

## Remote Sensing-Based Ice-Water Classification for the Inner Mongolia Reach of the Yellow River: Postprint

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### Abstract

Timely acquisition of the spatial distribution characteristics of river ice and water during the ice flood period is of great significance for predicting ice flood disasters and improving the information management level of ice flood prevention. Remote sensing technology is currently one of the primary means for obtaining the spatial distribution of river ice and water. However, the high concentration of suspended sediment in the Yellow River water body poses a challenge for high-precision ice-water classification based on remote sensing technology. Taking the Inner Mongolia section of the Yellow River as an example and based on Landsat 8 OLI remote sensing imagery data, this study compared the performance of near-infrared band reflectance values, Normalized Difference Water Index (NDWI), Normalized Difference Snow Index (NDSI), Modified Normalized Difference Snow Index (MNDSI), and Normalized Difference Unfrozen Water Index (NDUWI) in classifying river ice and water in typical river channels of the Inner Mongolia section of the Yellow River, after excluding irrelevant ground objects using NDSI and river channel vector data. The overall classification accuracy and Kappa coefficient of each index were calculated, and threshold stability analysis was conducted. The results demonstrate that after excluding irrelevant ground objects outside the river channel using NDSI and high-definition historical imagery, the overall classification accuracy and Kappa coefficient of NDUWI in each sub-section image both exceeded 90.00% and 0.90, respectively, with the optimal discrimination threshold for river ice and water generally distributed near the median threshold value. The research findings can provide a basis for selecting ice flood monitoring methods for the Yellow River and determining ice blasting locations during the ice flood period.

## Full Text

# Ice-Water Classification in Inner Mongolia Reach of the Yellow River Based on Remote Sensing Images

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**Abstract:** Timely acquisition of spatial distribution characteristics of river ice and water bodies during the ice-flood season is of great significance for predicting ice disasters and improving the level of information management for ice flood prevention. Remote sensing technology is currently one of the most important means to obtain the spatial distribution of river ice and water bodies. However, the large amount of suspended sediment in the Yellow River water poses a challenge to high-precision ice-water classification based on remote sensing technology. Taking the Inner Mongolia reach of the Yellow River as an example, based on Landsat 8 OLI remote sensing image data, and after excluding irrelevant ground objects using the normalized difference snow index (NDSI) and river channel vector data, this study compares the performance of near-infrared band reflectance values, normalized difference water index (NDWI), normalized difference snow index (NDSI), modified normalized difference snow index (MNDSI), and normalized difference unfrozen water index (NDUWI) in classifying river ice and water bodies in typical river channels of the Inner Mongolia reach of the Yellow River. The overall classification accuracy and Kappa coefficient of each index were calculated, and threshold stability analysis was performed. The results show that the overall classification accuracy and Kappa coefficient of NDUWI in each sub-section image both exceed 90.00%, and the optimal discrimination threshold between river ice and water bodies is generally distributed near the median threshold value. The research results can provide a basis for the selection of ice monitoring methods and the determination of ice blasting locations on the Yellow River during the ice-flood season.

**Keywords:** river ice; remote sensing index; threshold stability; uncertainty; Landsat 8; Inner Mongolia reach of the Yellow River

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## Introduction

Ice jams are formed by the freezing and accumulation of river water, and their accumulation in river channels can easily trigger ice blockages and ice dams, ranging from ice piling up on banks to severe dike overflow and breaching [1,2]. The Inner Mongolia reach of the Yellow River features diverse channel patterns and complex river regimes, making it prone to ice jam disasters [3]. Therefore, accurate extraction of river ice and water body information is crucial for

studying the formation and dissipation processes of river ice, spatial changes in river ice, and the assessment of ice flood risks. Traditional field observations are limited to localized “point-to-point” measurements and cannot obtain complete river ice information, restricting ice regime observations. Satellite remote sensing, with its advantages of large observation range, strong timeliness, and objective data content, has been widely applied in river ice research in recent years [4].

Currently, remote sensing techniques for extracting river ice and water body information mainly rely on visual interpretation, single-band reflectance thresholding, normalized difference snow index (NDSI), normalized difference water index (NDWI), and combinations of modified normalized difference snow index (MNDSI) with single-band thresholds. NDSI is a snow information extraction index proposed by Dozier [9] in 1989 for monitoring snow cover changes. This index shows high discriminability between snow and soil and has been applied to large-scale glaciers and lake ice [10,11]. Yang et al. [6] were the first to apply remote sensing technology to monitor ice conditions on the Yellow River in China based on a “four satellites, three sources” model, but were limited by the spatial resolution of satellite imagery at the time and conducted only large-scale macro observations without micro-analysis of local river sections. Zhao et al. [7] used Landsat 8 color composite images to visually interpret river ice processes and distribution in the Shisifenzi Bend of the Yellow River, but did not verify extraction accuracy. Chaouch et al. [8] monitored river ice processes in Canada’s Slave River using MODIS near-infrared band data, but did not determine reflectance values for river ice and water in the near-infrared band, instead assuming that when near-infrared reflectance was at its maximum, the channel contained only river ice, and when at its minimum, only water. Mou et al. [13] constructed a normalized difference unfrozen water index (NDUWI) using blue and green bands based on the spectral characteristics of Yellow River water bodies, and performed river ice and water extraction after excluding soil, trees, and other ground objects using NDUWI, but the accuracy of this water-body-focused extraction method requires further verification. Gou et al. [16] found that the distance between the two peaks in the histogram of the normalized index constructed from near-infrared and shortwave infrared bands was greater than that in the NDWI histogram, which is beneficial for distinguishing river ice and water. They established a modified normalized difference snow index (MNDSI) to identify lake ice in Nam Co Lake with good results.

Overall, current remote sensing technology and satellite imagery spatiotemporal resolution basically meet the requirements for ice monitoring on the Yellow River during the ice season. However, using a single remote sensing index model makes it difficult to distinguish river ice and water from soil, and river channel boundaries are hard to extract. Meanwhile, the accuracy of various index models for monitoring river ice and water on the Yellow River remains to be verified.

Due to the unique hydraulic conditions of the Inner Mongolia reach of the Yellow River, ice jam dams are prone to form during the ice-flood season, increasing

the risk of “violent ice breakup” [17,18]. In view of this, this study selects typical river sections in the Inner Mongolia reach of the Yellow River as the research area. Based on Landsat 8 OLI remote sensing imagery and after excluding irrelevant objects outside the river channel using Google Earth historical high-definition images combined with the NDSI index model, we classify river ice and water using near-infrared band reflectance values, NDWI, NDSI, MNDSI, and NDUWI. We then calculate the classification accuracy of each index, evaluate threshold stability and method applicability, to provide a reference for remote sensing monitoring of river ice conditions and ice flood risk assessment.

### 1.1 Study Area Overview

The study area begins at the Haibowan Reservoir in the Inner Mongolia reach of the Yellow River and ends at the tail area of the Wanjiashai Reservoir, with a total length of approximately 650 km and an overall “几” shape distribution. Test sections were selected from the upper, middle, and lower reaches, including transitional, wandering, and meandering channel types. Transitional sections feature numerous shoals and large channel swing amplitudes, while wandering sections suffer from severe sedimentation and frequent ice flooding and dike encroachment [19]. The main ground objects in the experimental area include main channel ice, floodplain ice, open water leads (clearings), and soil, with smooth ice and impact bank ice as the primary ice types. The river section begins to drift ice in early December each year, and all ice melts by late March of the following year. Influenced by inflow conditions and channel characteristics, water freezes within the riverbed and on floodplains, while narrow strips of unfrozen open water (clearings) often appear in rapids, shoals, or drainage outlets with higher flow velocities.

### 1.2 Data Sources and Preprocessing

**1.2.1 Landsat 8 Remote Sensing Imagery for River Ice Information Extraction** The experiment is based on Landsat 8 OLI imagery data obtained from the United States Geological Survey website (<https://earthexplorer.usgs.gov/>). All used images are Landsat 8 OLI Level-1 products, which are precisely corrected using ground control points and digital elevation model data with errors less than 12.5 m. The experimental images are cloud-free or cloud-free over the river channel and nearby areas. Image information is shown in Table 1.

**1.2.2 Validation Data** Google Earth images are used as reference images, selecting historical high-definition images on the same date or close to the acquisition date of the Landsat 8 OLI images. Since the acquisition dates fall within the stable ice cover period of January-February, ice cover remains basically unchanged when the time difference between the images and reference images is within 15 days. Vector data of various main ground objects visually interpreted from reference images are used for classification accuracy evaluation.

As the spatial resolution of reference images is sub-meter, visual interpretation errors are considered negligible.

**1.2.3 Data Preprocessing** Landsat 8 OLI image preprocessing includes radiometric calibration and atmospheric correction. The preprocessing uses the FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) atmospheric correction tool integrated in ENVI 5.5 to obtain surface reflectance data. FLAASH radiometric calibration and atmospheric correction model parameters are determined based on atmospheric column water vapor content on the morning of image acquisition, obtained from the MOD05 dataset in MODIS standard atmospheric products (download address: <http://ladsweb.nascom.nasa.gov>). Atmospheric correction parameters are shown in Table 1. All images are clipped using dike vector data to retain only the area between both banks. First, river channel vector boundaries visually interpreted from Google Earth historical high-definition images are used for clipping to exclude most irrelevant objects outside the channel. Second, NDSI is used to further exclude soil and other irrelevant objects at riverbank edges. As the experimental area is located within the river channel between both banks, and relevant laws prohibit buildings, roads, and other facilities within dikes and prohibit occupation of floodplains, the clipped image data can effectively exclude nearby residences, roads, factories, and other irrelevant objects. Additionally, since there are very few trees in the channel and it is winter, ground objects in the channel are assumed to be only river ice and water. The classification accuracy of NDSI for soil and snow/ice has been verified by previous studies [20,21] and is not repeated here. To retain as many river ice and water pixels as possible,  $NDSI < 0.1$  is used as the classification threshold between soil and river ice/water. The image preprocessing and classification workflow is shown in Figure 2. After workflow processing, the pixels to be extracted are only river ice and water, with almost no other irrelevant objects.

### 1.3 Research Methods

**1.3.1 Five Remote Sensing Index Models** Five remote sensing index models were selected to classify river ice and water information in the Inner Mongolia reach of the Yellow River:

- 1) **Near-infrared band reflectance threshold method** [8]. Water bodies have low reflectance values in the near-infrared band, while snow/ice have high reflectance, making this suitable for classifying snow/ice and water. The classification algorithm is:

$$\text{pixel} = \begin{cases} \text{ice}, & \text{NIR}/10000 < \text{threshold} \\ \text{water}, & \text{NIR}/10000 > \text{threshold} \end{cases}$$

where NIR is the near-infrared band reflectance value and threshold is the threshold value (same below). To save storage space, pixel reflectance

values in Landsat 8 OLI image data are multiplied by 10,000; during calculation, dividing by 10,000 restricts the value range to 0-1 for easier comparison with other index values.

- 2) **Normalized difference water index (NDWI) threshold method** [20]. This index uses green and near-infrared bands to construct a normalized difference water index. Since the channel does not involve construction land, NDWI's shortcomings do not affect river ice and water extraction. The classification algorithm is:

$$\text{pixel} = \begin{cases} \text{ice}, & \frac{\text{Green}-\text{NIR}}{\text{Green}+\text{NIR}} > \text{threshold} \\ \text{water}, & \frac{\text{Green}-\text{NIR}}{\text{Green}+\text{NIR}} < \text{threshold} \end{cases}$$

where Green is the green band reflectance value (same below).

- 3) **Normalized difference snow index (NDSI) threshold method** [9]. NDSI is a normalized difference index constructed from green and shortwave infrared bands, with a formula consistent with the MNDWI index. This index can effectively distinguish water bodies from other ground objects. The classification algorithm is:

$$\text{pixel} = \begin{cases} \text{ice}, & \frac{\text{Green}-\text{SWIR}}{\text{Green}+\text{SWIR}} > \text{threshold} \\ \text{water}, & \frac{\text{Green}-\text{SWIR}}{\text{Green}+\text{SWIR}} < \text{threshold} \end{cases}$$

where SWIR is the shortwave infrared band reflectance value (same below).

- 4) **Modified normalized difference snow index (MNDSI)** [16]. This method constructs a normalized difference index using near-infrared and shortwave infrared bands, with a calculation method consistent with the NDWI3 water index. It performs well in extracting water body edges. The classification algorithm is:

$$\text{pixel} = \begin{cases} \text{ice}, & \frac{\text{SWIR}-\text{NIR}}{\text{SWIR}+\text{NIR}} > \text{threshold} \\ \text{water}, & \frac{\text{SWIR}-\text{NIR}}{\text{SWIR}+\text{NIR}} < \text{threshold} \end{cases}$$

- 5) **Normalized difference unfrozen water index (NDUWI)** [13]. Mou et al. [13] constructed a normalized difference index using blue and green bands to monitor river ice in the Inner Mongolia reach of the Yellow River. The classification algorithm is:

$$\text{pixel} = \begin{cases} \text{ice}, & \frac{\text{Green}-\text{Blue}}{\text{Green}+\text{Blue}} > \text{threshold} \\ \text{water}, & \frac{\text{Green}-\text{Blue}}{\text{Green}+\text{Blue}} < \text{threshold} \end{cases}$$

where Blue is the blue band reflectance value.

**1.3.2 Accuracy Assessment** To compare the classification accuracy of each algorithm, overall classification accuracy ( $p_0$ ) and Kappa coefficient ( $\kappa$ , an index measuring river ice and water classification accuracy based on the confusion matrix, ranging from -1 to 1) are used to evaluate the extraction accuracy of each classification method [24]. Based on the extraction results of each method, a confusion matrix for river ice and water bodies is created (Table 2), and the classification accuracy of each index is calculated separately. The calculation process is shown in equations (1)-(3). Landis and Koch [24] proposed that when  $\kappa > 0.81$ , classification is almost in perfect agreement, but for precise extraction,  $\kappa > 0.90$  is selected as the standard for almost perfect agreement.

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## Results

### 2.1 River Ice and Water Classification Results

The five remote sensing index models were used to extract river ice and water information in the Inner Mongolia reach of the Yellow River. Due to space limitations, only the extraction results from two periods are shown (Figures 3-4). Overall, NDSI and river channel boundaries excluded soil and snow/ice on riverbanks and floodplains, reducing the impact of irrelevant objects on subsequent overall classification accuracy and Kappa calculation accuracy. In terms of classification effectiveness, the five methods ranked from high to low as: normalized difference unfrozen water index, normalized difference water index, near-infrared band reflectance value, modified normalized difference snow index, and normalized difference snow index. In the 2016 image, NDSI extraction was suboptimal (Figure 3) with serious misclassification. All five methods demonstrated high classification accuracy in extracting river ice and water information. The maximum (minimum) threshold ranges corresponding to each remote sensing index model are shown in Table 3. NDSI has the largest threshold range, but its classification results are unstable in the test area. NDUWI has a moderate threshold range and shows good classification results across three test areas. Further analysis reveals that the optimal discrimination thresholds for river ice and water in NDUWI from the two remote sensing images are generally distributed near the median threshold value. For example, in the 2018 remote sensing image, the NDUWI threshold range is 0-0.46, with an optimal threshold of 0.24.

### 2.2 Threshold Stability and Uncertainty Analysis

**2.2.1 Sensitivity Analysis** Figure 5 shows the response of  $p_0$  and  $\kappa$  to threshold values in the test area. Regarding the response of classification accuracy to threshold changes in river ice and water classification for each period, NDUWI shows the best classification effect in remote sensing images. In the 2016 image, the near-infrared band reflectance threshold method demonstrates the highest extraction accuracy compared to other methods, with  $p_0$  and  $\kappa$  values of 99.18% and 0.98, respectively. In the 2018 image, the NDUWI threshold method shows

the highest classification accuracy compared to other methods, with  $p_0$  and values of 99.98% and 0.99, respectively. Further analysis (Figure 5) shows that when appropriate thresholds are adopted, the highest achievable accuracy for the five remote sensing index models ranks from low to high as: MNDSI, NDSI, near-infrared band reflectance threshold method, NDWI, and NDUWI. Additionally, regarding the response mechanism of classification accuracy to threshold changes, the near-infrared band reflectance threshold method shows the largest variation amplitude—a small threshold change causes significant changes in extraction results, with overall accuracy differences reaching 50.10%. In contrast, NDUWI shows lower sensitivity of threshold changes to classification accuracy; selecting an appropriate threshold yields good accuracy. For the other four index models, the sensitivity of threshold to classification accuracy ranks from low to high as: MNDSI, NDSI, NDWI, and near-infrared band reflectance threshold method.

Comprehensive analysis of classification performance across the two periods shows that the near-infrared band reflectance threshold method achieves  $p_0$  and values exceeding 90.00% in both periods. NDWI achieves  $p_0$  and values exceeding 90.00% in both periods. NDSI shows unsatisfactory classification results in the first two periods but achieves  $p_0$  and values exceeding 90.00% in the latter two periods. MNDSI achieves  $p_0$  and values exceeding 90.00% in both periods, but shows negative values in the 2016 image, indicating serious misclassification and omission. NDUWI achieves  $p_0$  and values exceeding 90.00% in both periods, demonstrating high classification accuracy.

**2.2.2 Uncertainty Analysis** In extracting ice-water information from the Inner Mongolia reach of the Yellow River based on remote sensing imagery, subjective and objective factors often affect the final extraction accuracy. For example, NDUWI shows high classification accuracy in the 2016 image but is less satisfactory in the latter two periods. The uncertainty in this study stems from several aspects: remote sensing image selection, manual visual interpretation experience, and environmental changes in the study area.

In winter, due to the presence of fog, clouds, and haze over the river channel, the amount of usable optical data for ice regime monitoring is limited, with only two images per test area available for the experiment [25]. The Landsat 8 OLI images used in this study are all cloud-free or cloud-free over the river channel and nearby areas, ensuring data quality and reliability to the greatest extent possible. Due to objective factors, other satellite images have not yet been introduced as supplementary data sources. Errors in manual visual interpretation mainly come from mixed pixels. The raster data calculated using threshold models generally contains information from multiple ground objects. Except for a small amount of smooth bank ice [26] (i.e., static bank ice referring to relatively smooth river ice that develops both longitudinally and transversely in the channel under hydraulic conditions where the average flow velocity is below the critical flow velocity), there are few pure pixels, especially at channel boundaries where

boundaries between river ice, water, snow, and soil are difficult to accurately define, affecting classification accuracy during manual judgment [27]. In terms of changing environmental conditions, water vapor, aerosols, and ozone in the atmosphere, sediment content in open water leads within the channel, and soil moisture at riverbank boundaries cause phenomena such as “same spectrum, different quality” and “same quality, different spectrum,” creating uncertainty for boundary extraction and ice-water monitoring [28]. To minimize misjudgment in river channel boundary extraction, this study designed a workflow extraction operation using Google Earth high-definition images for boundary extraction, maximizing the exclusion of irrelevant objects such as soil.

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## Discussion

The Inner Mongolia reach of the Yellow River spans approximately 650 km with large east-west span and an overall “几” shape distribution, limiting field ice observations. Remote sensing-based ice monitoring shows good results [29]. Meanwhile, Yellow River ice information monitoring is limited by temporal resolution of data and weather conditions, often resulting in missing data for certain stable ice cover periods [30]. Unlike traditional large-scale sea ice (lake ice) monitoring, due to the sediment characteristics and channel sedimentation spread of the Yellow River itself, this study based on Landsat 8 OLI imagery first excluded irrelevant objects such as soil, buildings, and vegetation outside the river channel using Google Earth, retaining only ice-water information to ensure the authenticity of studied pixels, solving the problem of difficult identification of river ice and water information at channel boundaries.

This study found that remote sensing image selection, meteorological conditions over the river channel, and river water quality conditions are important factors affecting ice monitoring extraction accuracy. Regarding data selection, due to the presence of fog, clouds, and haze over the river channel in winter, classification thresholds for different indices are difficult to determine, with large threshold fluctuations. Therefore, satellite images from stable ice cover periods (when river ice no longer develops laterally along the channel) that are cloud-free, snow-free, and have good meteorological conditions should be selected [31]. In the workflow experiment, although MNDSI cannot precisely distinguish internal channel ice and water information, this index can be combined with historical high-definition images as the first step in the classification workflow to extract river channel boundaries and exclude irrelevant objects outside the study area, maximizing the retention of authentic river ice and water pixels. The near-infrared band reflectance threshold method shows high sensitivity in extraction accuracy to threshold response—small threshold fluctuations cause large changes in extraction accuracy. MNDSI shows moderate sensitivity in extraction accuracy to threshold response, but its accuracy is slightly lower than the near-infrared band reflectance threshold method. NDUWI shows high extraction accuracy in multi-temporal, multi-river-section studies, and the optimal

discrimination threshold for river ice and water is generally distributed near the median threshold value. Additionally, model index values on the concave bank side are slightly larger than on the convex bank side, possibly due to increased ice accumulation on the concave bank side caused by centrifugal forces at bends. Therefore, dike protection should be strengthened on the concave bank side [32].

Yellow River ice monitoring by remote sensing is affected not only by data quality, meteorological conditions, and illumination, but also by water level, discharge, and upstream reservoir ice flood control scheduling [33,34]. For example, higher temperatures result in smaller river ice distribution ranges and larger proportions of clearings during stable ice cover periods, leading to ice flood disasters. Higher water levels increase the contact area between the river channel and atmospheric surface, increasing the heat conditions required for river ice freezing, enlarging river ice distribution ranges, and increasing the risk of ice overtopping dikes [35]. Therefore, in future research, how to integrate meteorological conditions, hydraulic conditions, and other data into models, automate ice-water pixel extraction, and combine with hydrological station field observation data for comparative analysis is a direction worth considering, which may further improve the timeliness and accuracy of river ice and water monitoring on the Yellow River during ice-flood season.

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## Conclusions

The Inner Mongolia reach of the Yellow River has complex river regimes and diverse topography, making it difficult to obtain river ice and water distribution through remote sensing image models, and the applicability of each index model has not been evaluated. To address these issues, this study used Landsat 8 OLI image data, designed an experimental scheme to extract river channel boundaries, and used five remote sensing models (near-infrared band reflectance threshold, NDWI, NDSI, MNDSI, and NDUWI) to monitor river ice and water distribution in the study area. Threshold stability and uncertainty of each index were analyzed, leading to the following conclusions:

- 1) The experimental scheme combining Google Earth historical high-definition images for secondary exclusion of irrelevant objects can effectively remove surrounding irrelevant objects during river ice and water monitoring.
- 2) NDUWI achieves the highest classification accuracy in images of the Inner Mongolia reach of the Yellow River. In multi-temporal, multi-river-section studies, the overall classification accuracy and Kappa coefficient both exceed 90.00%, showing high overall classification accuracy and strong applicability. The optimal discrimination threshold for river ice and water in the two remote sensing images is generally distributed near the median threshold value. However, NDWI cannot effectively distinguish soil from

river ice, and river channel vector boundaries should be extracted first using NDUWI to exclude irrelevant objects before application.

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*Note: Figure translations are in progress. See original paper for figures.*

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