

# Comprehensive evaluation of ice disaster risk of the Ningxia–Inner Mongolia Reach in the upper Yellow River

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**Abstract** The Ningxia–Inner Mongolia Reach, in the upper Yellow River, is one of the most serious reaches suffering from ice flood disaster in China. Firstly, according to its characteristics of ice condition evolution and ice disaster, the concept of ice disaster risk of Ningxia–Inner Mongolia Reach was defined, the risk factors of ice disaster were discussed, and the theory and method of “risk identification–risk estimation–risk assessment–risk management” for the ice disaster risk analysis of Ningxia–Inner Mongolia Reach was proposed. Then, the comprehensive evaluation model of ice disaster risk was established using the projection pursuit, fuzzy clustering and accelerating genetic algorithm method. Finally, the ice disaster risk grade was formulated, and the ice disaster risk of 1991–2010 for the Ningxia–Inner Mongolia Reach was evaluated in this paper. The results show that the application results were consistent with the practical characteristics of water regime, meteorological and ice condition, revealing the rationality of the risk evaluation model. This study aims at enriching and developing the theory and method for the ice disaster risk analysis and providing scientific decision basis for the ice-prevention preparedness of Ningxia–Inner Mongolia Reach, in the upper Yellow River.

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**Keywords** Ice disaster risk · Risk comprehensive evaluation model · Projection pursuit · Fuzzy clustering · Accelerating genetic algorithm · The Ningxia–Inner Mongolia Reach

## 1 Introduction

River ice is a complex and dynamic evolution system involving hydraulics, thermodynamics, engineering and management, its evolution process of occurrence, development and extinction is crossly effected by the river hydrometeorological condition, morphology and trend of the river, discharge volume, floating bridge, river building, etc. Different degrees of ice disaster occurs in the Ningxia–Inner Mongolia Reach in the upper Yellow River and Songhua River basin in the Heilongjiang Province of China (Cai 2007; Ke et al. 2002). The Ningxia–Inner Mongolia Reach, located in the most north area of Yellow River basin, for its complex and variable river morphology, long and cold winter, is one of the most serious reaches suffering from ice flood disasters and losses in China. The minimum temperature can reach  $-40\text{ }^{\circ}\text{C}$ , the river frozen period can last 4–5 months, and most of the reaches are stable frozen in this area. So, centering on the river ice routing model, formation mechanism and condition forecasting, many practical research results have been achieved (Shen 2010). The research for the Yellow River ice phenomena in China was originated from the 1990s of twentieth century. In 1984, according to the heat-exchanging principle, it was concluded that the heat-exchanging process of the ice sheet was affected by the heaped frazil ice and snow cover in the water, and, then, the thermal growth model of the river ice was established (Shen and Yapa 1984); In 1995, the formation and evolution process of water ice, and the water temperature changing model of turbulence river were simulated, and the concept of ice transport capacity of the ice cover was proposed (Shen and Hammar 1995; Hammar et al. 1996). Besides, the related calculation formula of flow intensity and ice particle characteristic was developed (Hammar et al. 1996). In 1998, the improved dynamic programming algorithm was applied in the multi-objective long-term water scheduling study of cascade reservoirs, and the operation cost of the cascade reservoirs decreased (Maceira and Pereira 1996; Ferrero and Shahidepour 1998). In 2003, the under-ice device (IPS and ADCP), for measuring the real-time ice data of river ice density, thickness and position, was installed on the St. Lawrence River of Canada, and the remote observation of river ice condition was finally realized (Chave et al. 2004). In 2004, the satellite imaging technology was used for the real-time observation of river ice condition in the Exploits River of Canada; the observing data were constantly transferred to the background treatment system, so as to accurately supply scientific data information for the prevention and control of river ice evolution (Puestow et al. 2004). In 2011, the 3G wireless video monitoring system (the third-generation mobile communication technology), a new effective method for ensuring the safety of ice prevention, was firstly used for monitoring and tracking the ice condition of Ningxia–Inner Mongolia Reach by Information Center of Yellow River Conservancy Commission, and a clear, fluent, stable and reliable live condition was transmitted to the ice-prevention operation center of Yellow River Conservancy Commission, which can further improve the modern intelligent level of ice-prevention practice of the Yellow River.

Taking a wide view of the latest research progress for the disaster reduction and safe ice prevention of the Yellow River throughout the world, it is obvious that the systematic recognition for the ice-prevention problem of the Yellow River is limiting, and the research

results, lacking of practicality and maneuverability, are mostly on the theoretical level. The ice-prevention safety research of the Yellow River, as an optimization problem of large complex system involving hydrology, hydraulics, thermodynamics, meteorology, system dynamics and management, is needing to be further studied. So, basing on the definition of ice disaster risk and discussion for the theoretical framework of “risk identification, risk estimation, risk assessment and risk management”, the comprehensive evaluation model of ice disaster risk was established using the projection pursuit, fuzzy clustering and the accelerating genetic algorithm method, and the ice disaster risk degree of 1991–2010 for the Ningxia–Inner Mongolia Reach was evaluated in this paper. The research result, enriching and developing the theoretical and practical research system for the ice disaster risk analysis, would provide scientifically decision basis for the establishment of ice-prevention preparedness of Ningxia–Inner Mongolia Reach, in the upper Yellow River.

## 2 Analysis of ice disaster risk in Ningxia–Inner Mongolia Reach

### 2.1 Definition of ice disaster risk

From the view of risk management, the concept of complex system risk, originated from system engineering, includes three essential factors: adverse event, occurrence probability of the adverse event and the loss degree (Jin et al. 2002; Huang 2005; Collins 2013). Risk is the probability of the system and unable to accomplish the predetermined function and cause damage loss in the prescriptive working condition and time (Jin et al. 2002, 2009a; Santos 2014). The existing analysis methods of system risk, usually confusing the adverse event and its occurrence probability, have lost the abundant information of risk analysis and deviated the formation mechanism of risk events. As the ice disaster risk, previous studies have not provided a risk identification index, which can objectively reflect the drastic degree for the transformation from ice condition to ice damage from the disaster formation mechanism and cannot put forward an accurate and unified definition to describe the connotation of ice disaster risk. For example, the Ningxia–Inner Mongolia Reach, the channel-storage increment in the ice-prevention period can intuitively reflect the severities suffering from ice flood disasters, the channel-storage increment of the reach is high, but the probability of disaster is not definitive high, which is also seriously influenced by the changing process of the temperature in breakup period. Even the channel-storage increment is much higher, if the rising process of the temperature in breakup period is slower, the release process of the channel-storage increment is slower, and the probability of disaster will be lower conversely.

Therefore, the concept of ice disaster risk in the Ningxia–Inner Mongolia Reach is defined in this paper as: based on the comprehensive effects for the uncertain factors of temperature, river flow, channel morphology, channel-storage increment, etc., the probability (risk) of ice disaster loss caused by the adverse events of ice jam and ice dam in the Ningxia–Inner Mongolia Reach. The ice disaster risk has natural and social attributes; from the view of natural attribute, the ice condition occurs every year, but the ice does not. The occurrence of ice condition is inevitable and uncertain, which reveals that the probability for different grades of ice disaster risk remains to be identified and estimated, based on the further study for the development laws of ice condition; from the view of social attributes, the ice condition is inevitable, but the ice disaster loss can be reduced by constantly improve the adaptive capacity for the ice disaster risk of the reach.

## 2.2 Analysis method of ice disaster risk

The risk is caused by the uncertainty of the system, and even considering that risk is uncertainty, the risk analysis of complex system is studying the type of the adverse event, the probability for the occurrence of adverse event, and the loss degree that the adverse event might cause in a specific region and period, including risk identification, risk estimation, risk evaluation and risk management (Jin et al. 2002; Hao et al. 2014; Van Westen 2013). Risk identification is recognition, induction, inference and prediction continuously and systematically for the potential and objective influencing risk factors; risk estimation is quantification for the probability of adverse event and loss degree, based on the statistical analysis for the much uncertain risk factors and disaster loss; risk evaluation is synthesizing the index values to a single value for the probability of risk factors, loss degree and others, to represent the probability of risk and degree of loss; and risk management establishes and proposes a series of measures to change the evolution trend of risk event or reduce the disaster loss. The core problem for the risk management research of complex system is the effectively identification for the uncertain risk factors for risk management system and quantitatively estimation for the impact degrees of risk adverse event.

The difficulty for the ice disaster risk research of Ningxia–Inner Mongolia Reach is lacking the under-ice river flow evolution model for objectively and exactly simulating the channel morphology, temperature, river flow process after the frozen river. In addition, the stage-discharge relation, for the key controlling section (Shizuishan, Bayangaole, Sanhuhekou, Toudaoguai) of Ningxia–Inner Mongolia Reach after frozen, is inordinate and uncertain, increasing the complexity of ice disaster risk analysis. The main approaches for the risk analysis of complex system are stochastic simulation, fuzzy mathematics, gray theory, neural network, Bayesian theory, rough set, etc., which have been widely applied in practice, but remains much deficient. Generally, the ice disaster risk analysis of Ningxia–Inner Mongolia Reach includes as follows:

1. The modeling and evaluation theory of the system risk, based on mathematical statistics and probability analysis, includes the histogram estimation method, the most possibility estimation, interval estimation and Bayesian estimation. The risk rate result is essentially the statistical value of simulation and observation tests, and the key of the theory is recognizing and establishing the joint probability distribution function of uncertain factors.
2. The modeling and evaluation theory of the system risk is based on fuzzy set. Risk is essentially a fuzzy concept concerned with uncertainty and complexity, using the fuzzy mathematics method to process the system risk, which has natural advantage, would describe the evolution trend of the system risk from the genetic mechanism using fuzzy membership.
3. Qualitative and quantitative systematic analysis method. Focusing on the complexity and comprehensiveness of system risk analysis, for the risk event that the operating mechanism of the risk influencing factors is ambiguous, and the loss degree is immensurable, it is necessary to apply the qualitative and quantitative methods to describe the risk and loss degree of adverse event (as the uncertain factors of sediment deposition, river morphology evolution, etc.).

## 2.3 Research method

As the above, fuzzy mathematics theory is applied to process and describe the uncertainty of complex system, the membership function is always using to describe the dynamic

transformation process of the uncertainty to certainty, and the fuzzy reasoning, fuzzy relationship and fuzzy cluster are the three main application techniques. Considering the above characteristics of fuzzy membership, based on the comprehensive recognition and induction for the ice disaster risk factors for the Ningxia–Inner Mongolia Reach in the upper Yellow River, the fuzzy clustering method was used to describe the classification feature of the uncertain risk factors in the ice flood process, the projection pursuit method, a multi-dimensional data structure statistical analyzing method, was used to describe the difference and similarity of different grade of ice disaster risk, and then the ice disaster risk comprehensive evaluation model for Ningxia–Inner Mongolia Reach, based on projection pursuit cluster, was established. Finally, based on the statistical analysis for the ice flood process of Ningxia–Inner Mongolia Reach in the recent 20 years, the division standard of ice disaster risk grade for the Ningxia–Inner Mongolia Reach was proposed using the golden section method, and the technical measures for relieving the ice disaster risk and ensuring the ice-prevention safety of Ningxia–Inner Mongolia Reach was formulated. Therefore, the research scheme “risk identification–risk estimation–risk assessment–risk management” for the ice disaster risk analysis of Ningxia–Inner Mongolia Reach in the upper Yellow River was proposed.

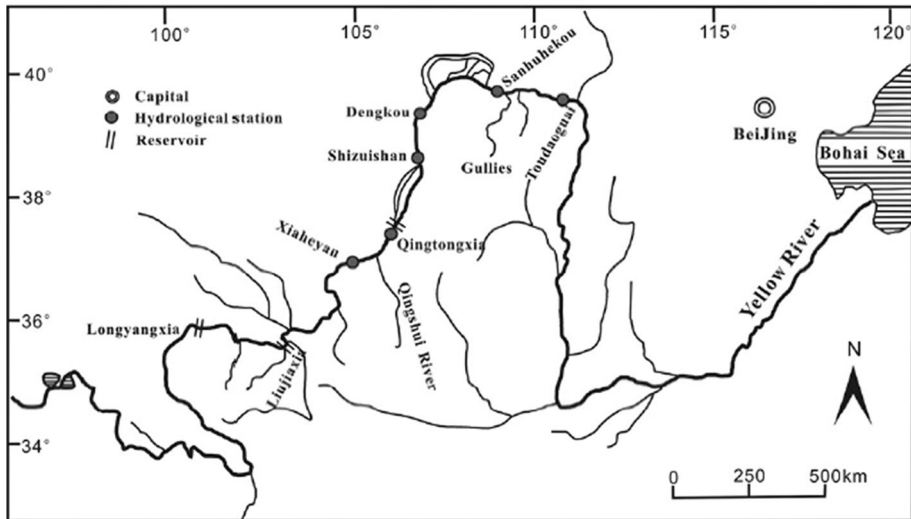
### 3 Theory and method for comprehensive evaluation of ice disaster risk of Ningxia–Inner Mongolia Reach

#### 3.1 Ice disaster risk identification

The Ningxia–Inner Mongolia Reach starts from Heishanxia located at the juncture of Gansu and Ningxia Province and ends at the Zhungeer Banner in Inner Mongolia (Fan et al. 2012), as shown in Fig. 1. The ice disaster risk identification for Ningxia–Inner Mongolia Reach is recognition, induction, inference and prediction continuously and systematically for the potential and objective influencing risk factors and disaster-inducing environmental factors in the generation and development process of ice disaster adverse event, in order to analyze the evolution process of the ice disaster leading to loss, identifying the sources, range and characteristics of risk and the uncertainty of risk event, and then establishing the main influencing factor set of ice disaster risk.

##### 3.1.1 Analysis for influence factors of ice disaster risk

Risk identification is the beginning of system risk analysis and also the basic work of risk assessment and management, which would describe the essential characteristic of ice disaster risk on a great extent, and the chosen impact factors need to be typical, representative and quantitative. Generally, the factors affecting the ice disaster risk of Ningxia–Inner Mongolia Reach include as follows: temperature, reservoir operation, river morphology evolution uncertainty, conveyance capacity of the key section and dangerous reach, flood control standard, ice flood diversion project, and river buildings; the occurrence of ice disaster advert event in the Ningxia–Inner Mongolia Reach is the comprehensive operating result of the above factors.



**Fig. 1** The Ningxia–Inner Mongolia Reach of the Yellow River in China

### 1. River morphology analysis

The Ningxia–Inner Mongolia Reach, with the total length of 1,237 km, flows from Nanchangtan in the Zhongwei of Ningxia Province to Mazhaxiang of Inner Mongolia Province. For the control of terrain, the canyon and strath reach appear alternately. In the Ningxia Province, the total length of the reach is 397 km, the channel morphology presents a situation of “deploying twice and retracting three times,” the flow direction is from southwest to northeast, and the geographic latitude increases by  $2^\circ$ . The reach from Heshanxia to Zaoyuan, canyon, precipitous, and is seldom-freeze-up reach, and the reach below Zaoyuan, 262 km, for the lower temperature, is stable-freeze-up reach. In the Inner Mongolia Province, the total length of the reach is 840 km, the flow is capacious, and the river bed becomes more and more wide shallow to the downstream. And the reach from Bayangaole to Toudaoguai, the number of river bend is 69, the crookedness for the biggest bend is 3.64, where the ice is always been blocking, and is the most dangerous reach evoking the ice disaster advert event. The characteristic parameters of the type and width for different reaches are listed as Table 1.

### 2. Temperature uncertainty analysis

River ice is the product of low-temperature process, when the temperature drops below  $0^\circ\text{C}$  in the winter, the ice appears in the river water, and the temperature process has a great impact on the thickness and amount of the ice (Kang et al. 2001). And when the temperature rises in the spring, the temperature process affects the breakup rate and the trend. Thus, the changing process of the temperature in the ice-prevention period is the key factor influencing the thickness and amount of the ice, and the rate of freezing and breaking up. To intuitively reflect the impact degree of the temperature process to the ice disaster risk and ice condition severity, taking the cumulative negative temperature of Bayangaole Station, for example, the hydrograph between the average temperature process in the ice-prevention period of the Ningxia–Inner Mongolia Reach and river frozen-up days, the maximal channel-storage increment every year of Shizuishan–Toudaoguai Reach is shown in Figs. 2 and 3.

**Table 1** The statistical characteristics for the channel morphology of Ningxia–Inner Mongolia Reach

Item	Name of the reach	Type	Length (km)	Average width (m)	Main width (m)	Gradient ratio (%)	Crookedness
Ningxia	Nanchangtan–Zaoyuan	Canyon	135.0	200–300		0.8–1.0	
	Zaoyuan–Mahuanggou	Transitional	262.0	500–1,000		0.1–0.2	
Inner Mongolia	Mahuanggou–Wuda Bridge	Canyon	69.0	400	400	0.56	1.50
	Wuda Bridge–Sanshenggong	Transitional	106.6	1,800	600	0.15	1.31
	Sanshenggong–Sanhuhekou	Wandering	205.6	3,500	750	0.17	1.28
	Sanhuhekou–Zhaojunfen	Transitional	126.2	4,000	710	0.12	1.45
	Zhaojunfen–Lamawan	Bending	214.1	Upper 3,000 Lower 2,000	600	0.10	1.42
	Lamawan–Yushuwan	Canyon	118.5				
Total	Nanchangtan–Yushuwan		1,237				

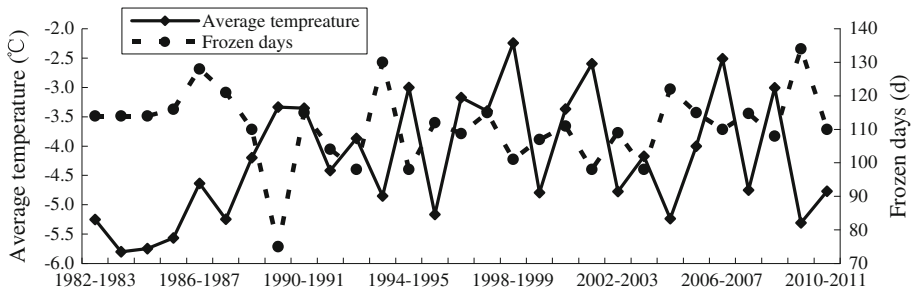
For the rising of global temperature, the average temperature for different section of Ningxia–Inner Mongolia Reach presents a rising trend, but the extreme lower temperature process is constantly intensifying, and the sustained time for the negative temperature is lengthened, which would increase the maximal channel-storage increment every year and intensify the probability for the occurrence of ice disaster advert event. In addition, it is revealed that the temperature is an important risk influencing factor for the evolution trend of ice condition and ice disaster risk in the Ningxia–Inner Mongolia Reach.

### 3. Impact analysis of reservoir flow

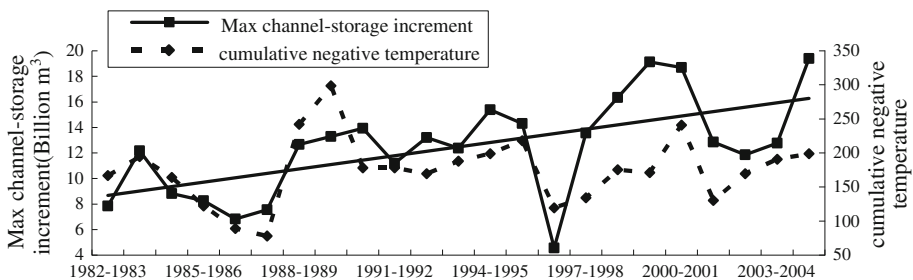
Reservoir operation for ice prevention, which is the focus for the related department to establish the ice-prevention preparedness, is the only controllable non-engineering measure for relieving the ice disaster risk in the Ningxia–Inner Mongolia Reach. The operation mode of Liujixia Reservoir in the ice-prevention period is as “scheduled monthly and operated for ten day”, that is, arranging the operation schedule of the next month or next ten days ahead for 5 days, the flow volume is strictly controlled for every 10 days, and the error for the day-average volume is less than 5 %. The reservoir operation for ice prevention has played an important role for the safety ice-prevention practice of Ningxia–Inner Mongolia Reach in the upper Yellow River, the joint operation of Long-liu Cascade Reservoirs in the upper Yellow River, directly affects the flow and temperature of the river in the ice prevention and the natural attribute of the river, which indirectly change the channel morphology, conveyance capacity and evolution trend of the ice condition.

### 4 Others

(a) **River flood control standard** The main continuous riverbank for the main stream of Ningxia–Inner Mongolia Reach is distributing on the plain field between the Xiaheyuan and Qingtongxia Station, the left bank between the Qingtongxia and Shizuishan Station, the right bank between the Qingtongxia and Toudaoguai Station and the plain river after the Sanshenggong Station. The main riverbank of Ningxia reach, with the length of 435 km, 379 dam buttresses and 375 building crossing the levee, is earth embankment, and the engineering degree is grade 3 for the reach from Qingtongxia to Cundu and grade 4 for the other. The flood control standard for the main riverbank of Inner Mongolia reach, with the



**Fig. 2** The annual temperature and frozen days process of Ningxia–Inner Mongolia Reach



**Fig. 3** The channel-storage increment and negative temperature process of Ningxia–Inner Mongolia Reach

length of 976 km, is 50-year frequency, that is, to say, the peak discharge of Bayangaole Station is  $5,920 \text{ m}^3/\text{s}$ .

**(b) Ice diversion project** Concerning the engineering state and protection form for the Inner Mongolia reach of Yellow River, using the emergency flood diversion project to reduce the peak discharge and store the ice flood, is an important measure for avoiding or reducing the ice disaster loss to the utmost extent. Now, along the riverbank of Inner Mongolia reach, there are six emergency flood diversion areas. In the frozen-up and breakup period, when serious ice condition occurs in the river, using the temporary ice diversion project, combining with the non-engineering measures of patrolling and inspecting the riverbank would further treat or reduce the ice condition.

**(c) River building** Now, there are four fixed railway bridges, ten highway bridges and 12 straddle pontoons on the reach between Sanshenggong and Lamawan in the Ningxia–Inner Mongolia Reach. These river buildings are mostly built on the bend or narrow part of the river, and the flow, influenced by the bridge and pier, is slow and centralized. And for the slow flow, the reach is easy to be frozen and advances the frozen-up date based on the same hydraulic conditions.

### 3.1.2 Recognition and extraction of the key risk factors

The risk impact factor set for the ice condition evolution trend of Ningxia–Inner Mongolia Reach incorporates quantitative and non-quantitative, certain and uncertain, controllable and uncontrollable, engineering and non-engineering, etc. As the risk influencing factors



for Ningxia–Inner Mongolia Reach, the river morphology evolution, embankment protection standard and river building are relatively fixed, which are concerned as certain factors and the ice disaster risk would be reduced adopting the engineering and non-engineering measurements. Therefore, the risk influencing factors for Ningxia–Inner Mongolia Reach would be divided into hydraulic and thermodynamics factors, as follows:

### 1. Hydraulic factors

The hydraulic factors include the runoff in the initial stage of frozen-up period, the flowing condition of the frozen river, the runoff of the frozen-up period and the discharge process of the Liujiaxia Reservoir in the frozen-up period. For the current operation schemes of the reservoir, the discharging principle of Liujiaxia Reservoir is increasing the reservoir flow moderately in the initial stage of frozen-up period to improve the frozen level of the lower river and then maintain the reservoir flow stably and uniformly, to ensure the river ice-prevention safety, and avoid the flow on the ice level.

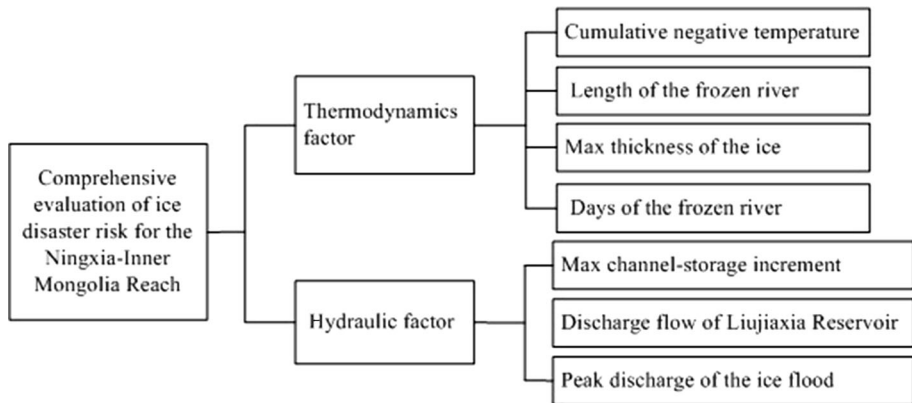
### 2 Thermodynamics factors

The thermodynamics factor is mainly the duration time of the low-temperature process in the frozen-up period of Ningxia–Inner Mongolia Reach, which is the cumulative negative temperature of the key section in the frozen-up period. If the cumulative negative temperature of the section is high and the low-temperature process is long, the thickness for the ice of frozen river would be large, and the ice disaster risk would be increased for the adverse frozen conditions. In the recent years, for the constantly aggravation of the extremely cold weather process, the influencing degree of the thermodynamics factors to the ice disaster risk of Ningxia–Inner Mongolia Reach is aggravating as well.

For the above, the primary influencing factor is thermodynamics condition, including the temperature process and the duration time of the low temperature for the key section, and the next is hydraulic conditions, including the frozen-up flow and the stable degree of the flow in the frozen-up period, maximal channel-storage increment every year, length of the frozen river, days of the frozen river and the maximal thickness of the ice. Therefore, combining the principles of typical, visual and quantitative for the risk evaluation of complex system, the comprehensive evaluation index system for the ice disaster risk of Ningxia–Inner Mongolia Reach can be shown in Fig. 4.

### 3.2 Establishment and solution for the ice disaster risk comprehensive evaluation model

For the complexity and diversity of the ice disaster in the Ningxia–Inner Mongolia Reach, it is impossible to determine the relationship between the ice disaster risk and risk influencing factors by the existing methods. The traditional risk evaluation of complex system, based on the establishment of the evaluation index and standard systems, is determining the membership degree for the risk indexes of different evaluation samples belonging to different risk grades and then calculating the risk grade of the evaluating year. As the research for the ice disaster risk evaluation is rare, which is lacking the evaluation index and grade standard, the projection pursuit, a clustering evaluation method using for disaster division, was introduced in the ice disaster risk evaluation, and the ice disaster risk evaluation model based on projection pursuit cluster for Ningxia–Inner Mongolia Reach was proposed in this paper. By the model solution, the risk grade of the evaluating year would be divided by calculating the membership degree of each evaluating sample.



**Fig. 4** The comprehensive evaluation index system of ice disaster in the Ningxia–Inner Mongolia Reach

### 1. Risk estimation method based on fuzzy clustering

Fuzziness is an important tie to objectively describing the complex correlation between the system, matter and phenomena, which is an expression for the fuzziness using accurate mathematical language. The common methods of fuzzy theory are fuzzy reasoning, fuzzy recognition, fuzzy cluster and fuzzy control, which have been widely applied in the research field of risk analysis of water resources system, flood season division, environmental monitoring, climate division, etc. (Chen 2004; Jin et al. 2009a, b; Li 2010, Ni and Cui 2007). In practice, the risk evaluation of regional natural disaster is evaluating the regional risk situation of the natural disaster in the future, based on the determination of the average or status level for the regional natural disaster.

### 2 Risk estimation method based on projection pursuit

The projection pursuit is a multivariate correlation statistical method, which is describing and analyzing the statistical characteristics of high-dimensional data by projecting the high-dimensional data to low-dimensional space and analyzing the projection characteristics (Fu et al. 2002; Fu and Zhao 2006). And the projection pursuit cluster model is a comprehensive evaluation model for reflecting the classification characteristics of high-dimensional data, which has been applied in the water quality assessment, environmental monitoring, risk evaluation, climate division, etc. (Fu et al. 2002; Wang et al. 2002; Zhang and Mao 2011; Wu et al. 2008). The key for the establishment of projection pursuit cluster model is how to propose the dimensionless principle of the evaluating system according to the data characteristics of the practical problem, and the constraint rules for the dispersion and concentration degree of the scheme projection value (Fu and Zhao 2006). Besides, several deficiencies for the projection pursuit cluster model remain to be improved, as the appropriate value of the density parameters, analysis for the rationality of the results for projection pursuit cluster model.

#### 3.2.1 Establishment of the ice disaster risk comprehensive evaluation model based on projection pursuit clustering

The ice disaster risk comprehensive evaluation for Ningxia–Inner Mongolia Reach is the basis for formulating the risk grade division, which evaluates the ice disaster risk degree of

the ice advert event for the whole ice-prevention period, based on the determination for the risk of influencing factors, vulnerability of the hazard-inducing environment and damageability of the disaster vector of the river and, then, the risk grade and clustering characteristics of the system would be excavated. The establishment for the ice disaster risk comprehensive evaluation model based on the projection pursuit cluster model is as the following steps:

*Step 1:* Normalization process for the indexes of the risk valuating system. And the purpose for this process is to eliminate the inconsistent influence for the different dimension and application direction of the index. The total sequence method, which can retain the structural characteristics of the original data of the evaluation system, is adopted in this paper for normalization. According to the given ice condition data of Ningxia–Inner Mongolia Reach for  $m$  years, showed as  $S = \{s_i | i = 1-m\}$ , and the ice disaster risk evaluation system consists of  $n$  indexes, denoted as  $R = \{r_j | j = 1-n\}$ , where  $i, j$  and  $m$  are all positive integers. Then, the ice disaster risk evaluating data set can be represented as  $X = \{x_{ij} | i = 1-m, j = 1-n\}$ , where  $x_{ij}$  stands for the index value of the ice flood process of  $i$ th year and  $j$ th index. To eliminate the dimensional influence of different index and uniting the application direction of the index, use the total sequence method for normalized treatment, and the steps are listed as follows: For the index (the bigger the better),

$$y_{ij} = \frac{x_{ij} - \min_i(x_{ij})}{\max_i(x_{ij}) - \min_i(x_{ij})} \tag{1}$$

For the index (the smaller the better),

$$y_{ij} = \frac{\max_i(x_{ij}) - x_{ij}}{\max_i(x_{ij}) - \min_i(x_{ij})} \tag{2}$$

where  $i$  and  $j$  are the serial number of the scheme and index, respectively;  $m$  and  $n$  are the total number of the scheme and index, respectively;  $\min_i(x_{ij})$  and  $\max_i(x_{ij})$  are the minimum and maximum for the scheme indexes including the  $j$ th index.

*Step 2:* Linear projection. The projection pursuit cluster model is synthesizing the multi-dimensional data set  $\{x_{ij} | i = 1-m, j = 1-n\}$  as one-dimensional projection value  $U = \{u_i | i = 1-m\}$  by the optimum projection direction  $W = \{w_j | j = 1-n\}$ , as follows:

$$u_i = \sum_{j=1}^n w_j \cdot x_{ij} \quad (i = 1 - m, j = 1 - n) \tag{3}$$

where  $u_i$  stands for the risk grade value of the ice flood process for the  $i$ th year;  $W = \{w_j | j = 1-n\}$  is the projection direction, which satisfying the normalization condition  $\sum_{j=1}^n w_j = 1$ .

*Step 3:* Establishment of the projection index function. The key for this step is reflecting the risk grade and classified information for the ice flood process of historical years by the clustering method. Firstly, let  $l(u_a, u_b) (a, b = 1-M)$  stands for the absolute distance for the ice disaster risk grade value of arbitrary 2 years, such as  $l(u_a, u_b) = |u_a - u_b|$ ; If the ice disaster risk grade of Ningxia–Inner Mongolia Reach is divided into  $M$  types, let  $Q_h (h = 1-M)$  stands for the risk set of  $h$ th ice disaster risk, as follows:

$$Q_h = \{u_a | d(A_h - u_a) \leq d(A_t - u_a), \quad h, t, a = 1 \sim M, t \neq h\} \tag{4}$$

where  $d(A_h - u_i) = |u_i - A_h|$ ,  $d(A_t - u_i) = |u_i - A_t|$ ;  $A_h$  and  $A_t$  are the clustering center for the  $h$ th and  $t$ th risk grade, respectively. And the initial value is:

$$A_h^0 = h \cdot \frac{\max(u_i) - \min(u_i)}{M + 1} + \min(u_i) \quad (i = 1 - m, h = 1 - M) \tag{5}$$

Repeating for the steps until satisfying  $\sum_{h=1}^M \left[ \frac{A_h^k - A_h^{k-1}}{A_h^k} \right] \leq \varepsilon$  where  $k$  is iteration times, and  $\varepsilon$  is the permissible error. Secondly, the internal aggregation degree  $d_d(\mathbf{a})$ , describing the adjacent degree for the samples with the same risk degree, is as follows:

$$d_d(\mathbf{a}) = \sum_{h=1}^M \left[ \sum_{u_a, u_b \in Q_h} l(u_a - u_b) \right] \tag{6}$$

Obviously, the smaller for  $d_d(\mathbf{a})$  and the higher for the adjacent degree of the internal samples. Thirdly, the dispersion  $l_l(\mathbf{a})$ , describing the difference degree for the different samples, is as follows:

$$l_l(\mathbf{a}) = \sum_{u_a, u_b \in U} l(u_a - u_b) \tag{7}$$

Obviously, the bigger for  $l_l(\mathbf{a})$  and the higher for the dispersion of different samples. Finally, according to the clustering principle for the projection value of ice disaster risk evaluation, the projection index function is denoted as  $Q_Q(\mathbf{a}) = l_l(\mathbf{a}) - d_d(\mathbf{a})$ . Obviously, when  $Q_Q(\mathbf{a})$  is maximum, and the clustering purpose “dispersed interval and centralized internally” would be realized.

*Step 4* Optimization of the projection index function. When the ice flood samples for the historical years of Ningxia–Inner Mongolia Reach are given, the projection index function  $Q_Q(\mathbf{a})$  changes only with the projection direction  $\mathbf{W}$ . And different projection directions reflect different structure feature, and the best projection direction, which would be estimated by solving the maximization problem of projection index function, is most probably exposing the classification characteristics of the high-dimensional data.

$$\begin{aligned} \max Q_Q(\mathbf{a}) &= l_l(\mathbf{a}) - d_d(\mathbf{a}) \\ \text{s.t. } \sum_{j=1}^n w_j &= 1 \end{aligned} \tag{8}$$

This is a nonlinear optimization problem of complex system with the optimization variables of  $\mathbf{W} = \{w_j | j = 1 - n\}$ , which is solved by the accelerating genetic algorithm (Jin et al. 2001), simulating the evolutionary programming for biological survival of the fittest and the exchange mechanism of population chromosome information.

### 3.2.2 Solution of the ice disaster risk comprehensive evaluation model

The above is the establishment process of ice disaster risk comprehensive evaluation model based on projection pursuit clustering for Ningxia–Inner Mongolia Reach, and the population intelligent optimization method is of great advantage for solving the optimization problem. Accelerating genetic algorithm (AGA) is improving the optimizing efficiency and

stable ability of the algorithm, by reducing the optimizing space of the optimization variables in the iterative process (Jin et al. 2001). AGA is taking the constant intervals of the population individual after iteration for twice as the new optimizing space of variables, which makes the optimizing space close to the optimal space gradually. The technology roadmap for AGA is shown in Fig. 5:

### 3.3 Grade division of ice disaster risk

Risk evaluation is reasonably assessing the risk estimating result of the system, determining the risk grade and then proposing the scientific basis for risk management and control, by establishing the risk grade standard based on the risk estimation and risk identification. The risk grade of ice disaster for the Ningxia–Inner Mongolia Reach was divided into three types: grade 1 (light risk), grade 2 (moderate risk) and grade 3 (heavy risk), as follows:

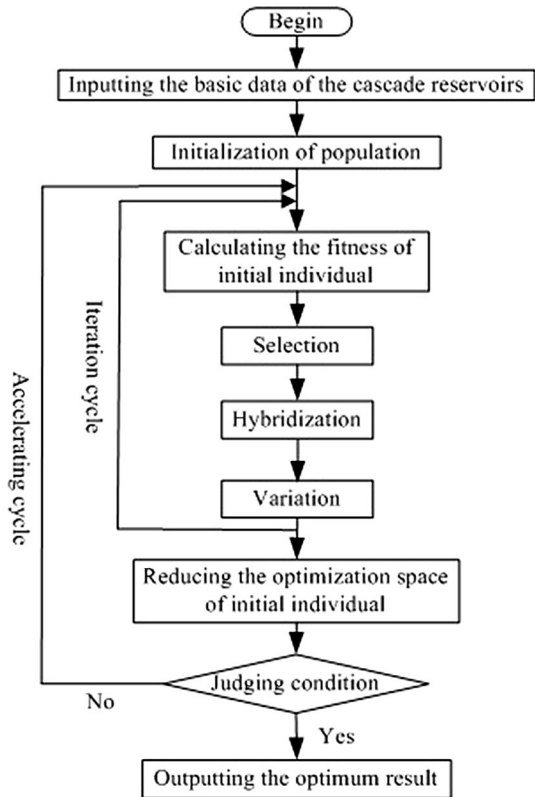
1. For the 42 years of 1969–2010 after the operation of Liujiaxia Reservoir, about 132 ice advert events (including ice dam and ice jam), with 56 disasters 17 years of disaster, occurred in the Ningxia–Inner Mongolia Reach. So, the average probability for the ice condition transforming into disaster condition is 40 %, and the frequency (probability) for the ice condition transforming into disaster condition is 40 %.
2. Taking the ice disaster risk 0.40 as the division joint of acceptable ice disaster risk and non-acceptable ice disaster risk of Ningxia–Inner Mongolia Reach, and the ice disaster risk grade is grade 3 (heavy risk) when the ice disaster risk degree is more than 0.40, that is, non-acceptable ice disaster risk.
3. Concerning the practical probability of ice disaster and combining the golden section method, the corresponding golden section point is 0.2472 within the acceptable risk range of  $[0, 0.40]$ . Therefore, taking the ice disaster risk 0.25 as the division joint of grade 1 (light risk) and grade 2 (moderate risk), that is, the ice disaster risk grade is grade 1 (light risk), when the ice disaster risk degree  $d$  belongs to  $[0, 0.25]$ , and the ice disaster risk grade is grade 2 (moderate risk), when the ice disaster risk degree  $d$  belongs to  $[0.25, 0.40]$ .

So, the division standard for ice disaster risk grade of Ningxia–Inner Mongolia Reach is shown in Table 2.

### 3.4 Ice disaster risk management

Risk management is proposing the project technical measures for reducing, alleviating and avoiding the ice disaster risk, through the induction and analysis for risk controllable factors for system, based on the risk identification, risk estimation and risk evaluation. Now, the main engineering measures for the ice disaster governance of the Ningxia–Inner Mongolia Reach in the upper Yellow River are flood control embankment, ice diversion project, reservoir ice-prevention, ice-breaking prevention, etc.; the reservoir ice prevention is the only controllable and initiative engineering measure for reducing the ice disaster risk fundamentally, and the ice diversion project is an auxiliary engineering measure when the emergency of ice condition occurs. The reasonable establishment of ice-prevention preparedness, needing the combination of practical ice condition, water condition, meteorological characteristics, multi-objective comprehensive utilization requirements of the cascade reservoirs in the upper Yellow River, is striving for reducing the ice disaster risk to a great extent.

**Fig. 5** The computational flow diagram of accelerating genetic algorithm



#### 4 Comprehensive evaluation examples for the ice disaster risk of Ningxia–Inner Mongolia Reach

##### 4.1 Ice condition data of 1991–2010

To further analyze the rationality and practicality for the established theory and method of ice disaster risk comprehensive evaluation model of Ningxia–Inner Mongolia Reach, taking the measured ice condition data of 20 years for 1991–2010 as the samples, shown in Table 3.

##### 4.2 Calculation results

Ice disaster risk comprehensive evaluation model based on projection pursuit clustering evaluates the risk condition for 1991–2010 of Ningxia–Inner Mongolia Reach, and the objective function value is stable after circulation for 20 times of the accelerating genetic algorithm, as shown in Fig. 6 below.

Therefore, the projection vector of different evaluating indexes for ice disaster risk of Ningxia–Inner Mongolia Reach is  $\omega = \{0.01, 0.02, 0.01, 0.03, 0.01, 0.29, 0.02, 0.06, 0.29, 0.15, 0.11\}$ , and the ice disaster risk grade and degree of different years are listed in Table 4.

**Table 2** The division standard of ice disaster risk grade in the Ningxia–Inner Mongolia Reach

Grade of risk	Grade 1 (light risk)	Grade 2 (moderate risk)	Grade 3 (heavy risk)
Risk degree	[0, 0.25]	[0.25, 0.40]	above 0.40

For the above, ice disaster loss does not occur in the year of grade 1 (light risk), and the ice condition for the years of grade 3 (heavy risk) is always serious, resulting in disaster loss. Besides, to further reflect the evolution situation of ice disaster risk of historical years, the distribution for the scattered points of ice disaster risk for 1991–2010 is shown in Fig. 7. According to the standard of ice disaster risk grade for the historical years, it is concluded that the year of grade 3 (heavy risk) is 4, with the proportion of 21 %, the year of grade 2 (moderate risk) is 11, with the proportion of 58 %, and the year of grade 1 (light risk) is 4, with the proportion of 21 %.

As shown in Table 4 and Fig. 7, the ice disaster risk grade for the years of 1991–2010 of the Ningxia–Inner Mongolia Reach is calculated and evaluated in this paper, and by the comparative analysis for the calculation results of ice disaster risk with the practical ice and water condition every year, the rationality for the calculation results of ice disaster risk is discussed as follows:

(a) Years of the grade 1 (low risk)

Among the 19 years of 1991–2010, the years with the ice disaster risk of grade 1 (light risk) is 4, with the proportion of 21 %. The ice disaster risk is lower, for the favorable temperature process to the frozen-up situation of Ningxia–Inner Mongolia Reach, as follows:

1. The main characteristics for the year of 2001–2002, 2003–2004, 2005–2006 and 2006–2007 are the higher temperature process in the winter, the delayed ice-occurring and frozen-up date, the faster frozen-up rate, the higher temperature in the breakup period and the faster breakup rate.
2. In the year of 2001–2002, the average temperature for the three weather stations (Dengkou, Baotou, Tuoketuo) in the ice-prevention period is higher for 2.7–3.4 °C than the synchronization of history, which is the sixteenth significant warm winter after the year of 1986, with the freezing and breaking twice for the first time.

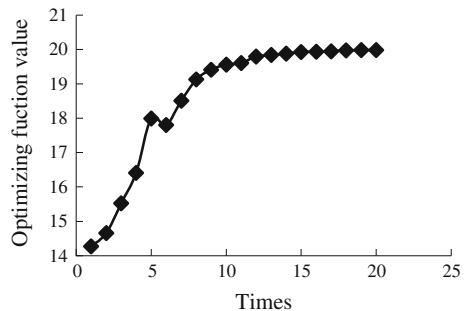
(b) Years of the grade 2 (moderate risk)

Among the 19 years of 1991–2010, the years with the ice disaster risk of grade 2 (moderate risk) is 11, with the proportion of 58 %. And the evolution condition of ice disaster risk is analyzed from the view of temperature and runoff in the following:

1. The temperature process: Same as the years with low risk, influenced by the factor of global warming, the average temperature in the winter of 1991–2000 is remarkably higher than before, especially the temperature after 1995 is continuously elevated. In the period of 1998–1999, the average temperature for the three weather stations (Dengkou, Baotou, Tuoketuo) is –2.9, –4.8 and –4.5 °C, respectively. Therefore, the temperature process in the winter for the years above is very favorable for the ice disaster risk of Ningxia–Inner Mongolia Reach.
2. The runoff of the upper river: The main characteristics for the ice condition evolution in the 1990s of last century are the reducing runoff in the upper river of the ice-prevention period, especially after the year of 1995, the runoff in the upper river is remarkable

**Table 3** The evaluation scheme set for the ice disaster risk of Ningxia–Inner Mongolia Reach

Number	Year	Frozen-up flow (m <sup>3</sup> /s)	Max channel-storage increment (billion m <sup>3</sup> )	Frozen-up date (month/day)	Breakup date (month/day)	Frozen days (d)	Remark
1	1991–1992	603	1.12	12/12	3/26	104	Disaster
2	1992–1993	588	1.32	12/16	3/24	98	Disaster
3	1993–1994	755	1.24	11/17	3/27	130	Disaster
4	1994–1995	610	1.54	12/15	3/23	98	Disaster
5	1995–1996	577	1.43	12/8	3/30	112	Disaster
6	1996–1997	522	0.46	11/17	3/18	121	Disaster
7	1997–1998	691	1.36	11/17	3/12	115	Disaster
8	1998–1999	553	1.64	12/4	3/15	101	Disaster
9	1999–2000	556	1.91	12/9	3/26	107	Disaster
10	2000–2001	676	1.87	11/16	3/24	128	Disaster
11	2001–2002	491	1.29	12/6	3/14	98	Non-disaster
12	2002–2003	446	1.19	12/9	3/28	109	Non-disaster
13	2003–2004	423	1.28	12/7	3/15	98	Non-disaster
14	2004–2005	485	1.94	11/28	3/30	122	Disaster
15	2005–2006	510	1.30	12/4	3/24	110	Non-disaster
16	2006–2007	468	1.30	12/4	3/23	109	Non-disaster
17	2007–2008	470	1.80	12/11	3/26	105	Disaster
18	2008–2009	472	1.70	12/8	3/25	107	Non-disaster
19	2009–2010	527	1.62	11/18	3/31	133	Non-disaster

**Fig. 6** The objective function trend for the ice disaster risk evaluation of Ningxia–Inner Mongolia Reach

reducing. The monthly average discharge of 1990–1998 for Lanzhou Station is reducing for 10 % than the mean annual discharge of 1970–1989, and the monthly average discharge of 1995–1998 is reducing for 13–25 % than the average value. In particular, for the years of 1996–1997 and 1997–1998, the monthly average discharge for the ice-prevention period is the minimum for the years after 1970, and the runoff volume for the ice-prevention period reduced for 31.6 and 31.7 %, respectively.

(c) Years of the grade 3 (heavy risk)

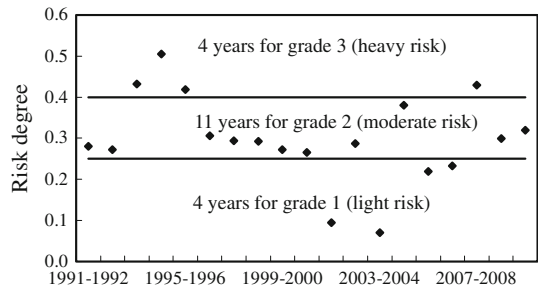
Among the 19 years of 1991–2010, the years with the ice disaster risk of grade 3 (heavy risk) is 4, (1993–1994, 1994–1995, 1995–1996, 2007–2008), with the proportion of 21 %.



**Table 4** The evaluation results of ice disaster risk for the Ningxia–Inner Mongolia Reach of 1991–2010

Number	Year	Risk degree	Grade of risk	Number	Year	Risk degree	Grade of risk
1	1991–1992	0.2803	Grade 2 (moderate risk)	11	2001–2002	0.0953	Grade 1 (light risk)
2	1992–1993	0.2721	Grade 2 (moderate risk)	12	2002–2003	0.2872	Grade 2 (moderate risk)
3	1993–1994	0.4318	Grade 3 (heavy risk)	13	2003–2004	0.0700	Grade 1 (light risk)
4	1994–1995	0.5050	Grade 3 (heavy risk)	14	2004–2005	0.3800	Grade 2 (moderate risk)
5	1995–1996	0.4179	Grade 3 (heavy risk)	15	2005–2006	0.2200	Grade 1 (light risk)
6	1996–1997	0.3059	Grade 2 (moderate risk)	16	2006–2007	0.2333	Grade 1 (light risk)
7	1997–1998	0.2943	Grade 2 (moderate risk)	17	2007–2008	0.4300	Grade 3 (heavy risk)
8	1998–1999	0.2927	Grade 2 (moderate risk)	18	2008–2009	0.3000	Grade 2 (moderate risk)
9	1999–2000	0.2725	Grade 2 (moderate risk)	19	2009–2010	0.3200	Grade 2 (moderate risk)
10	2000–2001	0.2660	Grade 2 (moderate risk)				

**Fig. 7** The distribution of the ice disaster risk degree for the Ningxia–Inner Mongolia Reach of 1991–2010



The ice condition is serious for these years, and resulting in disaster, which brings great pressure for the ice-prevention safety of Ningxia–Inner Mongolia Reach.

1. The ice disaster risk grade for the year of 1993–1994, 1994–1995 and 1995–1996 is higher, which is relevant for the abrupt temperature change in the ice-prevention period.
2. In the year of 2007–2008, the ice condition is the most serious for the recent 40 years, the thickness for the ice is higher, and the length for the frozen river is the longest. The channel-storage increment of the river is 1.8 billion m<sup>3</sup>, with the Inner Mongolia Reach of 1.6 billion m<sup>3</sup>, which is the third place of the history years, and increasing for 43 % than the average value (1.12 billion m<sup>3</sup>).
3. The ice disaster risk grade for these years is higher, with serious disaster loss, and the dangerous or disaster situation is occurring more than once in a year. As the year of 1993–1994, for the frozen-up level is higher, dangerous or disaster situation occurred for eight times in the frozen-up and breakup period.
4. For the above, the calculation result is nearly consistent with the average occurrence probability of Ningxia–Inner Mongolia Reach, and the ice disaster risk grade of different years is consistent with the practical ice condition characteristics, revealing the rationality and practicality for the calculation result of the ice disaster risk comprehensive evaluation model based on projection pursuit clustering for Ningxia–Inner Mongolia Reach.

## 5 Conclusions

The veracity for the risk evaluation result depends on the qualitative and quantitative analysis on the uncertainty of risk factors and the impact degree of the risk advert events. The ice disaster risk of Ningxia–Inner Mongolia Reach is caused by the uncertainty of hydraulic and thermodynamic factors comprehensively, with the dynamic evolution process of generation, development and extinction. Based on the risk analysis method of system theory, using the impacts of the risk factors to the risk advert event as the input, the risk degree as the output to the external environment, and the ice disaster risk grade is calculated in this paper, as follows: (1) The concept of ice disaster risk was defined, and the theoretical framework of “risk identification, risk estimation, risk assessment and risk management” for ice disaster risk analysis was proposed. (2) The comprehensive risk evaluation model based on projection pursuit clustering and accelerating genetic algorithm was established. (3) Basing on the establishment for the standard of ice disaster risk grade, the risk degree for the period of 1991–2010 in the Ningxia–Inner Mongolia Reach was evaluated by applying the proposed model. The above research results, enriching and developing the theoretical and practical research system, would provide scientific decision basis for establishing the ice-prevention preparedness of Ningxia–Inner Mongolia Reach in the upper Yellow River.

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