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# Sediment Transport under Ice Conditions

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## 1. Introduction

Every winter, a vast majority of rivers in cold regions undergo freeze up and subsequent ice jam events. Historically, ice jamming on rivers has led to extensive flooding and damage of property. As humans tend to settle near rivers, the impact of river ice and transport of sediment under river ice is an important phenomenon in engineering design and construction. River ice can easily build up around bridge abutments and piers, impacting not only the structure itself but also the local river bed morphology. In the past 30 years much research has led to increased knowledge of ice jams and associated river hydraulics. Studies have documented changes in break up timing during spring (Prowse & Bonsal, 2004), characteristics of ice jam release surges (Jasek, 2003; Beltaos & Burrell, 2005) and the impacts of climate variability on ice jam events (Beltaos, 2002; Prowse & Conly, 1998; Prowse & Beltaos, 2002).

The confluence of rivers is a location where ice jams often form. Shallow mixing layers are generally found at river confluences. Large-scale structures are found in these flows and should play a significant role in the transverse exchange of mass and momentum. The merging of ice runs, differences in hydrodynamic pressure between channels, ice congestion at a confluence bar, and riverbed deformation should be responsible for the evolution of ice jams at river confluences. A number of studies have documented the occurrence of ice jams at river confluences: Andres (1997) reported flooding caused by an ice jam at a river confluence in Prince George, Canada; Wuebben and Gagnon (1996) described the formation of an ice jam near the confluence of the Missouri and Yellowstone Rivers in Montana; Jasek (1997) presented a case study of an ice jam formed at the confluence of the Porcupine and Bluefish Rivers in Yukon; Andres & Doyle (1984) and Prowse (1986) gave descriptions of ice jams at the confluences of the Clearwater and Athabasca Rivers and the Liard and Mackenzie Rivers, respectively; Ettema et al. (1999, 2001) conducted experimental studies regarding ice processes at river confluences.

In general, very few records can be found detailing ice jam events supported by field measurements. Sediment transport under ice cover and characteristics of ice jam events present obstacles for field examination. Access issues and safety concerns often make it difficult for ice jams to be properly documented. In addition, sediment recording equipment in rivers can often be washed out and destroyed during winter freeze up. If ice jams do not incur damage or flooding, ice events and subsequent under ice sediment transport are often not sufficiently examined or measured.

The purpose of this chapter is to examine sediment transport under ice cover. In order to bring attention to the importance of the matter, this chapter will begin with a brief account of ice related disasters. Next will be review of sediment transport characteristics under open channel and ice cover conditions. The incipient motion of frazil ice and sediment under ice cover will be discussed. Lastly, two case studies will be reviewed: riverbed deformation of the Hequ Reach of the Yellow River in China and the Nechako River in Canada will be examined.

## 2. Historical ice related disasters

River ice build-up and subsequent ice jams have caused bridge failure, flooding of land and damage to property. Since man has been constructing bridges and crossing structures over river channels, there have been a number of accidents involving ice build up, ice jams and sediment scour. Between 1989 and 2000 there were over 500 bridge collapses in the United States alone (Wardhana & Hadipriono, 2003). River bed scour was responsible for 165 of the failures and ice was the cause of 10 of the collapses (Wardhana & Hadipriono, 2003). In April of 1987, the Schoharie Creek Bridge in New York collapsed due to sediment scour around the bridge pier (Hains & Zabilansky, 2007). During the collapse 5 vehicles plunged into the river, killing 10 people.

Over time, bridge structures can become unstable due annual ice jams and sediment scour. A bridge over the White River in Vermont experienced a number of ice jam breakups over several years; in the winter of 1990 the White River Bridge failed. Examination into the failure revealed that the bridge foundation gradually became deteriorated due riverbed scour around the piers (Zabilansky, 1996). Eastern Canada has also experienced numerous structure failures due to ice jams and sediment transport. An ice jam flood during 1987 in New Brunswick caused river levels to rise in the Perth-Andover region. Ice build up along the bottom structures of a railroad bridge eventually caused the bridge to fail, taking with it rail cars (Beltaos & Burrel, 2002). As early as 1902, New Brunswick records indicate that ice jam flooding caused the Nashwaak River to rise, resulting in severe damage and flooding to the area. When the Nashwaak ice jam released, the flow of ice was so powerful it destroyed a 53 meter long bridge (Beltaos & Burrel, 2005). While research has focused on river ice processes and sediment scour, there still remain gaps in our knowledge about sediment transport processes due to the difficulty in studying ice jams and their impact on the river bed.

## 3. Flow hydraulics of open channel and ice covered conditions

Sediment transport processes and riverbed deformation is different under ice covered conditions in comparison to open channel conditions. Open channel flow conditions have been widely examined; one of the most popular equations governing open channel flow is the Manning equation,

$$V = \frac{R^{2/3} S^{1/2}}{n} \quad (1)$$

where $V$ is the fluid velocity, $R$ is the channel hydraulic radius, $S$ is the hydraulic gradient and $n$ is the roughness coefficient. The roughness coefficient represents the resistance the bed material exerts on the water flow. Many studies have explored Manning's roughness coefficient in relation to bed material size and configuration and developed sets of resistance values (Fasken, 1963; Limerinos, 1970). Generally, the larger and more angular the riverbed material, the greater the resistance coefficient.

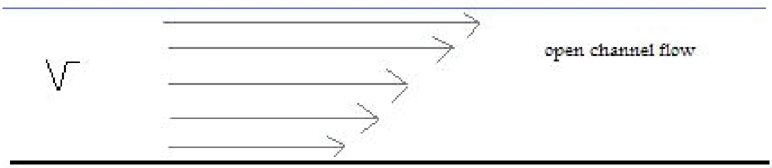


Fig. 1. Velocity profile of river under open channel flow.

For open channel flow, the flow velocity is highest near the water surface and lowest near the channel bed. The drag forces exerted on water near the river bed generally account for the decrease in flow velocity. River ice cover imposes an extra boundary on flow, altering the flow velocity and water level in comparison to open channel flow (Shen and Wang, 1995). For ice cover conditions, the portion of upper flow is mainly influenced by the ice cover resistance while the lower flow is mainly influenced by the channel bed resistance (Sui et al., 2010). The maximum flow is located between the channel bed and ice cover depending on the relative magnitudes of the ice and bed resistance coefficients. Generally, the maximum flow velocity is close to the surface with the smallest resistance coefficient. In the case of narrow river channels or near river banks, the maximum flow velocity will not occur at the surface but rather slightly below the surface due to the resistance forces of the side banks (Wang et al., 2008). The velocity profile under ice conditions also depends on the relative roughness of the ice. Wang et al., (2008) examined the location of the maximum velocity under rough ice cover, smooth ice cover and open channel flow (Figure 2). As the ice resistance increases (from smooth ice to rough ice cover), the maximum flow velocity moves closer to the channel bed.

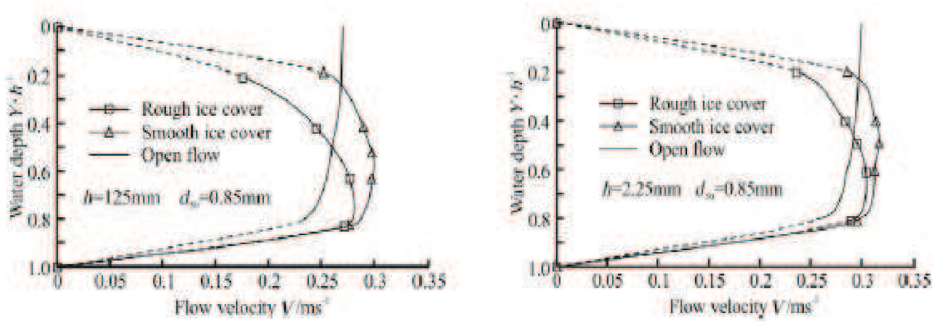


Fig. 2. Velocity profiles under ice cover with difference resistance coefficients (from Wang et al., 2008).

### 3.1 Incipient motion of frazil ice

Frazil is randomly oriented ice crystals that form in turbulent, supercooled water. Supercooling of river water occurs when cold air temperatures persist and cause river water to rapidly decrease in temperature below its freezing point of zero degrees Celsius. If the decrease in temperature happens very quickly crystal nucleation can be avoided; water can be well below its freezing point without being in solid phase (forming ice). The occurrence of supercooled water is important for the development of frazil ice. Frazil ice formation occurs when turbulent flow causes supercooled river water to mix throughout the entire channel depth. The mixing of supercooled water throughout the channel depth encourages the formation of small ice crystals. Through the process of secondary nucleation, more ice crystals form and continue to grow. These growing ice crystals are termed frazil ice. Frazil ice crystals will then begin to adhere to sediments in the water and continue to grow.

The conditions for incipient motion of sediment was first introduced by Shields in 1935 and is generally studied through examining the shear stress as given by,

$$\tau_* = \frac{\rho u_{*c}^2}{g \Delta \rho d_e} \tag{1}$$

Where $\tau_*$ is the shear stress, $\rho$ is the mass density of water, $u^2_{*C}$ is the critical bed shear velocity, $g$ is the gravitational acceleration, $\Delta\rho$ is the difference in the mass density of the studied sediment and water and $d_e$ is the grain size of the sediment particle.

The conditions required for incipient motion of sediment are normally compared with the critical shear stress of the river bed. In order for a river to begin to transport sediment resting on the riverbed, the bed shear stress must be greater than the critical shear stress. The Reynolds number characterises the ratio of viscous to inertial forces for a given flow condition. The shear Reynolds number ($R_{e*}$), is used to study the initial motion of sediment particles,

$$\mathrm{R_e} = \frac{U *_c d_S}{\nu} \tag{2}$$

where $u_{*C}$ is the critical bed shear velocity, $d_s$ is the sediment grain size and $v$ is the kinetic viscosity of the fluid. Water flowing under ice can exert forces that will entrain or move sediment or ice particles that are located under the ice cover. The forces that act against the flowing water depend on the particle grain size and particle size gradation. As shown in Figure 3, there are 3 main forces that act upon a non-cohesive frazil particle.

$F_B$ is the buoyancy force of the submerged frazil particles, $F_L$ is the hydrodynamic force acting downward perpendicular to the ice cover and $F_D$ is the drag force parallel to the ice cover. In order for incipient motion to occur the drag force should be equal to the resistance force (Sui et al., 2010). When a frazil particle is just about to move, the resultant of the drag and resistant forces is along the direction of the friction angle as given by,

$$tan\theta = \frac{F_D - F_B\ sin\theta}{F_B\ cos\theta} \tag{3}$$

When a frazil particle is about to move, it will lose contact with the frazil particle just above it. The buoyancy force, $F_B$, can be defined as the following,

$$F_B = C_1 g(p - p_1) d_i^3 \tag{4}$$

where g is gravitational acceleration, $p$ and $p_i$ is mass density of water and frazil particles, $d_i$ is the median grain size of frazil particles and $C_1 d_i^3$ is the volume of the frazil particle. The drag force, $F_D$, is defined as follows,

$$F_D = C_2 \tau_c d_i^2 \tag{5}$$

where $C_2$ is the particle area coefficient, $\tau_c$ is the critical shear stress for incipient motion of a frazil particle and $C_2 d_i^2$ is the effective area of contact between a studied frazil particles and other particles. By replacing $F_B$ and $F_D$ in Eq. 3 by their above expressions, the critical shear stress for incipient motion of frazil ice particles can be given by,

$$\tau_{cs} = \frac{c_1}{c_2} g \Delta\rho_s d_s cos\theta \left( tan\theta_s - tan\theta \right) \tag{6}$$

As examined by Sui et al., (2010) the required shear stress for incipient motion of frazil particles is larger than the shear stress required for incipient motion of sediment particles. Also, the shear stress required for incipient motion of frazil particles is larger under smooth ice conditions in comparison to rough ice conditions (Sui et al., 2010). The authors also found that the coarser (or larger) the frazil particle, the larger the shear stress required for incipient motion of frazil ice.

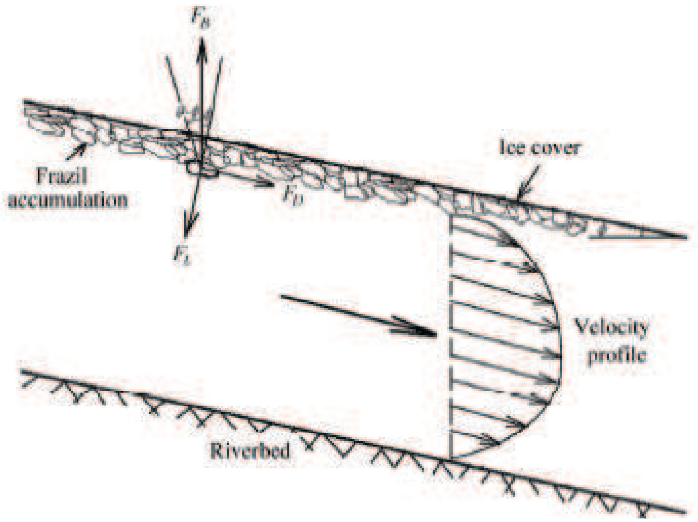


Fig. 3. Forces acting on frazil ice under a sloping ice cover (from Sui et al., 2010)

### 3.2 Incipient motion of sediment under ice cover

As discussed, the conditions required for incipient motion of sediment are normally compared with the critical shear stress of the river bed. Since ice cover imposes an added boundary on flow conditions, the incipient motion of sediment under ice cover is different than for open channel flow. Wang et al. (2008) conducted a number of clear water flume experiments examining the relationship between incipient motion of bed material and ice cover conditions. Since near-bed velocity is higher under ice covered conditions, a higher shear stress is exerted on the river bed under ice covered conditions (Wang et al., 2008). The threshold velocity for the incipient motion of sediment under ice cover decreases as the ice cover resistance increases. This is due to the increased kinetic energy exerted on the bed material as the near-bed velocity increases. The flow velocity required for initial movement of bed material under ice cover also increases with water depth (Wang et al., 2008). This relationship is only valid if the resistance coefficients of the ice cover and channel bed remain constant. It was also found that the larger the bed material the greater the velocity required for incipient motion (Figure 4).

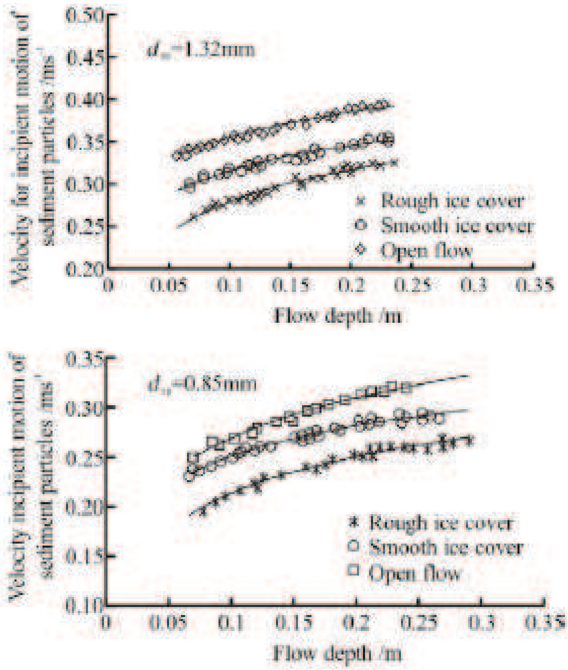


Fig. 4. The relationship between velocity and flow depth and grain size for incipient motion (from Wang et al. 2008).

The Froude number is used to determine the resistance of an object flowing through water. The ability of an object to move through water will depend on its size (object length and area) as well as the relative velocity of water. The greater the Froude number, the greater the resistance exerted on water flow by the river bed material. The incipient motion of sediment depends not only on hydraulic variables but also on the characteristics of the bed material itself. The densimetric Froude number is given by,

$$F_0 = \frac{v_i}{\sqrt{\dfrac{g d_{50}(\rho_s - \rho)}{\rho}}} \tag{7}$$

where $d_{50}$ is the median grain size of the bed material. Generally, the larger the roughness coefficient for ice cover, the greater the near bed flow velocity. In this situation, the larger the roughness coefficient for ice cover, the smaller the densimetric Froude number for incipient motion of river bed material (Wang et al. 2008). Since the near bed velocity is relatively high, larger sediment particles can be moved. However, if the roughness coefficient of the river bed is high, the near bed velocity will decrease; this in turn will increase the densimetric Froude number required for incipient motion of bed material.
The shear velocity for near uniform flow, $U_*$, in Eq. 2 is given by the following equation,

$$U_* = \sqrt{gRS} \tag{8}$$

where $R$ is the hydraulic radius and $S$ is the hydraulic slope. When examining the incipient motion of sediment, the shear velocity is an important parameter in the Shields criterion as outlined in Eq. 1. The Shields criterion typically considers sediment to be uniform and therefore can be defined by one grain size value. In the real world, sediments are non-uniform. To account for this natural variability in sediment size, Wang et al. (2008) studied the Shields criterion under 3 different sediment types. The authors found that the larger the shear Reynolds number, the greater the shear stress for initial motion of river bed material.

## 4. Riverbed deformation under ice jam conditions

### 4.1 Hequ Reach, Yellow River, China

This section examines sediment transport and riverbed deformation in the Hequ Reach of the Yellow River in China, as outlined by Sui et al. (2000, 2006). The Hequ Reach of the Yellow River is approximately 700 kilometres in length and has a broad and shallow morphology. The channel width of the middle reach varies between 400 and 1000 metres. Upstream of the Longkou Gorge (Figure 5) is a reach of open water with numerous localized rapids. During cold winter temperatures, frazil ice forms in the channel and can lead to the formation of large ice jams further downstream in the reach. During the years from 1982 to 1992 the river experienced a large number of ice jams; some lasting well over 100 days. In 1982, a frazil jam caused water levels to rise to extremely high levels, flooding the area and causing extensive damage.

Generally, characteristics of sediment transport during ice jam formation and ice jam breakup are poorly understood. During an ice jam breakup sediment transport can increase due to higher flow velocities, increased river bank erosion and high water levels (Prowse, 1993; Beltaos, 1998).

During an ice jam event, sediment can be transported in water and ice moving down the river channel. Sediment can become attached to frazil ice if supercooled water is moved through the water column to the river bed. Through ice nucleation occurring at the river bed ice can attach to bed sediments and form anchor ice. Anchor ice can form around very large or small particles. Heat transfer from turbulent water can eventually weaken the bond anchor ice forms with the bottom of the river bed causing it to become buoyant. During frazil jam events in the Hequ Reach, pebbles ranging in size from 0.2 to 0.5 kilograms have been observed in ice cover. The largest recorded sediment concentration in frazil ice in the Hequ Reach was 25 kilograms per metre cubed of ice; this is a much larger sediment concentration than what has been recorded in water flowing under the ice (7 kilograms per cubic metre of water).

During an ice jam event from December 1986 to March 1987 Sui et al. (2000) examined riverbed deformation at a cross section in the Hequ Reach. As shown in Figure 6, over the period of approximately 3 months, the river width expanded and sediment scour expanded the deepest parts of the river channel. The following sediment transport and riverbed deformation processes were observed during frazil ice jams in the Hequ Reach:

a. once frazil ice is formed in the upstream river reach, it is moved underneath the ice in the jam head area. This process causes frazil ice to accumulate under the head region of an ice jam, and leads to a reduced cross section. As a result, the head of the ice jam becomes thicker, water levels rise and increased scouring occurs.
b. since the cross sectional area at the ice jam head is decreased, local flow velocities are increased. Increased flow velocities move frazil ice accumulated in the ice jam head

region to the toe. The ice jam toe region then becomes thicker, the river cross section in the toe location decreases, water levels rise and riverbed scour increases.

c. the latter processes will continue as the air temperature drop. Once the air temperature begins to warm, frazil ice development will decrease. Any frazil ice will be transported to the ice jam toe and deposited.

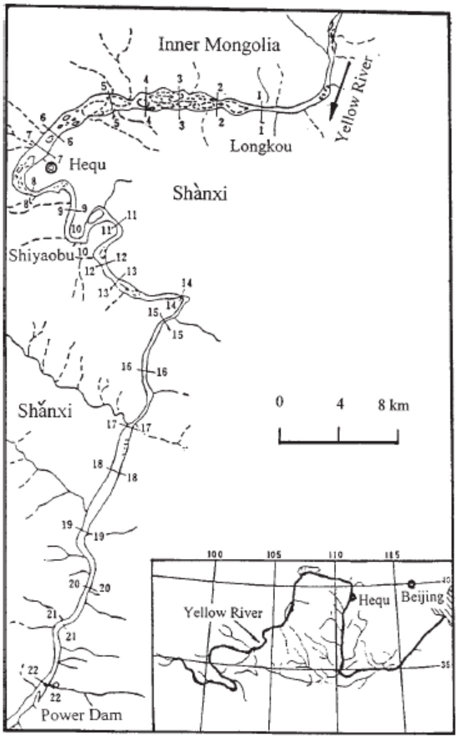


Fig. 5. Hequ Reach of the Yellow River, China.

Based upon extensive field observations of ice jam formation and frazil ice transport, Sui et al., (2000) proposed that frazil ice formation and riverbed deformation reinforce each other. The authors found:

a. as an ice jam grows, the riverbed will be scoured. Once an ice jam begins to decrease and diminish, the riverbed material will undergo deposition. During the entire life of an ice jam, patterns of scour and deposition will be repeated.
b. river flow during an ice jam becomes covered flow. The decrease in river cross section causes river flow to take a path of least energy consumption. As a result, the riverbed will become deformed.

Generally, as indicated by the study of sediment transport under ice for the Hequ Reach, it can be concluded that the larger the flow velocity under an ice cover, the larger the sediment concentration. Also, the sediment concentration during stable jamming period is smaller than the sediment concentration during ice jam breakup period. During a frazil jam it is important to note that sediment can not only be transported through suspension in current, but also through attachment to frazil ice.

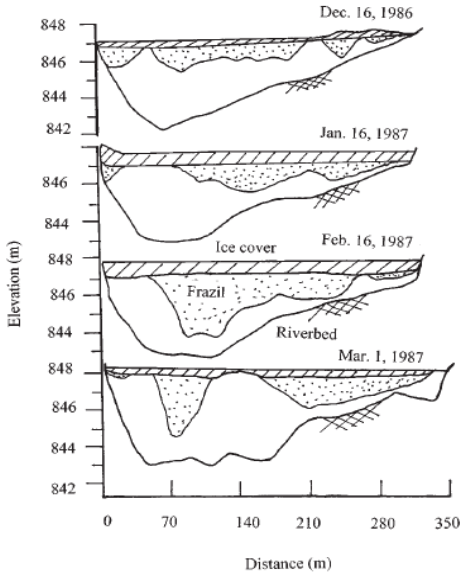


Fig. 6. Changes incurred at cross section of Hequ reach of Yellow River during ice jam period (from Sui et al., 2000).

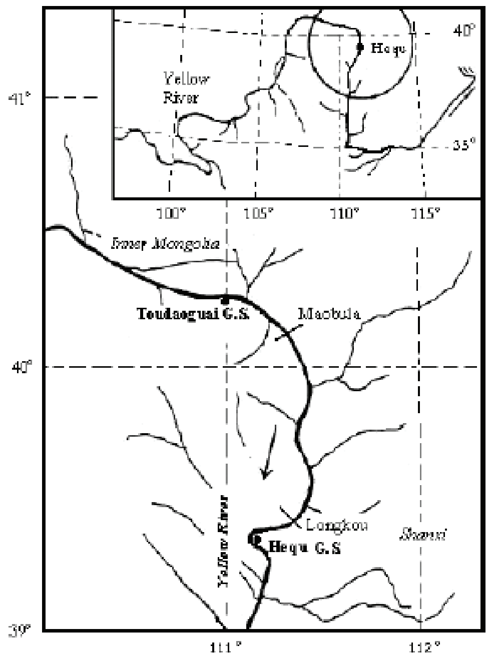


Fig. 7. Location of Hequ gauging station and depiction of river reach between Maobula and Longkou.

Frazil ice transport can also facilitate the formation of a hanging dam. Frazil ice is carried in suspension until it joins the head of an ice jam or gets carried underneath the ice cover. Frazil ice transported underneath the ice cover will become attached to the underside of ice at such a point in which the flow velocity cannot facilitate further transport. Hanging dams are often formed around the Hequ gauging station (Figure 7). The river channel between Maobula and Longkou (Figure 7) has a relatively steep slope, 1.17 percent, exhibits high flow velocity and generally remains clear of ice during the winter season. This relatively straight and open river reach is an area of frazil ice production during the winter season. Due to the river bend that occurs at the Hequ gauging station a river ice cover will often form. Frazil ice from the upstream open water reach will become entrapped on the underside of the ice cover at the Hequ gauging station and form a hanging dam.

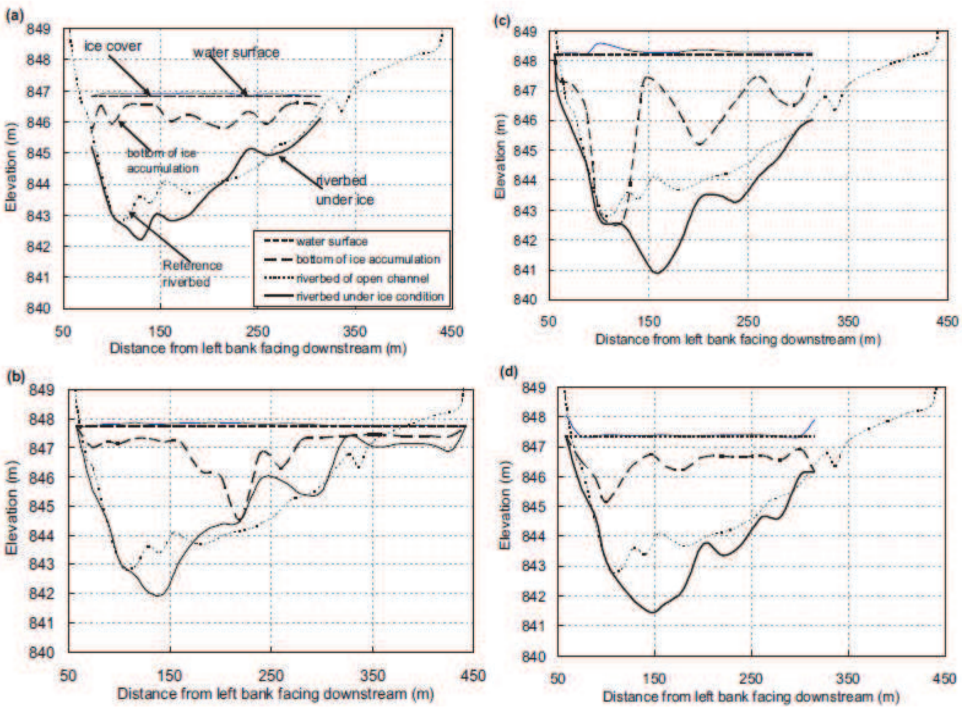


Fig. 8. Riverbed scour under ice cover conditions during the 1982 to 1983 ice jam season (from Sui et al. 2006).

During stable jamming periods in 1982-83 a number of cross sections on the Hequ gauging station were examined (Figure 8). As illustrated in Figure 8, the ice accumulation in the water profile is in the form of a hanging dam. The hanging dam formation and subsequent growth is responsible for the deformation of the river bed. As ice accumulation increases so does the amount of riverbed scour. In Figure 8a, the river had just undergone freeze up in January, a small amount of ice had accumulated, and the riverbed had been scoured by approximately a depth of 0.5 metres. Over the course of the next month, frazil ice continued to accumulate at the Hequ gauging station and a large ice dam was formed (Figure 8b, 8c). By the middle of February (Fig. 8c) the riverbed had been scoured by 2 meters. By around mid

March, temperature began to warm and frazil ice accumulation decreased. Ice accumulation at the Hequ gauging station decreased and sediment deposition occurred (Figure 8d).
Generally, as shown by the cross sections at the Hequ gauging station, the increase in ice accumulation in the form of a hanging dam, decreases the river cross section. The reduction in flow area will increase the velocity of the river flow and causes increased scouring of the riverbed. By examining riverbed scour depth as it relates to ice accumulation, Sui et al. (2006) developed the following equation,

$$\frac{A_D}{A_{IE}} = 0.202\frac{A_I}{A_{IE}} + 0.095 \quad (9)$$

where $A_D$ is the area of riverved scour in metres squared, $A_{IE}$ is the cross sectional area under the hanging dam, $A_I$ is the cross sectional area of the ice accumulation.

### 4.2 Nechako River, Canada

The next section is an examination of riverbed deformation at a river confluence in Prince George, Canada. The Nechako River in central British Columbia (BC), Canada, experienced a severe ice jam event that caused flooding and damage during the winter of 2007/2008. Ice jams have been documented for the past 100 years at the confluence of the Nechako and Fraser Rivers. During 1979 and 2008, cross section surveys along the Nechako River were completed (Figure 9). The Nechako River morphology in the 2 kilometre reach, close to the confluence has significantly changed. Here the Nechako River is more unstable. As the Nechako River approaches the confluence, the channel also becomes wider and the flow velocity decreases. As a result of a decrease in flow velocity, sediment deposition in the form of point bars and mid channel islands have evolved near the confluence. It is evident by examining the cross sections that sediment transport has been responsible for the change in channel morphology near the confluence.

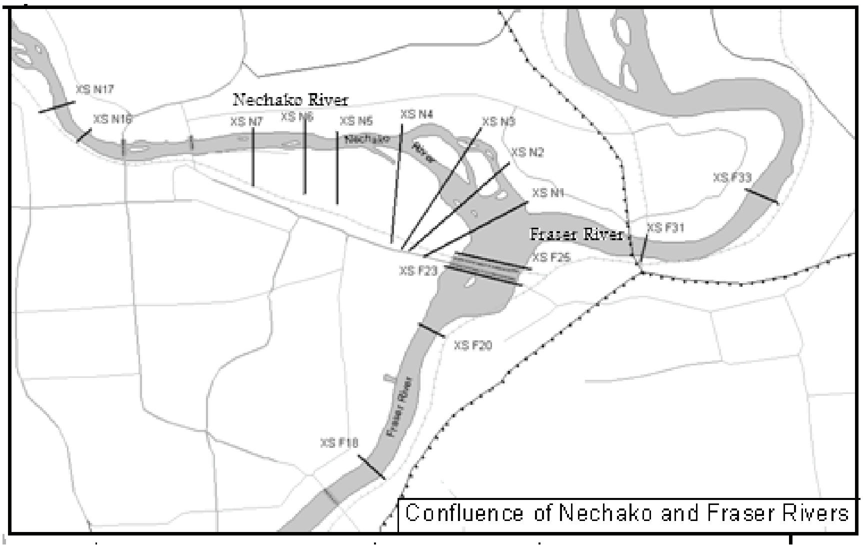


Fig. 9. Confluence of the Nechako River and Fraser River, Prince George, Canada.

The decrease in flow velocity and increase in sediment deposition at the confluence is reinforced by the Nechako River gradient (average bed elevation) as shown in Figure 10. The channel slope close to the river confluence decreases as the channel becomes flat. In addition, since the Nechako River is a secondary branch river of the Fraser River, flow current from the Fraser River may impede the flow out of the Nechako River resulting in backwater effects to the Nechako River. This phenomenon will clearly cause a decrease in flow velocity near river confluence in the Nechako River. When flow velocity or flow Froude Number is low enough (Sui et al, 2005), an ice cover near river confluence will be result.

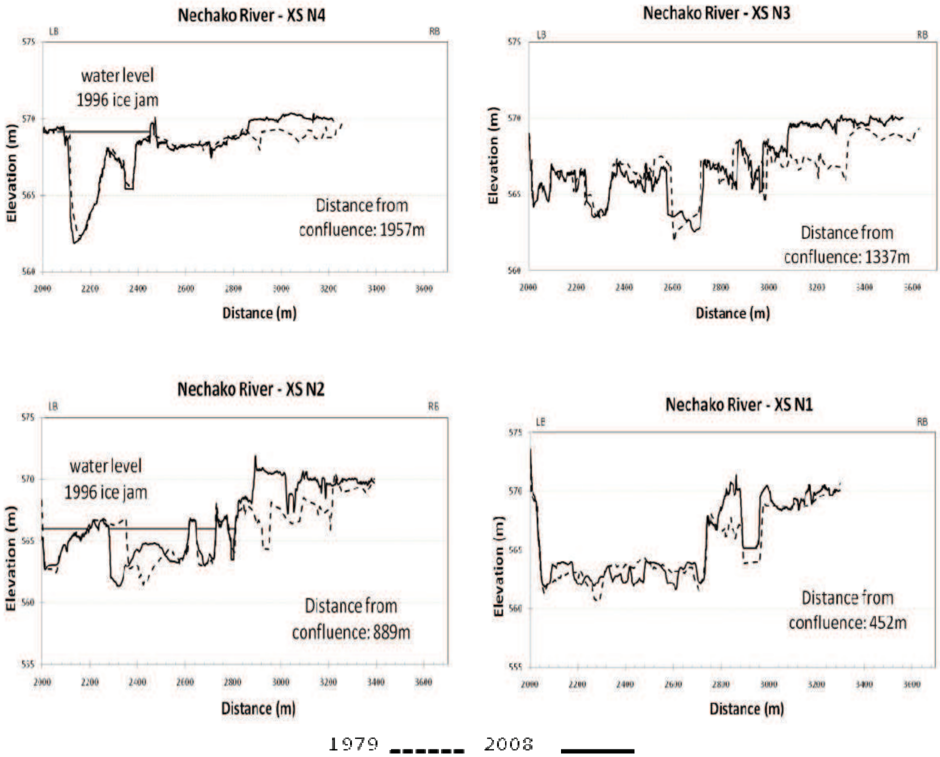


Fig. 10. Comparison of Nechako River cross sections near the river confluence for the 1996 and 2008 ice jams.

With the replenishment of frazil from the upstream river reach in midwinter, frazil ice will accumulate under ice cover initiated near the river confluence. Thus, the thickness of the ice jam will grow during winter period. This increased 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 periods, causing the jam to grow and water level to increase.

## 5. Conclusion

This chapter examines characteristics of sediment transport and riverbed deformation under ice cover. Historically, ice jams have led to bridge collapse, flooding and damage to property. It is important to understand ice jam characteristics and subsequent sediment transport processes that occur simultaneously. Sediment transport under ice cover is different than that of open channel flow. For open channel flow the maximum flow velocity will occur at the water surface. The maximum flow velocity under ice cover depends on the roughness coefficients of the ice cover and the bed material. The location of maximum flow velocity will be closer to the surface with the smallest resistance coefficient.

Due to the boundary conditions imposed by river ice, ice jams can significantly deform a river bed as compared to deformation observed under open flow conditions (Shen and Wang, 1995; Sui et al, 2000). The presence of ice cover reduces the river channel cross section which will in turn increase the river flow velocity. Larger flow velocity will have greater kinetic energy and cause increased sediment transport and riverbed scour. Generally, as an ice jam continues to grow and develop, more scouring of the river bed occurs. Frazil ice development and the formation of hanging dams have a direct relationship with riverbed deformation; the larger the ice accumulation and hanging dam, the larger the depth of sediment scour. As temperatures warm and existing sediment entrapped in frazil ice is transported downstream until such time that jamming diminishes and the sediment is deposited. As presented in the examination of the Hequ River and Nechako River ice jam history, a riverbed can undergo significant changes to morphology as a result of sediment scour as it occurs under ice cover.

## 6. Acknowledgements

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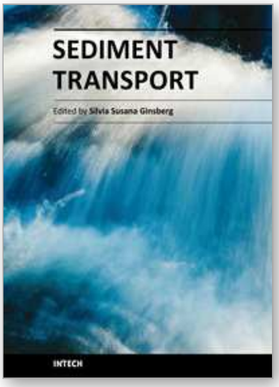


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Sediment transport is a book that covers a wide variety of subject matters. It combines the personal and professional experience of the authors on solid particles transport and related problems, whose expertise is focused in aqueous systems and in laboratory flumes. This includes a series of chapters on hydrodynamics and their relationship with sediment transport and morphological development. The different contributions deal with issues such as the sediment transport modeling; sediment dynamics in stream confluence or river diversion, in meandering channels, at interconnected tidal channels system; changes in sediment transport under fine materials, cohesive materials and ice cover; environmental remediation of contaminated fine sediments. This is an invaluable interdisciplinary textbook and an important contribution to the sediment transport field. I strongly recommend this textbook to those in charge of conducting research on engineering issues or wishing to deal with equally important scientific problems.