NOTE / NOTE

Observations of riverbed scour under a developing hanging ice dam

Jueyi Sui, Faye E. Hicks, and Brian Menounos

Abstract: This paper illustrates the importance of river ice accumulations in changing river channel geometry based on field investigations carried out at the Hequ gauging station on the Yellow River in China. A relationship is established between riverbed deformation and ice accumulation.

Key words: river ice, hanging dam, ice accumulation, river scour, Yellow River.

Résumé : Cet article illustre l'importance des accumulations de glace de rivière à changer la géométrie du canal d'une rivière, selon l'étude sur le terrain effectuée à la station hydrométrique Hequ située à la rivière Jaune, en Chine. Une relation entre la déformation du lit de la rivière et l'accumulation de glace est établie.

Mots clés : glace de rivière, barrage de glace suspendu, accumulation de glace, affouillement de rivières, rivière Jaune.

[Traduit par la Rédaction]

1. Introduction

In turbulent river flow, frazil ice is the dominant ice formation phenomenon. Frazil ice forms in supercooled water and thus is only generated in open reaches. In rivers with fast-flowing sections where an ice cover cannot form, tremendous quantities of frazil ice can be generated throughout the winter. This frazil ice is carried in suspension, moving with the flow to be deposited as hanging dams on the underside of the ice cover at some point downstream where flow velocities are insufficient to facilitate further transport. Examples of hanging dams in Canada include one documented by Beltaos (1995) on the Smoky River in Alberta and a 56×10^6 m^3 dam documented by Michel and Drouin (1981) on the La Grande Rivière in Quebec.

The effects of river ice processes on sediment transport have been an active area of research in recent years and, despite the obvious logistical difficulties, some researchers have successfully measured suspended sediment concentrations in the field during the ice breakup period (Prowse 1993; Beltaos and Burrell 1998; Sui et al. 2000; Milburn and Prowse 2002). On the other hand, few studies have been conducted on the impacts of ice accumulation (ice jams and dams) on riverbed deformation. In particular, there have been only a few case studies documenting the impacts of river ice on the geometry of natural channels during the dynamic periods of freeze-up and breakup (Smith 1979; Hicks 1993; Sui et al. 2000; Smith and Pearce 2002). Based on field investigations of ice accumulation and riverbed deformation at the Hequ gauging station on the middle reach of the Yellow River, China, this paper presents some results regarding the evolution of a hanging ice dam and the associated riverbed deformation.

2. Geographic location

The Yellow River, with a total length of 5464 km, is the second largest river in China, draining an area of 795 000 km^2 with an erodible area of 454 000 km^2, including the Loess Plateau. The average annual sediment inflow to the downstream is 1.6×10^9 t, with an average sediment content of 35 kg/m^3. Every year, an average of 400×10^6 t of sediment is deposited in the lower reach of the Yellow River, resulting in riverbed aggradation at a rate of 10 cm/year (CAHE 1992).

The Hequ gauging station is located on the middle reach of the Yellow River, as shown in Fig. 1. The Inner Mongolia reach of the Yellow River (the lowest section of the upper reach of the Yellow River) flows approximately from west to east and is characterized by a wide, shallow channel with a relatively gentle slope (less than 0.12%). Toudaoguai is the

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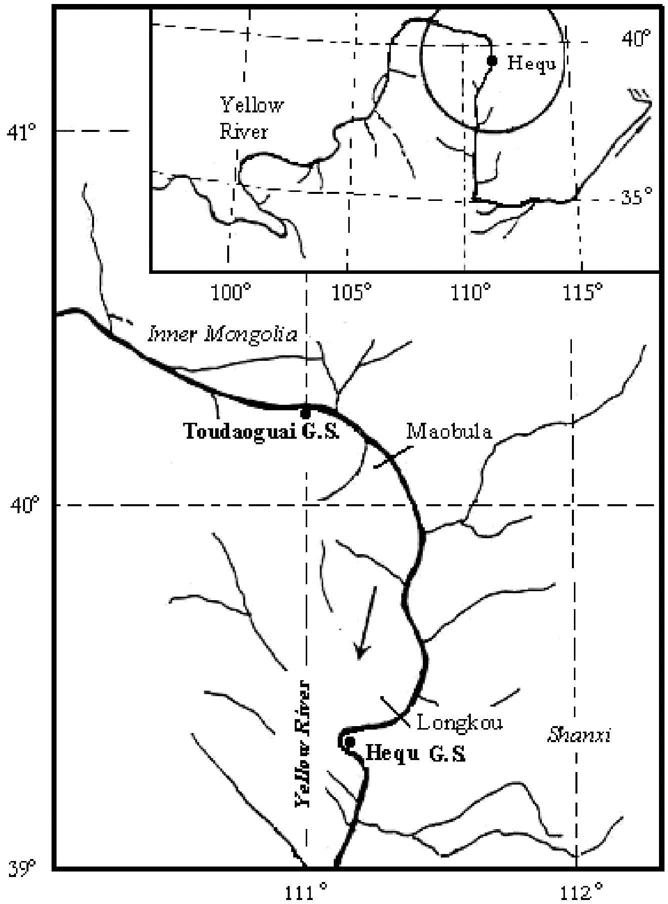
Fig. 1. Far north reaches of the Yellow River, China. Arrows indicate direction of flow. G.S., gauging station.



lowermost gauging station along the upper reach of the Yellow River. After passing the Toudaoguai gauging station, the Yellow River flows approximately from north to south to the middle reach with an average slope of 8.4% (CAHE 1992). The middle reach is relatively straight, and the channel width varies between 400 and 1000 m.

In the vicinity of the Hequ gauging station, the slope of the riverbed is 2.5% and the channel width is approximately 450 m. Figure 2 shows three detailed surveys of the channel cross section at the Hequ gauging station under low open flow conditions (62.8 m^3/s on 16 June 1978, 92.0 m^3/s on 30 May 1979, and 97.3 m^3/s on 3 June 1980). As illustrated in Fig. 2, the geometry of the cross section is relatively consistent under open flow conditions for low discharges (comparable to winter flows). The cross section measured on 30 May 1979 was used here as the reference cross section because it represented an average of the three surveys. The channel is asymmetric in shape, with a deep scour hole along the left bank.

3. Observations of riverbed deformation caused by ice accumulation

It is clear that the deformation of a riverbed under ice-covered conditions is fairly complicated, and field data are essential to advancing our understanding of the effects of ice accumulations on bed topography, although such measurements are generally quite expensive and logistically difficult to obtain. For this study, such observations were made at the cross section of the Hequ gauging station and included measurements of ice accumulation thickness and bed topography over six winters from 1982 to 1988. The source of the ice accumulations is a 113 km long, relatively steep reach of the Yellow River between Maobula and Longkou, located 23 km upstream from the Hequ gauging station (Fig. 1). Because of its steep slope (1.17%), this reach remains open throughout the winter, generating significant quantities of frazil ice. This ice is transported downstream and collects on the underside of the ice cover at the Hequ station, forming a hanging ice dam.

Figures 3 and 4 show eight surveys obtained at the Hequ gauging station cross section under ice conditions during the 1982–1983 and 1983–1984 winter periods, respectively. These figures illustrate the impacts of ice accumulation (in the form of a hanging ice dam) on the deformation of the riverbed by comparing the reference cross section. Figure 5 illustrates the corresponding accumulated degree-days of freezing (ADDF) for these 2 years based on air temperatures measured at the Hequ climatic station, which is located 2.5 km from the Hequ gauging station. The ADDF was calculated starting with the first 5 consecutive days of subzero mean daily air temperatures.

As illustrated in Figs. 3 and 4, scour was occurring under ice conditions, with increased scour associated with the increasing size of the ice accumulation at the Hequ gauging station. Immediately after river freeze-up in 1982 (Fig. 3*a*) with only a small amount of ice accumulation in place, the maximum riverbed scour was only about 0.5 m. Between mid-January and mid-February 1983, with the rapid increase in ADDF (at a fairly consistent rate of 9.8 °C-days per day), the incoming frazil ice from the upper open water area of the Hequ reach led to significant growth of this ice accumulation (Figs. 3*b*, 3*c*), with a corresponding increase in the associated deformation of the riverbed. On 13 January 1983, the ice was obstructing much of the right side of the channel, causing the scour hole along the left bank to deepen to about 1 m below the reference section. By 8 February 1983, the riverbed had been scoured by approximately 2 m (Fig. 3*c*). It is interesting to note that at this time a large portion of the ice accumulation had shifted to the left bank, causing a dramatic shift of the thalweg towards the centre of the channel. Temperatures started to warm in late February and, as seen in Fig. 5, the ADDF leveled off; consequently, upstream ice production decreased dramatically. As a result, by 10 March 1983 the ice accumulation at Hequ station had diminished considerably and at the same time deposition of bed material returned the riverbed geometry to a shape comparable to that of the reference (unscoured) cross section (Fig. 3*d*).

As Fig. 5 illustrates, cooling began about 1 week earlier in the winter of 1983–1984, and the winter was slightly colder, with the rate of accumulation of degree-days of freezing averaging 13.3 °C-days per day (35% higher than in 1982–1983). Bed scour was again observed to increase as the ice accumulation increased. The December measurement was taken 1 week later than in the previous year and thus represents approximately 2 extra weeks of frazil ice production. This is reflected in the slightly greater accumulation of ice

Fig. 2. Channel geometry under low flow conditions of a cross section at the Hequ gauging station on the middle reach of the Yellow River on 16 June 1978, 30 May 1979, and 3 June 1980.

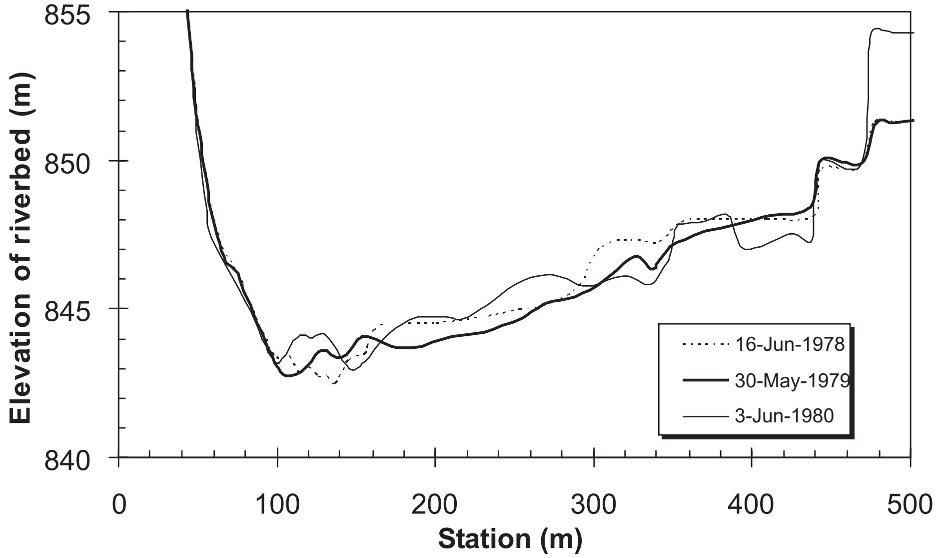
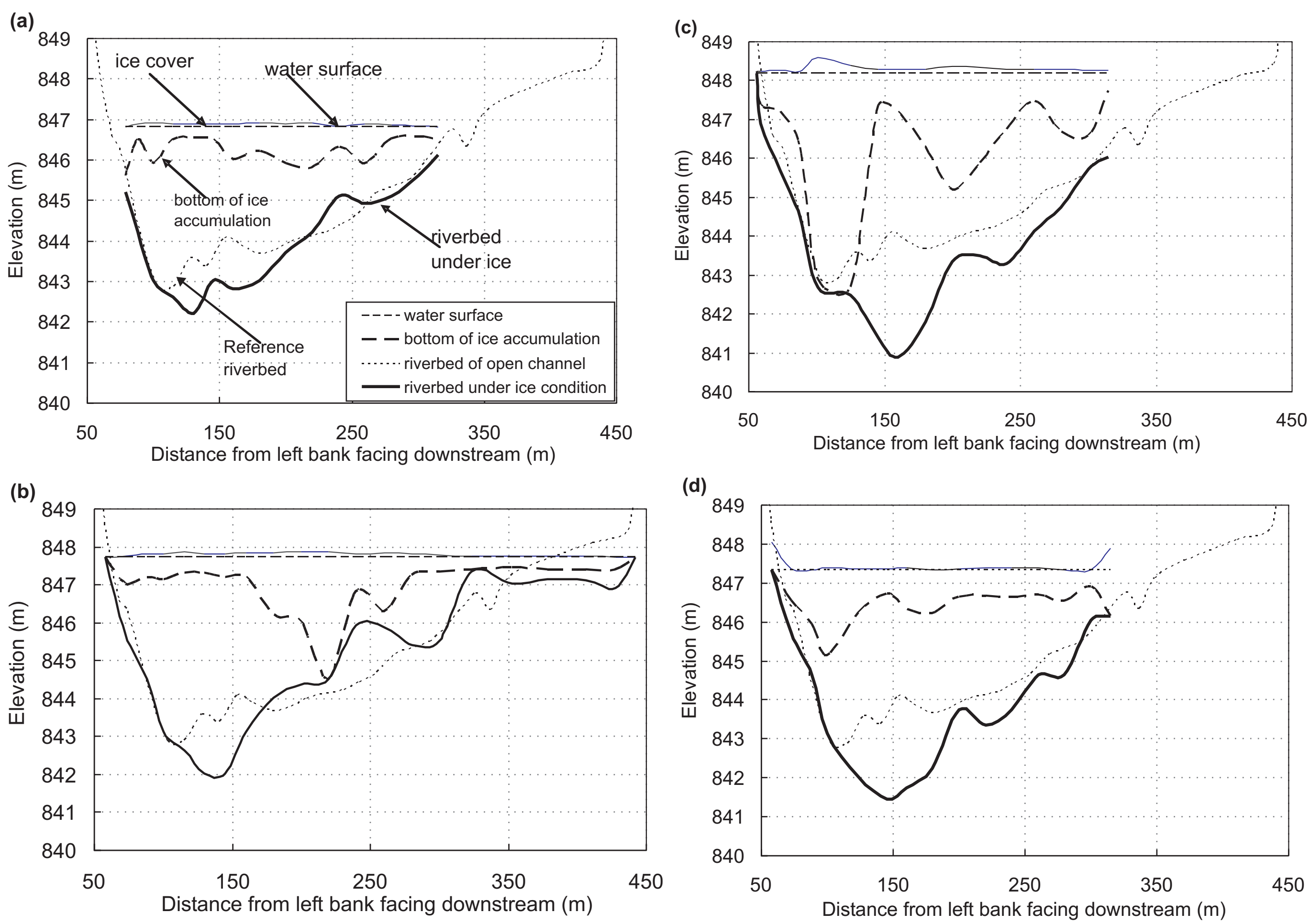


Fig. 3. Riverbed scouring under ice-covered conditions (Hequ gauging station, 1982–1983 ice season): (*a*) 23 December 1982; (*b*) 13 January 1983; (*c*) 18 February 1983; (*d*) 10 March 1983.



in December 1983 (Fig. 4*a*) as compared with that seen in December 1982 (Fig. 3*a*). Interestingly, the accumulation of ice decreased over the ensuing 2 weeks and, although the maximum scour did not increase, the channel enlarged slightly (Fig. 4*b*). Increased frazil ice accumulation near the middle of the channel extended to the bed by 8 February

Fig. 4. Riverbed scouring under ice-covered conditions (Hequ gauging station, 1983–1984 ice season): (*a*) 31 December 1983; (*b*) 14 January 1984; (*c*) 8 February 1984; (*d*) 12 March 1984.

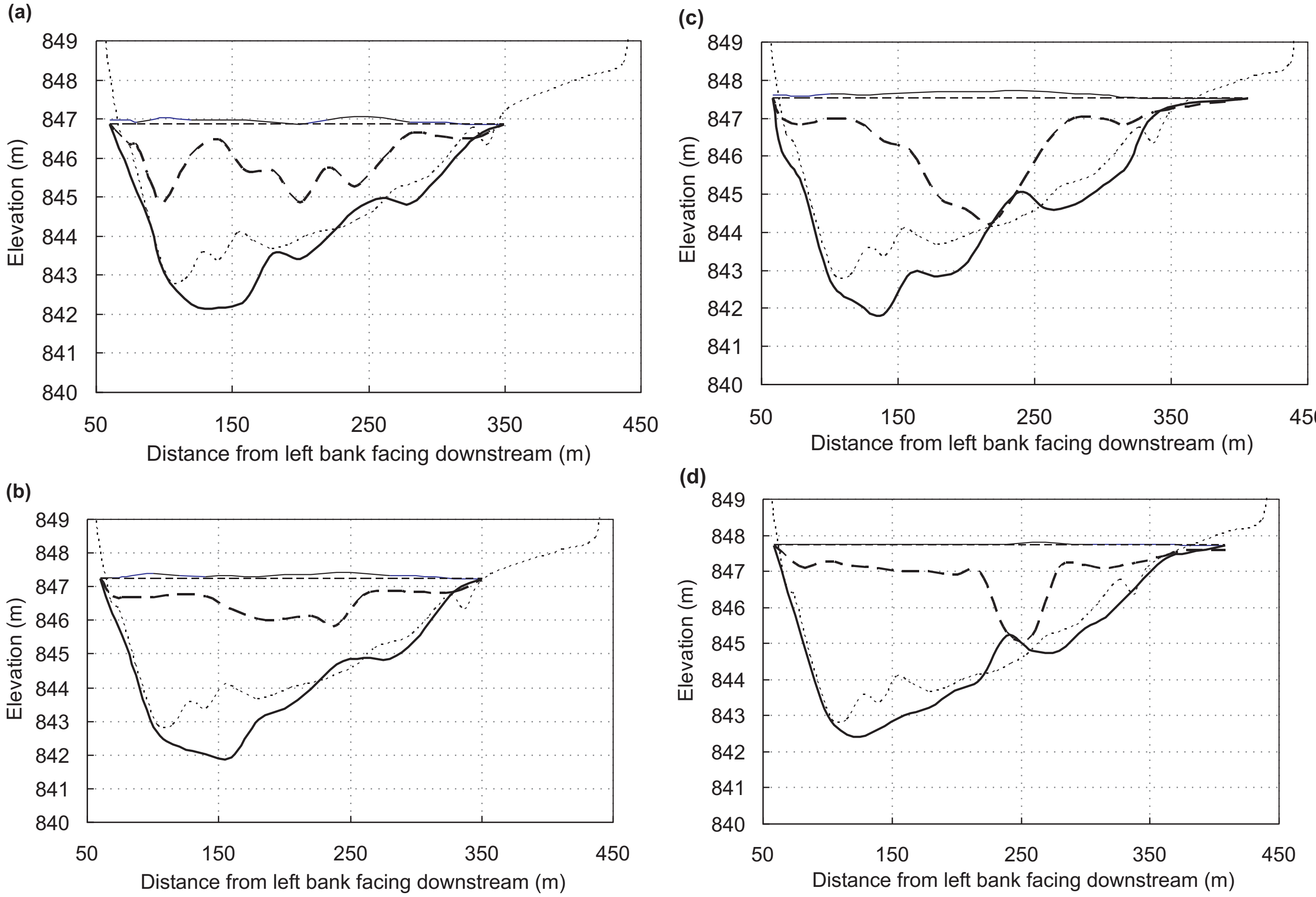
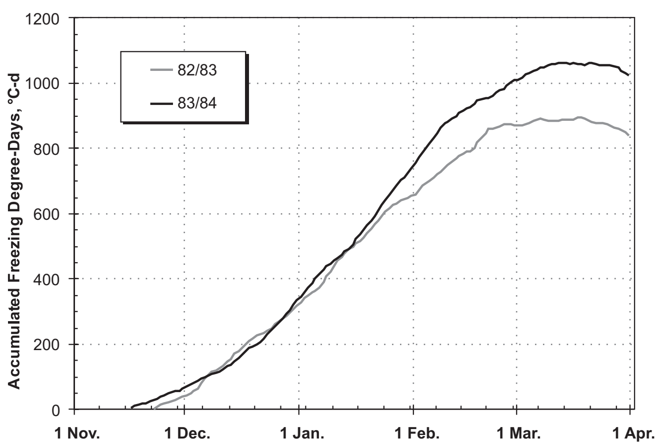


Fig. 5. Accumulated freezing degree-days measured during the 1982–1983 and 1983–1984 winter periods.



1984 (Fig. 4*c*), and there was a corresponding shift in the thalweg to the left bank as a result. The weather started to warm in early March 1984, and there was a reduction in the size of the ice accumulation by 12 March, although it still extended to the bed (Fig. 4*d*). There was a reduction in maximum scour of about 0.5 m over this same interval.

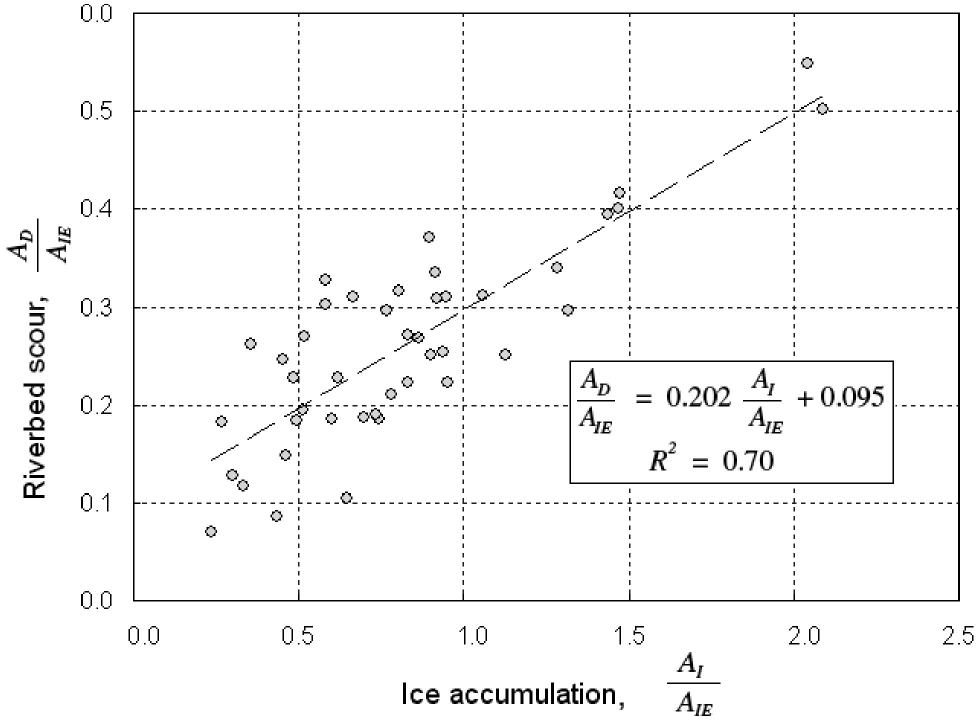
Overall, the data presented in Figs. 3 and 4 suggest that there was a substantial amount of frazil ice in transport, as the ice configuration changed dramatically from month to month, much more so than the bed shape. It appears that the accumulation of ice reduces the flow area and thus increases the velocity of flow, which in turn leads to increased bed scour.

4. Scour analysis

Ideally, it would be desirable to quantify the expected scour and deposition of the riverbed under ice-covered conditions. In this case, the scour and deposition of the riverbed would be expected to depend on hydraulic factors (such as flow velocity and channel geometry, including the extent of ice accumulation) and on the intrinsic properties of the bed material (such as the size, mass density, shape, and friction angle).

Unfortunately, it was not possible in this study to obtain data describing the nominal diameter of bed sediment particles or the flow velocity or shear flow velocity for incipient movement of the bed material. As a first step in investigating the potential influences of the hydraulic parameters, however, the potential relationship between the degree of bed scour and the accumulation of ice was investigated. Figure 6 presents the results for the Hequ gauging station for all 6 years of data (1982–1988). Based on these data, the scour of the riverbed at the Hequ gauging station cross section can be described by the following equation:

Fig. 6. Riverbed scour as a function of ice accumulation at the Hequ gauging station.



[1] $A_D/A_{IE} = 0.202A_I/A_{IE} + 0.095 \qquad R^2 = 0.70$

where A_D is the area of riverbed scour (m^2) referenced to the low flow cross section measured on 30 May 1979, A_{IE} is the cross-sectional area under the hanging dam (m^2), A_I is the cross-sectional area of the ice accumulation (m^2), and R is the correlation coefficient.

5. Summary

As evidenced by the scatter in the plot shown in Fig. 6, other important factors clearly play a role in determining riverbed deformation. The data presented in Figs. 3 and 4 clearly show that the degree of bed scour is affected by the distribution of the ice deposits within the cross section, and not simply by the total area of ice accumulation. Sediment parameters and ice properties must also play a role. Hydraulic parameters also have a significant effect on the transport and deposition of the frazil ice. Lastly, this investigation considered only a single river cross section. Data over the entire reach encompassing the hanging ice dam would also be useful in developing a more sophisticated relationship.

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