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The nature and structure of a hanging dam in a gravel-bed river

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Abstract

The town of St. Raymond (QC, Canada) is subject to frequent ice-induced flooding of the St. Anne River. In addition to breakup ice jams, a major cause of winter flooding is associated with massive frazil deposition in the form of a hanging dam in the downtown reach of the river. Recent studies have identified a number of potential solutions to attenuate the flood risk. An important aspect of these solutions is associated with the reduction of frazil deposition, which amount had not been estimated before. The purpose of this study was to answer this need by quantifying the hanging dam's dimensions (volume and mass) and structure.

The 2014-2015 frazil dam's length was 9.5 km, its volume was 620 000 m^3 and its mass was 440 000 tons. Most of the hanging dam mass (74%) originated from the upstream part of the St. Anne River, where frazil transport in the water column was measured by manual sampling. In turn, most of the frazil was deposited in the downtown reach because of low velocities caused by the presence of the Chute-Panet dam located 3 km downstream of the town. The hanging dam core was also surveyed at multiple cross-sections. It presented frazil layers and accumulation zones of different densities. The hanging dam structure presented a greater complexity in town and was simpler near its head and its toe.

1. Introduction

The town of St. Raymond (QC, Canada) has been repeatedly subject to flooding of the St. Anne River since the first reported incident in 1893. According to Leclerc (1966), about 40 % of these floods are caused by some form of ice. Since the end of the 19^{th} century, several engineering structures have been constructed and various channel modifications have been made in order to attenuate flood risks, but their (independent or global) efficiency is difficult to assess. Also, most interventions have been made in a context of poor or partial understanding of the ice regime of the river. One example is the ice control structure (ICS, known as the *Barrage Estacade*) that has only sporadically controlled downstream ice conditions since its completion in 1976. Another example is the dyke that has been built along the banks in 2009 at an elevation of about 0.5 m above the 100-year open water flood level. This dike was overtopped in 2012 and 2014 in breakup ice jam conditions. Prior to this, another major ice flooding event, this one caused by frazil rather than by a broken ice cover, had occurred in 2003. Frazil had also caused flooding that lasted many weeks in January 2005 while the river discharge was small. It seems that frazil accumulates in the form of a large, grounded, hanging dam in the downtown reach every year.

The St. Anne is a gravel-bed river flowing south-westward from the Laurentians to the St. Lawrence River. Upstream of St. Raymond, the river channel is highly turbulent and is formed by several kilometers of riffle-pools and rapids. This is where most of the frazil is generated. The St. Raymond reach has a catchment area of about 750 km^2 and its gradient is very low. At the beginning of winter an ice cover quickly forms by frazil interception over this 6.2 km-long reach limited downstream by a dam (*Chute-Panet* dam) and upstream by the ICS. Once the ice cover is formed, frazil begins to accumulate under the ice cover, downstream of the ICS, in the downtown reach. The massive frazil accumulation can be locally several meters thick within a few days. An upstream part of the hanging dam can extend several kilometres upstream of the ICS once its 3 m-high weir gets submerged from downstream by the downtown section of the hanging dam.

Before adequate ice-induced flooding mitigation measures were recommended (Turcotte and Morse, 2015), the objective of this study was to quantify frazil in the St. Anne River. An intensive field campaign was conducted during the winter of 2014-2015 to investigate the amount of frazil flowing to the downtown reach and to determine the dimensions (mass and volume) and structure of the hanging dam.

2. Background

Frazil deposition under an ice cover forms a “hanging dam” when the size of the deposition is such that it obstructs the flow. This excessive accumulation process occurs when an important source of frazil generation is present, for instance when a river section remains open and exposed to cold air during a prolonged period of time due to the presence of rapids (Beltaos, 2013). Hanging dams can grow to tremendous dimensions: Beltaos and Dean (1981) reported a 300 m-long and 13 m-thick hanging dam in the Smoky river; Gold and Williams (1963) reported a 1200 m-long and 10 m-thick hanging dam in the Ottawa River; and Michel and Drouin (1975) measured a longitudinal dimension of 16 km for a hanging dam with a thickness greater than 10 m in the La Grande River (see Figure 3.8b, Beltaos, 1995).

The deposition mechanism under the ice cover can be considered as analogous to sediment deposition, but triggered by buoyancy forces instead of sinking forces (Shen and Wang, 1995). However, sedimentation morphologies such as dunes, antidunes and ripples have not been found in this inverse sedimentation case (Daly, 1994). Beltaos and Dean (1981) measured some material properties in the hanging dam of the gravel-bed Smoky River, such as shear strength, density and porosity. They constructed an empirical relationship between shear strength and density, which both increased with height above the bottom. The measured dry densities varied between 450 and 600 kg/m^3 for this hanging dam. In the gravel-bed Tanana River in Alaska, White and Lawson (1992) observed a frazil deposition in homogeneous, isotropic layers, suggesting that deposition occurred in horizontal layers during discrete events. Horizontal layers varied in thickness between 1 cm and 1.5 m. They determined the intrinsic permeability of the frazil deposition by use of the borehole dilution method, which revealed that this property was highly variable over short distances.

Despite these hanging dam investigations with respect to deposition properties, and a few records of hanging dam dimensions, a case study investigating the complete mass, volume and three-dimensional structure of a hanging dam is, to our knowledge, new in the literature.

3. Field campaign

Study area. Study sites extended from the Chute-Panet dam (km 0.0) up to the downtown area (km 4.5 to km 6.1) and then up to the Tourrilli River Bridge (km 32.4). The river width varies between 40 and 70 m, and the downtown winter discharge normally declines from 20 to 8 m^3/s. Figure 1 to 3 present an overview of the hanging dam location with some landmarks along the river. Between the Chute-Panet dam and the downtown reach (km 4.5) lies a reservoir. This latter reach extends to km 6.1 and presents small riffles and a slope of 0.06 %. Upstream of the ICS location (km 6.1), sequences of riffles and pools extend to km 13.6 with a slope of 0.2 %. From km 13.6 to km 22.5, the river remains ice-free during a prolonged period at the beginning of winter due to the presence of rapids (0.6% slope), forming an extensive frazil production zone. Upstream of km 22.5, the river flattens out (0.2%) and the morphology becomes dominated by riffles and pools with few rapids that also remain ice-free during several cold days. The delay between the development of a complete ice cover in the downtown reach and in the rapids was approximately 40 days in 2014-2015. During this period, frazil slush accumulated in dynamic and passive modes between km 2.2 and 11.7, forming a continuous frazil jam and hanging dam of 9.5 km-long.

Quantification of frazil transport. To quantify the total amount of frazil transported by the St. Anne River, the frazil transport intensity was measured in the rapids at km 15.3 using a manual sampler. The sampler consisted of a pole with three circular rings of 10 cm diameter, spaced by 15 cm. A one leg nylon stocking was fixed over each ring (Figure 4). The sampler was submerged in the river during a measured time interval, usually until the stocking visually began to fill (about 1 minute), after which the mass of its frazil content was measured with a balance. After each measurement, new nylon stockings were used. The dimensions (length and diameter) of the frazil filled nylon stockings were also measured, in order to determine the volume and the porosity of the frazil accumulations. Porosity values were used to verify the accuracy of frazil mass measurements.

A typical day in the field proceeded as follows. Waders, headlamps, watertight gloves, a chronometer, a measuring tape, a balance and the frazil sampler were brought in the river channel and small grounded ice cover patches were used as working platforms. The research team arrived at the sampling site at 5 a.m. Sampling before sunrise was necessary to quantify the frazil production of the preceding night. During the two remaining hours before sunrise (around 7 a.m.), samples were taken at 5 locations equally spaced along the river cross-section (about 60 m-wide and 0.35 to 0.50 m-deep). Afterward, the surface velocity was measured using floating ice pieces, the chronometer and the measuring tape at the same 5 locations. A second sampling event took place at around 11 a.m. to see the effect of short wave radiation and increasing air temperatures on frazil transport (production). Samplings took place on December 5, 10, 13, 14, 15, 20 and 29 as well as on January 8, at air temperatures ranging from 1 to -35 °C. After January 8 the ice cover was almost complete and no more frazil was transported by the river.

Hourly pictures of the river surface were used as an additional source of information for frazil transport quantification. The pictures were taken by a time-lapse camera installed 2 km upstream of the frazil sampling site. For each daylight hour from November to January, a frazil concentration index between 0 (no frazil visible) and 5 (water surface dominated by drifting frazil) was visually attributed to each image (Figure 5). To reduce subjectivity, pictures were disordered in time, the river surroundings were made invisible and two people interpreted photo series independently. Resulting indices were averaged. In addition, air temperature and water temperature were measured continuously. These data were needed for the hourly heat budget calculations.

Hanging dam investigation. Investigation of the hanging dam was carried out during mid-winter conditions, when the dimensions of the dam were stable. A total of 20 transversal sections of 3 to 7 boreholes were sampled over the 9.5 km length of the hanging dam. The locations of the sections are indicated in Figure 1 and 2. In each borehole, measurements included ice cover thickness, water level, frazil thickness and riverbed elevation. Distinct deposited frazil layers were measured and classified in 3 density indices (1 for light, 2 for dense, 3 for very dense), according to the resistance manually felt when turning a home-made shear vane (no resistance but frazil present, moderate resistance, impossible to turn the vane; Figure 6). For each section, the stratigraphy of boreholes data was interpreted to illustrate the hanging dam structure (Figure 7).

To convert the volumetric dimensions of the hanging dam into a mass, manual density samples were taken in secondary boreholes using transparent tubes (of different length, depending on the thickness of top frazil layer) mounted on an extension equipped with an airtight valve (see Figure 8). The density tube was inserted in the top frazil-water mixture, and upon closing the valve, a sample of known volume was retrieved, drained, and weighted. At least 10 layers of each frazil density class were sampled and results were averaged for each density index. To our knowledge, this is one of the first attempts to measure the three-dimensional spatial density distribution of a hanging dam.

4. Results and discussion

Frazil mass transported to the hanging dam. Table 1 gives the measured frazil transport intensities during the different sample events. Values of 0 to 890 tons/h were measured. Using the hourly photo indices and the calculated heat budget (considering the observed and estimated daily ice coverage of upstream reaches), hourly frazil transport rates could be calculated. The total amount of frazil transported by the St. Anne River was estimated to 220 000 tons from November 26, 2014, to January 8, 2015. According to the heat budget alone, and on the basis of a theoretical ice production equation with knowledge of the ice coverage, the amount of frazil produced by the St. Anne River during the same period was 310 000 tons. To these values, 60 000 tons of snow slush were added to account for snow falling in the water and being transported by the flow downstream to the hanging dam.

Quantification and structure of frazil deposition. Comparable to the hanging dam in the Tanana River described by White and Lawson (1992), the hanging dam of the St. Anne River consisted of distinct homogeneous layers of frazil, suggesting the occurrence of discontinuous deposition events. Layers varied in thickness between 10 cm (e.g. in sections 7 and 11 at km 4.1 and 4.9) to 270 cm (in section 12 at km 5.2). Close to the hanging dam toe (km 2.2), transversal sections where occupied by single frazil layers (section 1, 2 and 3 at km 2.6, 2.9 and 3.1). Vertical and horizontal stratigraphy in distinct frazil layers began at section 4 (km 3.4), where dominant hanging dam grounding started, and increased in complexity in the upstream direction, reaching its more heterogeneous distribution at section 13 (km 5.3, downtown St. Raymond). In complex sections, water channels through the frazil mass were smaller and were apparently meandering from one bank to the other, sometimes dividing into subchannels. Between the ICS (km 6.1) and the head of the hanging dam (km 11.7), the complexity of frazil pockets and layers decreased again as the water to frazil ratio increased. In most sections, frazil deposits extended from ice cover to the riverbed, often lifting the ice cover or preventing its sag as the discharge dropped. At sections 11 (km 4.9) to 15 (km 5.7) and at section 21 (km 11.3), frazil layers emerged above the water level, resulting in a dry frazil mass. At section 16 (not drawn), the emerged frazil was dense and hard, making it impossible to reach the riverbed through boreholes. At sections 15 (km 5.7) and 21 (km 11.3), the result of a secondary consolidation event (e.g. Andres et al., 2005) was found as ice floes had been incorporated into the hanging dam core.

A Matlab program was used to calculate the area of each frazil layer for each documented cross-section. These areas were multiplied by a length corresponding to the distance between halfway to the next upstream cross-section and halfway to the next downstream cross-section. The resulting volumes were converted into mass using the density data for each frazil type (Figure 9). The densities of frazil types 1 to 3 were respectively 350, 550, and 630 kg/m^3. Table 2 also gives the corresponding porosities.

Figure 10 gives a longitudinal overview of the central part of the hanging dam, downstream and upstream of the ICS. The calculated volume and mass of the 9.5 km-long hanging dam were respectively 620 000 m^3 and 440 000 tons. The hanging dam was not only made of frazil slush coming from the St. Anne River. For instance, a small amount (6%) was estimated to be snow ice from in situ snowfalls. Note that most of this snow ice was not associated with the submergence of the ice cover under the weight of the snow, as it is normally the case for white ice (e.g. Ashton, 2011), but to the rain-on-snow event of December 24 to 26 that soaked the snow layer on top of the largely grounded hanging dam.

Also, the ice covering most of the hanging dam, initiated by drifting frazil slush interception, was dominated by solid frazil ice (frazil slush frozen in a thermal ice matrix). This cover was estimated to originate from a type-2 frazil layer (moderate density of 550 kg/m^3) occupying a corresponding thickness (and volume). As a result, the ice cover represented 47 000 tons frazil downstream and 73 000 tons frazil upstream of the ICS. Thermal processes added 42 000 tons ice downstream and 47 000 tons ice upstream the ICS.

Moreover, it was required to estimate the amount of frazil that had travelled downstream of the hanging dam, before its formation. An initial frazil slush thickness of 20 cm frazil type 1 (low density frazil of 350 kg/m^3) was estimated between km 0.0 and km 2.2 (the hanging dam toe). From a discharge ratio distribution, and based on local observations of drifting frazil slush and on the ice cover formation timing, the amount of frazil coming from the Bras du Nord River (at km 3.3) was estimated to be 27 000 tons. Of this amount, only 18 000 tons were included in the toe part of the hanging dam (a contribution of 4 % to the total mass of the hanging dam). Based on observations at the Chute-Panet dam at freeze-up, probably no frazil ice escaped its reservoir.

In order to provide information that can be used to identify flooding mitigation measures, it was necessary to distinguish the mass of the hanging dam downstream and upstream of the ICS. This was respectively estimated to be 224 000 tons and 102 000 tons. Snow falling on the hanging dam during winter can also impact the identification of flood mitigation measures. After formation of the hanging dam, about 60 cm of snow fell on its surface, which corresponds to 46 000 tons downstream of the ICS and 44 000 tons upstream of the ICS.

The mass and volume budget of the hanging dam are presented in table 3. The mass budget of produced, transported and deposited frazil is given in Figure 11 and Table 4. Balancing in- and outgoing components, a total slush mass of 290 000 to 380 000 tons accumulated in the hanging dam, depending on the type of calculation: based on frazil transport measurements (290 000) or based on a theoretical heat budget approach of frazil production (380 000). Both values are comparable to the total of 330 000 tons of slush (comprising frazil and snow) measured using information from the 20 surveyed sections of the hanging dam.

The results (particularly those presented as mass) should be interpreted with care, considering the subjectivity related to the interpretation of frazil layers in the cross-sections as well as by the manual interpretation of the frazil density index. There is also a possible error induced in extrapolating cross-section frazil budgets longitudinally and an uncertainty with respect to the shape of the river bottom. Nevertheless, estimates and interpretations based on different approaches yield comparable results and this combination probably provides an accurate order of magnitude (and a reasonable overall approximation) of the frazil ice problem at St. Raymond. To our knowledge, a similar investigation of mass and volume of a hanging dam has not been executed before.

5. Conclusion

The hanging dam that forms on an annual basis in St. Raymond was 9.5 km long during the winter of 2014-2015. Cross-sections show that frazil extended from ice cover down to the riverbed, lifting the ice cover by up to 0.6 m above the water level. Deposition was observed to occur in discontinuous layers of different densities, which were classified in 3 frazil indices. Average densities for these frazil indices were 350, 550 and 630 kg/m^3. The complexity of the deposition stratigraphy increased from low at the dam's toe to high in the dam's centre, immediately downstream of the ice control structure (ICS). The hanging dam had a volume of 620 000 m^3 and a mass of 440 000 tons, of which 330 000 tons (or 74 %) originated from transported frazil slush and snow slush from upstream reaches and 27 000 tons or 6 % of snow ice. The remaining ice mass (20%) was formed in situ by thermal processes.

Despite inherent uncertainties associated with frazil measurements in the field, the mass of transported or produced frazil and snow slush both correspond to the mass of the hanging dam: Incoming (frazil and snow) slush was evaluated to 290 000 tons (based on frazil transport measurements) and 380 000 tons (based on a theoretical heat budget approach of frazil production), compared to a frazil (and snow slush) deposition of 330 000 tons in the hanging dam. This supports the fact that both estimation methods ((a) suspended frazil ice transport measurements supplemented by time-lapse photos, a heat budget and ice coverage measurements and (b) theoretical production estimates based on knowledge of ice coverage and heat budget alone) can be used to evaluate frazil slush mass. The knowledge gained through this hanging dam research will help identify efficient ice control mitigation measures (Turcotte and Morse, 2015) and thereby help prevent the town of St. Raymond from repeatedly being flooded.

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Table 1. Frazil transport intensity FTI for each event, BS (before sunrise) and AS (after sunrise). T_a is the average air temperature during the sampling event, N is the number of samples retained for analysis, Q is the flow measured by CEHQ.

Event	T_a (°C)	N	Q (m^3/s)	FTI (tons/h)
5 December BS	-24	10	24	891
5 December AS	-14	10	24	877
13 December BS	-2	13	15	15
13 December AS	0	3	15	0
14 December BS	-2	3	14	0
15 December BS	-2	4	13	4
15 December AS	-4	12	13	10
20 December BS	-19	18	9	320
20 December AS	-8	15	9	93
29 December BS	-7	5	17	211
29 December AS	-13	14	17	682
8 January BS	-35	3	9	0

Table 2. Average density ρ and porosity p for each frazil type and the range of both variables. N is the number of samples, σ_s is the sample standard deviation.

Frazil type	N	ρ (kg/m^3)	range	σ_s (kg/m^3)	p	range	σ_s
1	10	350	170-550	140	0.6	0.4-0.8	0.15
2	14	550	410-750	90	0.4	0.2-0.6	0.10
3	15	630	540-710	50	0.3	0.2-0.4	0.05

Table 3. Different mass components of the hanging dam, expressed in tons of ice contained in the hanging dam and in its parts downstream and upstream of the ICS. Volume of ice cover and frazil ice below the ice cover, expressed in m^3.

		Downstream	Upstream	Total	%
a	Frazil below ice cover	159 000	29 000	188 000	43
b	Frazil in ice cover	47 000	73 000	120 000	27
c	Frazil from Bras du Nord	18 000	0	18 000	4
d	Snow ice	13 000	14 000	27 000	6
e	Thermal growth	42 000	47 000	89 000	20
	Total mass (tons)	**279 000**	**163 000**	**442 000**	**100**
	Of which frazil ice (a+b+c)	224 000	102 000	326 000	74
f	Ice cover volume	130 000	140 000	270 000	44
g	Frazil volume	290 000	60 000	350 000	56
	Total volume (m^3)	**420 000**	**200 000**	**620 000**	**100**

Table 4. The frazil budget of the hanging dam.

		Transported	Produced
IN	Frazil from Ste. Anne	220 000	310 000
	Frazil from Bras du Nord	30 000	
	Snow slush	60 000	
OUT	Km 0.0 – 2.2	20 000	
BALANCE		**290 000**	**380 000**
Deposition in hanging dam		**326 000**	

Figure 1. Map of the St. Anne River in St. Raymond between Panet dam and the ice control structure. Numbers 1 to 16 indicate the cross-sections where the hanging dam was measured.

Figure 2. Map of the St. Anne River upstream of St. Raymond. Numbers 17 to 21 indicate the cross-sections where the hanging dam was measured. The right picture below shows frazil slush travelling downstream the river.

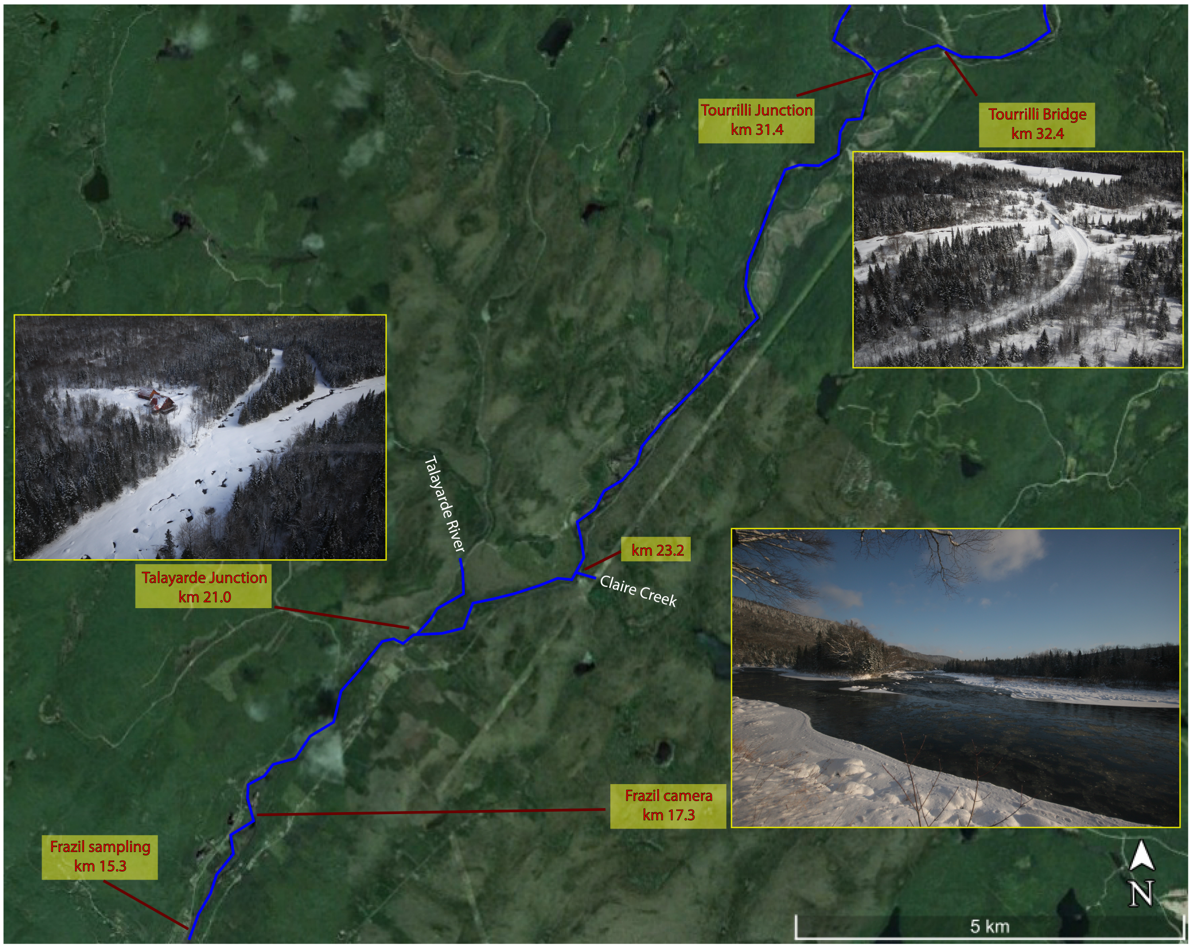
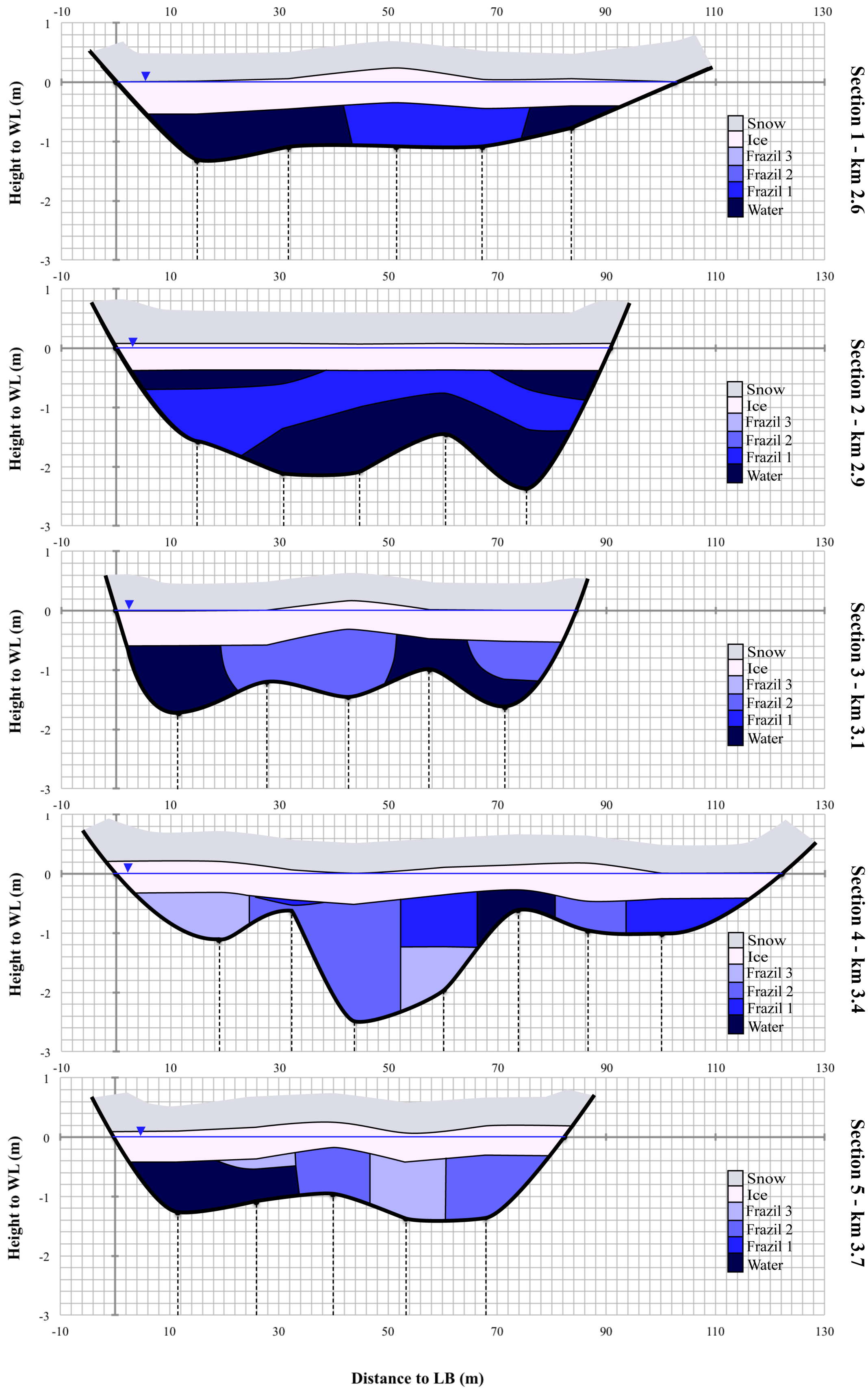


Figure 3. Map of the St. Anne River upstream of the frazil sampling site up to the Tourrilli Bridge.

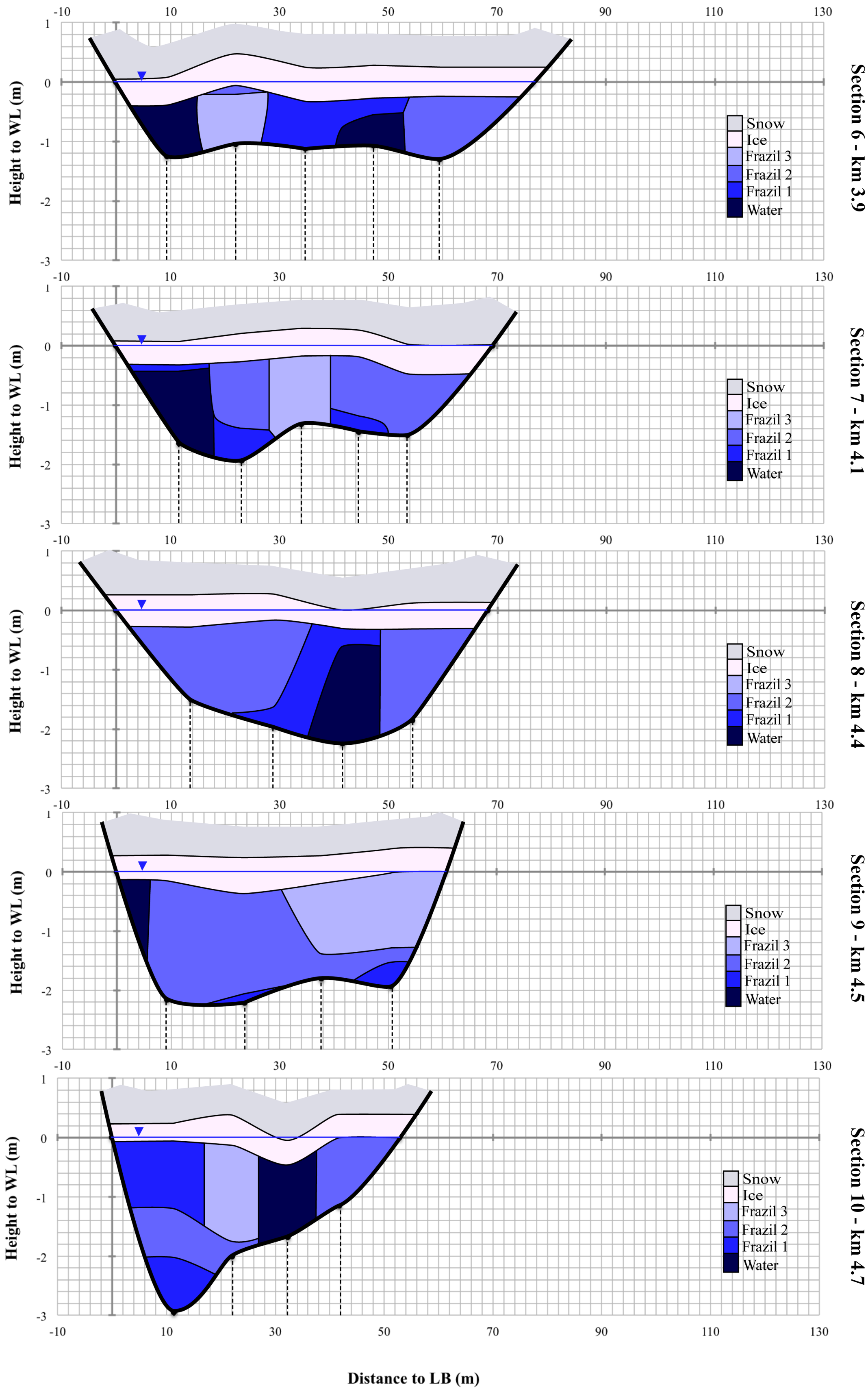
Figure 4. The manual frazil sampler with nylon stockings (left). Submerging and filling the nylon stockings with frazil (right).

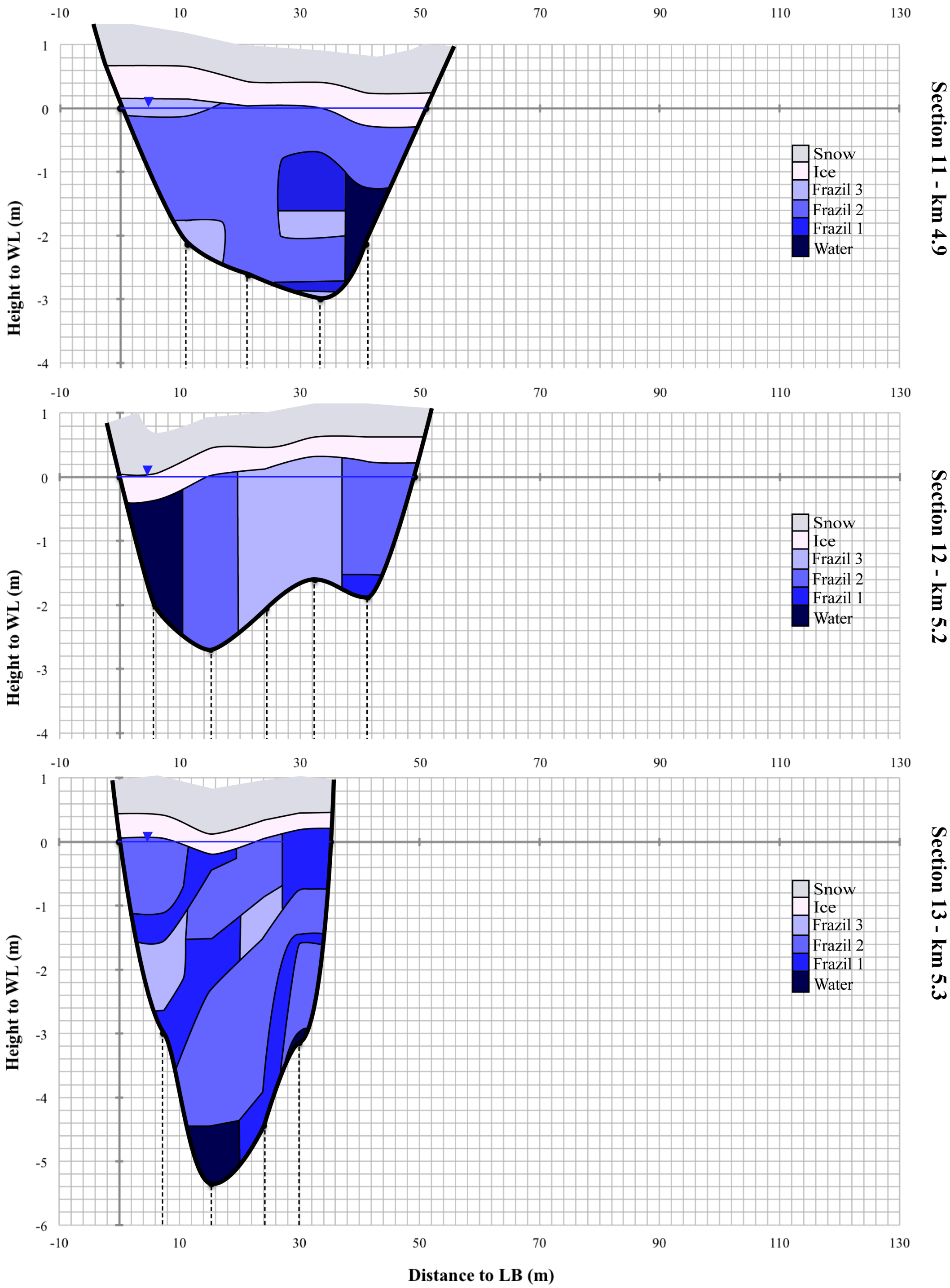
Figure 5. Frazil picture attributed index 2 (above) and index 5 (below) at km 17.3.

Figure 6. The shear vane used to manually determine the density class of the different frazil layers in the hanging dam.

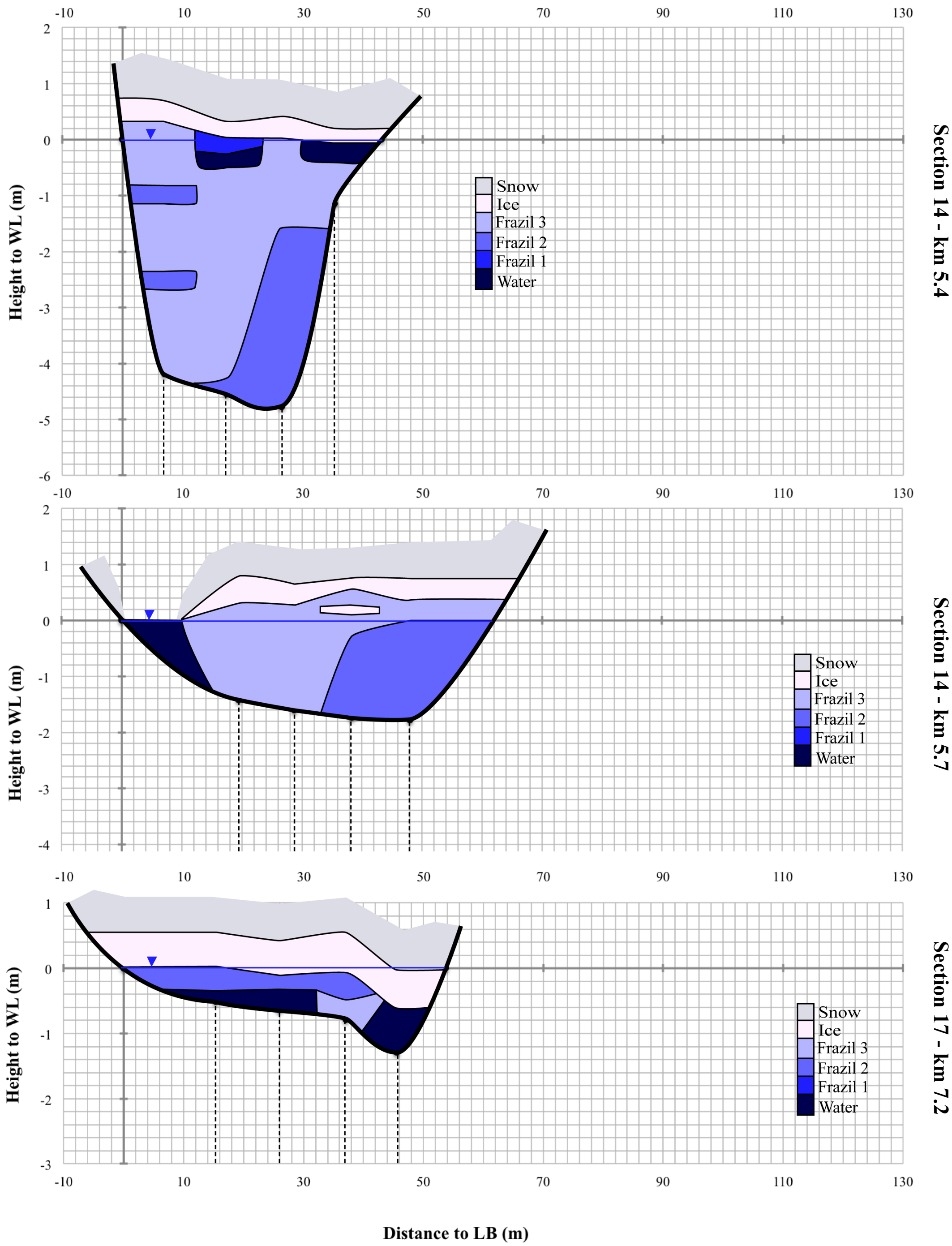


Section 1 - km 2.6
Section 2 - km 2.9
Section 3 - km 3.1
Section 4 - km 3.4
Section 5 - km 3.7
Height to WL (m)
Distance to LB (m)
Snow
Ice
Frazil 3
Frazil 2
Frazil 1
Water


Section 6 - km 3.9
Section 7 - km 4.1
Section 8 - km 4.4
Section 9 - km 4.5
Section 10 - km 4.7
Height to WL (m)
Distance to LB (m)
-10
10
30
50
70
90
110
130
1
0
-1
-2
-3
Snow
Ice
Frazil 3
Frazil 2
Frazil 1
Water



Section 11 - km 4.9
Section 12 - km 5.2
Section 13 - km 5.3
Height to WL (m)
Distance to LB (m)
Snow
Ice
Frazil 3
Frazil 2
Frazil 1
Water
-10
10
30
50
70
90
110
130
1
0
-1
-2
-3
-4
-5
-6


Section 14 - km 5.4
Section 14 - km 5.7
Section 17 - km 7.2
Snow
Ice
Frazil 3
Frazil 2
Frazil 1
Water
Height to WL (m)
Distance to LB (m)
-10
10
30
50
70
90
110
130

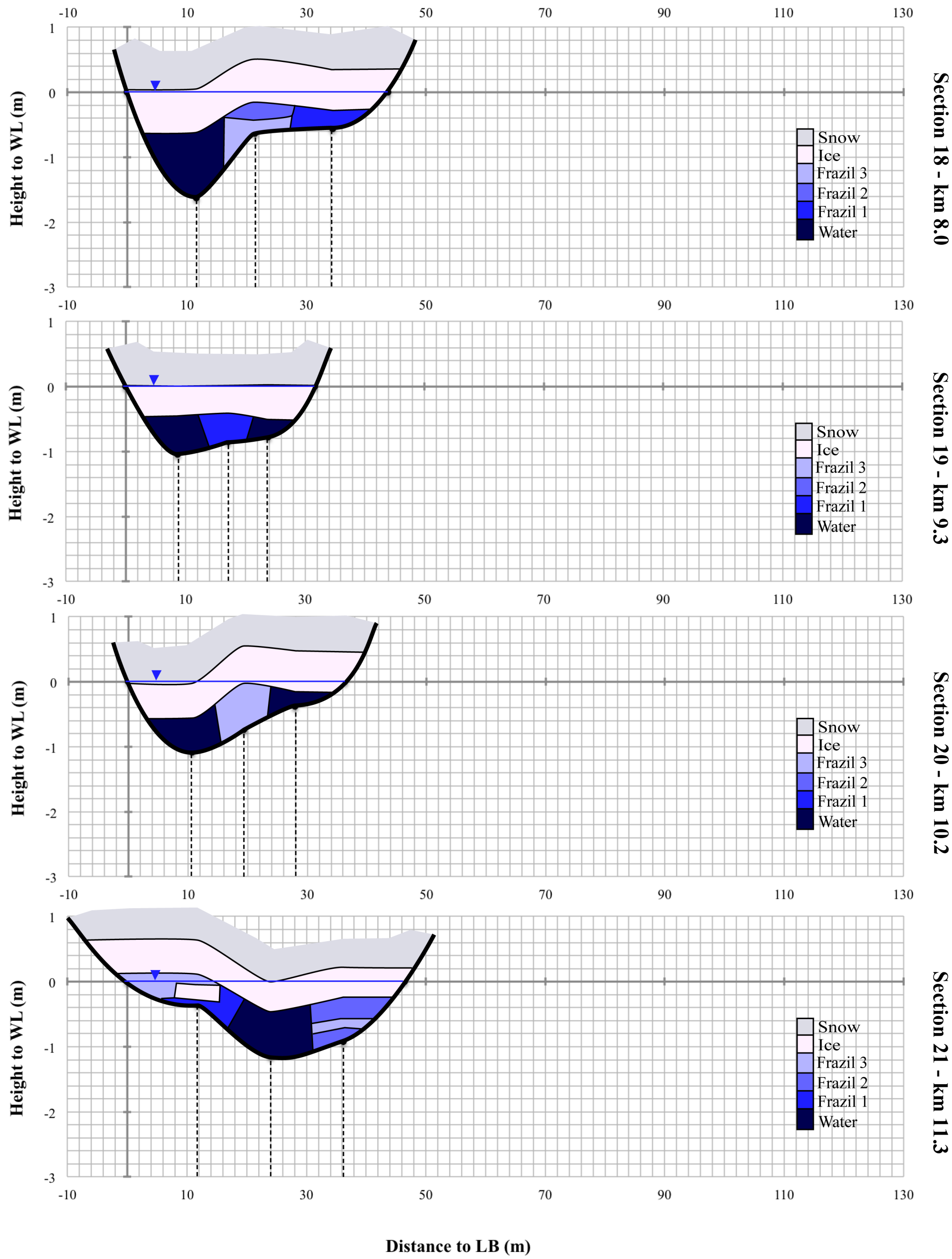


Figure 7. Cross-sections of the hanging dam showing its internal structure and stratigraphy. Section 16 could not be drawn, because a thick emerged frozen frazil mass made it impossible to complete the five boreholes at this location.

Figure 8. The tube used to measure density of the frazil layers in the hanging dam, by weighing a drained sample of known volume.

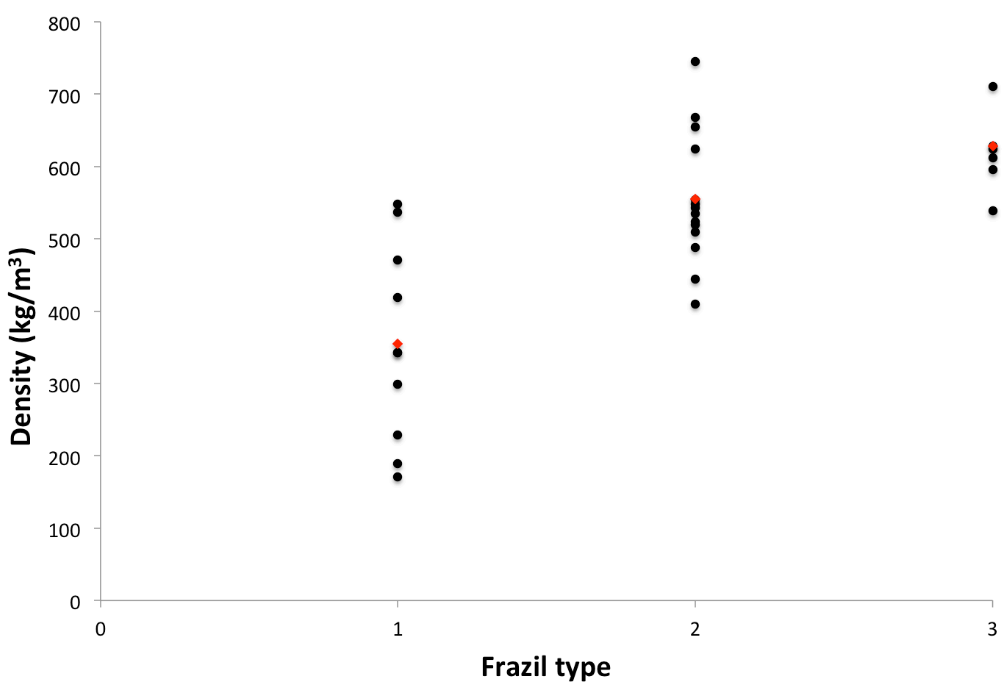


Figure 9. Density distribution of each frazil type and the average density per type (red dots).

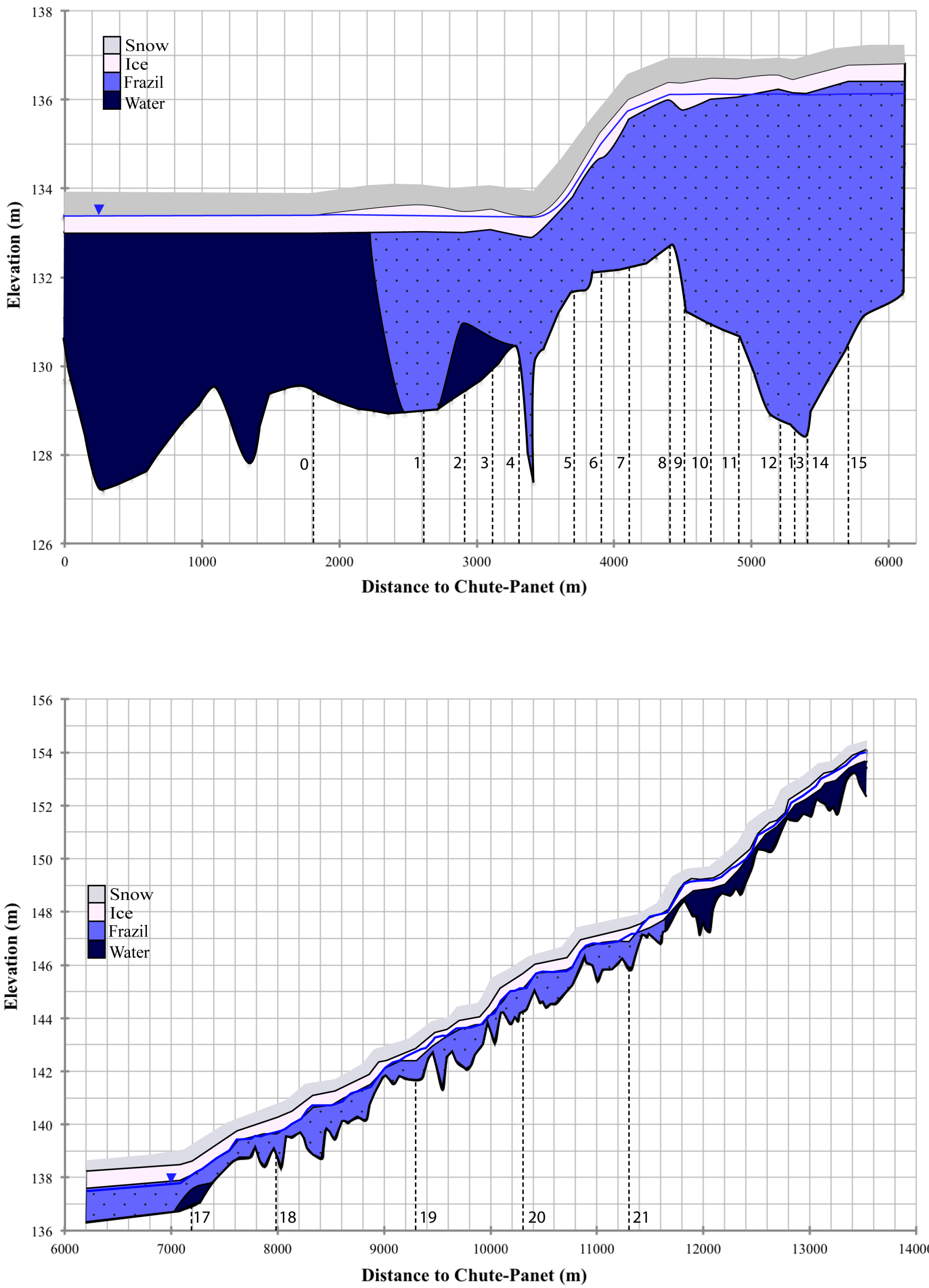


Figure 10. Profile of the hanging dam center downstream (above) and upstream (below) of the ice control structure.

Figure 11. Scheme of incoming and outgoing components in the hanging dam.