Variation in water level under ice-jammed condition – field investigation and experimental study

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Abstract This paper presents the impacts of frazil ice jams on the variation in water level at the Hequ Reach of the Yellow River in China. Based on both field observations and experimental studies, it is found that both the evolution of frazil ice jams and the associated variation in water level depend upon an interesting interaction between hydraulic variables during the ice-jammed period. In particular, the critical Froude number governing the formation of river ice jams and their upstream propagation is about 0.09. The water level during ice-jammed periods depends not only on the slope of the water surface and the water level under open-water conditions with the same discharge, but also on the length of the ice jam and the ice concentration in the water. Moreover, the field investigations show that the thickness of river ice strongly influences the variation in water level during ice-jammed periods. Empirical relationships are derived to quantify the relationship between the highest water level during ice periods and related physical parameters. To confirm the field results, and to explore the influence of ice discharge on the variation in water level, experimental studies were also conducted. These results confirm that the ice concentration plays a key role in the variation in water level and the jam thickness. Given the complexity of the jamming processes, surprisingly good agreement is observed between field and experimental investigations.

Keywords Froude number; ice accumulation; ice concentration; ice jam; water level; Yellow River

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Introduction

A major consequence of ice-cover formation on many rivers is the associated jamming that occurs, particularly during periods of fall freeze-up or spring break-up. In fact, ice jamming is one of the most conspicuous and momentous of the ice-related phenomena. Ice jams form when the ice transported by the current is arrested by obstacles such as stationary ice cover, or congested, say from a local reduction in ice-transport capacity (Beltaos 1983, 2000). Due to a large aggregate ice thickness and a high hydraulic resistance relative to the sheet ice, ice jams tend to disturb the riverbed, can cause high water stages and many other impacts. Gerard and Davar (1995) reviewed the flooding caused by river ice jams across Canada and found that ice jam floods are not only less predictable and sudden, but they are usually accompanied by low temperatures, and that massive ice slabs and blocks often move with the floodwaters. Thus, river ice has many repercussions for operation and design including determining the overturning moment on structures, estimating the forces on ice booms, controlling the severity of spring flooding and assessing the associated stage–frequency relationships, or of predicting river bed scour due to surges associated with suddenly released jams (Beltaos 1995, Beltaos *et al.* 1996; Hicks *et al.* 1995; Prowse 1986; Tuthill *et al.* 1996).

Fig. 1 shows the influence of ice jams on the variation in water level in the Hequ Reach of the Yellow River. Clearly, the water level caused by ice jams is about 2 m higher than those under open-water conditions with the same discharge. On 24 February 1982, the increase in water level caused by an ice jam at the Hequ gauge station was measured as 2.79 m with a

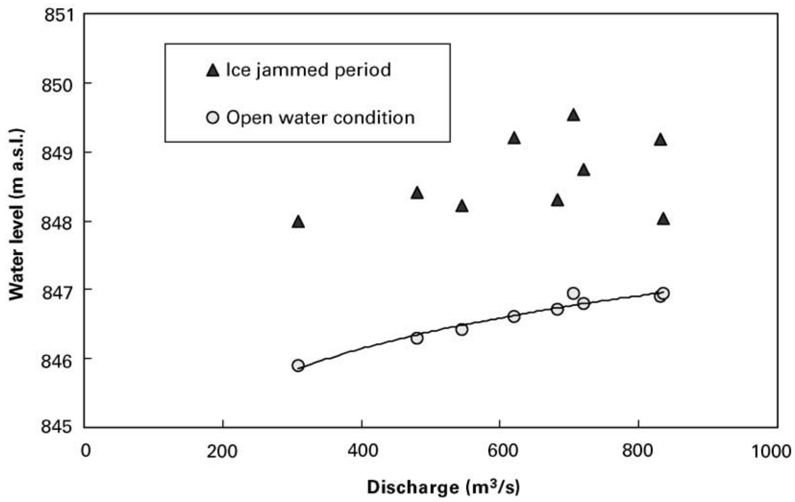


Figure 1 Comparison between water level during stable jamming period and those under open-water conditions with the same discharge at the Hequ gauge station (from 1978 to 1988)

discharge of 705 m^3/s and, on 14 February 1986, an increase in water level of 2.60 m was recorded with a discharge of 620 m^3/s. Clearly, the investigation of water levels during the ice-jammed period is profoundly important.

Geography and morphology of the Hequ Reach

The Hequ Reach (Fig. 2) of the Yellow River is located between 39° and 40°N latitude and between 110° and 112°E longitude. It extends 70 km from Longkou Gorge (near section 1) to Tianqiao Power Dam (section 22). Upstream from Longkou Gorge (section 1), a stretch of water over 100 km long remains open during winter because of numerous rapids and high flow velocities. In winter this long reach is exposed to cold air temperatures that generate an enormous amount of frazil ice, leading directly to the formation of large frazil jams. The associate frazil particles usually have a flat elliptic shape; the specific depositions observed in this study consisted of frazil granules with a mean diameter of about 1 cm (Shen and Wang 1995; Sui 1988).

After passing Longkou Gorge, the river broadens and meanders; the width between sections 2 and 8 in the upper Hequ Reach varies between 500 m and 1500 m, and exceeds 600 m between sections 5 and 7. Between sections 5 and 6, the river is about 1500 m wide and has numerous shoals. The river width of the lower Hequ Reach between sections 8 and 17 is usually less than 350 m. The riverbed slope exceeds 0.15(between sections 1 and 2, is more than 0.06% between sections 2 and 7 and is less than 0.06% between sections 7 and 17.

The riverbed of the Hequ Reach is alluvial, broad and shallow. The bed material is mainly fine sand, although pebbles are present in some stretches. Ice jam effects occur typically for about 100 days per year. Frazil ice jams of tremendous size have often been formed upstream of Shiyaobu (near section 10), leading to high water levels and causing a severe ice flood in 1982. Prompted by this event, extensive measurements of the ice jam profile along this river reach have been made each winter. By the winter of 1986, 21 additional measurement sections (besides the Hequ gauge station, section 9) had been installed to measure water levels, thickness of ice cover and profile of frazil jams, flow velocities under ice jams, sediment concentration during jamming periods, water and air temperatures, etc. The backwater from the reservoir reaches section 17. As the ice cover in the backwater region is usually thin and unstable, only occasional measurements were made in this region.

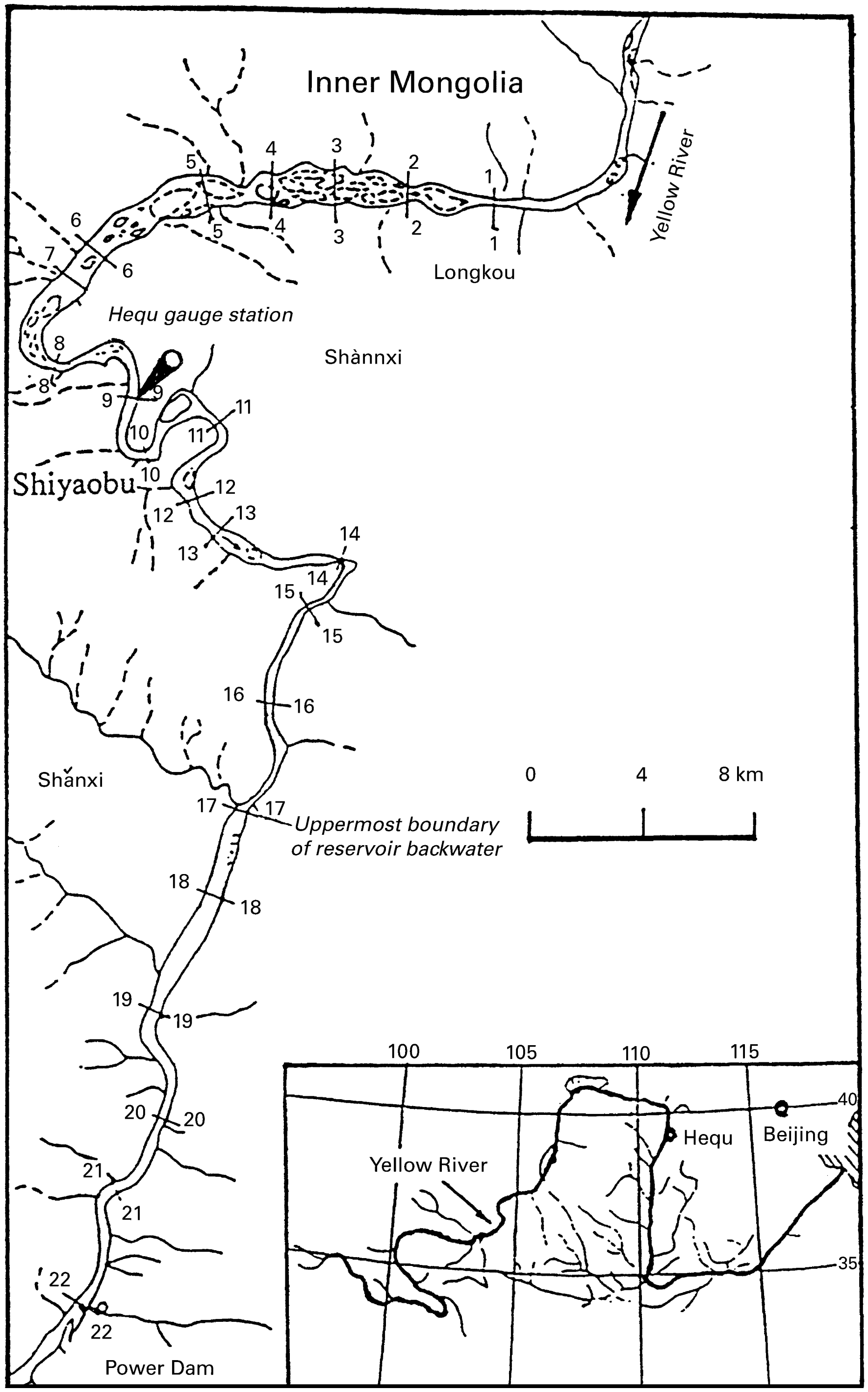


Figure 2 Hequ Reach of the Yellow River

The measurements of ice-cover thickness and jam profiles were conducted once every 5 days for sections 1–17. Water levels at all cross sections, as well as water discharge and water temperature in the Hequ gauge station (section 9), were measured daily (Sui 1988; Sun *et al.* 1986).

On average, the long-term (1955–1986) daily mean temperature at the Hequ climate station are negative from 16 November to 7 March, leading to an average of 108 days with subzero temperatures. The long-term mean air temperature during this period is −6.96 °C (Sui 1988). The average air temperature in December, January and February is −7.8 °C, −10.04 °C and −5.83 °C, respectively; the highest air temperature for the same months is −3.6 °C, −6.4 °C and −0.7 °C, respectively. The lowest air temperature in December, January and February is −13.5 °C, −14.6 °C and −9.8 °C, respectively. Although the thermal processes controlling the ablation of ice jams are important and often play a significant role in river breakup (Prowse 1990; Prowse and Marsh 1989), the present study has not focused directly on thermal processes in view of the shortage of related data.

Mechanisms of ice jam evolution and variation in water level

Field investigations and observations from 1970 to 1987 at the Hequ gauge station show the mean monthly discharge for November to March is 637, 409, 481, 745 and 740 m^3/s, respectively. The average frazil ice running date is 20 November with an average duration of 14 days. The average date of freeze-up is 4 December and the average date of break-up is 23 March. Thus, the average duration of ice cover is 109 days (Sui 1988).

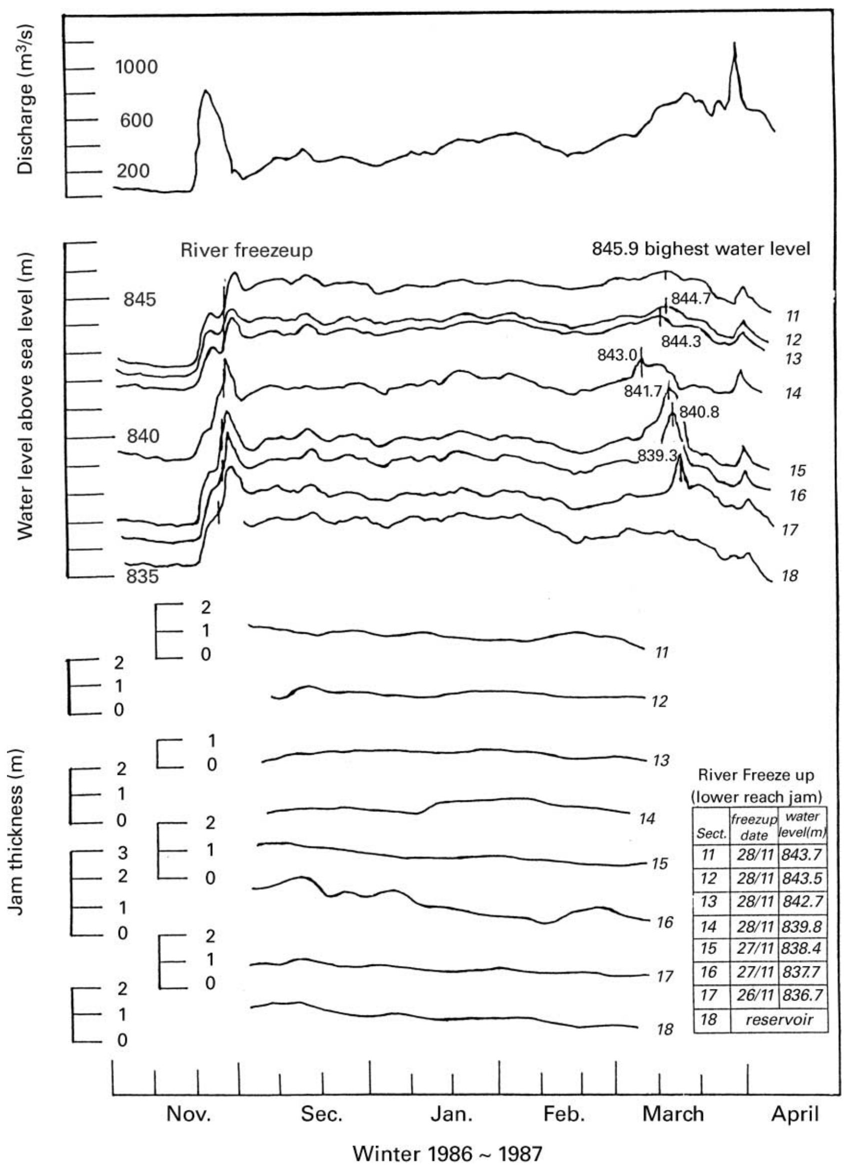
In Chinese, the name "Hequ" is derived from "he" (river) and "qu" (bend), an appropriate name given the river morphology. Both the backwater profile originating at the reservoir and the river bends play an important role during the formation of river ice jams. The river bend near section 10 has a radius of curvature of only 0.7 km. A rock on the concave bank there projects over the water, which leads to ice bridging. Each winter, ice jams initiate at the Power Dam and, an ice cover accumulates upstream. Before the arrival of the leading edge of this ice jam, another ice jam often initiates from ice bridging near section 10. Because of the influence of both the rapids and the curved channel, a short open-water reach is preserved between sections 10 and 11. Field investigations have shown that, after the formation of the initial frazil jams along the 70 km reach between section 1 and section 22 (Tianqiao Hydro-Power Station), most frazil ice generated in the open-water reach upstream from Longkou (near section 1) is stored in the upper reach jams between sections 1 and 9, with only a tiny proportion transported downstream. As a result, formation of the initial jams causes the upper-reach jams to grow rapidly while the downstream jams evolve more slowly due to the reduced rate of frazil-ice replenishment. The so-called upper reach jams between sections 1 and 9 are hence different from the so-called lower reach jams between sections 11 and 17. Frazil jams between sections 17 and 22 form in the reservoir and are thus classified as reservoir jams.

Field observations of ice jams in the Hequ Reach and subsequent analyses have shown there is an inter-dependence between the variation in water levels during the ice period and the evolution of frazil jams. More specifically, variation in water levels and evolution of frazil jams depend not only on the river discharge, but also on the frazil-ice discharge, the configuration of the channel section and climatic factors. It is seen from the observed data at the Hequ Reach that the following regularities prevail with respect to variation in water levels and frazil movement.

(1) The formation of frazil jams in the Hequ Reach begins at the dam of the Tianqiao Hydro-Power Station. Because of low flow velocity in the reservoir, ice cover formed by pancake ice (a circular shape with upturned edges) progresses upstream quickly. Because of water-level fluctuations in the reservoir from hydro-power operation, the ice cover tends to form a "shaved and packed" structure that fosters the formation of the initial ice jam.

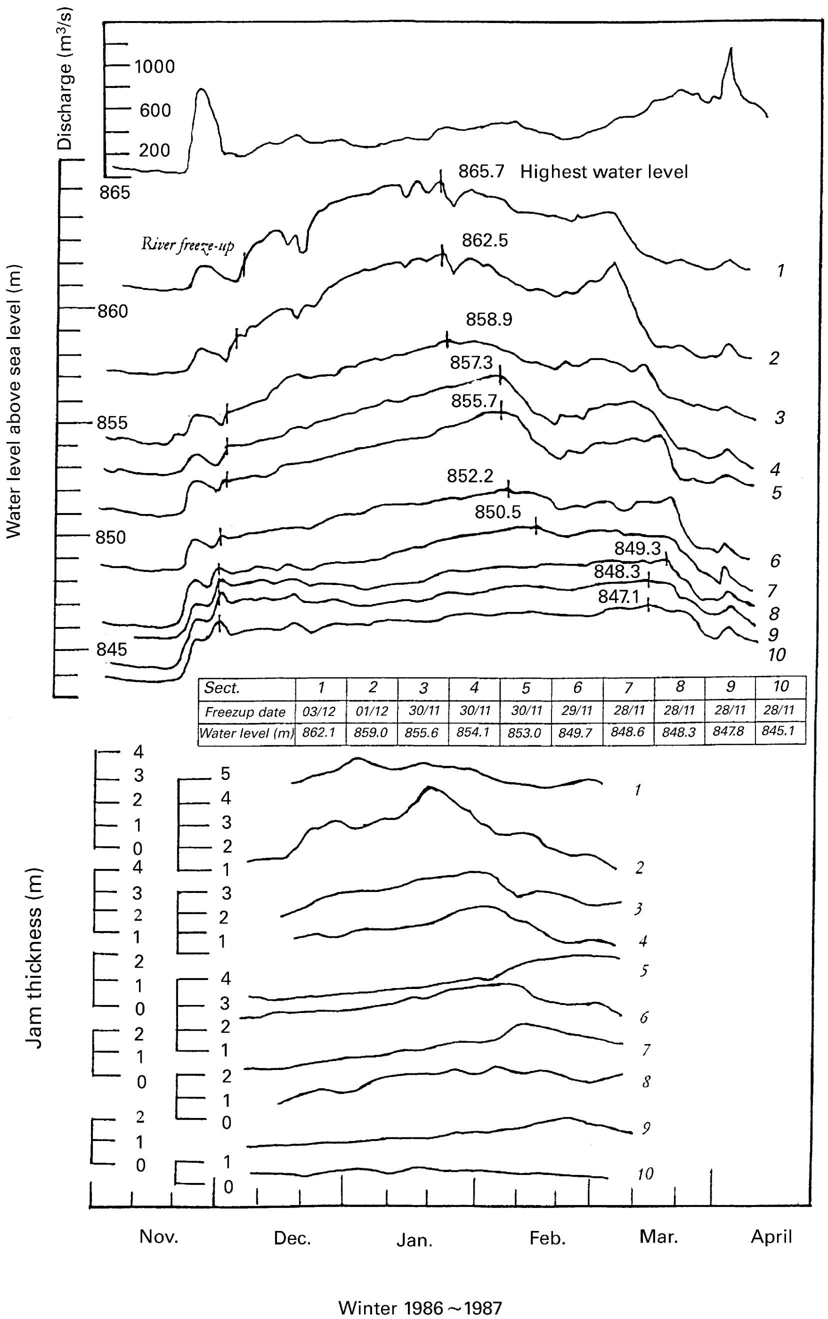
(2) After the formation of an initial frazil jam along the river reach, frazil pancake ice and sometimes also ice blocks (generally detached from shore ice along the river bank

through the fluctuation of water levels) plunge under the foremost upstream edge of the jam and accumulate there. Thus, the head region (Beltaos 1983, 1995) of an ice jam tends to become thicker, causing a partial flow restriction and a further rise in water level. By contrast, erosion of the frazil jam at the toe region (Beltaos 1983, 1995) causes the relevant water level to decrease, as shown in Figs 3 and 3(a). Fig. 4 shows the variation in ice jam thickness between sections 1 and 10. After the formation of an ice jam in the whole river reach in December, frazil ice was transported from the head region to the toe region and increased the ice jam thickness, as shown in the January accumulation. In the meantime, the water level increased. Depending on the flow velocity and hydraulic gradient, this scour–deposition–transportation process often continues throughout the whole winter.



Sect.	freezup date	water level(m)
11	28/11	843.7
12	28/11	843.5
13	28/11	842.7
14	28/11	839.8
15	27/11	838.4
16	27/11	837.7
17	26/11	836.7
18	reservoir	

Figure 3 Hydrograph of water level and jam thickness in the Hequ Reach (ice jam between sections 1 and 10) (a) Hydrograph of water level and jam thickness in the Hequ Reach (ice jam between sections 11 and 17) (see over).



Sect.	1	2	3	4	5	6	7	8	9	10
Freezup date	03/12	01/12	30/11	30/11	30/11	29/11	28/11	28/11	28/11	28/11
Water level (m)	862.1	859.0	855.6	854.1	853.0	849.7	848.6	848.3	847.8	845.1

Figure 3 *Continued*

(3) Upstream from section 1, in view of the locally high flow velocities in this reach, a 100 km open-water stretch is permanently maintained. This open-water reach permits the formation of large quantities of frazil. With the unceasing replenishment of frazil from this upstream stretch in midwinter, the accumulation under the head region intensifies. Thus, the recorded thickness of the ice jam is usually over 2 m during this time, and sometimes exceeds 4 m at cross sections 1, 2 and 3. This increased

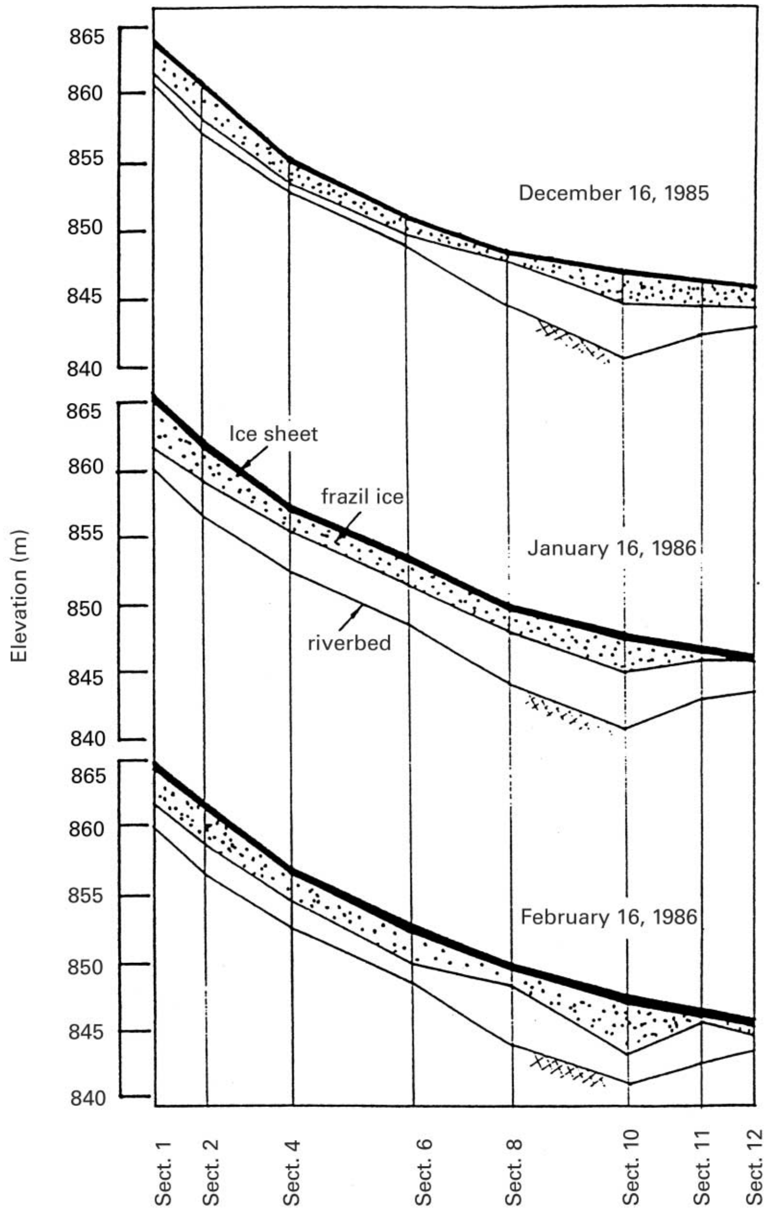


Figure 4 Longitudinal evolution of ice jams in the Hequ Reach in the ice period 1985–1986

accumulation leads to a reduction of the flow area and a consequent rise in upstream water levels. With the increase in local flow velocity caused by the reduced cross section, frazil from the jam head is increasingly transported toward the toe, causing water levels there to increase as well. These mechanisms are maintained throughout the ice period, causing the jam to grow.

(4) As mentioned, the 100 km open-water reach upstream of section 1 generates a large amount of frazil. In mid-January the air temperature typically drops to its minimum and thus ice discharge reaches a peak as confirmed by site visits. Therefore, the jam thickness near the jam head, the water level and the ice transport capacity reach their maximum values at this time. After this, rising air temperatures begin to decrease frazil

production and both the supply and accumulation of frazil under the head jam decrease. However, the existing frazil ice that has accumulated continues its migration to the toe of the jam. Thus, during this period, water levels tend to decrease in the head region but continue to increase in the toe region.

(5) The frazil jam begins to dissipate before and during break-up, causing the water levels and thickness of the frazil jam along the 70 km river reach to decrease dramatically.

Analyses of field data

Water level during freeze-up

During the formation of an ice jam, the water level varies dramatically because of the blockage of the channel and additional resistance to the flow under the jam. The water depth at the leading edge of the jam depends primarily on the specific discharge per unit width and the backwater effects of the jam itself. Generally, the freeze-up depends on the surface water velocity or Froude number, based on the flow depth of the open-water flow approaching the jam. Early field data by Kivisild (cited by Beltaos 1995) indicated that the maximal Froude number for freeze-up condition is between 0.06 and 0.09. Michel felt that such values are reasonable for freeze-up conditions (Beltaos 1995) while Shen and Ho (1986) suggested that it is more correct to consider local values and their variation across the river. From data on the St. Lawrence River, they found a consistent value of maximal Froude number equal to 0.09.

The discharge is measured daily at the Hequ gauge station. Based on the measured water level during river freeze-up at sections 1, 2, 4 and 6, the average water depths were determined. These calculations were based on the measured cross section under open flow conditions with the provisional (and certainly approximate) assumption that this cross-sectional area remains representative. In this way, an average Froude number of 0.09 was found for river freeze-up for the Hequ Reach. Specifically, the frontal edge of the ice jam at the Hequ Reach of the Yellow River will extend further upstream only if the Froude number (Fr) of stream flow at the upper end of the jam is less than 0.09; the ice jam will not propagate upstream if $Fr > 0.09$. Using this critical value we have

$$F_r = \frac{v}{\sqrt{gh}} = 0.09 \tag{1}$$

in which $h =$ mean depth of water at the leading edge of ice jam (m); $g =$ gravitational acceleration (m/s^2) and $v =$ mean low velocity at the leading edge (m/s). Since $v = Q/(Bh) = q/h$, in which $q =$ the discharge per unit width (m^3/(s m)) and $B =$ the width of the water surface at the section in question (m), Eq. (1) can be solved for h to give

$$h = 2.33 \ q^{2/3} \tag{2}$$

Eq. (2) was used to calculate the mean depths of stream flow at the leading edge of the ice jam during freeze-up periods.

Table 1 and Fig. 5 show good agreement between the measured mean depth and the calculated results based on this simple Froude number relation. At section 6, however, consistently large differences in $(H_O\text{-}H_C)$ occur. One reason for this might be the influence of the easily movable channel which should be scoured during ice-jammed periods. Therefore, Eq. (2) may provisionally be used to predict the water level at the leading edge of the frazil ice jam during freeze-up periods. It should be noted that this critical condition for ice-jam propagation is only valid for the frazil jam. For ice jams caused by solid blocks, the critical submergence condition depends not only on the velocity of the stream flow at the leading edge of the ice cover (jam), but also on the dimensions of the solid block (Pariset and Hausser

Table 1 Comparison of computed and observed values of water depth at the beginning of the freezing up at the Hequ reach of the Yellow River in China (from 1987 to 1988)

Section no.	Date dd/mm/yy	Daily mean discharge (m^3/s)	Width of river (m)	Unit discharge ($m^3/s/m$)	Observed water level (m a.s.l.)	Observed mean depth (H_O) (m)	Computed depth (H_C) (m)	Diff. (H_O-H_C) (m)	Ratio: (H_O-H_C)/H_O
1	6/12/85	170	320	0.531	861.22	1.250	1.526	−0.276	−0.221
1	3/12/86	148	315	0.470	861.59	1.504	1.406	0.098	0.065
2	11/12/82	235	452	0.520	858.33	1.510	1.505	0.005	0.003
2	24/12/83	108	452	0.239	857.40	0.950	0.896	0.054	0.057
2	17/12/84	430	452	0.951	859.10	2.350	2.251	0.009	0.004
2	6/12/85	170	452	0.376	857.94	1.340	1.212	0.128	0.096
2	1/12/86	260	452	0.575	858.23	1.560	1.609	−0.049	−0.031
4	11/12/82	230	530	0.434	853.34	1.205	1.334	−0.129	−0.107
4	24/12/83	108	400	0.270	853.21	1.150	0.972	0.178	0.155
4	11/12/84	218	510	0.427	853.63	1.370	1.320	0.050	0.036
4	4/12/85	215	520	0.413	853.67	1.350	1.291	0.059	0.044
4	30/11/86	229	525	0.436	853.71	1.380	1.338	0.042	0.030
6	6/12/82	200	600	0.333	850.07	1.400	1.120	0.280	0.200
6	23/12/83	218	590	0.369	850.00	1.400	1.198	0.202	0.144
6	5/12/84	250	640	0.391	850.15	1.402	1.243	0.157	0.112
6	1/12/85	180	640	0.281	850.19	1.410	1.000	0.410	0.291
6	30/11/86	229	620	0.369	850.17	1.402	1.198	0.204	0.146

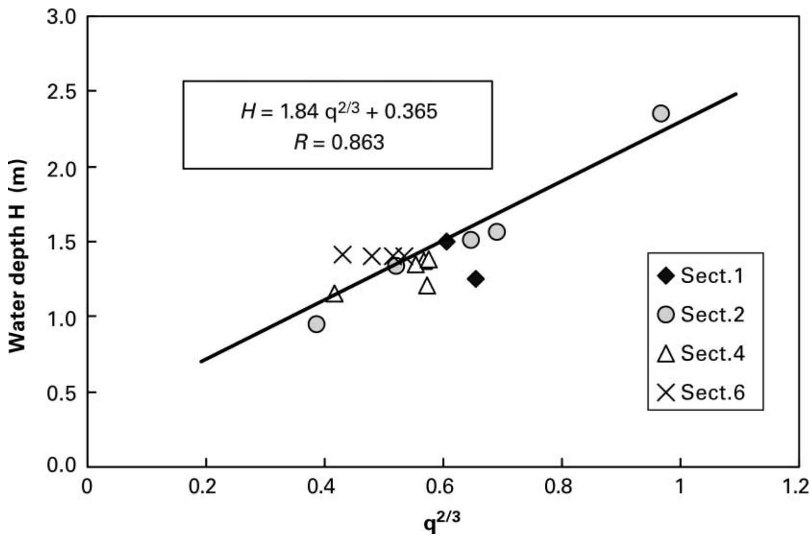


Figure 5 Relationship between water depth and the discharge per unit width during the formation of ice jams

1961; Uzuner and Kennedy 1972; Ashton 1974, 1986; Wong and Beltaos 1985; Daly and Axelson 1990; Sui *et al.* 1993).

Water level during stable jamming periods

In winter, after the formation of river-ice cover (jam), the hydraulic and boundary conditions of the river are clearly different from those under open-water conditions with the same discharge. Figs 6 and 7 show the velocity distribution for open-water and ice-jam conditions (in view of the shortage of funding, it was impossible to conduct the field observations regarding the distribution of flow velocity under ice cover at every cross section during the whole winter period, and thus average flow velocities were used in the calculation).

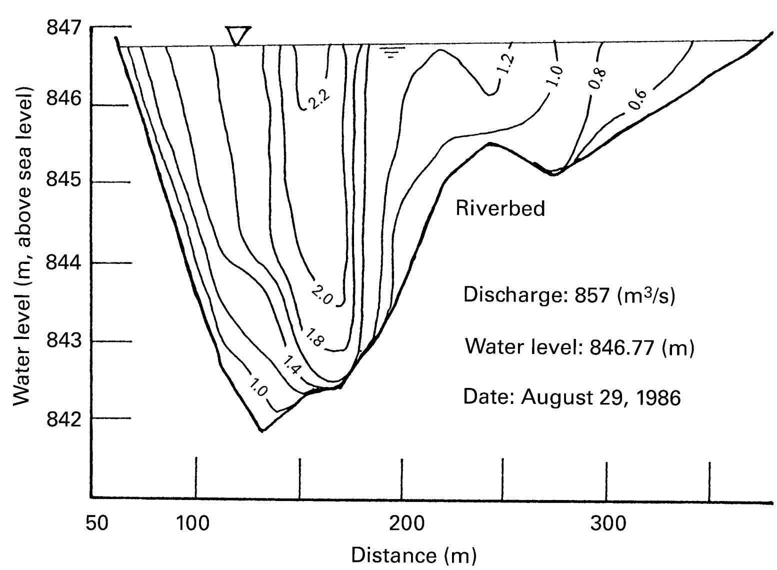


Figure 6 Distribution of flow velocity under open-water condition

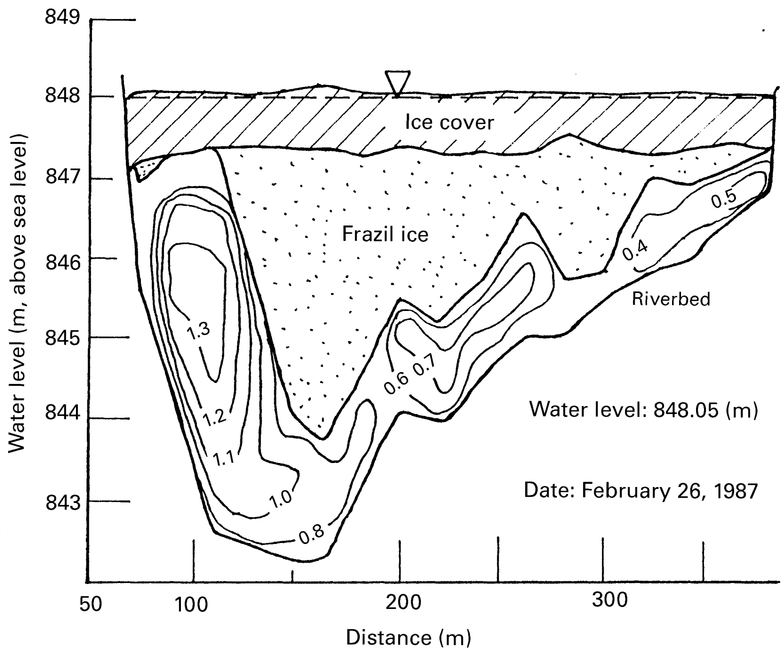


Figure 7 Distribution of flow velocity under ice-jammed condition

Conceptually at least, the addition of an ice cover (jam) results in an increase in flow resistance and thus leads to a decrease in flow velocity. As shown in Figs. 6 and 7, flow velocity under ice-jam conditions is generally less than 1.1 m/s though it sometimes exceeds 1.5 m/s. On the other hand, oncoming ice discharge directly affects the size and shape of the ice jam. If other flow conditions remain the same, the larger the ice concentration the more severe will be the ice jam that develops, and the higher the water level; these conditions then lead to increased flow velocity and intensified erosion of the frazil jam. Overall, increased blockage of the channel leads to increased flow velocities and intensified erosion of the frazil, ultimately limiting the accumulation and producing a kind of natural but shifting equilibrium.

Field investigations and analyses show that the variation in water level during the stable jamming period (from late December to early March) in the Hequ Reach is directly proportional to the variation in ice jam thickness. The thicker the ice jam, the higher the water level. On the basis of the observed data at sections 1, 2, 4 and 6 from 1982 to 1987, a first-order empirical relationship between the thickness of frazil jam t and the increment of water level $\Delta H =$ (difference between water level during jamming period and those under open-water conditions with same discharge H_O) has been established. The result is

$$\Delta H = 0.94t + 0.11 \tag{3}$$

As shown in Fig. 8, the correlation between ΔH and t does predominate. Thus the water level H during the stable jamming period is $H = H_O + \Delta H$.

Although Eq. (3) generally indicates the dependence of the increment of water level on the thickness of the ice jam, the thickness of the ice jam itself depends on ice discharge (ice concentration), which thus effectively summarizes several thermodynamic factors, as well as the flow velocity, the turbulence intensity and the boundary conditions of the river reach. In view of the impracticality (and extreme danger) of measuring the ice concentration during ice periods, a more direct relationship between water level and ice discharge in the Hequ Reach unfortunately could not be established.

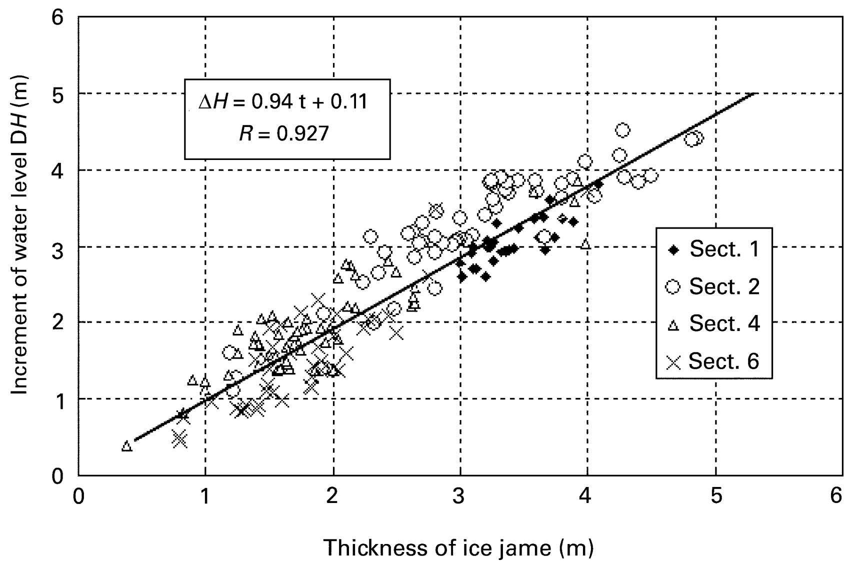


Figure 8 Relationship between increment of water level and thickness of ice jams in the Hequ Reach

Highest water level during ice periods

The thickness of the ice jam in the Hequ Reach varies throughout the ice periods and from location to location. For example, as Fig. 3 indicates, the thickness of the ice jam may exceed 4 m at section 2 while it is less than 1 m at section 1 (during river freeze-up and break-up periods). Not surprisingly, this variation itself leads to dramatic adjustments in water level along the jammed river reach.

Determining the highest water level during the ice period is clearly important when designing hydraulic and flood-protection structures. Both field observations and related analyses have shown that the highest water level during ice periods at the Hequ Reach always occurred during stable jamming periods (Figs 3 and 3(a)). The highest water level depends on the specific discharge, the jamming length and the hydraulic slope under open-water conditions with the same discharge. On the basis of the observed data at the sections for the upper reach jams, a first-order empirical relationship between the highest water level and the related parameters has been established. The result is as follows:

$$H_M = H_O + 4.07\ q^{0.033} S_O^{0.213} \left(\frac{L}{L_O}\right)^{0.809} \tag{4}$$

in which H_M = highest water level during ice periods (m); H_O = water level under the open-water conditions with the same discharge (m); S_O = hydraulic slope under open-water conditions with the same discharge; L = jamming length between the calculated section and section 10 and L_O = 38.5 km = average jamming length from the leading edge of the jams to section 10. As shown in Fig. 9, the calculated water levels using this are generally in reasonable agreement with the observed water level.

Eq. (4) shows the intuitively satisfying result that the highest water level is a relatively weak function of unit discharge. However, if it is assumed that hydraulic radius equals the average water depth (h) for this wide and shallow river; the hydraulic slope (S_O, under open-flow conditions) can be described as follows (based on the Manning equation):

$$S_O = \frac{q^2 n_O^2}{2 n_O^2 h_O^{10/3}} \tag{4a}$$

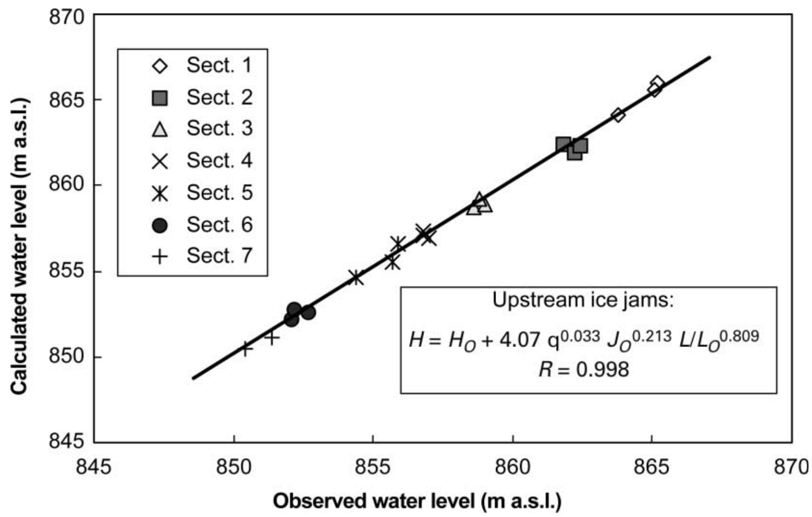


Figure 9 Relationship between the highest water level during ice periods and the related parameters at the Hequ Reach (upstream jams)

Combining Eqs (4) and (4a) shows that the unit discharge plays a more important role in determining the maximum water level than Eq. (4) itself implies.

For the ice jams in the lower reach (between sections 11 and 17), there is no clear relationship between these parameters, because of the greatly reduced input of frazil to the lower reach compared to that of the upper reach jams. Field observations show that almost all of the frazil generated in the open-water reach upstream of Longkou Gorge (near section 1) is initially intercepted in the upper-reach jam. Only a small portion of the frazil is transported to the lower-reach jam and then discharged to the reservoir jam. Additionally, the thickness of the ice jam changes little during the winter period, as shown in Fig. 3(a). That means the upper-reach jam is dominated by saturated ice transport and the lower-reach jam generally balances ice transport and ice storage (jam thickness); thus this portion is classified as an equilibrium ice jam. Overall, it is the ice transport process that leads to differences in the water level over this reach.

The islands at sections 2 and 4 (Niang-Niang-Tan), between sections 5 and 6 as well as within the river bends between sections 7 and 10 play a crucial role in the stabilization of the upper-reach jam, although the unstable frontal edge of the upper-reach jam at Longkou Gorge continually migrates up and down the river during the winter period. Conceptually, the frazil under upstream jams is expected to be transported downstream whenever the flow velocity increases. However, in view of the large size of the stable upper-reach jam (26.66 km from sections 1 to 10), the process of self-regulation of this relatively stable ice jam through the water under the ice jam is not readily achieved. This might partly account for the apparent stability of this region.

According to field observations, the incoming ice discharge to the lower-reach jam might be considered to be equal to the ice output from the lower-reach jam, although it is much less than the oncoming ice to the upper-reach jams. This is the main reason for the less dramatic development of the lower-reach jam. In addition, the smaller river-bed slope of the lower reach is also an important factor that influences the evolution of the frazil jam.

Experimental investigation

Since ice discharge plays such an influential role in water-level variation, and since it is extremely difficult to obtain reliable field data about ice concentrations, laboratory simulations were conducted to verify at least in a general way the results of field investigations, and to further study the mechanism of frazil-jam evolution. Under a non-frozen condition, the experimental studies were conducted using a horizontal 36 m long, 0.5 m wide, 0.6 m deep recalculating flume. The flume comprises one 180° bend, with a radius of curvature of 1.5 m that is connected by 16.8 m and 4.8 m long straight reaches. Frazil ice was simulated using wax particles, 5 mm thick and right parallelepiped. A hopper located at the upstream reach of the flume discharged simulated frazil particles at controlled rates into the flume.

Variation in water level of simulated ice jam

The formation of ice cover under laboratory conditions obviously differs from that at the Hequ Reach. After putting the continuous "ice cover" on the water surface in the flume, the simulated frazil ice particles were discharged. The simulated jam was initiated at an upstream section and propagated downstream. Thus, the experimental simulations of the variation in water level and evolution of ice jam did not include the first phase (a) described in section 3 (in fact, installing a continuous ice cover in the experimental study is quite similar to the process of "formation of the surface ice jam" in the Hequ Reach). However, the mechanisms of variation in water level and evolution of "ice jamming" in the laboratory are conceptually similar to those observed in the field, as are the subsequent three phases of development (as shown in Fig. 10).

(1) When the simulated ice particles are swept under the ice cover and begin to accumulate, downstream propagation of the ice jam is initiated. Experimental studies show that initial jam thickness depends on both water depth and flow velocity under open-water conditions. The water level increases along the reach upstream from the toe of the downstream-propagating ice jam. Water levels did not vary downstream from this edge.

(2) The jam grows continuously with the unceasing replenishment of frazil particles. The jam thickness also increases continuously with time and the water level rises simultaneously. As was the case in the field, the increment of the water level increases with the relevant increment of jam thickness (Fig. 11). However, the influence of experimental conditions again needs to be considered, since the "ice particles" used in

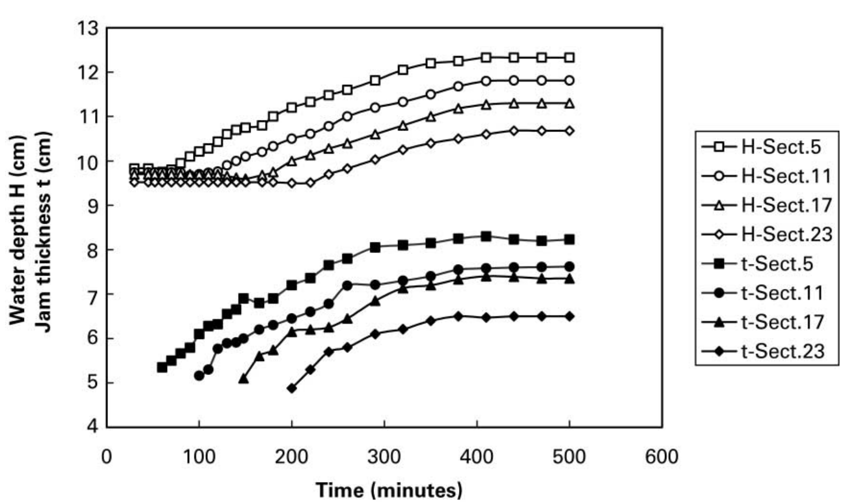


Figure 10 Water level and thickness of ice jams in the laboratory

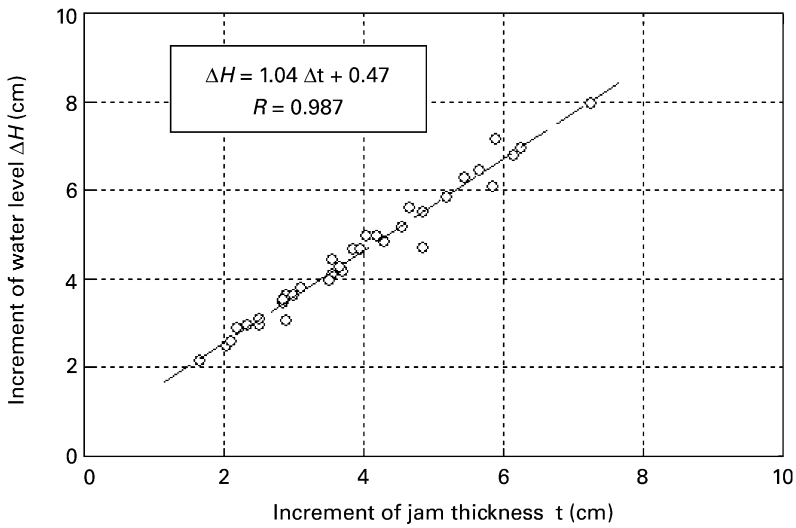


Figure 11 Relationship between increment of water level and thickness of ice jams in the laboratory

the physical modelling are different from the frazil ice in natural rivers. This may lead to the difference in the variation in water level caused by ice jams.

(3) When the inlet ice discharge is the same as the outlet discharge, this frazil jam reaches an equilibrium state. Under steady flow conditions, the jam thickness and water level remain approximately the same with unceasing frazil replenishment. By changing flow conditions, the jam thickness and the water level react and a new equilibrium frazil jam is eventually established.

Analyses of experimental data

Conceptually, the variation in water levels may be evaluated by means of a general computational relation:

$$H = f\left(v,\ h,\ S,\ n_b,\ n_i,\ g,\ \rho,\ \rho',\ \sigma_d,\ d_{50},\ Q_i,\ B,\ t,\ L,\ \Delta L\right) \tag{5}$$

in which H = mean overall water depth (m); v = mean velocity of flow under ice jam (m/s); h = mean effective depth of water under jam (m); n_b, n_i = roughness coefficient of river bed and ice jam, respectively; S = hydraulic slope; ρ, ρ' = density of water and frazil ice (kg/m^3), respectively; d_{50} = median diameter of frazil particles (m); σ_d = mean square deviation of grain size of frazil particles; t = mean thickness of jam (m); B = width of river (m); ΔH = (difference between water level during jamming period and those under open-water conditions with the same discharge H_O); Q, Q_i = flow discharge and ice discharge (m^3/s), respectively; and L, ΔL = frazil jam length from section 1 to section 23 and frazil jam length between the computation section and section 1, respectively.

Field investigations and experimental studies show that the variation in water level in a jammed reach depends not only on hydraulic parameters of flow (Froude number), but also on ice concentration. In addition, jam length plays also an important role in water level variation. Figs 12–15 summarize the relationships between the variation in water level ($\Delta H/H$) and related variables. These results show that $\Delta H/H$ depends on the hydraulic conditions of flow under the ice jam $\{v/(gh)^{0.5}\}$. The ice concentration (Q_i/Q) and jam length parameter ($\Delta L/L$) also play important roles during jam evolution and on variations in water level. The larger the ice concentration, the larger is the variation in water level, as shown in Fig. 13. Fig. 13 includes only low and a small range of ice concentrations. The larger $\Delta L/L$ (the further downstream), the smaller the variation in water level, although Fig. 14 indicates

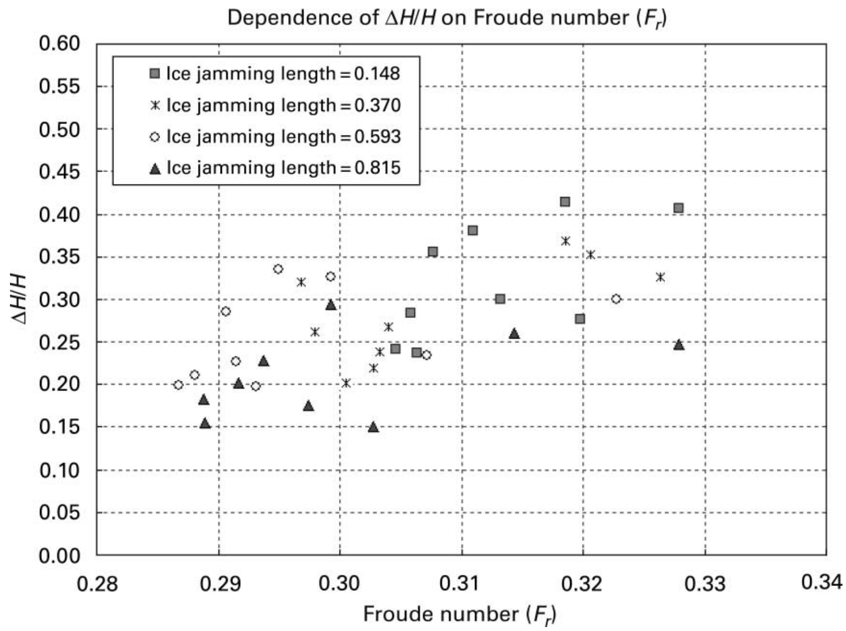


Figure 12 Variation in water level ($\Delta H/H$) as a function of Froude number (Fr) – laboratory results

significant scatter. In other words, the deviations of some data groups with the single variable correlations does indicate that the variation in water level during the ice jammed period depends also on other parameters. Thus, the relationship between $\Delta H/H$ and $v/(gh)^{0.5}$, Q_i/Q as well as $\Delta L/L$ is described as follows:

$$\frac{\Delta H}{H} = 0.265 Ln\left\{\left(\frac{v}{\sqrt{gh}}\right)^{-0.182}\left(\frac{Q_i}{Q}\right)^{0.461}\left(\frac{\Delta L}{L}\right)^{-0.231}\right\} + 0.756 \tag{6}$$

As shown in Fig. 15, the correlation between $\Delta H/H$ and $v/(gh)^{0.5}$, Q_i/Q and $\Delta L/L$ does indeed predominate. Eq. (6) shows the relationship among these variables. The results of field

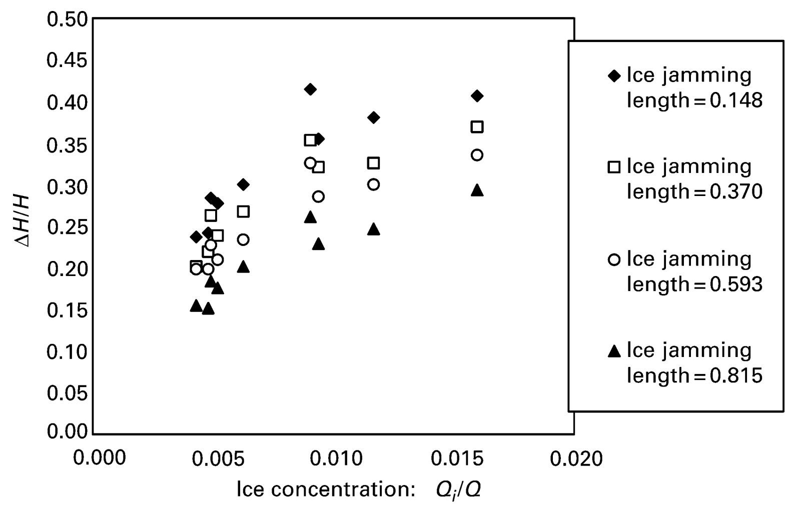


Figure 13 Variation in water level ($\Delta H/H$) as a function of ice concentration (Q_i/Q) – laboratory results

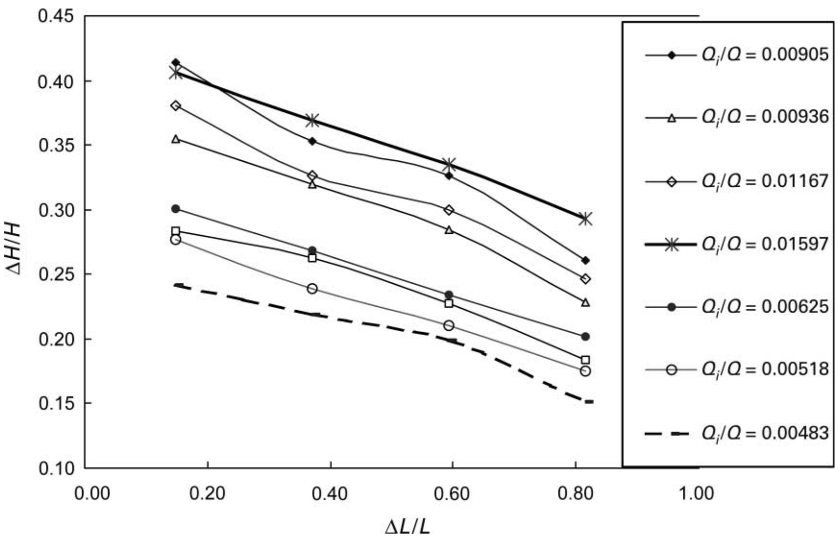


Figure 14 Variation in water level ($\Delta H/H$) as a function of ice jamming length ($\Delta L/L$) – laboratory results

investigations and experimental studies show that both the mechanisms of variation in water level and accumulation of frazil in a jammed reach are in quite good agreement.

Figs 12 and 15 show the dependence of $\Delta H/H$ on Froude number. In Fig. 12, $\Delta H/H$ increases with Froude number across the whole data set, although the correlation is weak. In Fig. 15 and Eq. (6), however, $\Delta H/H$ decreases with Froude number. In fact, there is no contradiction here. Fig. 12 shows the dependence of variation in water level on Froude number under the condition of different ice concentrations at different cross sections. Under the condition with the same ice concentration (Q_i/Q), the variation in water level at the same cross section ($\Delta L/L$) should decrease with Froude number. However, as shown from Fig. 14, we did not repeat the experimental studies under the same Q_i/Q. From Figs 13 and 14, we

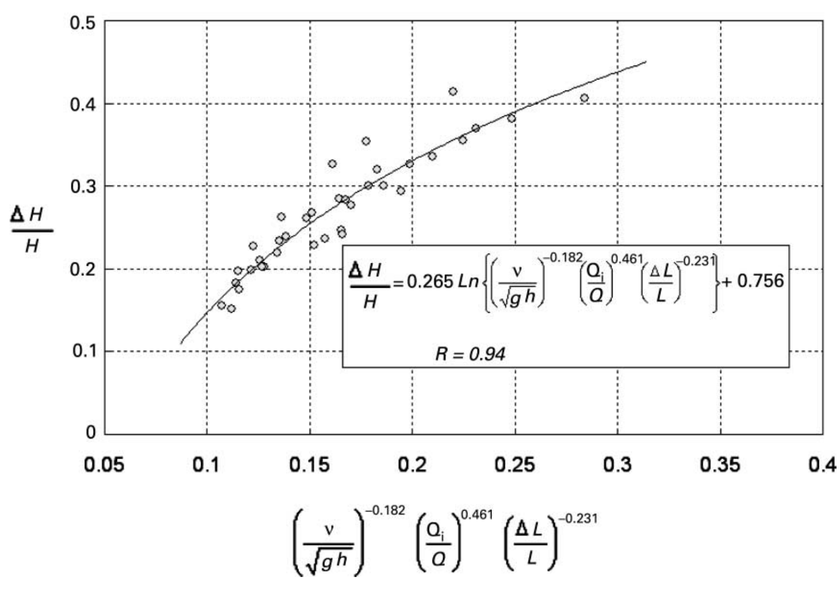


Figure 15 Variation in water level ($\Delta H/H$) as a function of Froude number (Fr), ice concentration (Q_i/Q) and ice jamming length ($\Delta L/L$) – laboratory results

found that Q_i/Q and $\Delta L/L$ (in fact the impact of the backwater caused by the ice jam itself) also play an important role in $\Delta H/H$.

Discussion

In general, the blockage of the channel by ice produces an increase in the water level of 0.9 of the ice thickness (the "0.9t theory") without any contribution to flow resistance. Eq. (3) predicts an increase in water level only slightly larger than that corresponding to a blockage. This might imply that the ice accumulation is very smooth and flow resistance is minor. In fact, the ice accumulation along the Hequ Reach consists of submerged frazil particles only with the porous spaces between frazil particles filled with water. This could result in a "saturated frazil medium" somewhat analogous to a saturated soil. Clearly, the total mass density of a control volume of such a material is different from solid ice, and the "0.9t" relation might partly account for this.

In general, the roughness of ice jams would be expected to significantly affect water level, especially for ice jams accumulated at least partly by ice blocks. Thus, the roughness of ice jams should be considered in studies regarding the variation in water level during an ice jam period. However, neither the roughness coefficient of frazil ice jams nor that of simulated ice jams in the laboratory was determined. After formation of the frazil ice jam, the roughness of a frazil ice jam is thus assumed to change little, particularly during a stable ice period, a reasonable assumption give that the shape and size of frazil particles themselves change little during the whole winter period (with experimental studies, we used only one size and the same shape for the simulated ice particle). In many obvious ways, frazil ice accumulation is different from the accumulation of simulated ice blocks. Because of thermal and shear effects, the roughness coefficient of an ice jam accumulated by ice blocks will be significantly reduced (as shown in Fig. 16, Water Resources and Hydropower Planning and Design General Institute (1985)) comparing to that of an ice jam accumulated by frazil ice. Further research on this topic of frazil ice resistance should be conducted in the future.

Conclusions

Using field observations of frazil jams in the Hequ Reach and the experimental simulations from a laboratory, the mechanisms of the variation in water level during ice periods are investigated. Field investigations and experimental studies as well as the subsequent analyses show that the propagation of ice jams depends mainly on the hydraulic conditions of the stream flow at the leading edge of the ice jams. The critical Froude number during the progress of upstream propagation of ice jams in the Hequ Reach is about 0.09.

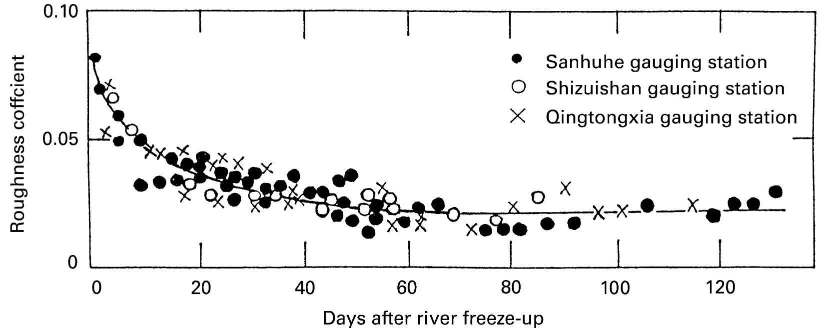


Figure 16 Variation of roughness coefficient of ice jam with time (three gauge stations on the Yellow River)

An empirical linear equation shows the relationship between the ice jam thickness and water level. In addition to the thickness of the ice jam, the ice concentrations in water as well as the length of ice jams are another two important variables relating to the variation in water level. For the ice jams in the Hequ Reach, a strong empirical relationship was found between the highest water level and the discharge per unit width, the length of the ice jam as well as the hydraulic slope under the open-water conditions with the same discharge.

On the basis of studies on the field ice jams, experimental studies were conducted to verify the results of field studies and to explore the influence of ice discharge on the variation in water level. Experimental results show that the variation in water level ($\Delta H/H$) depends to a large extent on the hydraulic conditions of stream flow under the ice jam $v/(gh)^{0.5}$. The larger the value of $v/(gh)^{0.5}$, the smaller the $\Delta H/H$. On the other hand, the larger the ice concentration Q_i/Q, the larger is $\Delta H/H$. Conversely, the larger the jam length parameter $\Delta L/L$, the smaller the $\Delta H/H$. The results of field investigations and experimental studies, both in terms of the mechanisms of variation in water level and the accumulation of frazil in a jammed reach, are in generally good agreement.

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