Ice Problems of the Yellow River, China

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Historically, the Yellow River has frequently suffered from ice flooding, specifically in its upper and lower reaches. However, thanks to the construction of a number of reservoirs on its master reaches, disastrous ice floods have not occurred for 40 years. Nonetheless, the risk of ice flooding still exists, and so the operation of reservoirs under ice conditions has become a new topic. Therefore, there has been monitoring and regulation of ice formation for many years. Numerical models and decision-making support system have been developed in cooperation with Finland and United States. This paper presents a brief introduction on ice problems of the Yellow River with an emphasis on recent developments.

1. Yellow River and its ice regime

The Yellow River basin is situated at 32° to 42° N and 96° to 119°E (Figure 1). At 5464 km long, China's second largest river passes three terraces: Tibetan highland, loess highlands, and Northern China plain. The River extends across both frigid and temperate zones. Ice conditions occur in the whole basin with the upper and lower reaches suffering the most severe problems (Li, 1996, 1998; Ke and Lu, 1996).

1.1a Upper Yellow River (Ningxia Reach)

The Ningxia reach starts from Heisanxia and ends at Sizhuisan with a total length of 397 km. The River course turns from southwest to northeast and passes over 2 latitudes. The upper segment is 135 km long and is dominated by valleys. The channel varies from 200 to 300 m and channel slope is about 0.08-0.1%. This segment of the river freezes only in winter because of its relatively steep channel and rapid flow. The lower segment is 262 km long; the river course is meandering and braided. Channel width varies from 500 m to

1000 m and the slope is 0.01 to 0.02%. Since this segment is flat, the flow is slow and the temperature is usually lower than the upper segment, the river freezes frequently. In this reach, the river freezes from downstream to upstream and ice breaks up from upstream to downstream.

1.1b Upper Yellow River (Inner Mongolia Reach)

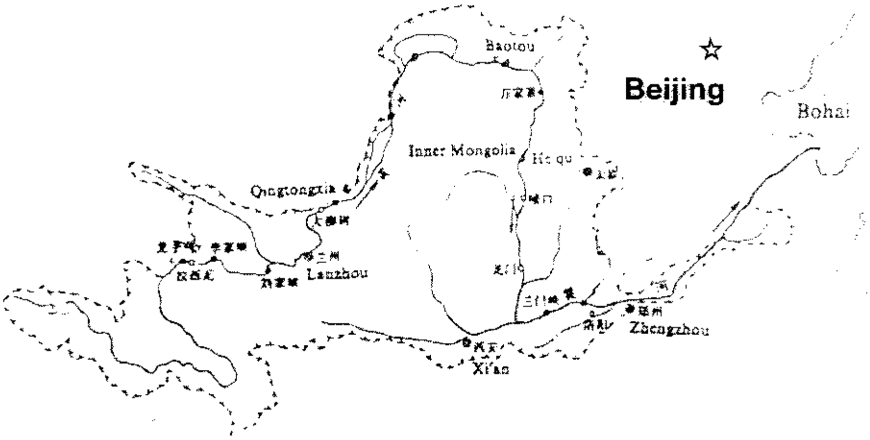

Figure 1. River course of Yellow River (Li, 1996)

The Inner Mongolia reach is 820 km long. It starts from Sizhuisan and ends in Hequ county, Shanxi province. This reach is in the most northern part of the Yellow River. Winter is long and cold in this region because it is controlled by the Mongolia high pressure jet. Subzero air temperatures usually persist for 4 or 5 months. Most parts of this reach freeze solid.

Since this reach turns from the southeast and then turns to the east, the latitude difference is 2°. The river freezes from downstream to upstream and the ice breaks up from upstream to downstream.

From Sizhuisan to Doukoutang, the river flows through valleys and the channel is steep. During break up, the ice flows often jam at narrow bends and forms ice dams. Downstream of Doukoutang, the channel widens gradually and the slope is gentle. Bars and guts frequently appear in the channel, and during freezing and can cause jams at locations where the channel width varies from narrow to wide, thus damming water upstream and causing flood plain inundation. During ice break, ice may jam at the bends or in places where the channel changes from wide to narrow, thus forming an ice dam and causing flooding.

There is no water supplied from tributaries during the frozen season in this reach. Most of the flow comes from regions upstream of Lanzhou. Flow at Lanzhou station is reduced steadily during winter. This flow process varies largely when it enters the Inner Mongolia reach due to the influence of ice. Part of the water turns to ice and part of it is stored in the channel during freezing. As a result, the flow rate decreases downstream. During ice break up, water stored in the channel is released, and discharge increases gradually downstream.

Influenced by air temperature, channel morphology, and dynamic conditions, freezing usually starts at Sanhukou and then develops up and downstream. Large amounts of water are stored in the channel during freezing time, and during ice break, ice can jam easily and form ice dams thus causing ice-induced flooding.

1.2 Lower Yellow River

The lower Yellow river starts at Taohuayu in Henan province and ends at the river mouth with a total length of 786 km. The river course stretches from the Southwest and passes over 3 latitudes. The river is constrained by embankments on both sides and the channel bed is higher than the ground elevation outside the embankments. The channel is wide at the upstream (in Henan Province) and narrow downstream (in Shandong Province). The river course is gentle and irregular.

Since the channel orientation in the Yellow River is similar to that of the Ningmeng reach, the ice regime in the Lower Yellow River has the same sorts of characteristics as it has in the Ningmeng reach. From Huayuankou to Gaocun, flowing ice dominates and the probability of freezing is less than 20%. Downstream of Sunkou, the air temperature is low, the channel is narrow and meandering, and ice jams easily causing ice dams. River freezing is dominant.

Ice floods in the lower Yellow River are well known in history. Embankment breaches during ice floods are documented as early as 168 B.C. and from 1855 to 1936 the embankment was breached 21 times. In 1951 and 1955, serious ice flooding caused the embankment to be breached twice.

1.3 Ice regime change after the construction of reservoirs

Since 1960, reservoirs have been built in the upper reach of the Yellow River. Especially after the Liujiaxia (1968) and the Longyangxia (1986) reservoirs were constructed, water stored in reservoirs in flood season has been released during dry season to generate electricity. This has altered the hydraulic conditions of the river downstream, and consequently, the ice regime has been changed. For example: (1) runoff has increased during winter and the unfrozen distance has increased; (2) during freezing, the discharge is unstable and ice jams can readily occur; (3) the flow rate is larger than before the freezing season, water stage is higher and discharge capacity under ice cover is larger than before. More water is stored in channels during the frozen period. For instance, discharge in Ningmeng reach has increased by 150 to 250 m^2/s during the frozen period. Water stage has elevated by 0.1 to 0.4 m on average. These changes are favorable to ice break up since the discharge capacity under ice cover is increased. Nevertheless, they also present a flood threat when water stored in channels is released in a short period of time; (4) during ice breakup, fewer ice dams are formed, and ice breaks up gradually. During ice break up, the Liujiaxia reservoir is used to reduce the flow rate thus reducing the hydrodynamic force and increasing the action of thermodynamic factors. The situation of ice break up is improved and fewer ice dams are formed.

Before the construction of the Sanmenxia reservoir, runoff of the Lower Yellow River in winter was mainly affected by the flow and ice from the Ningmeng reach. From late December to early January, there was a small flow process (discharge was about 100 to 200 m^3/s) that encountered cold weather in the lower Yellow River. The river may freeze easily when there is only a small flow. When the river freezes at a small flow rate, ice cover is low and the discharge capacity under the ice cover is small. When discharge increases, especially at a rapid rate, ice cover may break up suddenly. In spring, weather turns warm earlier upstream. When ice flows downstream, the river downstream is still frozen. With the unfavorable morphological condition of the river downstream, an ice dam is very likely to form, thus causing ice-induced flooding.

Since the use of the Sanmenxia reservoir in 1960, especially since the full operation of this reservoir for ice flood control in 1973, water has been stored in the reservoir prior to freezing time to supply the small flow rate. With this, the flow rate during freeze up is increased, the freezing date is delayed and the discharge capacity under ice cover is increased. At time of ice break, the flow rate is controlled by the reservoir. By reducing the peak discharge, the date of ice break at downstream can be postponed. In addition, the action of the thermodynamic factor is enhanced, and water stored in the channel is released slowly. All of these factors help to improve the conditions around ice break up. Observations show that during 1950s and 1960s, freeze up started on December 28 (on average) and the ice was completely melted by February 12. After the full operation of the Sanmenxia reservoir, the date of freeze up has been postponed until January 6 and the melting date has been delayed to February 28. The phenomenon of sudden ice break up is eliminated.

2. Empirical relationships of ice regime

The Yellow River Conservancy Commission has been developing a number of empirical, semi-empirical and theoretical methods to predict the ice conditions and ice regime change since regulation by reservoirs.

The empirical method is developed from statistics of ice regime and the conditions behind these phenomenon, including the index approach (Chen, 1996) and multiple regression analysis (Wang, 1996; Li and Zhu, 1998). Variables such as the highest and lowest air temperature, daily average temperature, density of flowing ice, and the others are considered as indices. Using historical records, statistic relationships between the index and the freeze/thaw date have been set up. Therefore, the accuracy of a forecast depends largely on the meteorological and geographical conditions.

2.1 Relationship of river freezing and breaking

The semi-empirical method considers the physical process behind the phenomenon. Mainly thermodynamics, hydraulic forces, and river morphology affect the ice regime of the river. Usually, for a short reach of river, thermodynamic and hydraulic forces influence the ice regime since river morphology varies only slightly. Thus, only these two major factors are used in considering the special characteristics of ice regime at a certain reach. For example, Ke and Lu (1996) presented a few relationships indicating the river freezing

$$T_{cr} = 1 - \frac{Q}{C}. \qquad (1)$$

For either sudden or gradual ice break up

$$\sum_{1}^{3} T_i = C_1 \sum_{i}^{6} Q_i - C_2 \qquad (2)$$

where T_{cr}, T_i are the critical and average temperature for river freezup at a certain station, respectively, Q and Q_j are the discharge (m^3/s), and the C_1, C_2, C are constants.

2.2 Study of Ice Jam

Since 1960, the probability of ice jam formation has increased significantly in the Yellow River. There have been three major studies about ice jamming in the Yellow River.

In the winter of 1961, a huge ice dam formed on Liu-Yan reach of the Yellow River. The backwater height was 11 m at the Liujiaxia dam, which was 7 m higher than the crest of the downstream cofferdam. Systematic observations and research was carried out on the jams from 1961 to 1964. The results of this research can be found in Chen et al. (1998) and Ke and Lu (1996).

The ice jam development can be divided into three sections with six period. The formation of ice jam depends on the amount of sludge ice from the upstream as well as the velocity. The critical velocity of sludge ice to submerge at the freeze up boundary (V_c) is 0.7 m/s (surface velocity) with a Froude number, F_r, of 0.09.

Ice Jams in Qingtongxia Reservoir during 1967 to 1968 were observed and studied. The development of ice jam, the cause of ice jam formation, and the preventive measures were analyzed.

A serious ice jam took place at the Tianqiao hydropower station due to specific climate and hydraulic conditions. The open-river course was approximately 200 km, 1.7 times longer than the length in a normal year. The backwater level at the end of the reservoir was 2 m higher than the historical maximum flood water level.

There were five stages in the course of the development of ice jam formation upstream of Tianqiao hydropower station. It was believed that the movement and development of the ice jam depended on two factors: Froude number and discharge. The accumulation of ice with water under ice cover was considered to be analogous to the movement of a sand wave. The state of sludge ice accumulated under the ice cover can be summarized as steady neat, ice veins, ice raise, transition (the ice raise is being melted), dynamic neat and reverse ice wave. The Froude number of the ice with water in dynamic neat state is regarded to be 0.28. It was regarded that the integrated roughness of the ice jammed river course is related not only to the flow rate Froude number, but also the relative thickness of ice with water. A few empirical relationships were established to calculate the flow under the ice condition (Chen, Yang, and Li, 1998).

3. Ice Regime Models in lower Yellow River

3.1 Chinese-Finnish Project

China and Finland jointly developed the "Mathematical Model of Ice Flood in the Lower Yellow River." The Finnish Mathematical Model of Ice Flood (JJT-model) combines a one dimensional unsteady flow model with water temperature, flowing ice, ice cover formation, and the process of freezing. The Mathematical Model of Ice Flood in the Lower Yellow River was based on the JJT-Model and introduced the characteristics of wide ice dam, ice break up, and ice bridging. This model can simulate the process of freeze up in the Lower Yellow River.

The freeze up condition used in this model is

$$|q_0| \geq 986(n / \tau) * 0.39 * (B_i / h)^{0.78} V^{1.56} \tag{3}$$

$$q_0 < -200 W / m^2 \tag{4}$$

$$\tau > 150 \tag{5}$$

where q_0 is the heat flux from water surface to air, n is Manning's coefficient, h is the water depth, t is the routing time of surface ice (hr), V is the average velocity, and B_i is the width of ice.

3.2 Chinese Practical Prediction Model

The Yellow River Conservancy Commission developed the "Practical Model of Ice Regime in the Lower Yellow River." This model is established using theories of thermodynamics and hydraulics combined with practical experience. It is simple and fairly accurate. The prediction errors of air temperature and flow run-off during the dry season are considered when performing ice regime prediction. The accuracy meets the requirements specified. This model is well suited to the situations of a frequently varying river course and the low level of monitoring currently used.

The freezing condition for the Lower Yellow River derived from the model is

$$C_i T_{a-} \geq \alpha Q \qquad (6)$$

where α is the coefficient of freezing and equals 0.008, C_i is the density of the flowing ice, T_{a-} is the negative temperature, and Q is the discharge.

The breaking condition of ice cover for the Lower Yellow River derived from the model is

$$Q_t \geq \frac{10\beta h_t^{0.95}}{\sum T_{a+} + 1} \qquad (7)$$

Where Q_t is the total incoming flow rate, h_t is the thickness of ice when air temperature turns to positive; $\sum T_{a+}$ is the accumulated positive temperature; β is the coefficient of ice break up and equals 22 when breakup is gradual (4 for sudden ice break up).

Based on this model, an ice flood model was developed using a hydrological routing method. A calibration using many years' of data shows that this method is fairly accurate (Chen and Ke, 1996).

3.3 Chinese-USA RICEY model

The computer model, RICEY, has been developed for simulating flow and ice conditions in the lower Yellow River and is used to analyze the effect of the winter operation on the Xiaolangdi Reservoir. This model is developed from RICEN (Shen et al., 1995). The main modification is the improvement of the unsteady flow module with a refined Newton-Raphson scheme applicable to a river with shallow depth and abrupt changes in channel geometry (Wang and Shen, 1995; Wang et al, 1996).

The computer model was developed for the 820.78 km stretch of the lower reach downstream of the Xiaolangdi Reservoir. In spite of the lack of information on the changing bed geometry during the winter, the simulation results compared well with field observations. A scenario analysis using the model showed the effects of the weather and operation of the Xiaolangdi Reservoir on the ice conditions. Suggestions for the operational strategy of the Xiaolangdi Reservoir for ice control in the lower Yellow River were made based on the simulation results. A model for winter sediment transport and bed change is expected to be developed and incorporated into the river ice model as well.

4. Decision-support system

An ice-control decision-making support system for the lower Yellow River consists of five parts: ice prevention information retrieval; temperature and ice regime forecast; ice prevention regulation, and two databases of ice regime and management (Cai et al., 1996).

The operation mechanism of the system is each subsystem should be worked in order of priority in accordance with data flow. The first to be done is a long-term temperature and ice regime forecast. Secondly, the regulation schemes according to the forecast, then modification of those schemes according to the actual situation through the retrieval and analysis information. Finally, selection of the implemented scheme through expert-discussion and decision-making.

5. Ice problems of water-transfer projects

In recent years, studies of ice hydraulic problems in water transfer and diversion works including the northern part of the Middle Route Project of Water Transfer from South to North (Yang, 1996) and Beijing-Miyun Diversion Canal have been carried out successfully in northern China (Li, 1996).

As a strategic measure to alleviate the shortage of water in the Yellow River and Northern China, the West Route Project of water transfer, in Qinghai-Tibetan highland has been in the process of investigation for a few decades.

Transferring 2 billion cubic meters of water annually into the upper Yellow River from the upper Yangtze River would require the construction of three 175-300 m high dams, as well as long tunnels and open channels. Under this specific environment, ice problems related to construction and operation of hydraulic engineering has drawn increasing attention (Gao et al., 1996). Much work still needs to be carried out.

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