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Extraction and analysis of surface lake flow direction in Poyang Lake based on texture enhancement and Hough transform

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ABSTRACT

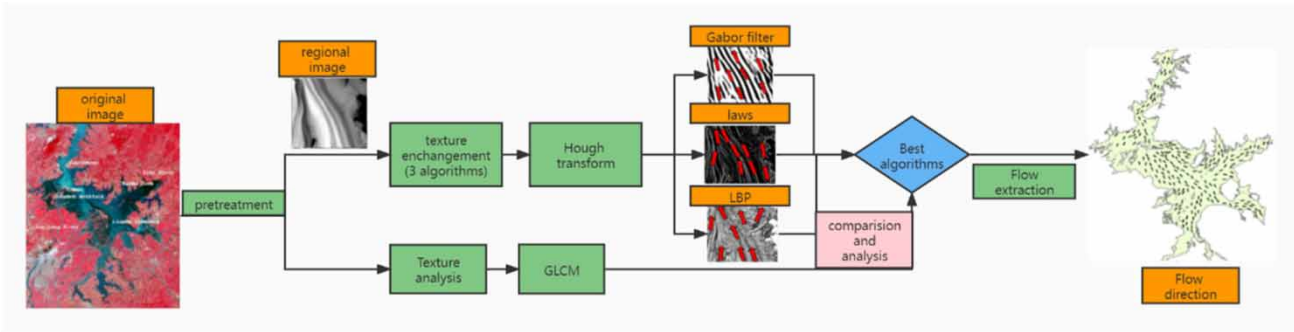
Lake flow is one of the common hydrological phenomena in nature. The water exchange of lakes and the circulation of natural water resources are realized by the water movement caused by various factors. Lake current is of great significance in the hydrological and ecological environment and it is one of the focuses of scholars' research. This paper takes Poyang Lake as the research area, and uses three texture enhancement methods of Laws, Gabor, and LBP operators to enhance the texture features of images based on multi-source remote sensing data, and uses the Hough transform to extract the flow direction of the Poyang Lake area. The results show that the three texture enhancement methods combined with Hough transform can extract the flow direction, but the Gabor filter has the best flow direction effect and the highest extraction accuracy. Gabor filter is the most adaptable for texture enhancement of images with different resolutions.

Key words: Gabor filter, Hough transform, Poyang Lake, texture enhancement

HIGHLIGHTS

- This paper compared the adaptability of Laws, Gabor filtering and LBP algorithms to the images with different resolutions and different regions.
- Hough transform was used to extract the water flow direction of Poyang Lake.
- The seasonal flow direction of Poyang Lake was analyzed.

GRAPHICAL ABSTRACT



INTRODUCTION

Lake flow is one of the common hydrological phenomena. Lake flow is of great significance to lake ecological environment and can provide technical support for lake water environment and wetland ecological monitoring, water resources development and waterway traffic construction (El-Manadely *et al.* 2017; Khwairakpam *et al.* 2019; Wang *et al.* 2021). At present, the conventional method to obtain lake flow is mainly to set up stations for on-site measurement (Toyota *et al.* 2010) and obtain

lake flow information through hydrodynamic numerical simulation. Although these methods have achieved good results in the study of lake flow, the deployment cost of manpower and material resources is high when the research scope is large, and more data support is needed, which is slightly insufficient in terms of timeliness. In the flow process of lake water, accompanied by the spatial diffusion of substances in the water, the lake flow presents certain texture characteristics under the influence of topography and other factors, and texture structures implicitly indicate water flow information. Remote sensing technology has the ability of synchronous monitoring in large-scale space. Through remote sensing images, texture phenomena with regular distribution can be observed, which can be used to monitor and analyze the motion characteristics of water bodies. The appearance of remote sensing technology makes it possible to extract and analyze water flow direction from remote sensing images.

Up to now, some studies have used remote sensing images to analyze water flow direction. Zhan *et al.* (2017) measured the displacement of tracer features in two temporally adjacent images based on Landsat7 and Terra thermal radiation images to extract the flow direction of Teshekpuk Lake. However, this method is affected by the physical and chemical properties of the tracer itself, and the accuracy also depends on the inversion model of the tracer. In addition to the 'tracer' method, there are also many scholars who qualitatively analyze water flow direction from the perspective of image textures. Cathcart *et al.* (2020) digitized the water streamlines of the Wax Lake delta based on sentinel-2 data and extracted the streamlines direction and their distribution in combination with the measured data. Zhu *et al.* (2021) proposed a water extraction algorithm composed of texture feature extraction, feature fusion and target segmentation, the algorithm can accurately segment complex coastlines with mountain shadow interference. Qiao *et al.* (2014) digitized the streamlines of water through visual interpretation, and then enhanced the texture information of water and extracted the flow information through Gabor filtering. The above methods have achieved some results from the perspective of ground object texture, but the texture characteristics embodied by water flow have not been studied in depth. This paper selects the Poyang Lake with seasonal height changes in hydrology, uses three texture enhancement methods to enhance the texture features of the Poyang Lake water flow based on multi-source data images, and extracts the water flow direction of the Poyang Lake based on the Hough transform.

The aim of the paper is to take Poyang Lake in China as the research object, use Remote Sensing and image processing technology to enhance the texture characteristics of the lake and extract the flow direction from it, so as to provide effective scientific theoretical basis for the water environment monitoring and water resources development of inland lakes.

In this research paper, the main innovativeness is as follows:

- Based on the texture information of lake flow, the direction of lake flow was extracted by several methods, and the extraction effect of different methods was compared based on the resolution of the data.
- In this paper, Gabor filter and Hough transform are combined to extract lake flow. The reliability and stability of lake flow extraction are superior to other methods.

Study area and data

Poyang Lake is located in the north of Jiangxi Province, China, with a length of 173 km from north to south, an average width of 17 km from east to west, and an average depth of 8.4 m (Xu *et al.* 2001). Figure 1 shows the area of Poyang Lake and its surrounding area after false color synthesis on August 19, 2019. Poyang Lake receives water from the rivers of Ganjiang, Fuhe, Xinjiang, Raohe and Xiushui and directly connects to the Yangtze River in the north, forming a complete Poyang Lake water system (Feng *et al.* 2012). Influenced by incoming water from the five rivers and the Yangtze River, Poyang Lake has a complex river-lake relationship, and its water situation varies greatly in different seasons, presenting a scene of 'The waters in wet season form a whole, and the waters in dry season form a line' (Liu & Ren 2014). There is a wet season from June to August, and a dry season from December to January (Sun *et al.* 2021). The average water changing cycle is 20 days. The general terrain of Poyang Lake is high in the south and low in the north, while the northern area is directly connected with the Yangtze River. It is lower in central and northern areas and tilts from south to north (Xu *et al.* 2014). The water current in Poyang Lake is mainly characterized by influent-effluent current and wind-driven current, which flows from south to north as a whole, but the local water flow is complicated due to the influence of the lake's topography, morphology and water regime.

Considering that spatial resolution may affect image data processing to a certain extent, images from different sensors were used to analyze the lake flow texture, which provides a basis for selecting the best image texture enhancement method. The remote sensing data used in this paper, including Landsat8 OLI, GF-1 WFV, GF-2 WFV and Sentinel-2 MSI, are shown in Table 1. Among them, GF-1 and GF-2 images were downloaded from China Centre For Resource Satellite Data and

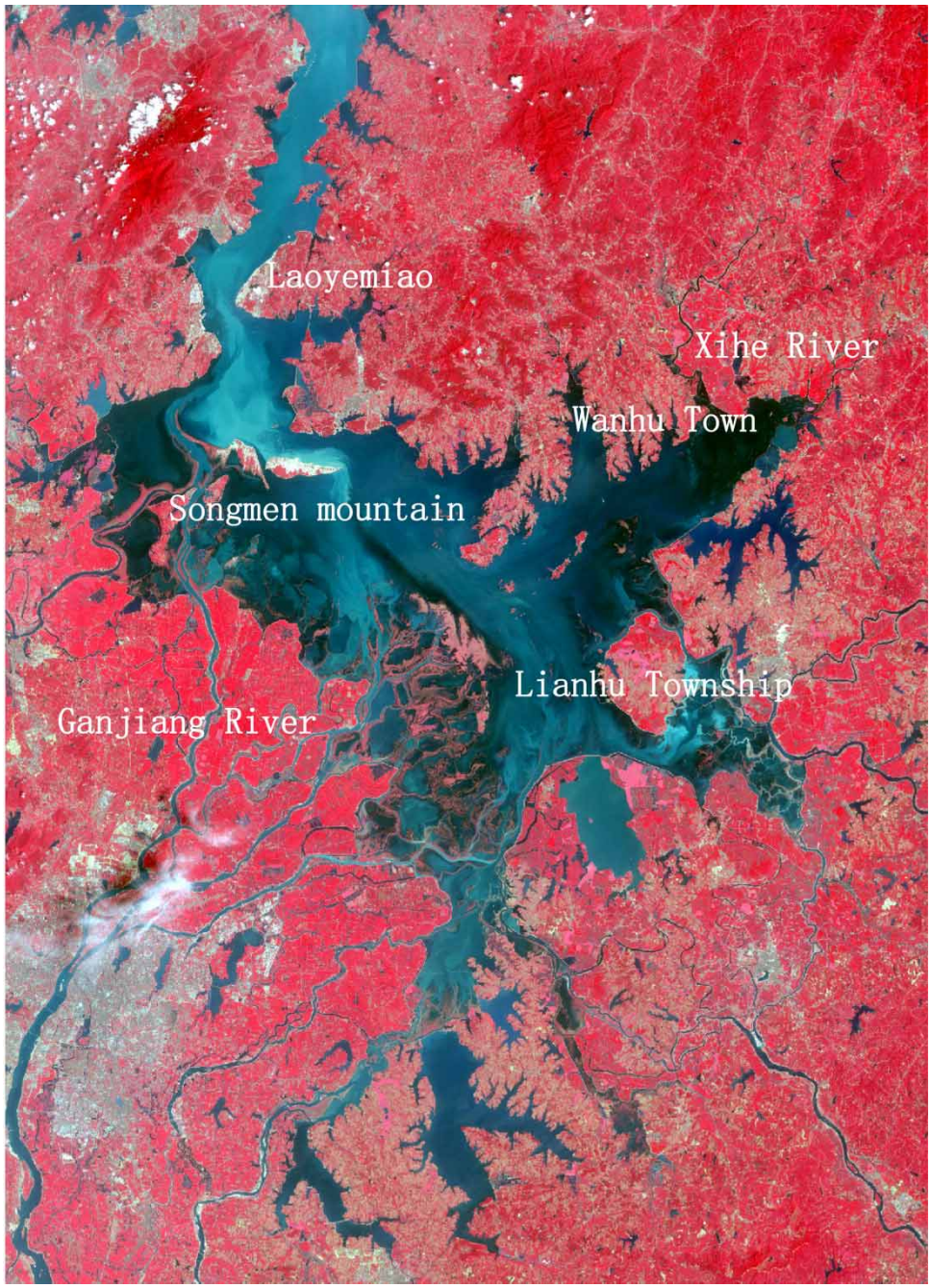


Figure 1 | Poyang Lake and its surrounding areas (Landsat 8 OLI false color synthesis).

Application (http://www.cresda.com/CN/), and the Sentinel-2 MSI image is available for download on the Copernican platform (https://scihub.copernicus.eu/dhus/#/home). The images of landsat8OLI were downloaded from the website http://www.gscloud.cn/search. Before texture analysis, the data were pretreated with geometric correction, radiometric calibration and atmospheric correction.

METHODS

Gabor filter

A Gabor filter can extract spatial local frequency features, which belongs to window-added Fourier transform and is an effective texture detection tool (Arivazhagan *et al.* 2006). A two-dimensional Gabor filter not only has good scale selection

Table 1 | The data used in this article

The sensor	The date	Resolution	Usage
Landsat8OLI	19 August 2019	30 m	False color synthesis
Landsat8OLI	April 20, July 25, And October 4, 2016	30 m	Texture analysis Analysis of flow change
Landsat8OLI	November 4, 2018	30 m	Texture enhancement, Flow extraction
GF-1	October 27, 2018	16 m	Texture enhancement, Flow extraction
GF-2	October 21, 2018	4 m	Texture enhancement, Flow extraction
Sentinel-2	October 28, 2018	10 m	Texture enhancement, Flow extraction

characteristics, but also has good direction selection characteristics. This paper adopts the normalized two-dimensional (2D) Gabor function proposed by Kamarainen *et al.* (2006). The 2-D Gabor filter function in the frequency domain is:

$$\psi(x, y, f, \theta) = \frac{f^2}{\pi\gamma\eta} e^{-\left(\frac{f^2}{\gamma^2}x'^2 + \frac{f^2}{\eta^2}y'^2\right)} e^{j2\pi f x'} \tag{1}$$

$$\begin{cases} x' = x\cos\theta + y\sin\theta \\ y' = -x\sin\theta + y\cos\theta \end{cases} \tag{2}$$

where f represents the frequency component of the filter, θ represents the angle component of the filter. Due to the conjugate symmetry of Gabor filter, the filtering effect of the angle component in the interval of [0,π] can be obtained in any direction, In order to better extract texture information from remote sensing images, Gabor filter banks with eight angles and five frequencies (Shen *et al.* 2007) are set up in this paper. γ and η represent the sharpness of the filter in the long and short axes respectively, which can be calculated according to literature (Wang *et al.* 2008). The frequency of the first filter in the filter bank is set as $f_i = k^{-i} * f_{max}$ $(i = \{0, 1, 2, 3, 4\}$, f_{max} is the maximum frequency of the filter, which is set to 0.1, the angle is set to $\theta_i = i * \pi/8$ $(i = \{0, 1, 2, 3, 4, 5, 6, 7\})$.

Due to the large area of the lake and the partial area containing beaches and islands, in order to better process the water texture information, this paper divides the lake into several 200×200 sub-areas. The selection of sub-regions is mainly based on water bodies, and tries to avoid exposed beaches and islands to achieve better filtering effects. According to the Gabor filter bank with eight angles and five frequencies set above, the image in each area is enhanced.

Laws algorithm

Laws algorithm is an image texture digitization method proposed by Laws (1980), which enhances the texture in the image through local template convolution. The basic idea is to replace the gray value of the center pixel in each processing window by the average gray value of pixels in filter window. In this paper, 16 kinds of two-dimensional convolution kernels were generated by four one-dimensional convolution kernels with length of 5. These 16 groups of convolution check images were respectively used for convolution operation, and 16 results were obtained. Then the gray value of each pixel in the 16 groups of images was replaced by the texture energy measure, which was obtained by the sum of the values of all pixels in the local area centered on each pixel, and finally achieved the image texture enhancement processing.

LBP algorithm

LBP (Local Binary Pattern) is an algorithm used to extract image texture features, proposed by Ojala *et al.* (2002). This method uses local area information to replace a single pixel and has good texture description power. The basic idea of LBP algorithm is to define a 3×3 square window, take the gray value of pixels in the center of the window as the threshold value, and compare the gray value of surrounding pixels with it. If the gray value is greater than the center value, it will be marked as 1, otherwise it will be marked as 0 (Yao & Pan 2020). After the image is converted into binary mode, the binary formed by each window is encoded and converted into decimal, and this value is taken as the LBP value of the center pixel of the window, so as to reflect the texture information of this 3×3 area.

Hough transform

Hough transform is a detection method to extract certain features (such as circles and lines) from images. Hough transform can be used to extract linear information from remote sensing image after texture enhancement. The basic idea is as follows: When all points on the image plane correspond to the parameter plane, if different points intersect at the same point after transformation, these points can be considered to pass through the same straight line of the original plane (Wang *et al.* 2019). Duda & Hart (1972) proposes that the line in the original image space is $y - kx - b = 0$, while the Hough space is the coordinate space with k and b as variables. Thus, the line $y_1 - kx_1 - b = 0$ in Hough space is represented as any line that passes through the original space (x_1,y_1).

Since the slope of a vertical line is infinite, the general expression $y = kx + b$ cannot represent a vertical line, so a polar coordinate system is used to express a straight line to solve this problem. Duda and Hart also propose that $r = x\cos\theta + y\sin\theta$x is used to express a line, then the slope of the original line becomes $F(\theta)$ and the conversion to Hough space is the trigonometric function $r = G(\theta)$ concerning θ and r. Therefore, by converting all coordinate points in the original space into Hough space, several trigonometric function curves can be obtained in Hough space, and the intersection points of these curves are the parameters of the connecting lines corresponding to the points in the original image. The linear monitoring problem of the original image is transformed into a problem of counting the number of curves passing through these intersections. By setting a certain threshold, the intersection points in Hough space that meet the conditions are counted as the parameters of the line, so as to achieve the goal of line extraction. The input image of Hough transform is the processed binary image, and there are many methods of edge detection through fast convolution calculation. Research (Mai *et al.* 2018) showed that Canny operator has good edge calculation effect, so this paper uses Canny operator for processing, and the steps of extracting a line by Hough transform are shown in Figure 2.

RESULTS AND DISSCUSSION

Texture enhancement

In order to compare the processing effects of the three texture enhancement methods on lake flow texture, the paper evaluated and analyzed the texture eigenvalues of gray level co-occurrence matrix (GLCM) proposed by Haralick *et al.* (1973). Two representative statistics feature of GLCM were calculated for texture analysis, namely, energy (ENE) and entropy (ENT). The amount of ENE indicates the uniformity of image gray distribution. When the image gray distribution is periodic, the ENE value is larger, and vice versa, while ENT is a measure of whether the image texture features are cluttered or not. To a certain extent, it shows the complexity of the image. The more cluttered the texture in the image is, the higher the ENT value is, and vice versa.

The 2018 Landsat8 OLI image in the central lake area (Songmenshan) of Poyang Lake is selected for Gabor filtering, Laws algorithm, LBP operator processing, and the processed GLCM feature values are calculated. The statistical results of the original image and the three texture enhancement methods are shown in Figure 3.

Figure 3 shows that the ENE value of the image processed by Gabor filtering and Laws algorithm is significantly improved, while the ENE value of the image processed by LBP operator is reduced, indicating that Gabor filtering and Laws algorithm have good texture enhancement effect. Compared with the ENT of the original image, the ENT of the image processed by Laws algorithm and Gabor filtering is lower, which can effectively reduce the texture complexity of the image, while LBP operator greatly enhanced the ENT value and improved the gray complexity of the image. It indicates that the effect of texture enhancement is not as good as the other two methods.

In the contrast between the original image and the enhanced image, the overall texture direction of the image is between 90 and 100°. After processing by Gabor filtering and Laws algorithm, it is more prominent in the 90° direction compared with other directions, and has obvious fluctuation between 45 and 90°. The Gabor filter highlighted the texture features in the main direction of the image. The Laws algorithm can also highlight the texture features in the direction, but the effect is not as good

Figure 2 | The steps of extracting a line by Hough transform.

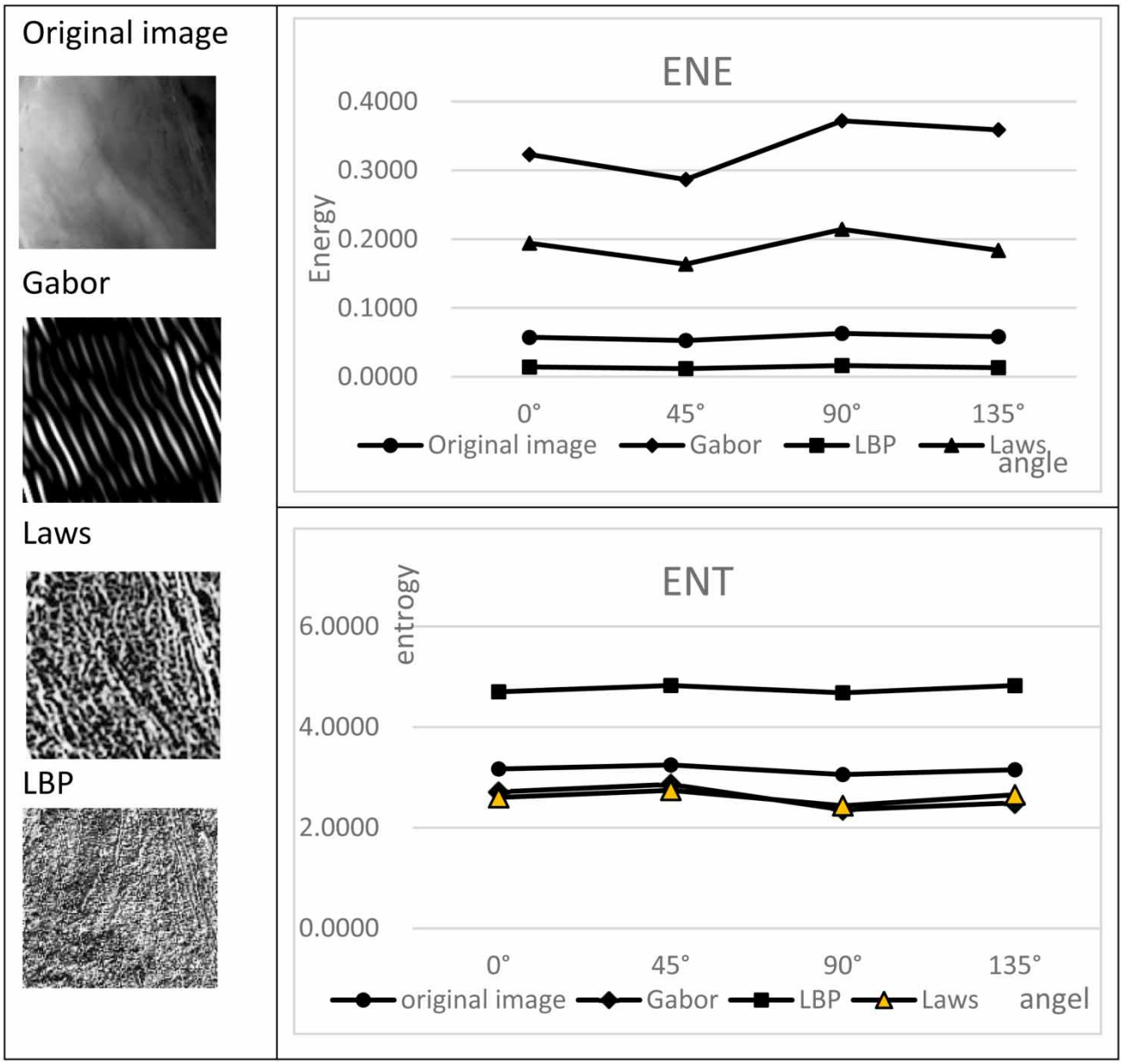


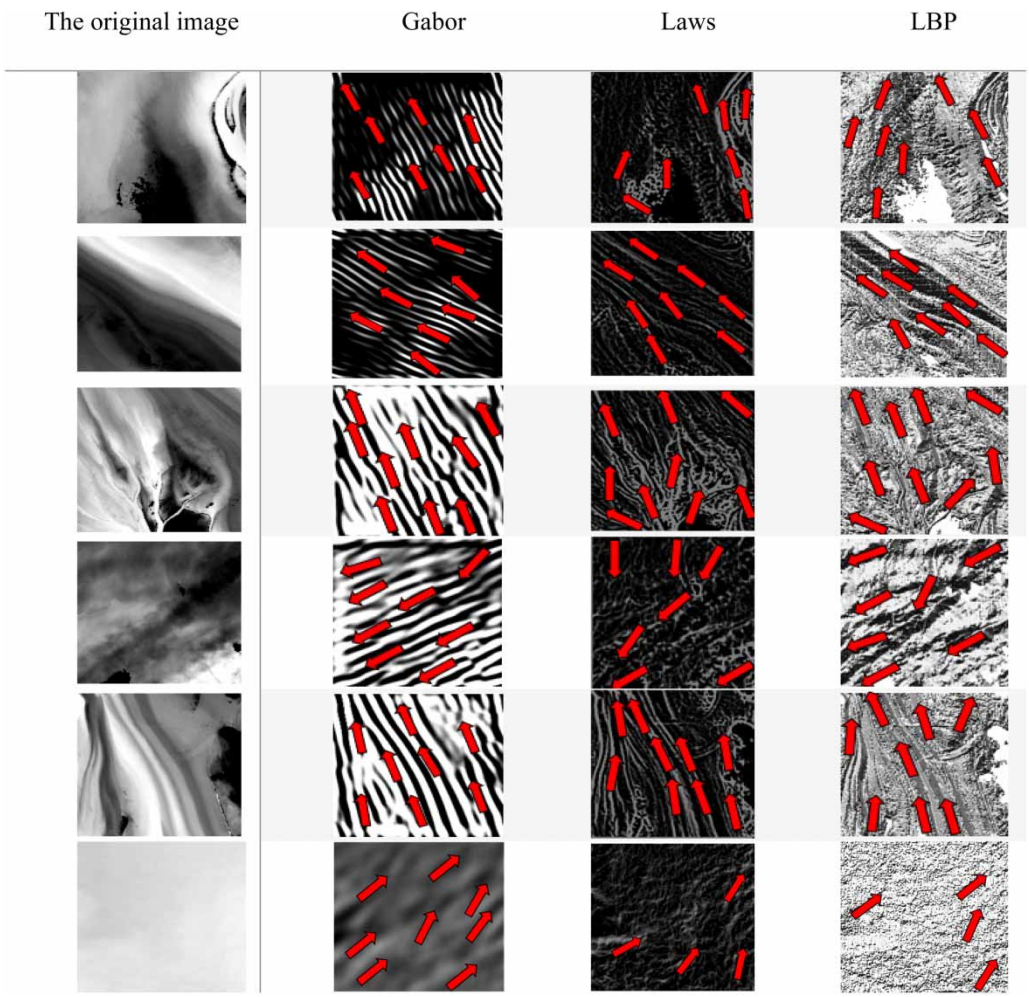
Figure 3 | Comparison of texture enhancement methods (Songmenshan area of Poyang Lake).

as the Gabor filter. Compared with Laws algorithm, the gray level fluctuation of the image processed by Gabor filtering is larger, and the image texture is more hierarchical. LBP operator can improve the gray complexity of the image, which is not obvious in all directions, whereas it significantly weakens the texture features in some directions. In general, texture features enhanced by Gabor filtering are relatively obvious, which is the most conducive to lake flow direction extraction.

Extraction of flow direction

In this paper, the measured flow direction data in the same period were taken as reference, and the flow direction extracted by the three enhancement methods were compared with each other to compare the accuracy of each method. By selecting several regions and processing the images with three methods based on the Matlab platform, the flow field distribution and flow direction information of each region were obtained by combining the local water level data and terrain data, and the measured flow direction angle of these regions in the same period was compared. The extracted flow direction and measured flow angle were calculated by rotating clockwise with due north of 0°. The extraction result is shown in Table 2.

Table 2 | Flow direction extraction after texture enhancement



Through visual interpretation of images before and after processing, it can be seen that the three methods can extract lake flow field well, but they had different effects on lake flow texture in different situations. For the region with obvious lake flow texture, the direction of flow field extracted by the three methods had little difference. However, in the area where the lake flow texture is not obvious, the number of flow fields extracted by Laws algorithm and LBP algorithm is less than the results extracted after the Gabor filtering process, indicating that the flow field extracted by Gabor filtering is relatively fine. For textures with slightly curved features, the flow field extracted by Laws produced obvious flow direction change at the bending point, while the flow field filtered by Gabor was more balanced and had no mutation. In some images with more messy texture features, the images processed by Gabor filtering and LBP algorithm had better linearity and the overall flow direction was relatively stable. The texture edges processed by Laws algorithm were more cluttered, and the extracted flow direction was more complex than the two. In some images with very clear texture and strong linearity, the directivity of the three methods is similar. To sum up, texture analysis after Gabor filtering had the best and most stable effect on the flow direction extraction of different regions, especially for the region where the lake flow texture was not obvious.

Effect evaluation

In this paper, the measured flow direction data of 10 stations in Poyang Lake area during the same period were used as reference to verify the flow direction extracted from the texture enhancement methods. The comparison results of the three methods are shown in Table 3.

Table 3 | Extraction angle and measured angle

Site	1	2	3	4	5	6	7	8	9	10
Measured	228°	236°	335°	342°	307°	24°	38°	48°	294°	282°
Gobor	217°	207°	298°	338°	318°	32°	29°	45°	286°	262°
Laws	173°	252°	343°	279°	285°	19°	45°	41°	267°	270°
LBP	196°	264°	271°	368°	264°	68°	62°	79°	257°	325°

By calculating the mean error and root mean square error (RMSE) between the three extraction results and the measured values, it could be obtained that the average relative errors of the three results of Gabor filtering, Laws and LBP were 0.0106, 0.0126 and 0.0456 respectively, and the root mean square errors were 17.57, 29.65 and 38.89° respectively. As shown in Table 4, it can be concluded that Gabor filtering had a higher accuracy than Laws algorithm, while LBP algorithm had the lowest accuracy among the three methods of texture enhancement extraction flow direction. As can be seen from the analysis of texture enhancement effect in the previous paper, Gabor filter has better directional enhancement effect on energy and texture, thus it has the strongest judgment on texture directivity. The image processed by Laws algorithm can highlight the linear features of the image, but the extraction effect is unstable, while LBP operator can enhance the complexity of the image gray. Therefore, for the extraction of lake flow direction, the complexity of the image should be as small as possible, and the texture of the image should have a certain direction. Gabor filtering is the most adaptable of the three methods.

In order to study the extraction effect of the above methods in different resolution, the above three methods were applied to data of different resolutions at the same location, and the lake flow direction is extracted through the Hough transform after image enhancement, combined with the water level data of various stations in the Poyang lake area during the same period and the topographic features of Poyang Lake high in the southeast, and low in the northwest, and the water level trend is used as the flow direction. Taking the waters near the Poyang Lake into the Yangtze River as an example, the adaptability of each method in different data sources is analyzed. The analysis results are shown in Table 5.

The flow direction extracted by Gabor filtering in different resolutions is consistent with the actual situation. Laws algorithm only had good effect in the GF-1 image and Landsat8 OLI image, while the flow directions extracted in Sentinel-2 and GF-2 is less. The flow trends extracted by LBP operator at medium resolution are not consistent with the actual situation, and it has a good performance in GF-2. In general, Gabor filter is more adaptable and can stably extract lake flow direction for images of different resolutions. Laws algorithm has a poor extraction effect for high-resolution images, but can extract fringe information for medium and high resolutions better. LBP algorithm has the highest resolution requirement, and texture particles were more disorderly under the condition of lower resolution, which was not suitable for flow direction extraction. Gf-2 multispectral image with only 4 m resolution achieved a better effect. Combining the enhanced results and flow direction extraction results of the above three methods for different regions, it is not difficult to conclude that Gabor filtering has good adaptability in different regions and images with different resolutions, and the enhancement effect is the best. The method combining Gabor filtering and Hough transform is helpful to enhance the texture features of lake flow.

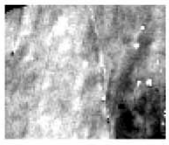
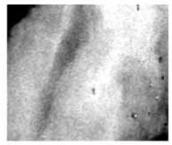
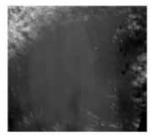
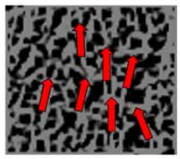
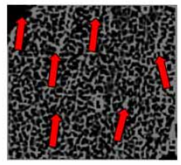
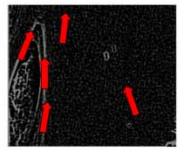
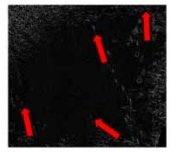
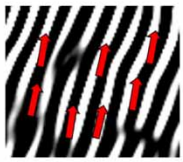
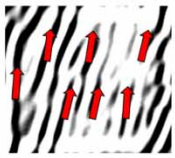
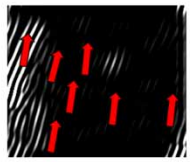
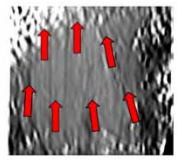
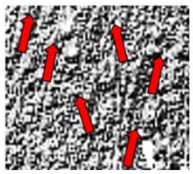
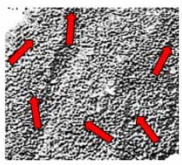
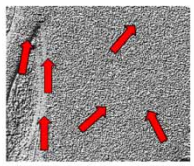
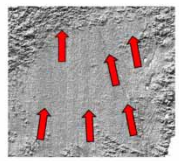
Based on the above analysis, Gabor filtering enhancement was performed on the images of Poyang Lake in different seasons in 2016, and the lake currents in the Poyang Lake area were extracted through the Hough transform. The result is shown in Figure 4.

It can be seen from the extraction results that the water area of Poyang Lake is the widest in the wet season of July. In April, the water area of the eastern area of Poyang Lake is large and the flow direction is dense. The lake flows from Ganjiang, Raohe and Xinjiang into the eastern area of the lake. In July, the maximum extent of the lake was reached, and the number of extracted flow field is also the largest. The lake flow from east to west was generated in the southeast, and the

Table 4 | The extraction accuracy of different texture enhancement methods

Methods.	Gabor	Laws	LBP
Average relative errors	0.0106	0.0126	0.0456
Root mean square error	17.57°	29.65°	38.89°

Table 5 | Flow direction extraction results of images with different resolutions

	Landsat8OLI	GF-1	Sentinel-2	GF-2
The original image				
Laws				
GABOR				
LBP				

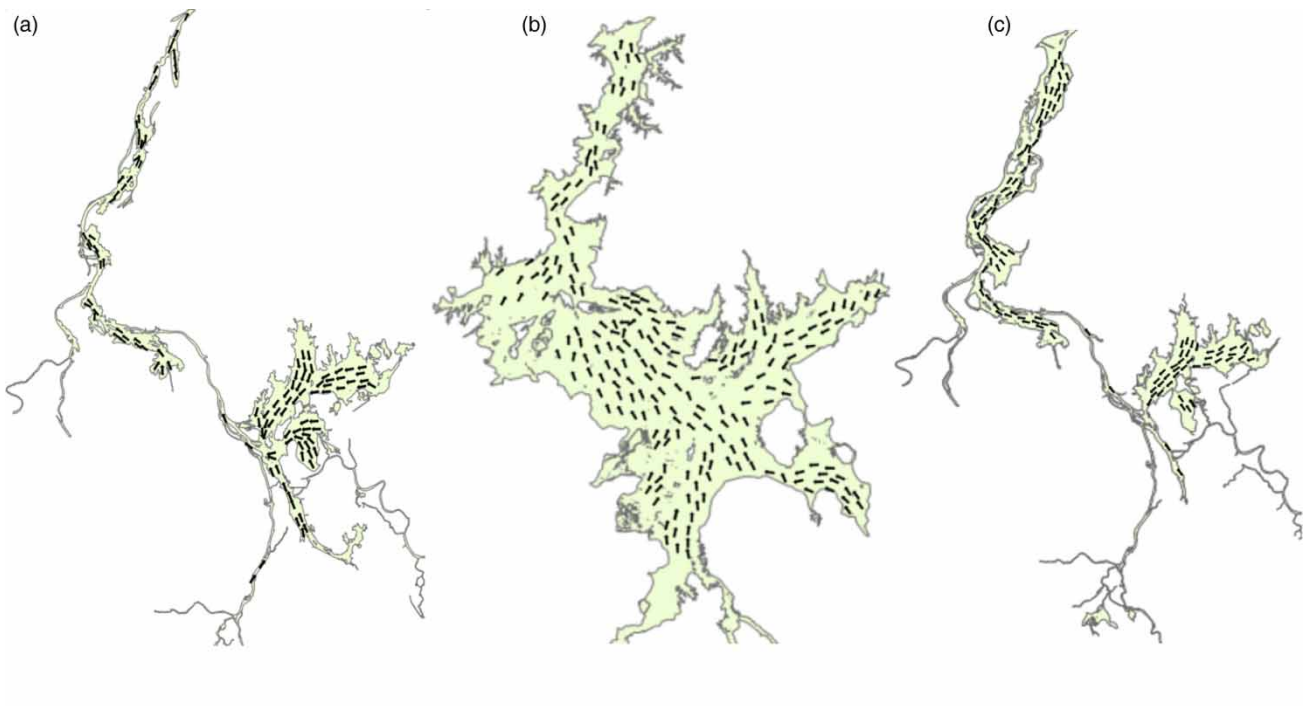


Figure 4 | Distribution map of Poyang Lake flow direction: (a) April; (b) July; (c) October.

overall flow was spread from the main river to the northwest, and the flow direction of the main lake was from south to north. The overall flow direction of Poyang Lake in October is similar to that in April, but the water area decreased. The water flow near Wanhu town in the east flows into the main river from northeast to southwest and then flows to northwest.

CONCLUSIONS

In this paper, the adaptability of three texture enhancement methods in different resolution images and different water areas was investigated and then the texture-enhanced image was used to extract the flow direction of Poyang Lake through Hough transform. The results show that the three algorithms can enhance the texture features of the image, among which Gabor filter has the best effect and the highest extraction accuracy. It was also found that when combining Gabor filter and Hough transform to extract the lake flow, the reliability and stability of lake flow extraction are better than other methods.

- Although this paper studied the texture characteristics of Poyang Lake flow and extracted the direction of lake flow, it has achieved good results and has certain research significance, but there are still limitations.
- The design of the algorithm needs to be improved and optimized. In some large areas, the algorithm is processed slowly, while for Poyang Lake, due to a large area, water extraction and segmentation are needed, and the automation of the method needs to be improved.
- The measured data is limited, and further and more measured data are needed for verification and analysis in large areas.
- There are not enough texture enhancement methods used in this paper. More texture enhancement methods can be used for further experiments

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CONFLICT OF INTEREST STATEMENT

The authors declare there is no conflict.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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