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Discriminant analysis of the freeze-up and break-up conditions in the Inner Mongolia Reach of the Yellow River

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ABSTRACT

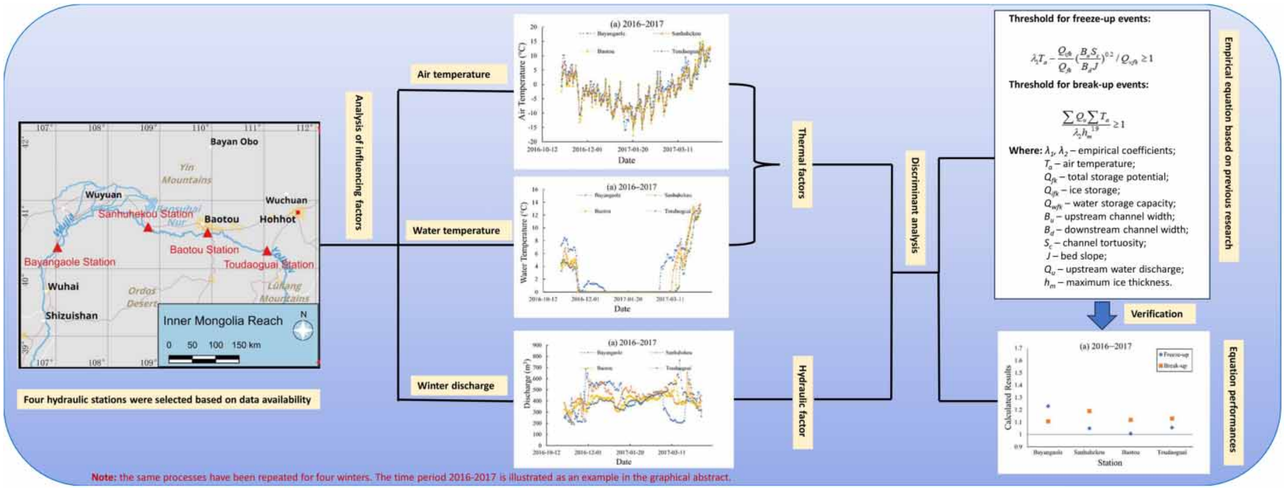
This study divided the total storage potential in a natural channel into the ice production volume and the water storage capacity volume. Thermal factors, hydraulic processes, topography, and ice formation were selected to derive a discriminant equation for freeze-up and break-up conditions in the Inner Mongolia Reach of the Yellow River. The trends observed from data for the freeze-up dates, break-up dates, and total frozen days from 2017 to 2020 conform to the principle that the river is gradually frozen from the downstream to the upstream and later thawed from the upstream to the downstream. The number of frozen days in the downstream is greater than in the upstream. Results indicate that freeze-up typically occurs when the proportion of ice in the channel is relatively high. Higher temperatures and greater discharges are required to facilitate the break-up of the river when the equilibrium ice thickness is greater. This study can provide a theoretical basis and framework for establishing an accurate freeze-up and break-up forecast model to prevent and mitigate ice-induced disasters.

Key words: ice jam, ice-water conversion, river break-up, river freeze-up, river ice forecast, Yellow River

HIGHLIGHTS

- Total channel storage potential can be divided into ice production amount and water storage capacity under the ice cover in winter.
- Thermodynamic factors, hydraulic parameters, topography, and ice production impact a river's freeze-up and break-up processes.
- Empirical equations can assist in determining whether freeze-up/break-up will occur.

GRAPHICAL ABSTRACT



1. INTRODUCTION

River ice formation affects the safety of residents living in the adjacent floodplain (Kovachis *et al.* 2017). In winter, 60% of the rivers in high latitudes are impacted by river ice formation (Rokaya *et al.* 2018). The evolution of ice formation and depletion is exceedingly complicated. As the temperature drops, rivers in high latitudes will successively experience frazil ice growth, freeze-up, and break-up processes. Each stage has its characteristics and governing laws. Frazil ice is the small ice particulates floating above the water surface. Frazil ice forms pans and eventually congregates to produce bigger ice floes. When the river is constrained by structures, the ice floes cause ice jams and pose flooding hazards when river break-up starts (Su *et al.* 1997; Beltaos 2012; De Munck *et al.* 2017; Kim *et al.* 2021). River freeze-up occurs when the formation of a continuous, immovable ice cover completely shuts down waterway transport. A break-up event is the opposite of a freeze-up event and occurs near the winter's end as temperatures rise. Freeze-up and break-up dates often mark the closing and re-opening of the navigation and boat traffic in winter, which is crucial for preserving ecohydrology and developing socioeconomics in cold regions such as Canada (Williams 1965; Lacroix *et al.* 2005).

Many scholars have attempted to simulate the river freeze-up and break-up processes. Adams (1976) established the relationship between surface heat loss and temperature drop and predicted the freeze-up of the upper reaches of the St. Lawrence River. The errors in the prediction of the freeze-up dates were within 2 days compared to the observed data. Ashton (1985) summarized the equations for heat exchange between the water surface and the atmosphere and between the ice cover and the atmosphere and revealed the ice melting mechanisms during the break-up stage by analyzing the influence of the surface energy budget on the ice cover temperature. Foltyn & Shen (1986) established a river freeze-up date forecast model using water temperature, air temperature, and flow velocity. When applied to the upper St. Lawrence River, the model results only showed 4.5 days error for 16 years of observed data. Palecki & Barry (1986) used regression analysis to determine the statistical relationship between the freeze-up dates and mean temperatures over different periods in 63 Finnish lakes and found a strong correlation (up to 88% for the proposed equations) between the mean temperatures of the months before the freeze-up event and the actual freez-up dates. Shen & Chiang (1984) and Shen & Wang (1995) analyzed measured data of Hequ Reach of the Yellow River and characterized the evolution of the ice jam regarding heat exchanges. The ice transport capacity was developed by analogizing with sediment transport, and numerical thermal-ice simulation models for natural channels were derived from their studies. Morales-Marín *et al.* (2019) coupled the hydrological and one-dimensional river temperature models into a new river ice modeling framework. This framework has been successfully applied to the Athabasca River Basin in Canada, and the simulated river break-up date was in good agreement with the hydrological station monitored data (e.g., $R^2 = 0.91$ for Fort McMurray station). Sun (2018) proposed a stacking ensemble tree model (STEM) framework that further enhances the freeze-up/break-up date prediction accuracy of the classification and regression tree (CART) and the modified version of the CART (M5) by 13.1 and 13.2%, respectively. With climate change becoming a heated debate topic, scholars have also examined how climate change may change the freeze-up/break-up processes. Sha *et al.* (2018) adopted a coupled model to the headwater reach of the Yalu River above the Balin Hydrological Gauge Station. They found that with earlier snowmelt peaks in spring, the total frozen days in winter would be reduced. The impacts of human activities on hydrological processes have also been studied by scholars considering multiple climate scenarios. Agashua *et al.* (2022) findings imply that the values for the post-impact (1967–2022) maximum flow rate dropped as the day advances in River Ikpoba. Garcia *et al.* (2022) investigated the effect of drought on the life cycle of barge transportation in Madeira River, Brazil. Their results demonstrated that during a drought, barge transportation is more detrimental to the environment.

The Yellow River is one of the rivers experiencing the most frequent ice jams in China (Chang *et al.* 2016). The major ice jam disasters occurred in the northernmost part of the Inner Mongolia section. This section of the Yellow River has an inverted U shape, with a steep upstream slope and a gentle downstream slope, causing ice dams to occur frequently in winter and attributing to massive casualties and property losses (Zhao *et al.* 2020). Ice prediction is an effective means to prevent or mitigate ice-induced natural disasters. Wang *et al.* (2008) used the artificial neural network model based on feed-forward back-propagation improved by the Levenberg–Marquardt algorithm to forecast the ice situation of the Yellow River in Inner Mongolia. The measured values in winter are in good agreement with observed data (the calculated R^2 ranges from 0.96 to 0.98).

Chen & Ji (2005) proposed a fuzzy optimization neural network method adopting the correlation coefficient method to select governing factors. Applying their method to the Inner Mongolia Reach of the Yellow River, the predicted errors were equal to or less than 6 days in 27 out of 30 cases. Fu *et al.* (2014) applied the Yellow River Conservancy Commission River Ice Dynamic Model (YRIDM) to the Ningxia-Inner Mongolia section of the Yellow River and verified the accuracy of their model based on observed data. The root mean square error (RMSE) for Sanhuhekou station during the winter of 2008/2009 is 0.85, deemed acceptable by the authors. The model can simulate water level, flow, water temperature and ice cover thickness under unsteady flow conditions. The continuous improvement of field observation methods and related research provides convenience for more accurate prediction of the freeze-up/break-up dates. Zhao *et al.* (2021) used a combination of observation and remote sensing monitoring to explore the interaction between sediment transport at the river bends and the river freeze-up process. The results showed that due to the convex bank's shallow depth and low flow velocity, smooth ice covers first appeared near the bank and then continued to develop upstream to freeze the river completely. Zhang *et al.* (2021) proposed an ice evolution monitoring system using the channel extraction method based on sparse reconstruction (CE-SR), adaptive threshold segmentation (Th), and Fuzzy C-means (FCM) methods to monitor the ice regime of the Yellow River. The optimal combination of CE-SR + Th + FCM can achieve 90.65% on the accuracy assessment factor. Its performance is ideal for detecting changes in river ice.

In previous studies, the simulation of the freeze-up and break-up processes mainly adopted mathematical model frameworks, statistical regressions, and neural network computations. The mathematical model frameworks are based on the physical mechanism of river ice formation and evolution. Based on the equations of hydrology, thermodynamics, and river ice hydraulics, a mathematical model framework is established to simulate river ice-related processes. The field-monitored data from hydrological stations are used to validate the equations and predict the freeze-up and break-up dates (Bian *et al.* 2015). The statistical regression analysis screens the factors that affect the freeze-up and break-up dates, such as factors influencing the momentum and thermodynamics of the system. Statistical regression analysis techniques establish the connections between freeze-up/break-up dates and the factors examined (Qiao *et al.* 2013). The artificial neural network is formed by the interconnection of a large number of nodes. It is an abstract mathematical model that reflects the structure and function of the human brain. The artificial neural network uses a large amount of data for repeated learning and summarizes the internal correlation of the data (Chen & Ji 2004). However, neural network methods are insufficient to generalize from limited training data. Due to the complexity of mathematical model construction, upstream and downstream neuron data support is often insufficient. The simplification of some parameters and constraints in the calculation process reduces the accuracy of the neural network models. To the best of the authors' knowledge, the existing models consider thermal, hydraulic, terrain, and other influencing factors but not the impact of ice production. If the impact of ice production on the freeze-up/break-up dates is considered, it will be beneficial to further improve the river ice-water conversion process simulation accuracy.

Based on Hou *et al.*'s (2022) study of ice production in the Inner Mongolia section of the Yellow River, this paper innovatively considers both the ice production and the storage capacity of the channel to calculate the total storage potential. Considering the thermal, geomorphologic, and river ice hydraulic factors, an empirical equation was derived to assess the river freeze-up and break-up conditions. This study can provide a theoretical basis for determining an accurate river freeze-up and break-up forecast model to mitigate and/or prevent ice-induced disasters.

2. METHODS

2.1. Study site and data

The study reach is located at the northernmost part of the Yellow River flowing through Inner Mongolia province, measuring a total length of 823 km, spanning in latitude from 39° to 41°N and in longitude from 106° to 112°E. Affected by the humid continental climate and coupled with its unique geographical location, channel morphology, and hydro-meteorological conditions, the study reach is an area with severe ice hazards (Figure 1). The Inner Mongolia Reach of the Yellow River is vulnerable to the long and cold winter lasting 4 months on average, during which the temperature can drop to –35 °C. The frazil ice starts to develop in November every year. The whole reach then completely freezes up in the coming January and gradually breaks up in March. Some river sections are frozen for an average of 100 days, with the longest being over 130 days. The ice cover's average thickness after the river's surface becomes completely frozen is 0.75 m, and the thickest ice cover can reach more than 1.1 m. The upper sections of the Inner Mongolia Reach flow from low latitudes to high latitudes. As the temperature drops, the river gradually freezes. The ice dam can form during the freeze-up of the river. Ice dam reduces the flow capacity under the ice but raises the water level, which correspondingly increases the water storage potential of the channel. Ice jams are prone to occur when the river starts to break up (Hou *et al.* 2022).

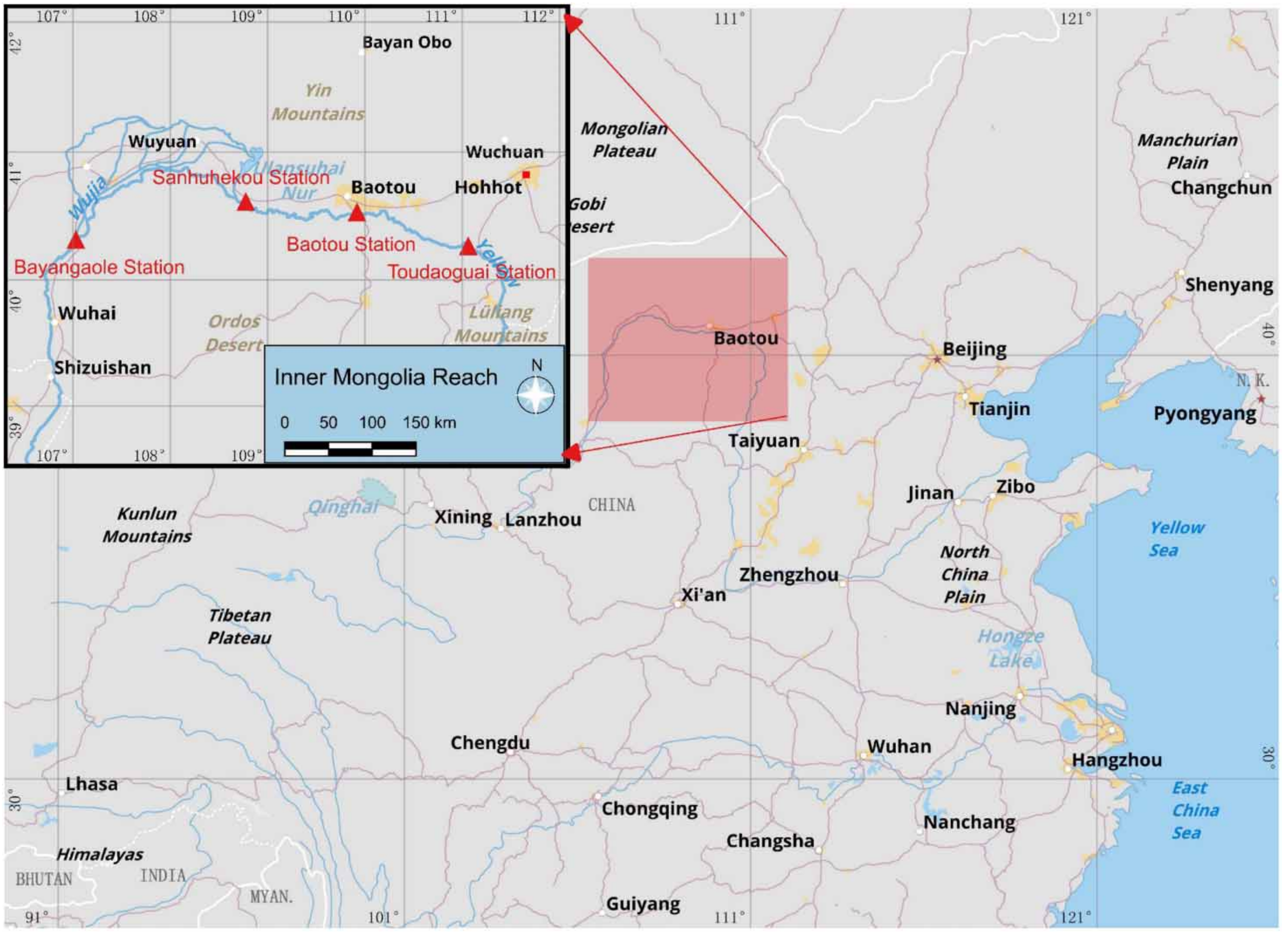


Figure 1 | Geographic location of Inner Mongolia Reach of the Yellow River and the selected gauging stations (made with QGIS using Natural Earth Data).

Field observation of a river's ice regime is the preliminary step for studying the initiation and development of river ice cover, during which the researchers can monitor the whole process intuitively. In strict accordance with the *Specification for Observation of Ice Regime in Rivers SL 59-2015* (Ministry of Water Resources of the People's Republic of China 2015), the Yellow River Institute of Hydraulic Research (YRIHR) conducted fixed-point observations of the entire Inner Mongolia Reach of the Yellow River in winter. The observed data from four gauging stations (Bayangaole, Sanhuhekou, Baotou, and Toudaoguai) were evaluated in the study. The assessed hydrological and meteorological data include cross-section data, freeze-up/break-up dates, air temperatures, water temperatures, wind speed, discharge, velocity, and ice thickness.

2.2. Mathematical frameworks

Mathematical frameworks that combine the governing thermodynamic and hydraulic equations and consider the influence of river channel morphology can better simulate the actual physical process of ice evolution during the freeze-up and break-up of a river. The total storage potential of the channel is divided into ice formed on the river surface and the water storage capacity under the ice cover. Considering the available data for parameters used in previous research (e.g., Chen & Ke 1994; Ke *et al.* 2001; Wang *et al.* 2021; Hou *et al.* 2022) that examined the influence of thermal processes, hydraulic processes, topography, and ice production of the river, the derivation of the empirical equation for freeze-up/break-up determinations is indicated below.

The ice-water conversion process in the river satisfies the relationship:

$$Q_{fk} = Q_{ifk} + Q_{wfk} \tag{1}$$

in which, Q_{fk} is the total storage potential of the study river reach, Q_{ifk} is the amount of ice storage in the study river reach, which can be converted from the ice production amount calculated based on equations proposed by Hou *et al.* (2022), and Q_{wfk} is the water storage capacity in the channel of the study reach. Q_{fk} is an important parameter in the derivation and study of freeze-up and break-up dates. The thermodynamic theory of heat transfer between ice, air, riverbed, and water was used to investigate ice generation in a natural river reach by Hou *et al.* (2022). However, Q_{wfk} can simply be acquired from hydraulic station observed data. Equation (1) combines estimated values with field observed data and is essential in the determination of freeze-up and break-up dates.

With the increase in ice production, the interplay among ice floes increases the ice resistance, which can be determined by the ice storage capacity of the channel and air temperature. Contrarily, the drag force on the ice floe in the river is determined by the water storage capacity, bed slope, and tortuosity (Ke *et al.* 2001). When the resistance exceeds the drag force of water flow or wind on the ice floe, the ice will reach static equilibrium, and the river freeze-up process will start. The equation for the determination of whether freeze-up will occur is expressed as:

$$\frac{F_s}{F_t} = \lambda_1 T_a - \frac{Q_{ifk}}{Q_{fk}}\left(\frac{B_u S_c}{B_d J}\right)^{0.2} / Q_{wfk} \geq 1 \tag{2}$$

in which, F_s is the ice resistance, F_t is the drag force on the ice floe, λ_1 is an empirical coefficient referring to the coefficient used for the Inner Mongolia Reach in Ke *et al.* (2001) modified with the field measured data, T_a is the air temperature, B_u is the width of the upper section of the channel, B_d is the width of the lower section of the channel, S_c is the tortuosity of the channel, and J is the channel bed slope.

As the temperature rises and the water stored in the channel is released, the flow increase will induce the river to break up, especially when the discharge increases sharply. Although the temperature may not turn above 0 °C, the flow will directly push the ice cover to break up (Chen & Ke 1994). The equation for the determination of whether break-up will occur is expressed as:

$$\frac{\sum Q_u \sum T_a}{\lambda_2 h_m^{1.9}} \geq 1 \tag{3}$$

in which, Q_u is the upstream water discharge, calculated by the improved Muskingum method considering the inter-conversion processes of ice and water (Wang *et al.* 2021), λ_2 is a modified empirical coefficient from Chen & Ke (1994) based on the field measured data, and h_m is the maximum ice thickness during the freeze-up period.

3. RESULTS AND DISCUSSION

3.1. Freeze-up dates, break-up dates, and total frozen days variations

Observatory data were analyzed regarding the freeze-up dates, break-up dates, and total frozen days of the four selected stations in the Inner Mongolia Reach of the Yellow River in winter from 2017 to 2020. The results are shown in Tables 1–3. It can be seen from Table 1 that the freeze-up order of the selected gauging stations is Toudaoguai, Baotou, Sanhuhekou, and Bayangaole, indicating that the water surface in the study reach gradually freezes from the downstream to the upstream. It is worth noting that the freeze-up date at Baotou station in 2016–2017 was 2 days later than that of Sanhuhekou, and the

Table 1 | Statistics on the freeze-up dates in winter

	Year				
Station	**2016–2017**	**2017–2018**	**2018–2019**	**2019–2020**	**Average date**
Bayangaole	2017/1/13	2018/1/3	2018/12/23	2020/1/2	1/3
Sanhuhekou	2016/11/23	2017/12/11	2018/12/7	2019/12/21	12/8
Baotou	2016/11/25	2017/12/7	2018/12/7	2019/12/14	12/5
Toudaoguai	2016/11/25	2017/12/4	2018/12/11	2019/12/6	12/4

Table 2 | Statistics on the break-up dates in winter

	Year				
Station	**2016–2017**	**2017–2018**	**2018–2019**	**2019–2020**	**Average date**
Bayangaole	2017/2/25	2018/3/3	2019/3/4	2020/2/20	2/27
Sanhuhekou	2017/3/12	2018/3/12	2019/3/16	2020/3/10	3/12
Baotou	2017/3/16	2018/3/15	2019/3/16	2020/3/13	3/15
Toudaoguai	2017/3/16	2018/3/16	2019/3/18	2020/3/14	3/16

Table 3 | Statistics on the total freezing days in winter (unit: days)

	Year				
Station	**2016–2017**	**2017–2018**	**2018–2019**	**2019–2020**	**Average date**
Bayangaole	43	59	71	49	55.50
Sanhuhekou	109	91	99	80	94.75
Baotou	111	98	99	90	99.50
Toudaoguai	111	102	97	99	102.25

freeze-up date of Toudaoguai in 2018–2019 was 4 days later than that of Baotou, which is inconsistent with the identified trend. Further research is required to investigate these anomalies.

It can be observed from Table 2 that the break-up order of the four selected stations is Bayangaole, Sanhuhekou, Baotou, and Toudaoguai, indicating that the stationary ice cover gradually breaks up from the upstream to the downstream. In the winter of 2016–2017, ice cover at Baotou and Toudaoguai shared the same break-up date. Similarly, in the winter of 2018–2019, break-up events occurred concurrently at Sanhuhekou and Baotou.

Table 3 indicates that the number of total frozen days in the lower reaches is greater than in the upper reaches, reflected by the descending order of Toudaoguai, Baotou, Sanhuhekou, and Bayangaole. Similar to the river freeze-up date statistics, the total freezing days in Toudaoguai in 2018–2019 were 2 days less than in Baotou. Freeze-up and break-up events happened simultaneously at Baotou and Toudaoguai in 2016–2017. The exact coincidence occurred for Sanhuhekou and Baotou in 2018–2019.

It is worth noting that Baotou and Toudaoguai had the same freeze-up date in 2016 (November 25th) and break-up date in 2017 (March 16th). Sanhuhekou and Baotou stations also recorded same-day freeze-up events in 2018 (December 7th) and break-up occurrences in 2019 (March 16th). In the Inner Mongolia Reach of the Yellow River, the upstream is closely connected to the downstream as an integrated water body between hydraulic stations. Under specific temperature and flow conditions, the freeze-up and break-up events of the upstream and downstream stations are very likely to occur on the same day within hours. For example, when the water in the upstream hydraulic station radically freezes up after the drastic temperature drop, the downstream flow will be reduced immediately following the upstream freeze-up occurrence. Therefore, the freeze-up of the downstream station will also be noticed under the consolidated influences of the temperature drop and the flow reduction. Contrarily, the upstream break-up occurs when the temperature rise, which increases the downstream flow, and the downstream ice cover will continue to thaw under the impacts of temperature rise and flow increase. If the weather and hydraulic conditions are ideal for fast thawing of the ice cover, same-day break-up can be expected between the upstream and downstream stations.

The Inner Mongolia Reach of the Yellow River is gradually freezing from the downstream to the upstream. Later, the ice cover broke up progressively from the upstream to the downstream. The number of freezing days in the downstream exceeds that in the upstream. These patterns are comparable with data from studies in other Yellow River tributaries (Ke *et al.* 2001; Qiao *et al.* 2013; Wang *et al.* 2021).

3.2. Analysis of influencing factors

Analysis of the gauging statistical data demonstrates that the freeze-up date, break-up date, and total frozen days of the study reach constantly change every year. Thermal factors determine the process of ice generation and melting in the river.

Hydraulic factors determine the ice transport capacity of the river. River regime and whether there are any in-stream structures determine the ice jam initiation location. Furthermore, the ice production amount in a river determines the thickness and shape of the formed ice jam.

Thermal factors mainly include air temperature and water temperature. The statistical analysis of the air temperature changes in Bayangol, Baotou, and Sanhuhekou Toudaoguai in the winter of 2016–2020 is illustrated in Figure 2. When the temperature drops intensely, freeze-up events are prone to occur. In late November 2016, the temperature dropped sharply. Subsequently, freeze-up events happened successively at Sanhuhekou, Baotou, and Toudaoguai on November 23, November 25, and November 25. In early December 2017, early December 2018, and mid-December 2019, freeze-up events occurred in the four selected stations after the temperature dropped abruptly. When the temperature warmed up and reached above 0 °C, the ice in the river channel gradually melted and finally started to break up. In late February 2017, the temperature turned above 0 °C, and a break-up event was observed at Bayangaole station on 25 February 2017. Baotou, Sanhuhekou, and Toudaoguai experienced break-up events in mid-March 2017.

The change in water temperature in Bayangaole, Baotou, Sanhuhekou, and Toudaoguai in the winter of 2016–2020 is illustrated in Figure 3. Changes in water temperature are dependent on the heat exchange between water and the surrounding environment. When the air temperature is lower than the water temperature, the water will dissipate heat to the atmosphere until the water temperature reaches 0 °C. The water temperature will have a lag time compared with the air temperature change. Frazil ice begins to form in rivers where the water temperature reaches 0 °C, during which the water body continues to lose heat. Frazil ice forms in river channels when the water temperature reaches 0 °C, and the water body loses heat continuously in the frazil ice forming process (Boyd *et al.* 2022). With the rapid drop in temperature in late November 2016, the water temperature in various places also dropped immediately to 0 °C, but the water temperature in Bayangaole later turned above 0 °C. Consequently, after freeze-up events were observed at the other three selected stations, Bayangaole did not

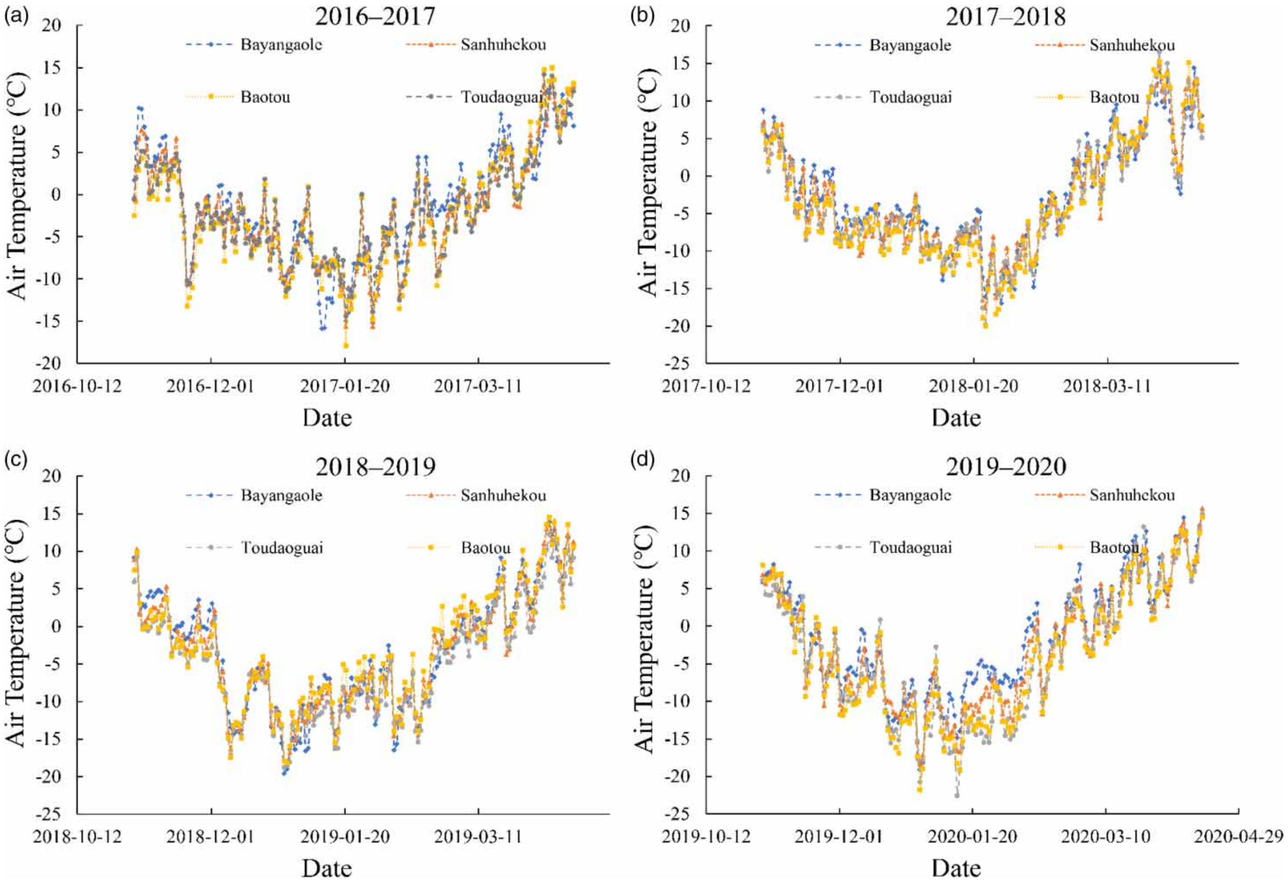


Figure 2 | Air temperature change of selected gauging stations in the Inner Mongolia Reach of the Yellow River.

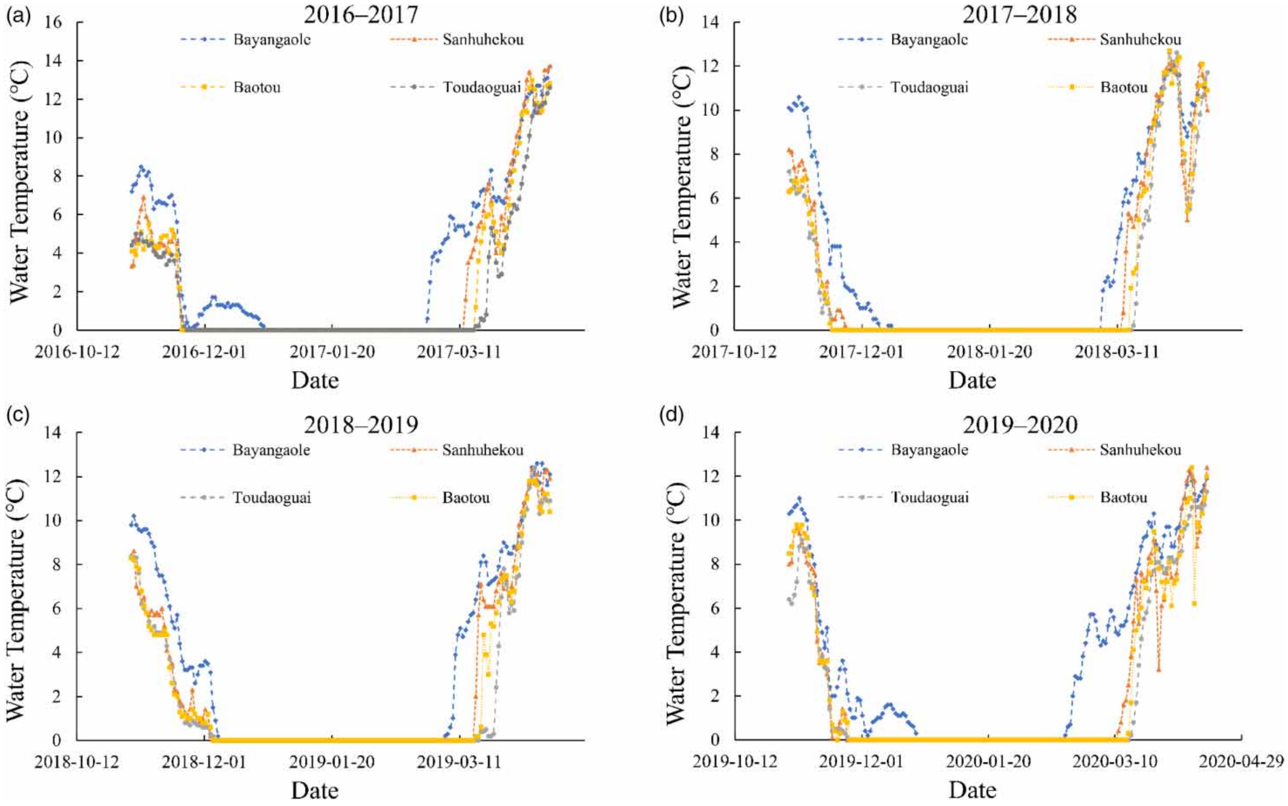


Figure 3 | Water temperature change of selected gauging stations in the Inner Mongolia Reach of the Yellow River.

experience freeze-up until 13 January 2017. In the winters of 2017–2018 and 2018–2019, it took longer at Bayangaole station for the water temperature to drop to 0 °C than the other three stations, and there were days when the temperature turned above 0 °C. When the temperature rose from February to March, the water temperature gradually turned above 0 °C. The water temperature in Bayangaole turned above 0 °C first, so break-up occurred at Bayangaole first. Trends can be observed that the upstream water temperature drops later than the downstream and that the upstream water temperature rises faster than the downstream. Therefore, the upstream gauging station experiences late freeze-up but early break-up events, leading to fewer total frozen days than the downstream stations.

Hydraulic factors mainly include discharge, water level, and approaching flow velocity. The change in the Yellow River's annual winter discharge significantly impacts the river ice's evolution process. Observation data shows that if the freeze-up date of a station is significantly different from the average date (i.e., over 30 days), the river's discharge is often larger compared to other years. The annual discharge change is shown in Figure 4. Compared to the freeze-up and break-up dates in the winter of 2017–2020, it can be seen that when the freeze-up season started in early December, Toudaoguai experienced freeze-up events first. The discharge at Toudaoguai dropped rapidly at that time. The low discharge at Toudaoguai remained until early January. Then Bayangaole started to freeze, and the decreasing trend of the discharge was consistent with the change at Toudaoguai when the freeze-up started. When break-up began, since the temperature in the upper reach rose earlier, ice cover at Bayangaole first began to thaw, and break-up occurred. Flow from the upper reaches quickly converged to the lower reaches, and the discharge at Toudaoguai increased rapidly during the ice melting process. Contrary to Toudaoguai station, during the ice melting process, the discharge at the upstream Bayangaole station showed a decreasing trend until the ice cover at Toudaoguai completely disappeared. When the water surface was frozen at Bayangaole, a large amount of water in the river channel contributed to the dynamic equilibrium of water and ice conversion. At the dynamic equilibrium state, there was both stationary ice cover at the surface and stagnant water underneath. When the ice melts during the break-up period, the stagnant water in the channel and the water from melting ice are released from the upstream simultaneously, resulting in a sudden increase in the discharge at Toudaoguai station, reaching up to four times the original discharge in a

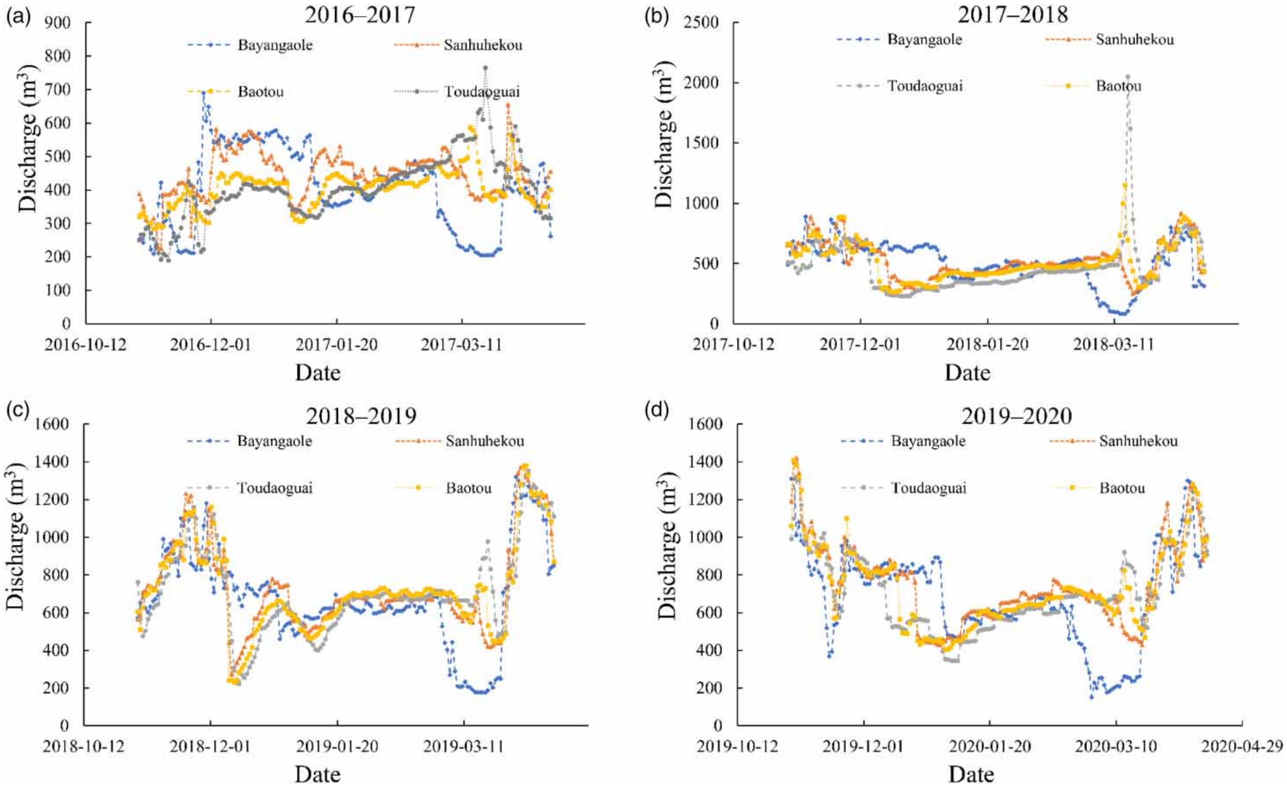


Figure 4 | Winter discharge change of selected gauging stations in the Inner Mongolia Reach of the Yellow River.

short period. The large discharge rate made it difficult for ice to accumulate in the river channel. Under high discharge conditions, it is challenging to initiate a free-up event but relatively easier to induce the break-up of ice cover. The difficulty is due to the movement of the water changing the shear force on the surface of the ice floe, causing the ice to be easily transported downstream.

River regime and in-stream structures also contribute to the formation of ice jams and ice dams in the river. Ice jams in the Inner Mongolia section of the Yellow River mainly occur in river sections where the gradient of the river channel changes from steep to slow and where river bends or in-stream structures exist. The upper reach Bayangaole section of the Inner Mongolia Reach of the Yellow River has a wider river body, with many shoals and bends. In contrast, the downstream Baotou section becomes gentler, with more numbers of large bends. The unique morphology and channel bed slope make it easier for ice to accumulate in places where the flow velocity is slow. Ice accumulation causes ice floes to build and leads to river freeze-up. The circulation formed at the bend or hydraulic structures such as bridge piers hinders the transport of ice, which will also decrease the probability of ice jams. In recent years, with the development of China's economy, many new bridges have been built in the Inner Mongolia Reach of the Yellow River (Wu & Hui 2021). The flow velocity around the bridges decreases, thus triggering an earlier freeze-up of the reach.

The peak time of ice production in the channel is often close to the freeze-up date, and the reduction in ice production is closely related to ice melting and the break-up of the river. During the field observation of the Yellow River, frazil ice density was selected to reflect the ice production process. Frazil ice density is defined as the ratio of the ice floe area to the total channel surface area. The winter observation results from 2017 to 2020 show that the channel experienced freeze-up events when the frazil ice density reached 0.6–0.9. Therefore, the river freeze-up process is not only determined by the timing of the peak ice production but also related to the ice transport capacity of the river channel impacted by other factors such as terrain and discharge. The break-up process is divided into gradual break-ups, rapid break-ups, and moderate break-ups. Due to different dominant influencing factors, the speed of break-up events will also vary. The temperature increase and the ice production decrease dominate the tranquil break-up events. The rapid break-up is dominated by the discharge surge and the river's steep bed slope. The moderate break-up is dominated by the combined effects of tranquil and violent break-up events.

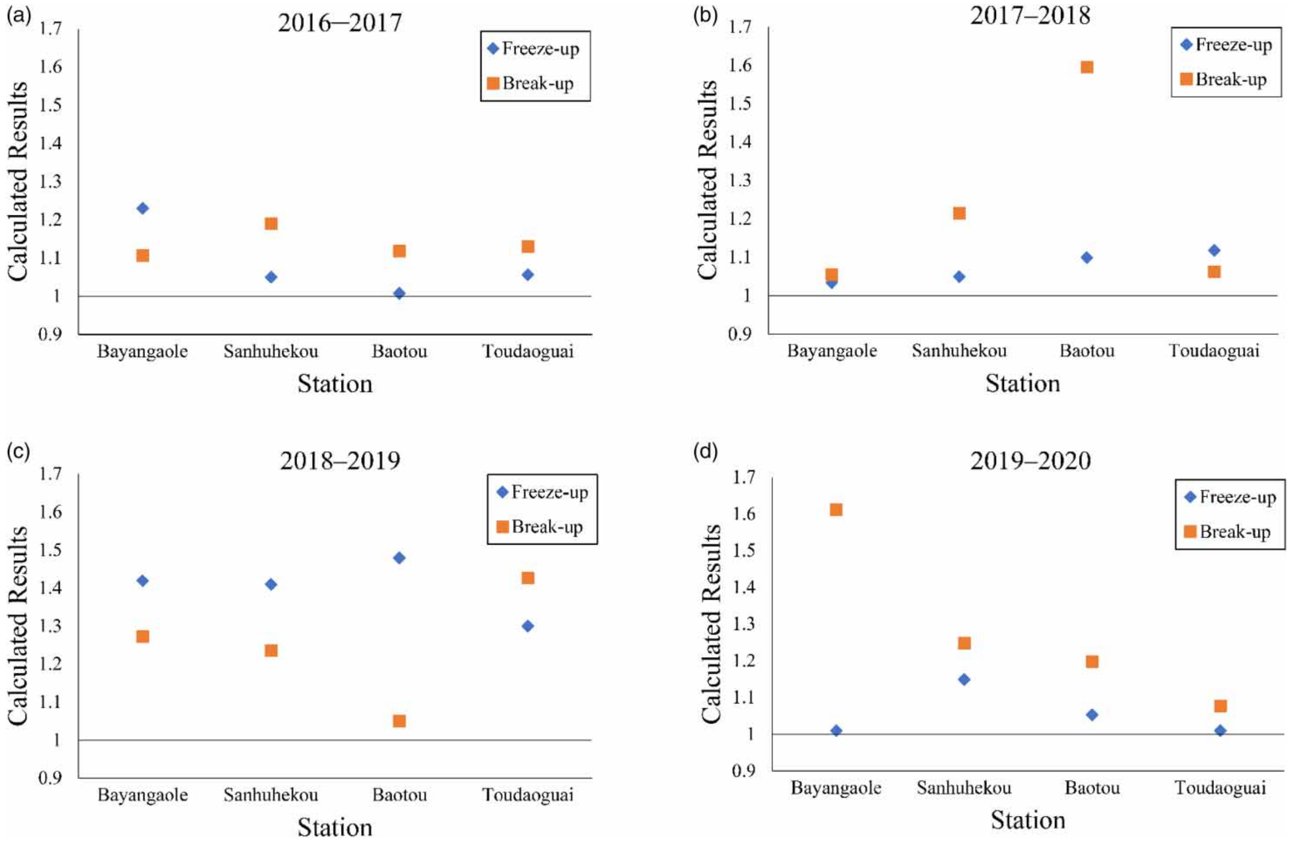


Figure 5 | Proposed discriminant equation calculated results.

3.3. Discriminant equation calculation

The proposed models (Equations (2) and (3)) and the empirical coefficients were established based on years of observation data from relevant research references (Chen & Ke 1994; Ke *et al.* 2001; Wang *et al.* 2021). The 4-year datasets from 2016 to 2020 are used for the verification of the model performances. Calculations for determining whether freeze-up and break-up would occur based on observed data from the winter of 2016–2020 are shown in Figure 5. The time step is selected in days considering the interval of the measured data and the trend of river ice conditions in winter. If a freeze-up/break-up event occurs on a specific date, the calculated results would fall above the threshold value (1.0). It can be seen that the observed freeze-up dates in four selected *gauging* stations have met the proposed empirical equation threshold for determining whether freeze-up will happen. The calculated values are all greater than 1, indicating that the ice resistance is dominant in causing freeze-up events in rivers. Break-up dates in the sour selected stations also met the proposed empirical equation threshold in a similar way, and the calculated values are all greater than 1. It is obvious from the proposed equations that a break-up event can be triggered when the proportion of ice production in the channel is high and the proportion of water storage is low. The sudden drop in temperature can often accelerate the freezing of a river, and the topographical conditions of the river also impact the freeze-up events. Similarly, the break-up determination equation demonstrates that a greater maximum ice thickness, a higher temperature, and a greater discharge are often required to facilitate the break-up of a river.

4. CONCLUSIONS

As extreme events associated with climate change become more prevalent in watersheds around the world, it is critical to understand how river freeze-up and break-up dates can be predicted to better regulate channel navigation. This study found that the Inner Mongolia Reach of the Yellow River is gradually frozen from the downstream to the upstream. Later, the ice cover gradually broke up from the upstream to the downstream. The total number of frozen days in the downstream is greater than in the upstream. These trends are consistent with findings from other reaches of the Yellow River. The influence of thermal factors, hydraulic factors, topography, and ice production process all have a significant effect on the dates when freeze-up and break-up will occur, with a strong correlation between the amount of ice formed in the channel and the water storage beneath the ice. The results imply that when the proportion of ice formed in the channel is high, and the proportion of water storage is low, freeze-up is prone to occur. Greater ice thickness, higher temperatures, and greater discharges are often required to facilitate the break-up of a river better.

The current discriminant study on the freeze-up and break-up conditions in the Inner Mongolia Reach of the Yellow River can provide a certain reference for the determination of the time of freeze-up and break-up in a year, but it can only assess the critical situation. Future study on the determination of freeze-up and break-up dates should focus on gaining an integrated understanding of the whole ice production process. Furthermore, while the current study examines the observed data of the freeze-up dates, break-up dates, and total frozen days of four gauging stations at the Inner Mongolia Reach of the Yellow River in winter from 2017 to 2020, more statistical analysis are needed to gain a better understanding of trends over break-up and freeze-up dates in a longer time span – for example, how the ice formation processes have evolved before and after the construction of any in-stream hydraulic structures.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Adams Jr., C. E. 1976 Estimating water temperatures and time of ice formation on the Saint Lawrence River. *Limnology and Oceanography* **21** (1), 128–137. https://doi.org/10.4319/lo.1976.21.1.0128.

Agashua, L. O., Dorcas, O.-A., Ihimekpen, N. & Igibah, E. 2022 Modeling the semivariogram of climatic scenario around rivers by using stream network mapping and hydrological indicator. *Journal of Human, Earth, and Future* **3**, 17–31. https://doi.org/10.28991/HEF-2022-03-01-02.

Ashton, G. D. 1985 Deterioration of floating ice covers. *Journal of Energy Resources Technology* **107** (2), 177–182. https://doi.org/10.1115/1.3231173.

Beltaos, S. 2012 Distributed function analysis of ice jam flood frequency. *Cold Regions Science and Technology* **71**, 1–10. https://doi.org/10.1016/j.coldregions.2011.10.011.

Bian, X., Ji, H., Jiang, X. & Gao, R. 2015 Huang he nei meng gu duan kai he ri qi yu bao mo xing ji ying yong [Development and application analyze of forecasting system of ice conditions in Inner Mongolia Reach of Yellow River]. *Advances in Science and Technology of Water Resources* **32** (2), 42–45. https://doi.org/10.3880/j.issn.1006-7647.2012.02.010.

Boyd, S., Ghobrial, T., Loewen, M., Jasek, M. & Evans, J. 2022 A study of supercooling in rivers. *Cold Regions Science and Technology* **194**, 103455. https://doi.org/10.1016/j.coldregions.2021.103455.

Chang, J., Wang, X., Li, Y. & Wang, Y. 2016 Ice regime variation impacted by reservoir operation in the Ning-Meng reach of the Yellow River. *Natural Hazards* **80**. https://doi.org/10.1007/s11069-015-2010-5.

Chen, S. & Ji, H. 2004 Bing ling yu bao mo hu you xuan shen jing wang luo BP fang fa [Fuzzy optimization neural network BP approach for ice forecasting]. *Journal of Hydraulic Engineering* **35** (6), 0114–0118.

Chen, S. & Ji, H. 2005 [Fuzzy optimization neural network approach for ice forecast in the Inner Mongolia Reach of the Yellow River] Approche d'Optimisation Floue de Réseau de Neurones pour la Prévision de la Glace Dans le Tronçon de Mongolie Intérieure du Fleuve Jaune. *Hydrological Sciences Journal* **50** (2), 330. https://doi.org/10.1623/hysj.50.2.319.61793.

Chen, Z. & Ke, S. 1994 Jian li huang he xia you bing qing shu xue mo xing you hua san men xia shui ku fang ling diao du de yan jiu [River ice modelling in lower reaches of the Yellow River and its utility in Sanmen Gorge Reservoir Regulation]. *Journal of Glaciology and Geocryology* **3**, 211–217.

De Munck, S., Gauthier, Y., Bernier, M., Chokmani, K. & Légaré, S. 2017 River predisposition to ice jams: a simplified geospatial model. *Natural Hazards and Earth System Sciences* **17** (7), 1033–1045. https://doi.org/10.5194/nhess-17-1033-2017.

Foltyn, E. & Shen, H. 1986 St. Lawrence river freeze-up forecast. *Journal of Waterway, Port, Coastal, and Ocean Engineering – ASCE* **112**. https://doi.org/10.1061/(ASCE)0733-950X(1986)112:4(467).

Fu, C., Popescu, I., Wang, C., Mynett, A. & Zhang, F. 2014 Challenges in modelling river flow and ice regime on the Ningxia-Inner Mongolia Reach of the Yellow River, China. *Hydrology and Earth System Sciences* **18**. https://doi.org/10.5194/hess-18-1225-2014.

Garcia, B. T. d. G., Medeiros, A. S. d., Nascimento, F. A. C. d. & Silva, M. A. V. d. 2022 Impact of drought on the life cycle of barge transport. *Civil Engineering Journal* **8** (12), Article 12. https://doi.org/10.28991/CEJ-2022-08-12-02.

Hou, Z., Wang, J., Sui, J., Zhang, B. & Zhang, F. 2022 Determination of ice production in a natural river: a case study in the Inner Mongolia Reach of the Yellow River. *Journal of Water and Climate Change* **13** (9), 3458–3472. https://doi.org/10.2166/wcc.2022.184.

Ke, S., Zhang, X. & Wang, Y. 2001 Feng he yu bao shu xue mo xing yan jiu [Study on mathematical models of river freeze-up forecast]. *Journal of Glaciology and Geocryology* **3**, 328–332.

Kim, J.-S., Jain, S. & Lee, T. 2021 Changes in the wintertime hydroclimatic regime in St. John River, Maine, USA. *Journal of Water and Climate Change* **12** (5), 2082–2092. https://doi.org/10.2166/wcc.2021.230.

Kovachis, N., Burrell, B. C., Huokuna, M., Beltaos, S., Turcotte, B. & Jasek, M. 2017 Ice-jam flood delineation: challenges and research needs. *Canadian Water Resources Journal/Revue Canadienne Des Ressources Hydriques* **42** (3), 258–268. https://doi.org/10.1080/07011784.2017.1294998.

Lacroix, M., Prowse, T. D., Bonsal, B., Duguay, C. & Menard, P. 2005 *River Ice Trends in Canada*.

Ministry of Water Resources of the People's Republic of China 2015 *He liu bing qing guan ce gui fan [Specification for Observation of Ice Regime in Rivers]*. Available from: https://www.wnwk.com/doc/77723.html.

Morales-Marín, L. A., Sanyal, P. R., Kadowaki, H., Li, Z., Rokaya, P. & Lindenschmidt, K. E. 2019 A hydrological and water temperature modelling framework to simulate the timing of river freeze-up and ice-cover breakup in large-scale catchments. *Environmental Modelling & Software* **114**, 49–63. https://doi.org/10.1016/j.envsoft.2019.01.009.

Palecki, M. A. & Barry, R. G. 1986 Freeze-up and break-up of lakes as an index of temperature changes during the transition seasons: a case study for Finland. *Journal of Applied Meteorology and Climatology* **25** (7), 893–902. https://doi.org/10.1175/1520-0450(1986)025 < 0893:FUABUO > 2.0.CO;2.

Qiao, J., Wang, F. & Dai, J. 2013 Huang he neng meng he duan feng kai he ri qi yu bao fang fa yan jiu [Study on freeze-up/break-up date forecasting methods in the Ningmeng Reach of the Yellow River]. *Yellow River* **35** (4), 6–7, 10.

Rokaya, P., Budhathoki, S. & Lindenschmidt, K.-E. 2018 Ice-jam flood research: a scoping review. *Natural Hazards* **94** (3), 1439–1457. https://doi.org/10.1007/s11069-018-3455-0.

Sha, J., Wang, Z.-L., Zhao, Y., Xu, Y.-X. & Li, X. 2018 Estimation of hydrological response to future climate change in a cold watershed. *Journal of Water and Climate Change* **10** (1), 78–88. https://doi.org/10.2166/wcc.2018.026.

Shen, H. T. & Chiang, L.-A. 1984 Simulation of growth and decay of river ice cover. *Journal of Hydraulic Engineering* **110** (7), 958–971. https://doi.org/10.1061/(ASCE)0733-9429(1984)110:7(958).

Shen, H. T. & Wang, D. S. 1995 Under cover transport and accumulation of frazil granules. *Journal of Hydraulic Engineering* **121** (2), 184–195. https://doi.org/10.1061/(ASCE)0733-9429(1995)121:2(184).

Su, J., Shen, H. T. & Crissman, R. D. 1997 Numerical study on Ice transport in vicinity of Niagara River hydropower intakes. *Journal of Cold Regions Engineering* **11** (4), 255–270. https://doi.org/10.1061/(ASCE)0887-381X(1997)11:4(255).

Sun, W. 2018 River ice breakup timing prediction through stacking multi-type model trees. *Science of The Total Environment* **644**, 1190–1200. https://doi.org/10.1016/j.scitotenv.2018.07.001.

Wang, T., Yang, K. & Gao, Y. 2008 Application of artificial neural networks to forecasting ice conditions of the Yellow River in the Inner Mongolia Reach. *Journal of Hydrologic Engineering* **13** (9), 811–816. https://doi.org/10.1061/(ASCE)1084-0699(2008)13:9(811).

Wang, K., Wang, J. & Zhang, F. 2021 Huang he nei meng gu duan kai he liu liang yu ce [Discharge in break-up period in the Inner Mongolia Reach of the Yellow River]. *South-to-North Water Transfers and Water Science & Technology* **19** (6), 1167–1174.

Williams, G. P. 1965 Correlating freeze-up and break-up with weather conditions. *Canadian Geotechnical Journal* **2** (4), 313–326. https://doi.org/10.1139/t65-047.

Wu, X. & Hui, X. 2021 Economic dependence relationship and the coordinated & sustainable development among the provinces in the Yellow River economic belt of China. *Sustainability* **13** (10), Article 10. https://doi.org/10.3390/su13105448.

Zhang, X., Yue, Y., Han, L., Li, F., Yuan, X., Fan, M. & Zhang, Y. 2021 River ice monitoring and change detection with multi-spectral and SAR images: application over Yellow River. *Multimedia Tools and Applications* **80** (19), 28989–29004. https://doi.org/10.1007/s11042-021-11054-0.

Zhao, S., Shen, H., Shi, X., Li, C., Li, C. & Zhao, S. 2020 Wintertime surface heat exchange for the Inner Mongolia Reach of the Yellow River. *JAWRA Journal of the American Water Resources Association* **56**. https://doi.org/10.1111/1752-1688.12831.

Zhao, S.-X., Wang, W.-J., Shi, X.-H., Zhao, S.-N., Wu, Y.-J., Quan, Q., Li, C., Szydlowski, M., Li, W. & Kolerski, T. 2021 Freeze-up ice jam formation in the river bend, a case study on the Inner Mongolia Reach of Yellow River. *Crystals* **11** (6), Article 6. https://doi.org/10.3390/cryst11060631.

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