in poor positioning accuracy of the approximate waterline. Although the positioning accuracy of the approximate waterline is not high, it has continuous, smooth and complete features, and it describes the outline of the real waterline well. Obviously, the establishment of a buffer zone based on the approximate waterline is very beneficial to the processing of high-spatial-resolution waterlines. In Figure 2, the yellow lines on both sides of the approximate waterline are the buffer boundaries, and the width of the buffer is approximately 4 times the maximum positioning error of the approximate waterline.

3.2 Multiscale spatial feature intelligent detection of high-spatial-resolution waterline results

The improved Canny operator is used to detect the edges of NDWI remote sensing images. In this process, the empirical thresholds of the size of the edge pixel gradient and direction difference are 0.15 and 22.5°, respectively, and the edge intensity threshold is the edge intensity value of the top 30% in the buffer. The results of edge detection with high spatial resolution are shown by the black line in Figure 3. The improved Canny operator detects the edge above medium intensity, while the weak edge in sea water is rarely detected. In the buffer zone of the waterline, in addition to the waterline, there are mainly the tidal ditch boundary, slope resident water boundary and a small amount of the weak edge of sea water.

According to the method in section2.3.2, the spatial relation characteristics of the edges in the buffer are calculated. Table 1 shows the calculation results of some edges. Edges with spatial relation characteristics are identified in sequence according to their length, shape similarity, direction and position. The empirical threshold is set to 8 pixels, 0.6, 15°, and 2 pixels in sequence. The waterline recognition result is shown by the red line in Figure 9. The knowledge rule of waterlines constructed by the spatial relation characteristics is very accurate in identifying waterlines.

The improved Canny detection of high-spatial-resolution waterlines has rich details, high positioning accuracy (for example, the magnified window corresponding to the green rectangular frame), and good continuity in most areas. Unfortunately, the edge detection of the waterline (in the black rectangle) in the area with a gentle slope failed, and the waterline broke.

Number(ID)	Position (D)	Length (L)	Shape (S)	Direction (A)
1	8.26	39	4.81	+1.27°
2	1.30	107	0.08	+0.01°
.....
n	1.28	449	0.04	+0.01°

TABEL 1. Calculation results of line element object properties (unit: pixel)

3.3 The results of the high-spatial-resolution waterline connection

The multiscale waterline fusion method is used to connect the high-spatial-resolution waterline. When connecting, the ratio of the waterline gap to the length of the adjacent waterline is set to 1:3. When the high-spatial-resolution waterline has the best overlap with the approximate waterline (the ratio of overlapping

is higher than 80%), the high-spatial-resolution waterline of the fracture is represented by an approximate waterline. It should be noted that the simplest line connection processing method is used for the case where the waterline break is short (generally less than 3 pixels). The red line and yellow line in Figure 9 are the final results of the waterline. Among them, the red line is the waterline detected by the improved Canny operator, and the yellow line is the approximate waterline obtained by the fusion method.

The black rectangle in Figure 9 is a partially enlarged view of the connected waterline. This figure shows that the approximate waterline improves its positioning accuracy through the adjacent spatial relation and completes the waterline connection. Inside the yellow rectangle is the waterline of the direct connection. It is difficult to see the traces of connection by magnifying it. The essence of the multiscale waterline fusion method is to use a high-spatial-resolution waterline to correct the approximate waterline based on the context of the waterline at the fault.

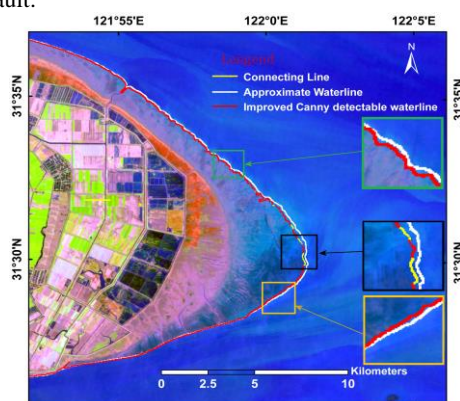


Figure 9. High spatial resolution waterlines extracted from remote sensing images from 20 April 2007.

The experimental results show that the spatial relationship can be used to automatically extract approximately waterline, detect, identify and connect waterline with high spatial resolution.

3.4 Performance analysis

By comparing with threshold segmentation, object-oriented classification, active contour and Canny edge detection, the performance of the remote sensing image waterline extraction method proposed in this paper is evaluated in terms of operation efficiency and waterline quality.

Perform efficiency analysis: The method proposed in this paper, the threshold segmentation method and edge detection method are used comprehensively, and the spatial relationship features of different scales are used to achieve the automatic detection, recognition and connection of waterlines. Therefore, the amount of calculation of this method is larger than that of the threshold method, edge detection method, and even some remote sensing classification methods. However, the latter require a certain amount of manual operation, and the efficiency of actual operation is not high. It is worth mentioning that the active contour model is also a highly automated method. However, this method requires iterative calculation in determining the waterline, which requires a large amount of calculation and is not efficient when calculating a large area. The execution efficiency of these five methods is evaluated in terms of automation and data processing time. Table 2 shows

the evaluation results of the efficiency of the above five methods for extracting the remote sensing waterline in the study area under the same conditions.

The processing time in this paper considers the total time, from inputting to outputting, required for manual operation and computer processing. Table 2. shows that the efficiency of the waterline extraction method proposed in this paper is the highest and that the efficiency of the Canny operator is the worst.

Method	Automation	Performance time	Continuity	Positioning accuracy
Threshold segmentation	higher	60 "	1	71.5m
Object-oriented	medium	600 "	4	268.4 m
Canny	low	840 "	18	25.4m
Active contour	highest	548 "	1	103.6m
Method in this paper	highest	15 "	1	12.4m

Table 2. Evaluation of the extraction efficiency and extraction quality of waterlines.

3.4.1 Waterline quality analysis: The evaluation indexes of the waterline quality mainly include the continuity and positioning accuracy. Continuity can be measured by the number of waterline segments, and the positioning accuracy is evaluated by the method introduced in section 2.5.

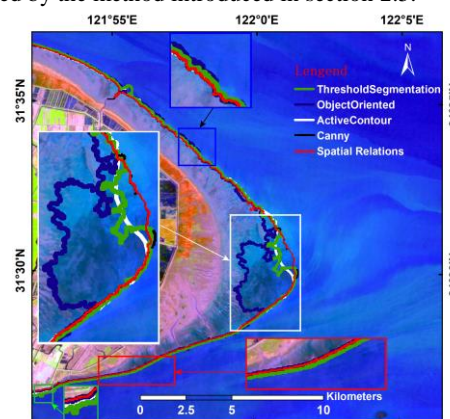


Figure 10. The waterline extraction methods are compared and analyzed on the remote sensing image of April 20, 2007.

The waterline results extracted by the five methods are superimposed on the false-color remote sensing image, the result of which is shown in Figure 10. The quality of the waterline extracted by the five methods is illustrated by partial magnification. The waterline in the red rectangular frame is the strong waterline. The accuracy of the waterline extracted by the five methods is high. In the green rectangular frame, the contrast between the sea and land is strong, but the positioning accuracy of the threshold segmentation method is poor due to the influence of the mixed pixels. The waterline in the blue rectangular frame is the middle-strength waterline, and the positioning accuracy of the object-oriented classification method is relatively low. It is the weakest waterline in the white rectangle, and the above five waterline extraction methods show great differences. The Canny operator does not detect the waterline in this area, and there is a large gap. The threshold segmentation method and object-oriented method wrongly distinguish between water and nonwater, and the waterline deviates seriously from the true position. The active contour method does not converge to the true position of the waterline in this area. Only the waterline extraction method proposed in

this paper accurately describes the true position of the waterline with the help of an approximate waterline.

According to the need for equal sampling point intervals, 50 sample points are selected from the northernmost end of the waterline to calculate the positioning error. Table 2. shows the evaluation results of the five waterline extraction methods in terms of continuity and positioning accuracy. In terms of continuity, Canny methods are the worst. In terms of positioning accuracy, the method proposed in this paper is the best. Figure 11 is a distribution diagram of the positioning error of the waterline extracted by the above five methods. Clearly, the waterline positioning error of each method mainly comes from the easternmost end of the study area, and the waterline positioning accuracy achieved by using the multiscale spatial relationship is the highest in the whole area.

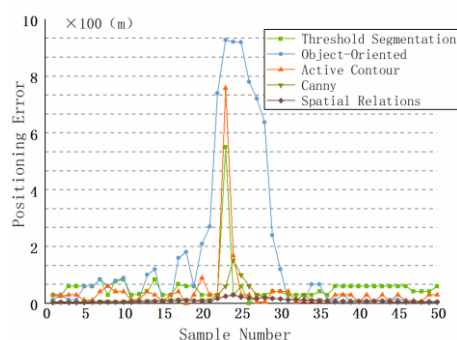


Figure 11. Error distribution of the five methods for waterline positioning

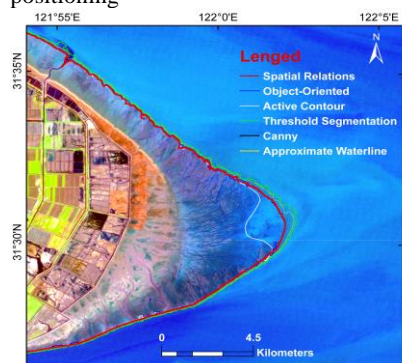


Figure 12. Waterlines of remote sensing images extracted on March 3, 2007.

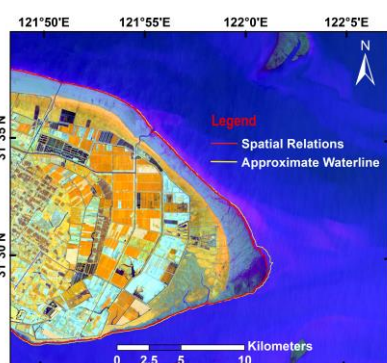


Figure 13. Waterline of Landsat-8 images were extracted.



Figure 14. Waterline of Lake Hara is extracted.

Based on the objective evaluation of efficiency, continuity, positioning accuracy and adaptability, the method proposed in this paper to extract the waterline of remote sensing images by using multiscale spatial relations is the best.

4. DISCUSSION

The use of multiscale spatial relations to extract the waterlines of remote sensing images requires a combination of threshold segmentation and edge detection. The spatial relation is the bridge and tie between these methods. The three-scale spatial relation features are used to realize the automatic extraction of the approximate waterline, high-spatial-resolution waterline detection, recognition and connection. The spatial relation, as the main line, runs through the entire process of waterline extraction from remote sensing images.

An approximate waterline is not only the first condition for the automatic extraction of waterlines but also an indispensable

3.5 Other experimental results

The above five methods were used to extract waterline from remote sensing images on March 3, 2007. The sea-land contrast at the imaging time was slightly stronger, but the waterline was still weak. The extraction results of waterline are shown in Figure 12. The method of using multiscale spatial relations to extract the waterline still shows great advantages. Note that all the parameters of the waterline extraction process for the two remote sensing images are exactly the same. The positioning accuracy of the waterline extracted by the five methods, including the spatial relation, Canny operator, active contour, object-oriented and threshold segmentation methods, is 10.6 m, 16.5 m, 32.9 m, 19.6 m and 46.3 m, respectively.

In order to illustrate the adaptability of the waterline extraction method proposed in this paper, we replaced the Landsat-5 image with the Landsat-8 image to extract the waterline of Chongming Dongtan and the waterline of Hala Lake, respectively. The imaging time of landsat-8 satellite remote sensing data was August 3, 2015 and July 25, 2015, respectively. Hala Lake is a large inland saltwater lake in the inland basin of the Qinghai-Tibet Plateau. The results of the waterlines are shown in Figures 13 and 14. The position accuracy of the waterlines reached 8.7 m and 7.8m respectively, which is better than the results of the previous experiment. This is because the contrast between land and water is strong and the approximate waterline position of the Landsat-8 image is more accurate.

source of basic data in key steps, such as calculation of the spatial relation features of edge objects with high spatial resolution and waterline connections. In this paper, the adaptive Otsu method is used to detect waterlines in the thermal infrared band, and large-scale spatial relationship features are used to automatically extract the approximate waterline by a computer. The efficient extraction of approximate waterline proves that the thermal infrared band is very sensitive to the temperature difference between water and land and overcomes the problem of inconsistent contrast between sea and land in remote sensing images. The approximate waterline is continuous, complete and reliable. At the same time, it has been proved that by introducing spatial relation features, the computer can effectively delete edges such as ponds and islands and that detecting and identifying the approximate waterline does not require manual intervention.

The detection, recognition and connection of high-spatial-resolution edge objects are the key steps to determine the

quality of waterline extraction. Using the spatial relation feature to improve the Canny operator, the ability to detect water edges is improved significantly. The waterline with spatial relation features provides theoretical support for accurate waterline identification. The waterline connection method is completed through the context of the waterline at the fracture under the guidance of the first law of geography. The fusion of waterlines of different scales inherits the continuity of approximate waterlines and the high precision of waterline with high spatial resolution. In the process of extracting the waterline of remote sensing images, the parameter settings are the same, and the results are the same, which proves the reliability of this method.

The method proposed in the paper is simple in principle and easy to implement by computers. The processing does not require manual intervention. The fusion of high- and low-spatial-resolution waterlines ensures the continuity and completion of the waterline and takes into account the positioning accuracy of the waterline. In addition, this method can better solve the problems of the active contour method, such as the complexity of the algorithm, the large amount of calculation, and the difficulty of convergence for a severely concave waterline.

In this paper, the IDL programming language is used to realize the extraction of the waterline of Landsat images using multiscale spatial relations, and waterlines of different tidal conditions are effectively extracted in the tidal flat of Chongming Dongtan of the Yangtze River Estuary. The paper also successfully addresses the difficulty in extracting the weak waterline of the tidal flat. The method of using multiscale spatial relations to extract waterlines provides technical support for using waterlines to study the dynamic changes in coastal zones.

5. CONCLUSIONS

To address the difficulty in extracting the waterline of a tidal flat, this paper analyzes the spatial relation features of waterlines at different scales, gives a method for applying the spatial relation in waterline extraction, and proposes a method for extracting waterlines from remote sensing images using multiscale spatial relation features. The experimental results show the following: (1) The edges in Landsat images have rich spatial relation features, and the use of spatial relations is beneficial to improve the efficiency and quality of waterline extraction. (2) The pixel-level spatial relation can improve the edge detection ability of Canny, and edges with spatial relation features can be intelligently identified. (3) The waterline can be connected by the multiscale waterline fusion method. (4) This method offers a high degree of automation, strong stability, simple principles, and a small amount of calculation. More importantly, the quality of the waterline that is extracted is high. This method is especially suitable for the extraction of the waterline of a tidal flat under the condition of low tide from Landsat remote sensing images.

The core content of using a multiscale spatial relationship to extract the waterline from Landsat images is to calculate the spatial relation feature of high-spatial-resolution edges by using an approximate waterline and treat the edge as a line element object for classification processing. Therefore, the essence of this waterline remote sensing extraction method is the expansion of object-oriented classification technology. Through the constraints of multiscale spatial relations, the detection, recognition and connection of high-spatial-resolution waterline

are realized, and the problem of extracting weak waterline from remote sensing images is solved. However, the following issues are still worthy of explanation: Our algorithm introduces the spatial relationship of the waterline through the thermal infrared band, but not all remote sensing images have the thermal infrared band. In future work, we will introduce methods for determining the spatial relation characteristics of remote sensing images to perform our research.

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