NEW DATA ON ICE JAM FORMATIONS ON THE BISTRIŢA RIVER

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Abstract: The forming of ice jams on the Bistriţa river upstream of the Izvorul Muntelui lake end has been thought to be caused by the lake itself. However, this article shows other reasons and situations when this occurred, with examples for the 2014 winter. Furthermore, several methods that can be used to identify potential problem areas are also presented.

Keywords*: frazil ice, ice jam inception, ice thickness*

1. Introduction

In the case of weather phenomena, the extreme vulnerability can be defined as an exposure of some territories or ecosystems to possible phenomena or probable weather order (Sfîca et al. 2013; Tutunaru et al., 2013; Crăciun et al. 2011; White, 1999).

Almost every winter, upstream of the Izvorul Muntelui Lake, on the Bistriţa River, ice jams occur and lead to a rise in the water level by 4-5 m. This phenomenon is especially intense in the Poiana Teiului – Borca 20-kilometre stretch. This occurrence has been studied and various methods to diminish the effects have been proposed.

1.1. Types of ice (USACE, 2006; Ashton, 2010)

1.1.1. Sheet ice

A sheet ice is a type of ice that forms in calm waters like lakes or reservoirs or even slow rivers with a flow speed lower than 0.5 m / s (1.5 ft / s). The ice crystals that form on the water surface bind together with a layer of ice that thickens downward as water heat is transferred through the ice to the air above it. The ice bridge usually forms along the banks and spreads to the middle. In the case of slow flowing rivers, the ice bridge can also be created by the overlapping of ice flowing from upstream. This type of ice block grows in place, being sometimes called black ice, due to its distinct colour. Another cause for ice blocks is snow melding with water, which gives a milky look caused by trapped air bubbles.

1.1.2. Frazil ice

Frazil ice forms in turbulent, super-cooled water, which is water cooled below the freezing point of 0°C (32°F) at a regular atmospheric pressure. This phenomenon occurs in lakes and rivers where water is turbulent, its surface is not covered with ice and air temperature is lower than 0°C (32°F) by a significant margin, -8°C (18°F) or even lower. If the surface is covered with ice, the temperature where the water meets the ice must be at the freezing point and all heat transfers will stop when water reaches 0°C (32°F). As a result, frazil ice is always associated with clear surface waters.

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The level of super-cooling must not be overestimated, as it will usually not be more a few hundredths of a degree, and never over 0.1°C (0.18°F). This is why super-cooling is only detectable with very sensitive thermometers. The first stage in frazil ice forming is the appearance of small crystals (0.1 mm every few millimetres) which are evenly distributed (in rivers, for instance, they form along the whole depth). Each crystal starts out as a perfect disk with a diameter that is 10 to 12 times its thickness. These disk-shaped formations are the main manifestations of frazil ice, although, in time, these evolve into greater masses of ice, sometimes stretching for several kilometres.

The forming of frazil ice is thus characterized by super-cooled water, a turbulent flow and the rapid formation of disk-shaped ice crystals. The sizes of these crystals range from a few micrometers to a few millimetres. This stage usually takes place during colder periods, when the heat loss at the water surface is more intense.

1.1.3. Dynamic forming of sheet ice

In most cases, sheet ice form on rivers as a result of free flowing ice pieces jamming up together. Starting with an inception point, these grow and progress upstream as more ice flows from that direction. The upstream end of this ice formation can evolve in a few different ways:

- a blockage of moving ice pieces in the shape of an arc between the river banks; this occurs at low water speeds;
- ice blocks join up as they flow downstream without vertical displacement; the water speeds at which this can occur depend on the general geometry of the ice block and on the water depth;
- ice blocks roll under the existing bridge; if water speeds are great enough, the newer pieces do not join up but instead flow beneath the ice jam;
- free newer ice blocks flow underneath the ice bridge; during this time, the ice bridge does not grow upstream; however, once a drop in water speed and a rise in water level occur downstream, water speed drops upstream as well and the phenomenon stops;
- the jam does not extend further upstream as long as water speed is high enough.

1.1.4. Structure for retention of ice formations

The formation of ice congestion is only possible if water flow speed is relatively low ($\leq$ 0.5-0.7 m / s [$\leq$ 2.3 ft / s]), with low slopes which lead to a small Froude number ($\leq$ 0.08). The hydraulic conditions must allow the ice to bunch up together and not be sucked underneath during the forming stage. The ice field that progresses upstream is made up of either frazil ice or floe. These structures can appear spontaneously when the conditions are met (low Froude number) or can be formed artificially. The beneficial effect of such an ice field is that it stops the heat transfer between water and air and thus the creation of frazil ice.

1.2. Ice blockage on the Bistrita River

The Bistriţa River basin is made up of three sections:

- the north section, upstream of Dorna Arini, with strong and lengthy ice formations that span almost the entire water stream;
- the section between Dorna Arini and Broşteni, a transition sector where fixed ice formations appear mainly in harsh winter conditions;
- the section downstream of Brosteni, where fixed ice formations occur seldom and only in
  harshest winters and ice formation along the banks is only present on short strips.

The cited studies refer to the section between Dorna Arini and Poiana Teiului localities, where a new phenomenon, not present prior to the development of the Izvorul Muntelui Lake, has been noticed – a huge torrent that forms in the frazil ice congested areas, with thicknesses exceeding 4-5 m and lengths of 20 km.

This phenomenon has been the object of many studies and research papers. Their conclusion is that “the formation of the ice bridge at the end of the lake prohibits the transit of frazil ice further downstream and thus makes it deposit on the riverbed.” In fact, the blockage of the riverbed starts within the lake basin, the first deposits appearing beneath the ice bridge in the Călugăreni section.

2. Experimental Approach

The observations made in January and February 2014 revealed a previously unknown phenomenon. The ice blockage inception point is no longer at the point where the river meets the lake’s end (or where the rivers moving water meets an area of stationary or much slower moving water). The forming of the blockage took place at the end of January 2014 in the area where the Bistriţa River meets the offtake of the Poiana Teiului hydroelectric power plant.

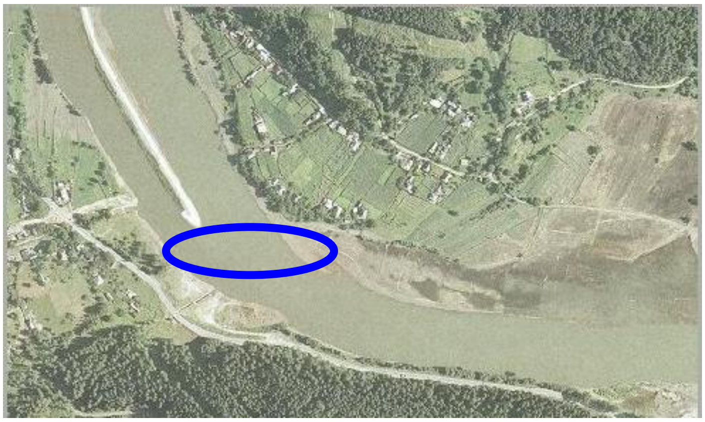

Figure 1: Initial blockage formation area (zone 1)

If this phenomenon (the blockage of frazil ice) could occur here, in an area other than the lake end, it is safe to assume that other regions along the river might meet the requirements for this to happen, too.

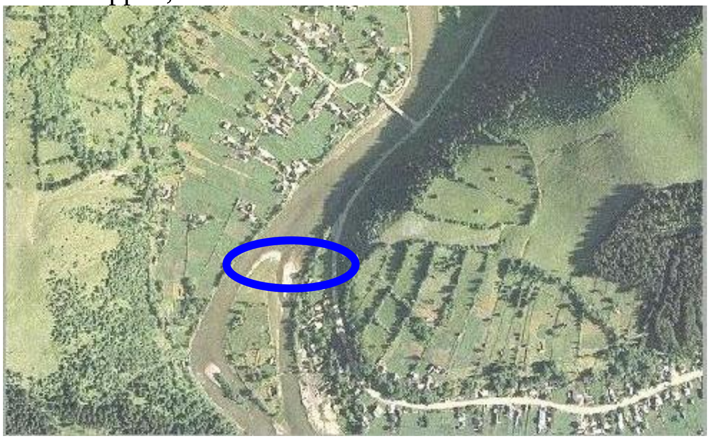

Figure 2: Ice jam area at the border between Neamt and Suceava counties (zone 2)

Several other areas where this occurred have been identified. These had a much shorter lifespan, their initial equilibrium being broken thus leading to the dislodging and transport of the ice downstream to the Poiana Teiului blockage. These areas were at the border of Neamţ and Suceava counties (fig.2) and downstream of Zugreni (fig.3).

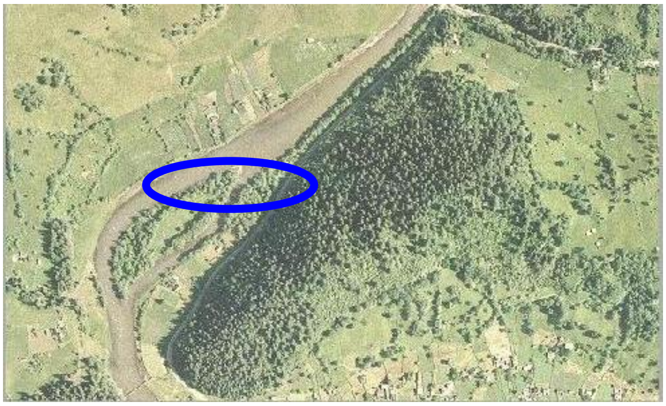

Figure 3: Ice jam area at 7 km downstream of Zugreni (zone 3)

Figure 4: Ice jam area (from Fig.2)

At the time of this investigation (between 3rd and 11th February 2014) the blockages in the areas showed in figures 2 and 3 were almost gone. Their existence was documented on the basis of the ice built up along the banks.

In order to determine the reasons behind this phenomenon occurring here, we took into account the riverbed characteristics, as well as the data on the river flow and air temperatures recorded at Frumosu station. With all these in mind, the following profile emerges: low grade slopes, wide riverbed, flow rates lower than the annual average, low temperatures (below 8^{o}C).

The average annual flow rate at Frumosu station is of 15.2 m^3/s, while the flow rate recorded for the month of January around the time of the jams (January 15) was of 11 m^3/s.


Figure 5: Ice jam area downstream of Zugreni

Going further, the three areas where jams occur will be appointed with numbers from 1 to 3, starting downstream and moving up: zone 1 (fig. 1), zone 2 (fig. 2) and zone 3 (fig. 3).

Finding the places where ice jams may occur can be done by listing the causes of Ice Jams (USACE, 2006).

Ice jams emerge in that area where the ice transport capacity or ice conveyance of the river is exceeded by the ice transported to that location by the river's flow.

Change in slope. The most common location for an ice jam to form is in an area where the river slope changes from relatively steep to mild. Since gravity is the driving force for an ice run, when the ice reaches the milder slope, it loses its momentum and can stall or arch across the river and initiate an ice jam. Islands, sandbars and gravel deposits often form at a change in water slope for the same reasons that ice tends to slow and stop. Because such deposits form in areas conducive to ice jamming, they are often mistakenly identified as the cause of ice jams. While these deposits may affect the river hydraulics enough to cause or exacerbate an ice jam, the presence of gravel deposits is usually an indication that the transport capacity of the river is reduced for both ice and sediment. All the three locations on Bistriţa river where ice jams occured in January 2014 are locations with a smaller slope than the adjacent ones (0.12% against 0.34% in zone 1; 0.14% against 0.39% in zone 2 and 0.18% against 0.36% in the zone 3).

Confluences. Ice jams also commonly form where a tributary stream enters a larger river, lake or reservoir. The ice run stalls at the confluence, forming a jam and backing up water and ice on the tributary stream. Zone 1 of Bistriţa ice jam is in this situation.

Channel features. River beds are frequently cited as ice jam instigators. While river beds may contribute to jamming by forcing the moving ice to change its direction and by causing the ice to hit the outer shoreline, water slope is often a factor in these jams as well. Obstructions to ice movement can cause ice jams. In location 3, there is an obstruction to ice movement performed by a huge rock in the river bed (Fig. 5).

Operational factors. Some structural or operational changes in reservoir regulation may lead to ice jams. For example, sudden releases of water may initiate ice breakup and subsequent jamming. The ice jam in locations 2 and 3 was released when equilibrium was broken.

3. Results and discussion

The way ice jams form and the thickness of the ice when equilibrium is reached is described by Beltaos (2005, 2012, 2013), Li (2012) and Ashton (2010). Here follows a brief calculation of the ice jam thickness.

For most natural streams (with a width / depth ratio larger than about 10), the thickness of an ice jam depends on the balance between the drag of the ice jam along the banks and the sum of the stress exerted by the flow on its underside.

By thinking of frazil ice as a granular material, the horizontal tensions σ_x can be related to the vertical ones σ_z.

The vertical tension due to ice weight is:

$$\sigma_z = \gamma_g \cdot t$$

and the horizontal one is

$$\sigma_x = k \cdot \sigma_z = k \cdot \gamma_g \cdot t \, ,$$

in which $\gamma_g = \frac{1}{2} s_i (1 - s_i)(1 - e)\rho g$ quantifies the unit weight of ice which is

$\gamma' = \rho_i \cdot g(1-e)$ over the water level by the tickness $t(1 - s_i)$

$\gamma' = \rho_i \cdot g(1-e) + \rho \cdot g \cdot e$ over the water level by the tickness $t \cdot s_i$

The ice jams drag along the banks for a thickness ***t*** is:

$$R = \sigma_x \cdot 2t = \mu s_i (1 - s_i) \rho g t^2$$

in which $\mu = k(1-e)$; $\rho \cdot g \cdot R \cdot S$, is the shear stress exerted by the flow on the underside of the jam; $\rho_i \cdot g \cdot t \cdot S$, is the downstream component of the own weight of the jam per unit area.

The equilibrium equation is (Beltaos, 1983; Ambtman, 2012):

(1) $$\mu \rho_i (1 - s_i) g t^2 = B(\rho \cdot g \cdot R \cdot S + \rho_i \cdot g \cdot t \cdot S)$$

The ice field thickness formed by the depositing of frazil ice in the regions where it stops flowing is (Beltaos, 1983; White, 1999):

(2) $$t = \frac{B \cdot S}{2\mu(1 - s_i)} \left[1 + \sqrt{1 + \frac{4\mu(1 - s_i)}{s_i} \frac{R}{B \cdot S}} \right]$$

The surface of the field thus formed is $H_g = h + t$, whereas at the water level it is $H = h + s_i t$

The used terms $R \approx h/2$ is the hydraulic radius (if the ice roughness and riverbeds are about equal), otherwise (Uzuner, 1975; White, 1999):

$$R = \left(\frac{n_i}{n} \right)^{3/2} \frac{h}{2}$$

where n_i is the ice roughness, n is the riverbed roughness and h the water depth below ice field

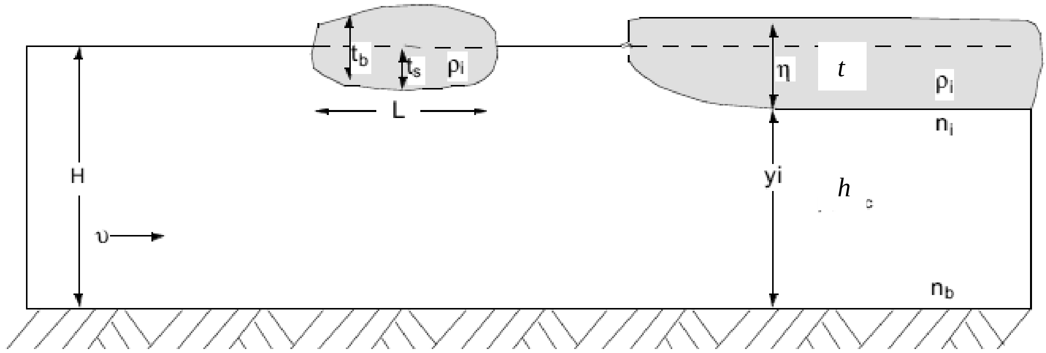

Figure 6: Definition sketch for ice block stability (White, 1999)

$h = \left[q/(4gS/f_0)^{1/2} \right]^{2/3}$ (Beltaos, 1983)

$$h = q^{\frac{2}{3}} \left(\frac{4gS}{f_o} \right)^{-\frac{1}{3}}$$

$f_o = \dfrac{8gRS}{v^2}$ hydraulic drag coefficient of the riverbed (Darcy – Weisbach)

where $q=Q/B$ is the specific flow; B, is the width of the riverbed; S is the water slope approximated as being the thalweg slope; $s_i=\rho_i/\rho$ is the specific density of ice, in which ρ_i = 916 kg/m^3 is the density of ice, ρ = 1000 kg/m^3 is the density of water and μ = 0.8 - 1.3 with an average of 1.2 (Beltaos, 1995) the dimensionless coefficient that depends on the friction between the ice particles in the jam itself.

The calculation of the thickness of the ice jam using the equation (2) highlights its dependence on the riverbed parameters (Wang et al., 2011; Wang et al., 2012).

However, before calculating the thickness of the ice jam, the conditions for its forming must be identified. The dynamic forming of ice jams in rivers by the joining together of ice blocks was first quantified by Michel (1978). He recorded a lower limit value for the Froude number of 0.06-0.12 for which ice blocks coming from upstream slip under the existing ice jam. Ashton (2010) shows that most labs have reached limit values between 0.08-0.13 for Froude's number.

In the case of the three sites on the Bistriţa River, the Froude number is 0.12 for zone 1, 0.13 for zone 2 and 0.14 for zone 3. This was calculated for a water flow regime in front of the cover.

The initial thickness of the ice jam in area 1 (using (2)) is 81 cm. The water depth without frazil ice is 47 cm. Before the ice jam formed, water flowed with a depth of 63 cm (the difference is a result of a diminished hydraulic radius caused by an increase in the wetted perimeter).

4. Conclusions

Izvorul Muntelui Lake is not the only cause for ice jams on the Bistriţa River. Three other zones that witnessed ice jams in January 2014 have been identified upstream of the lake. The theoretical possibility of these ice jams to form is described in specific literature. There is no existing quantification of the parameters which are necessary for the jams to occur.

This article proposed the following parameters for the formation of ice jams along the Bistriţa River:

- water flow levels lower than annual averages;
- longitudinal slope less than 0.18%;
- riverbed width greater than 60 m;
- presence of islands in the riverbed;
- riverbed areas with increased roughness (protruding rocks in the thalweg).

For this research, we conducted a topographic survey in the area, transverse profiles being measured twice every kilometre. It is possible that further investigation will yield more results in those other areas where ice jams might form and could be identified.

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