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Hydropower impact on the ice jam formation on the upper Bistrita River, Romania

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A B S T R A C T

In this work, we investigate the causes of ice jams along the Bistrita River, which has the longest mountainous course (216 km) of any river in Romania. Over a length of 25–30 km on the upstream portion of the Izvoru Muntelui Reservoir, ice block accumulations known as ice jams form almost yearly during the cold season. Analysis of the hydroclimatic and morphological conditions of the riverbed has revealed that a certain combination of their temporal variations is favourable to ice jam formation. The hydraulic geometry of the Bistrita river bed is favourable to the flow of frazil slush, frazil pans, and ice floes while the air temperature is below −7 °C and the water level of the Izvoru Muntelui Reservoir is below 500 m. Above this level, ice jams block the river bed, and this blockage advances upstream at velocities of several hundred meters per day. The most dramatic instances of this phenomenon were recorded during the winter of 2002–2003, when the thickness of the ice was on the order of 6 m and the resulting floods caused damages and claimed human lives. The appearance in 2003 of the Topoliceni Reservoir, 4 km upstream of the Izvoru Muntelui Reservoir, has complicated the evolution of these winter phenomena, with the lake itself acting as an accumulation pool for ice from upstream. This development has led to damages and inconveniences in canals and at the entrances to power plants, spillways, outlet works, and other hydraulic structures.

1. Introduction

Ice agglomerations or dams that form on rivers during the winter are a common phenomenon in temperate regions. The ice season can last more than 100 days for most of the rivers of Scandinavia, Russia, and Canada, and can reach latitudes of 42° to 30°N in North America and Asia (Bates and Billelo, 1966). Also known as ice jams (in Romanian as *zapor*; in Russian, *zator*; in French, *embâcle*; in German, *Eisbarre* according to Savin, 1996), these ice agglomerations can block the flow of the river and cause large floods, making them the most hazardous winter phenomenon on rivers (Ashton, 1986). For this reason, scientists have long attempted to establish the causes of ice jams and to find ways to avoid their negative effects. Numerous examples of damages and loss of human life have occurred during winters on rivers in Canada, the United States, Russia, the Scandinavian countries, Iceland, Japan (Shen and Liu, 2003), China, and other regions, all of which have been thoroughly commented on in a long series of studies by several Canadian scientists (Beltaos, 2007, 2008; Prowse and Conly, 1998; Beltaos and Prowse, 2001; Prowse and Beltaos, 2002; Prwose and Bonsal, 2004). In addition, inventory catalogues have been published for Siberian rivers (Korytny and Kichigina, 2006), and large works, inventories, and specialized web sites exist for other regions of the world. In particular, the website of the Cold Regions Research and Engineering Laboratory of the U.S. Army Corps of Engineers presents some of the most complex information available regarding the systematics of the ice jam phenomenon, including field and laboratory experiments, effects of their components of the environment, and a whole range of attenuation measures (see http://www.crrel.usace.army.mil/icejams/) (White and Eames, 1999; Weyrick et al., 2007). In addition, many ice jam case studies in Canada have been inventoried in Beltaos et al. (1990), Wigle et al. (1990).

In Romania, research interest in such winter phenomena on rivers dates back to the 1960s, at the beginning of the development of a national observation network of hydrological phenomena on rivers (Semenescu, 1960; Constantinescu, 1964; Ciaglic, 1965; Ciaglic and Vornicu, 1966; Ciaglic et al., 1975). Winter floods on mountain rivers

Table 1
General data on the Bistrita River in the gauging station points.

River	River cross-section	Drainage basin area A (km²)	River length L (km)	Mean yearly discharge Q ($m^3 s^{-1}$)	Suspended sediment load Qs ($kg s^{-1}$)
Golden Bistrita	(1) Carlibaba	471	32.5	7.86	
	(2) Dorna-Giumalau	721	62.5	12.2	1.45
Bistrita	(3) Dorna Arini	1687	73.4	22.3	3.70
	(4) Brosteni	1192	116.5	30.3	4.40
	(5) Frumosu	2901	143.5	37.9	6.68

(1) Cross-section numbers are shown in Fig. 1.

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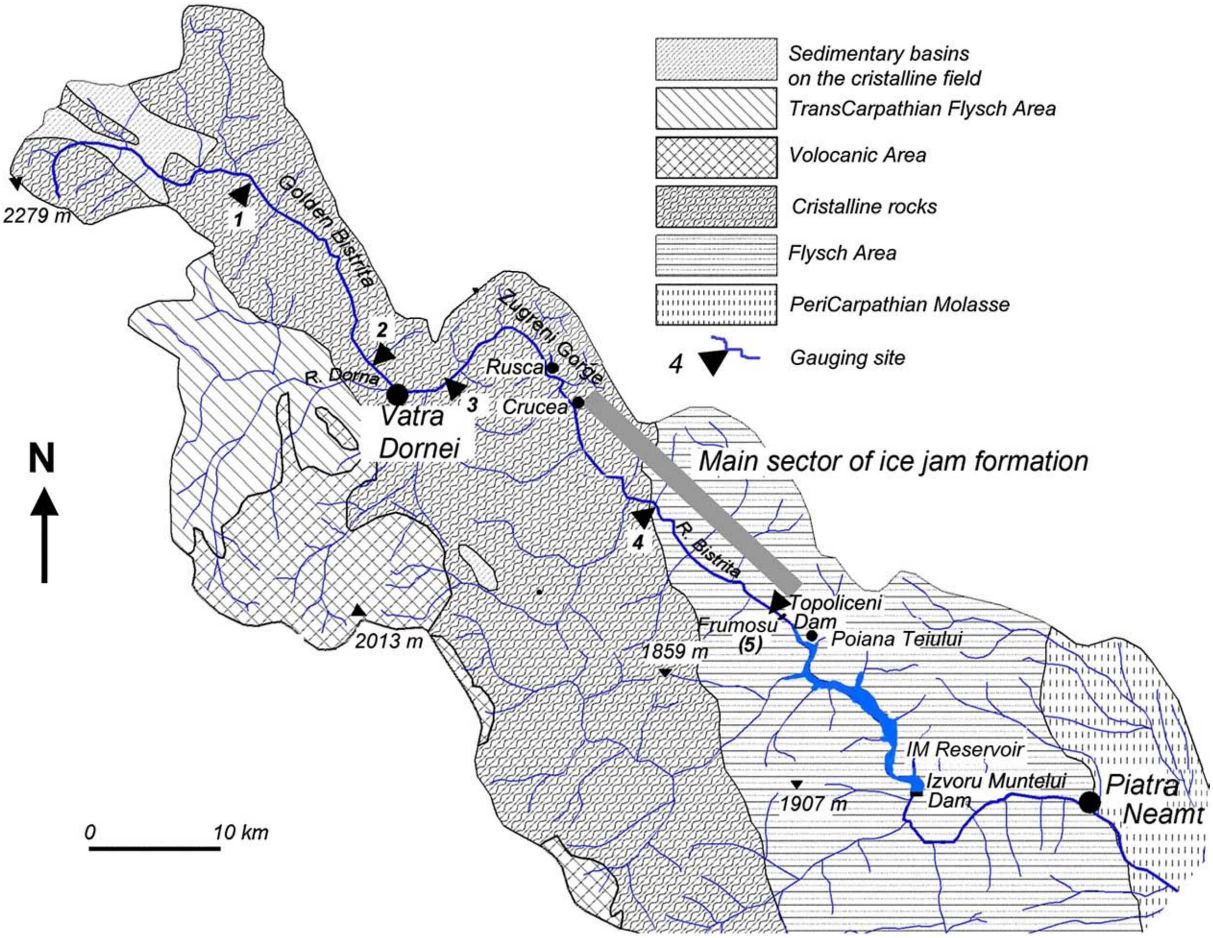

Fig. 1. Bistrita drainage basin upstream of Izvoru Muntelui Reservoir. Location of the area is discussed in the text.

in Romania (Moldavian Bistrita, Transylvanian Bistrita, the Mures, the Danube, etc.) have captured the interest of climatologists, hydrologists, and geomorphologists, as well as specialists in river engineering, resulting in PhD theses and numerous articles and book chapters (Miţă, 1977; Musteţea, 1996; Păvăleanu, 2003; Rădoane, 2004; Romanescu, 2003; Surdeanu et al., 2005; Ştefanache, 2007).

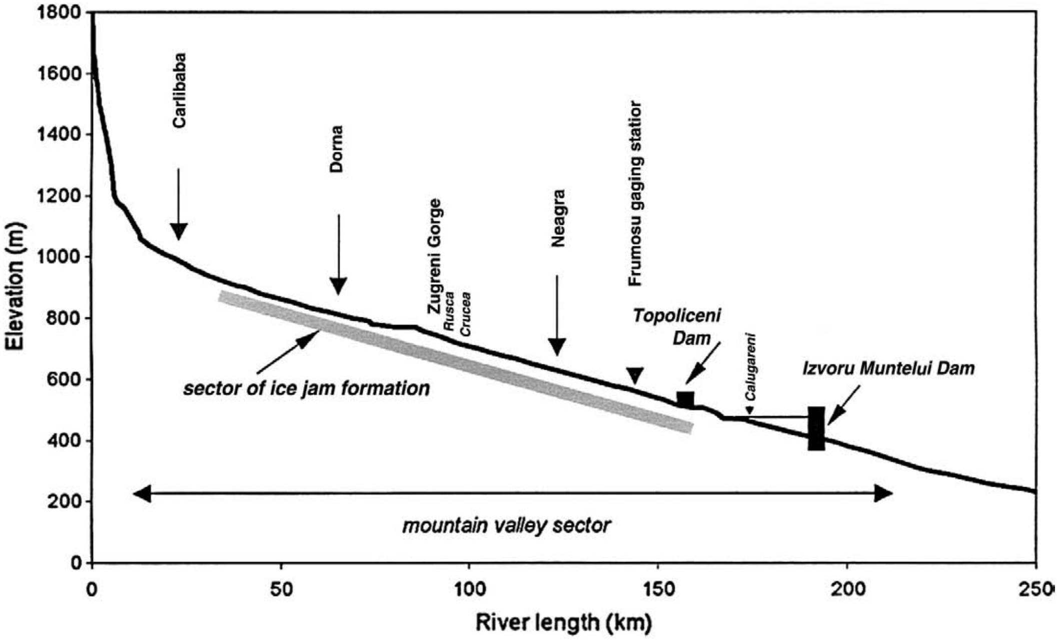

Fig. 2. Longitudinal profile of the Bistrita River, with the research location. The bold line represents river bed elevation.

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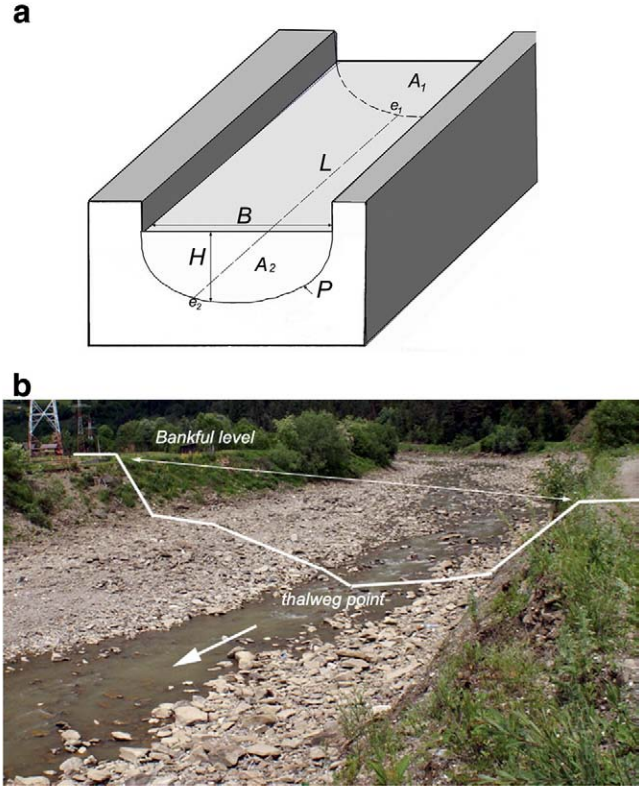

Fig. 3. a. Dimensional elements used in at-a-station hydraulic geometry determination (Bistrita River at Frumosu cross-section). b. Bistrita River at Frumosu cross-section.

Dangerous winter phenomena in the riverbed and valley of the Bistrita River upstream of the Izvoru Muntelui Reservoir have instigated a series of studies (Ichim and Rădoane, 1986), mostly by the Hydroelectrical Company (1997, 1998); most recent papers have resulted from collaboration with and financial support from the aforementioned company.

Our interdisciplinary team of hydrologists and geomorphologists have focused on analysis of the ice jam phenomenon on the Bistrita riverbed upstream of the Izvoru Muntelui Reservoir, with special emphasis on the sector between the tail of the reservoir and the Topoliceni dam. The analysis was based on the latest progress in ice jam research, our own experience in the region of study, and detailed observations during the cold season of 2007–2008. The main targets of our study are the following: a) presentation of the region of study with a closer look at the dynamics of Bistrita's riverbed upstream of Izvoru Muntelui Reservoir; b) characterization of the hydraulic geometry of Bistrita's riverbed in free conditions and in ice jam conditions; c) analysis of the climatic and hydrologic processes favourable to ice jam formation; d) consideration of the causes of ice jam formation upstream of Izvoru Muntelui Reservoir.

2. The zone of study

The Bistrita has the longest mountainous course of any river in Romania, with a total length of 216 km in the Carpathian Mountains (Table 1). Vatra Dornei to Piatra Neamt, the Bistrita riverbed winds through a narrow valley flanked by steep mountainsides (Fig. 1). On either side are two mountain chains with maximum altitudes of 1859 m (peak Budacu in the Bistrita Mountains) and 1529 m (peak Bivolul in the Stanisoara Mountains). The Bistrita Valley is a creation of the river itself, with a general fluvial outline composed of the riverbed, the floodplain, and the fluvial terraces. The height of the terraces varies from 0.5–4 m to a maximum of 280 m in the flysch area (Călugăreni, Izvoru Alb ş.a.) (Donisă, 1968). The terraces and certain floodplain sections in the Bistrita Valley are highly favourable for human activity and development. Along the valley are cities and villages, a railroad, and a road that generally follows the course of the river. From a climatic point of view, the mountainous valley is characterized by a general temperate-continental climate, with nuances depending on the altitude, the shape of the valley outline, and the particularities of atmospheric dynamics (Mihăilescu, 1975).

Figs. 1 and 2 show the Bistrita drainage basin and a longitudinal profile of the river, respectively, with the positions of dams, confluences, and the sector of ice jam formation marked. On these figures are the locations of the dam (with a height of 127 m) and

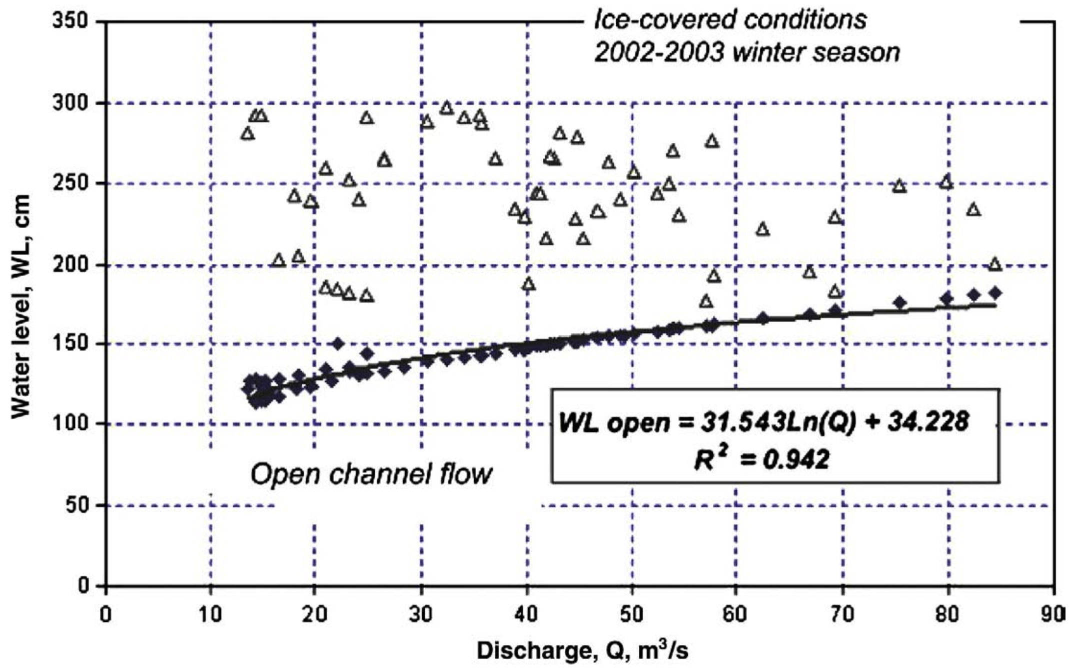

Fig. 4. Impact of ice on water level at the Frumosu Gauging Station, Bistrita River. Example for 2002–2003 winter season.

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Izvoru Muntelui Reservoir (put into use in 1960, with a volume of 1.23 billion cubic meters and a lake 33 km long) and the dam (height of 15.5 m) and Topoliceni Reservoir (put into operation in 2003, with a volume of 800 000 m^3 and a length of 3.6 km).

Ice jams happen almost yearly on the Golden Bistrita, upstream of the Dorna confluence, on the River Dorna itself, upstream of the Bistrita's confluence and on the Bistrita itself, between Vatra Dornei and Poiana Teiului. This phenomenon manifests itself most extensively in the upstream sector of Poiana Teiului, where, over a distance of 25–30 km, ice jams have reached thicknesses of 5–7 m. Monitoring of winter phenomena between 1996 and 2005 (Ştefanache, 2007) has shown that flows of frazil slush, ice cover, ice jams, and ice flows happen on an average of 94 days each year. The longest period of ice jam manifestation in this sector occurred between 2002 and 2003, with 84 days of ice jams out of 106 total days experiencing winter phenomena on the river.

3. Hydraulic geometry of Bistrita's riverbed in open-channel conditions and in ice jams formation conditions

Even though alluvial riverbeds display great mobility, they also exhibit a certain type of stability. This attribute, called dynamic stability, is a characteristic in which the different variables describing the system exhibit a resistance to small perturbations (Richards, 1982). This phenomenon is best described by the parameters of the at-a-station hydraulic geometry. The parameters most often used to characterize a riverbed are shown in Fig. 3a: *B* is the channel width, *P* is the wetted perimeter, *A* is the channel cross-sectional area, *H* is the mean depth of the riverbed, and *S* is the slope or the difference in the level of two points, e_1 and $e_{2,}$ along the riverbed.

Studies of large numbers of riverbed cross-sections have revealed two types of riverbed forms that exhibit great natural stability: a large parabolic shape in riverbeds with a perimeter of homogeneous,

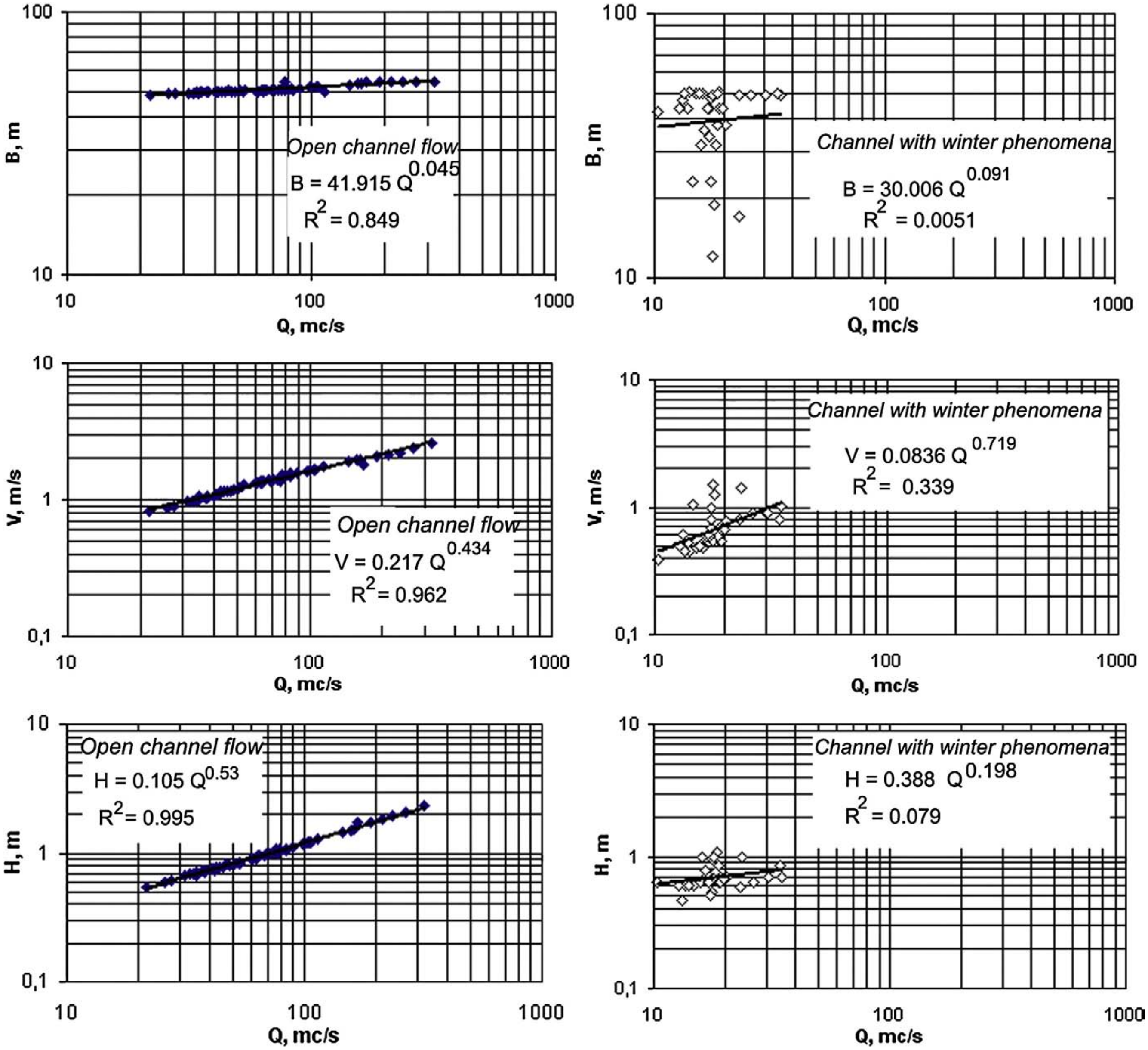

Fig. 5. The at-a-station hydraulic geometry for the Bistrita River for two conditions: open-channel flow and channel with winter phenomena (frazil ice flow, anchor ice, border ice, and ice jam).

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noncohesive sands, and a rectangular trapezoidal shape in riverbeds with a perimeter of highly cohesive clay–silt deposits (Ichim et al., 1989; Knighton, 1998). The Frumosu section of the Bistrita riverbed has a parabolic shape, with very well-outlined banks featuring sandy materials on its superior side and blocks and gravels on the inferior one (Fig. 3b). The latter material advances in the riverbed, making it rougher towards the thalweg line. In addition, the ratio between the riverbed depth and width varies between 20 and 80, resulting in an wide, shallow riverbed characteristic of rivers cut into noncohesive deposits.

The volumetric flow of the river is the single most important factor in determining the riverbed's dimensions, and the self-organizational properties and identity as a process-response system of a riverbed section are manifested through the response of its physical parameters as a function of the flow. A group of relations between the morphological system and the water–sediment cascade form what Leopold and Maddock (1953) have termed hydraulic geometry. The following three fundamental relations describe a riverbed's geometry: the width of the riverbed (B) is given by $B = A_B Q^b$, the mean depth of the riverbed (H) by $H = A_H\, Q^f$, and the flow velocity (V) by $V = A_V\, Q^m$. The product of the dependent variables gives an expression for the flow.

$$B \times H \times V = Q(\mathrm{m}^3/\mathrm{s}) \tag{1}$$

This relation is the clearest proof of the existence of a connection between these variables. From this identity which describes the continuity of movement, the multiplicative coefficients (A_V, A_B, A_H) and their exponents (b, f, m) must comply with the following conditions:

$$A_B \cdot A_H \cdot A_V = 1 \tag{2}$$

$$b + m + f = 1. \tag{3}$$

For stable, parabola-like sections, the three exponents are approximately equal ($b = m = f = 0.33$), while in rectangular sections, the exponent for the width is usually lower (~0.05). Measurements made on 139 rivers by Park (1977) and 587 rivers by Rhodes (1977) have found the following ranges for the three exponents:

$$b \approx 0.00\text{–}0.84,\ f \approx 0.01\text{–}0.84,\ m \approx 0.03\text{–}0.99.$$

On the basis of knowledge of the hydraulic geometry, one could identify dynamically stable sections of the riverbed, necessary in fitting but also in situations of modelling the transit of ice jams along the river. Also, it is important to establish the role of each variable in channel adjustment.

The ice jam reduces the flow conveyance of the channel through its blockage effect and the increase in flow resistance. This reduction in conveyance results in increase in water level, as shown in Fig. 4. A similar finding was obtained for the Mackenzie River (Chen, 1993). This backwater effect of an ice jam on water level increases with the jam thickness. The backwater caused by ice jams and its dependency

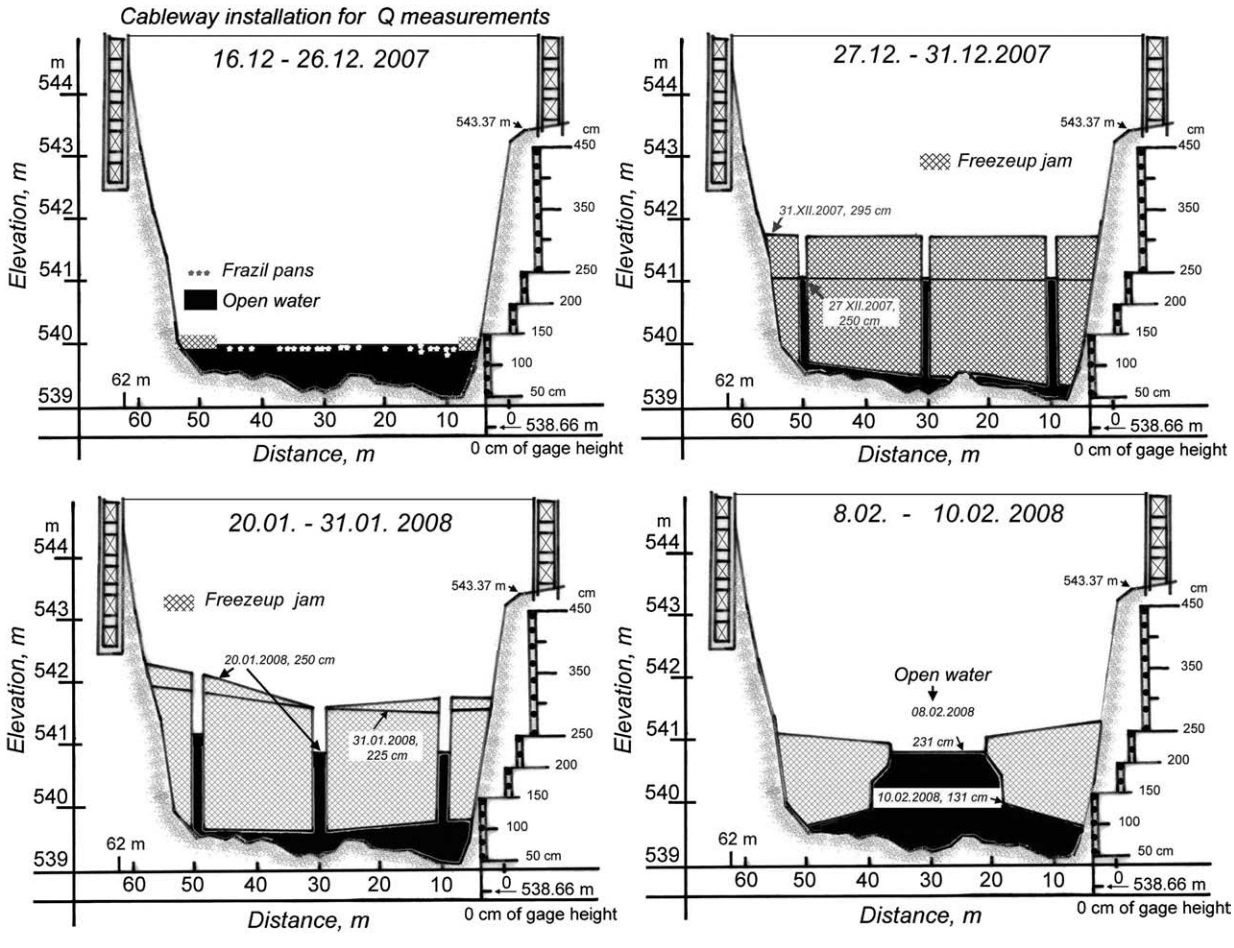

Fig. 6. Evolution of winter phenomena at Frumosu gauging station. Example for 2007–2008 winter season.

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on jam thickness, and on several other parameters, have been studied extensively (Beltaos, 1995; Sui, 2004).

To evaluate the hydraulic geometry of Bistrita's riverbed, in open-channel conditions and constrained by ices, hydrometric data have been acquired at the Frumosu station 14 km upstream of the maximal level of the Izvoru Muntelui Reservoir. Measurements have been made between 1999 and 2004 in open-channel conditions and during flow of frazil slush, border ice, ice cover and ice jams. Variations of the three fundamental variables, channel width B, average flow velocity V and the average depth H, are done by using correlation graphs function of the discharge, Q, mc/s. In Fig. 5 are shown the variations of the three parameters in open-channel conditions and in frazil slush and ice border.

In *open-channel conditions*, the hydraulic geometry of the Frumosu section is described by the following equations (Fig. 5):

$$B = 41.91\,Q^{0.04} \tag{4}$$

$$V = 0.217\,Q^{0.43} \tag{5}$$

$$H = 0.105\,Q^{0.53}. \tag{6}$$

Both the shape of the correlation curves and the sum of the exponents show that the riverbed of Bistrita in the Frumosu section is stable and uniform; its width varies from 44.4 m to 54 m, its velocity from 0.38 m/s to 2.58 m/s, and its depth from 0.38 m to 2.30 m, while the discharge varies from 6.5 m^3/s to 320 m^3/s. The sum of the exponents is $0.04 + 0.43 + 0.53 = 1.00$, which confirms a quasi-uniform flow condition.

When the *channel is constrained by the winter phenomena* (mostly border ice — there is little possibility of making measurements when ice cover or an ice jam is present), the hydraulic geometry is completely disrupted. First, the correlation graphs show a wider spread of points in the correlation space. The width and depth show the highest variation. The the width of the open-water section of the riverbed narrows from 55 m to below 10 m during the ice formation phase until it is covered completely by ice. Similarly, the depth of the riverbed falls to below 40 cm. Consequently, in the small portion of the riverbed remaining ice-free, the flow velocity increases to maintain the continuity of the flow. For this reason, the correlation slope for the flow velocity is much higher than in the open-channel case (0.719 as compared to 0.430).

In conditions of *channel constrained by the winter phenomena* (mostly border ice — there is no evidence of any possibilty of making measurements in conditions of ice cover or ice jam) the hydraulic geometry is completely bowled over. First, the correlation graphs show a wider spread of the points into the correlation space. The variables that show the highest variation are width and depth. The width of the open-water section gets narrower from 55 m to below 10 m during the ice formation phase, until it is covered completely by the ice cover. The depth of the riverbed varies in the same direction reducing to below 40 cm. Consequently, in the very low space left the river increases flow velocity to maintain the continuity of the flow. Due to this reason, the exponent for the flow velocity is much higher than in the case of the open-channel (0.719 as to 0.430).

The manner in which the measurements are made in winter at Frumosu gauging station is shown in Fig. 6. This station is equipped with a wire installation that monitors the cross-section. The period of time from the frazil pans stage to the formation of a freeze-up jam of 250 cm thick is very short — of several hours between 16 and 27 December 2007. As we will show in some other parts of our work, the phenomenon is directly influenced by the decrease in air temperature on the entire formation section of the ice jam of about 100 km, but especially in Rusca–Crucea area (localized in Figs. 1 and 2). The increase in the air temperature opened a channel in Bistrita flood plain, starting with 8 February 2008 that enlarged quickly and determined the reduction of the water level of Bistrita from 231 cm in February to 131 cm in 10 February 2008 (Fig. 6).

From this analysis of the hydraulic geometry, we conclude the following: flow in the riverbed section must be maintained by any interventional costs. No matter how much the flow space is reduced, the hydraulic parameters adjust such that the transport process is not interrupted; total blockage of this space, however, produces floods and damages. This conclusion is suggested by the images in Fig. 7 comparing the Bistrita riverbed when it is completely filled with a freeze-up jam and incapable of maintaining flow to the same riverbed in open-channel conditions.

Fig. 7. Bistrita river channel downstream Topoliceni Dam filled by freeze-up jam (February 6, 2008) and almost open (March 8, 2008). In June, the same river channel sector is showed with the bed morphology (a riffle and pool succession) and a rough surface of bed material.

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4. The analysis of the meteorological and hydrological processes that favour ice jam formation

An evaluation of the correlations among hydro-meteorological parameters on the river Bistrita has been performed with the measurements from a single hydrometric station Frumosu, on the river Bistrita, upstream of the Topoliceni Reservoir. The parameters considered are the daily values of air temperature, atmospheric precipitation, the water level of the Izvoru Muntelui Reservoir, the water level of the Topoliceni Reservoir, the water level of the river Bistrita, and the discharge of the river Bistrita. The periods analysed are the cold seasons of the years 1975–1976, 1981–1982, 1998–2004. The correlations have been analysed on the basis of time series presented in cascade (temperature → precipitation → the water level of the Izvoru Muntelui Reservoir and the Topoliceni Reservoir → the water level of the river Bistrita → the discharge of the same river) from which we extracted only a few representative examples (Figs. 8–11). Also, in the Table 2 a synthesis of these data is presented.

For the years 1976 and 1982 we analysed the variation of the hydro-meteorological factors for all the 366 days (Figs. 8 and 9, Table 2). Some years experienced climatic conditions highly favourable to ice formation on the rivers, especially air temperatures below −10 °C. The effects of these conditions appear evident in the variation of the water level of the Bistrita River at the Frumosu gauge. Comparing conditions in 1976 and 1982, we observed that in the winter of 1976, the water level of the Bistrita maintained a value of around 100 cm, while in the winter of 1982 the water level rose to about 350 cm (on the 15th of January 1982). We therefore investigated which conditions favoured the appearance of an ice jam in 1982 and not in 1976.

For 1976 and 1982, a comparison between the hydro-meteorological elements responsible for generating winter phenomena on the river Bistrita reveals that the only one that differs between the two years is the water level of the Izvoru Muntelui Reservoir. At this time, the Topoliceni Reservoir did not exist, so the Izvoru Muntelui Reservoir could directly influence the recordings from the Frumosu hydrometric station. In both years, the months January–March record a decrease in the water level of the lake, but in December 1981 and January 1982, the water level was about 1 m higher than it was in 1976.

Although this discrepancy may appear insignificant, previous research has proven that the reduction of the flow cross-section and the shutdown of flow from an ice jam spreads upstream at a significant speed of about several tens to hundreds of meters a day (She and Hicks, 2006). Our measurements made in 2007–2008 winter on the sector of 21 km upstream of Izvoru Muntelui Reservoir showed speeds of upstream propagation of this phenomenon of maximum 2 km in a single night, between 12 and 13.12. 2007. As we can see, a rise in water level is the response to such a blockage.

We also comment on another pair of charts presenting the conditions under which ice jams formed in the cold seasons 2002–2003 and 2003–2004 (Figs. 10 and 11, Table 2). In the winter 2002–2003, winter phenomena on the Bistrita River experienced one of its most complex and extended stages of evolution, with disastrous effects for the inhabitants of the villages on Valea Muntelui (3 dead

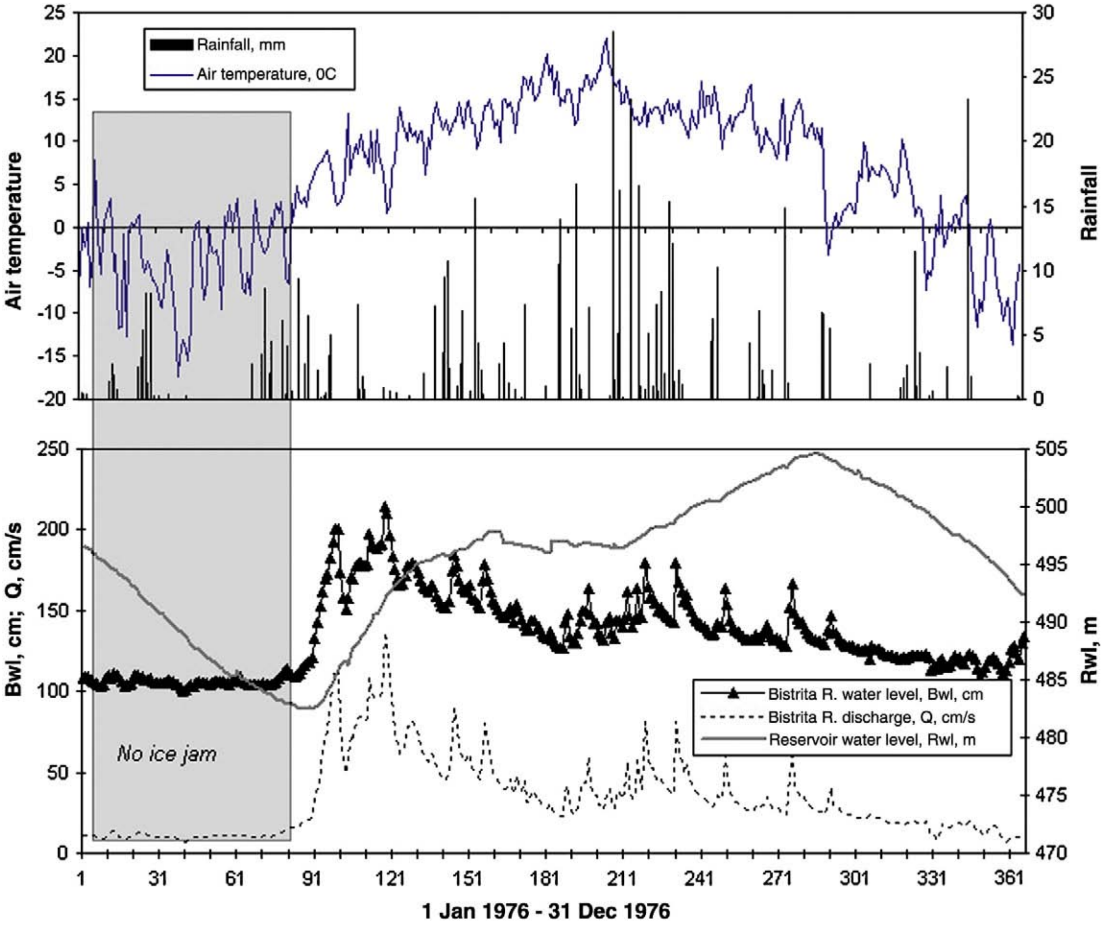

Fig. 8. Variation of the controlling factors of the ice jam at Frumosu station, Bistrita River in 1976. Other comments are in the text.

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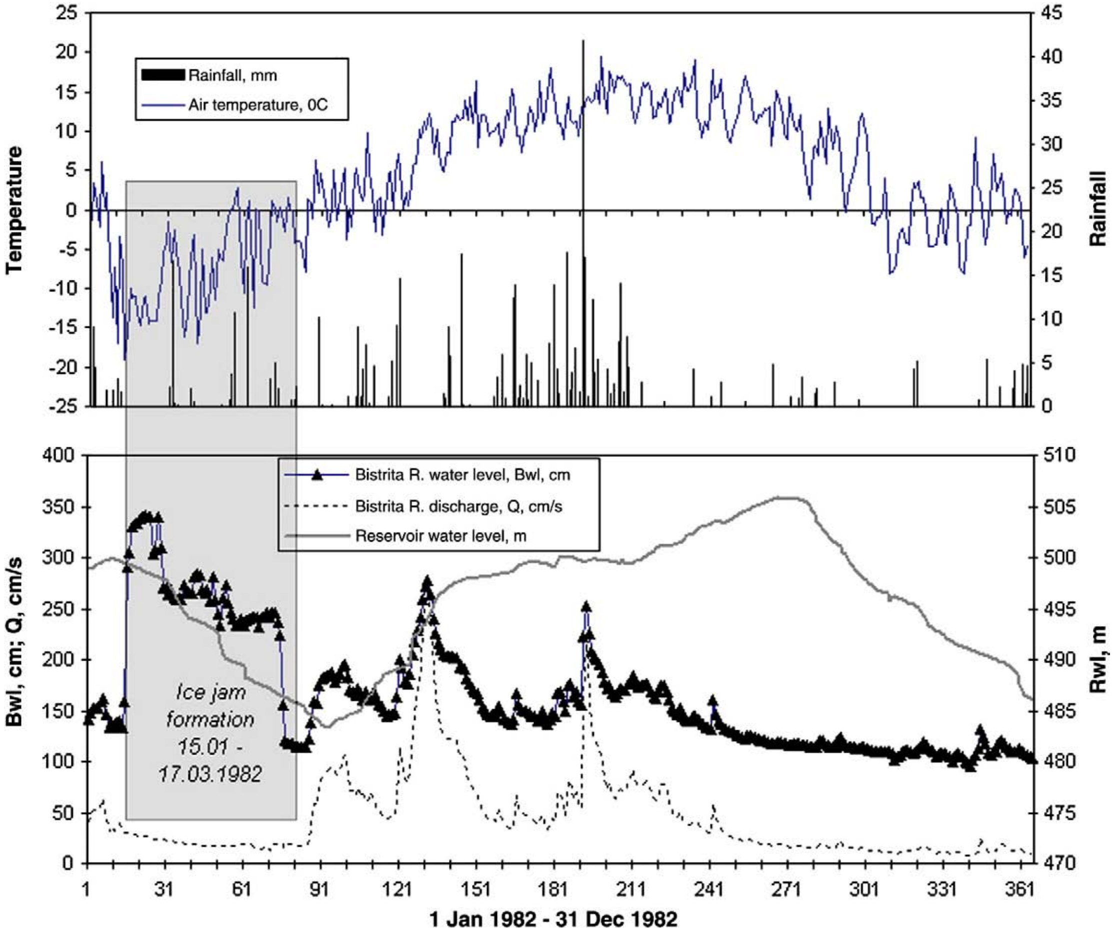

Fig. 9. Variation of the controlling factors of the ice jam at Frumosu station, Bistrita River in 1982. Other comments are in the text.

persons and 98 destroyed houses). Ice blockages from the tail of the Izvoru Muntelui Reservoir lay 21 km upstream, with a maximum thickness of 6 m (Surdeanu et al., 2005; Ştefanache, 2007). Between December 2, 2002, and March 7, 2003, the daily average temperature was almost continuously below zero except for two short periods when the temperature rose to 3–5 degrees above zero. The ice blockages eventually broke and, accumulating ice encountered on their way downstream, increased the pressure upon the downstream ice jam, causing the water discharge that led to the most damage. Significantly, during all this time of accumulation and overlapping of ice blocks, the level of the Izvoru Muntelui Reservoir remained high (between the 18th of November and the 9th of December, 2002, the water level of the lake was over 508 m). Only after the 10th of December did the water level start to decrease very slowly, yet the size of the massive upstream ice blockage on the river remained unaffected. The most compact ice jam appeared between the 3rd of February and the 6th of March, 2003, when the flood level was 3 m high.

The above situation must be compared with that in the following cold season (2003–2004) (Fig. 11). Between the 2002–2003 and 2003–2004 cold seasons, the Topoliceni Dam came into operation, leading to reservoir accumulation that created a new base level for the river Bistrita and a new interruption of the flow. The winter started rather mildly, with daily average temperatures of around −1 °C to 3 °C and culminating with −10.7 °C on the 26th of December, 2003, when the activity of the Topoliceni plant stopped because the accumulation had filled with ice from upstream. Two days later, on the 28th of December, 2003, at the Frumosu station upstream of the Topoliceni Reservoir, the water level of Bistrita rose suddenly by about 1 m and remained so until the 7th of March, 2004. At this point the blockages disappeared, and the Topoliceni Reservoir returned to its normal level of water retention. Throughout this time, the water level of the Izvoru Muntelui Reservoir remained low, below 487 m and even 483 m, but this fact had little influence on the hydrological activity in the Frumosu section. Instead, the effects of the Topoliceni Reservoir and the role of the accumulation basin of the ice prevailed.

The presented observations reveal that the causality of ice jam formation on the river Bistrita is neither simple nor reducible to an absolute generalization. To avoid the mistake of attributing a single, supreme cause to ice jam formation, we describe offer counter-examples where ice jams did not occur. For example, we noticed that ice jams did not automatically appear in 1976, 1999–2000, or 2000–2001, despite temperatures below −15 °C. In contrast, such phenomena did appear at milder temperatures.

For ice jams to form at milder temperatures, it could be that the ice that accumulates at the tail of the Izvoru Muntelui Reservoir – Farcaşa and that will appear upstream of the Topoliceni Reservoir originates farther upstream, where the climatic conditions are more severe. According to one of the authors (V. Ciaglic), the source of this ice is on the Bistrita river, in the Rusca – Crucea area (Fig. 1). We plan to investigate in future research.

Another puzzling factor was the role of the Izvorului Muntelui Reservoir. The effect of the new base level determined by the reservoir arrangement, with all the implicated hydraulic mechanism, is generally accepted as a primary cause for ice jam formation. Less understood are the mechanism by which the water level fluctuates

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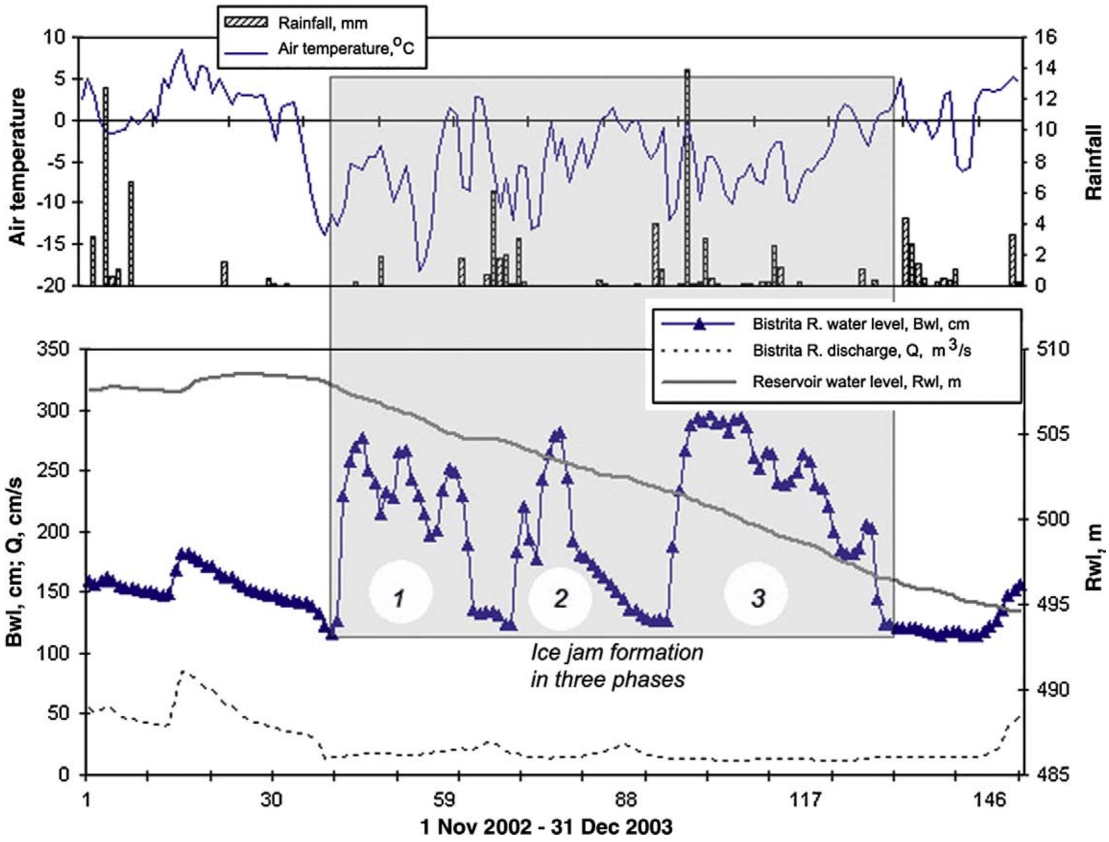

Fig. 10. Variation of the controlling factors of the ice jam at Frumosu station, Bistrita River in 2002–2003 (when the most dangerous ice jam had occurred). Other comments are in the text.

and the optimal level in order to avoid ice jam formation. We will offer a hypothesis later in this work, but, until then let us discuss the variation of hydro-meteorological parameters in the winter 1999–2000, when the air temperature decreased below −15 °C several times at Frumosu (with even lower upstream values), and yet no ice blockages appeared on the river. One possible cause is that the water level of the reservoir was below 499 m, because in 2001–2002 and 2002–2003, at similar air temperatures but at lake levels of over 508 m, blockages appeared on the river Bistrita lasting between 50 and 108 days with all the associated unwanted effects.

5. The role of the Izvoru Muntelui lake in determination of the upstream ice jam

The earliest information we have regarding ice jam formation on the Bistrita River upstream of the Izvoru Muntelui Reservoir appears in a study performed by the Piatra Neamt Hydrological Station in 1973 and published in 1975 (Ciaglic et al). The authors concluded that jamming of the riverbed with frazil slush starts not where the river enters the lake — Poiana Largu area, but much lower inside the lake's basin. To be more exact, the first blockade of the riverbed appeared under ice cover in the Calugareni area, near the left shore of the reservoir, where the river curves tightly (Fig. 12).

This observation was based on rills and ephemeral gullies starting at the riverbed, the presence of which suggests that water passing through the riverbed was forced by the blockage to find a new way to the interior of the lake. The same study notes that the blockage of the riverbed occurred while the level of the lake was slowly but continuously dropping. The transparency of the water at the confluence was very reduced, to 15–30 cm, compared to over 200 cm towards the interior of the lake. This unusual phenomenon was produced while, considering the very low flows inside the river (between 0.005 and 0.144 kg/m^3), turbidity was also reduced at the entrance in the lake. The increase of the turbidity and the consequently high decrease in transparency at the tail area of the lake thus appears as a paradox. The explanation is as follows: as the level of the lake dropped, particles deposited during the former submerse epoch were put into motion by the force of the current.

Our observations during February–March 2008 confirm the suppositions of these previous authors that the first blockade (ice jam) starts inside the lake under the ice cover and then gradually extends upstream. Once the ice cover from the lake's tail area had melted, along the entire course of the Bistrita River, from Calugareni to the Topoliceni dam, the riverbed was revealed to be completely filled with freeze-up jam clogged with deposits and covered with sediment layer of about 10–15 cm, on top of which there persisted some ice areas on the lake surface in an advanced stage of melting (Fig. 13).

The mechanism by which the first blockage forms is comprised of two stages: the *submersion stage*, consisting of the slow development of spongious ice (frazil ice) and the *emersion stage*, when the process moves into the riverbed and advances upstream at high velocity. From this moment onward, the evolution of the hydro-meteorological conditions in combination with the characteristics of the horizontal plane of the riverbed (bottlenecks, windings, sudden changes of movement) and the vertical plane (alternations of segments with broken slopes, segments with high slopes and steps, blocks in the riverbed) can produce uncontrollable situations.

6. Summary and conclusions

Our survey on thaw phenomenon falls into the broader category of the winter phenomena that appear upstream of the reservoir. Burgi and Johnson (1971) showed that where a river enters the backwater of a reservoir is one of the most common places that these jams occur. The problems created by ice jamming in Bistrita channels upstream of the reservoir manifest over a distance of 25–30 km. Here ice jams

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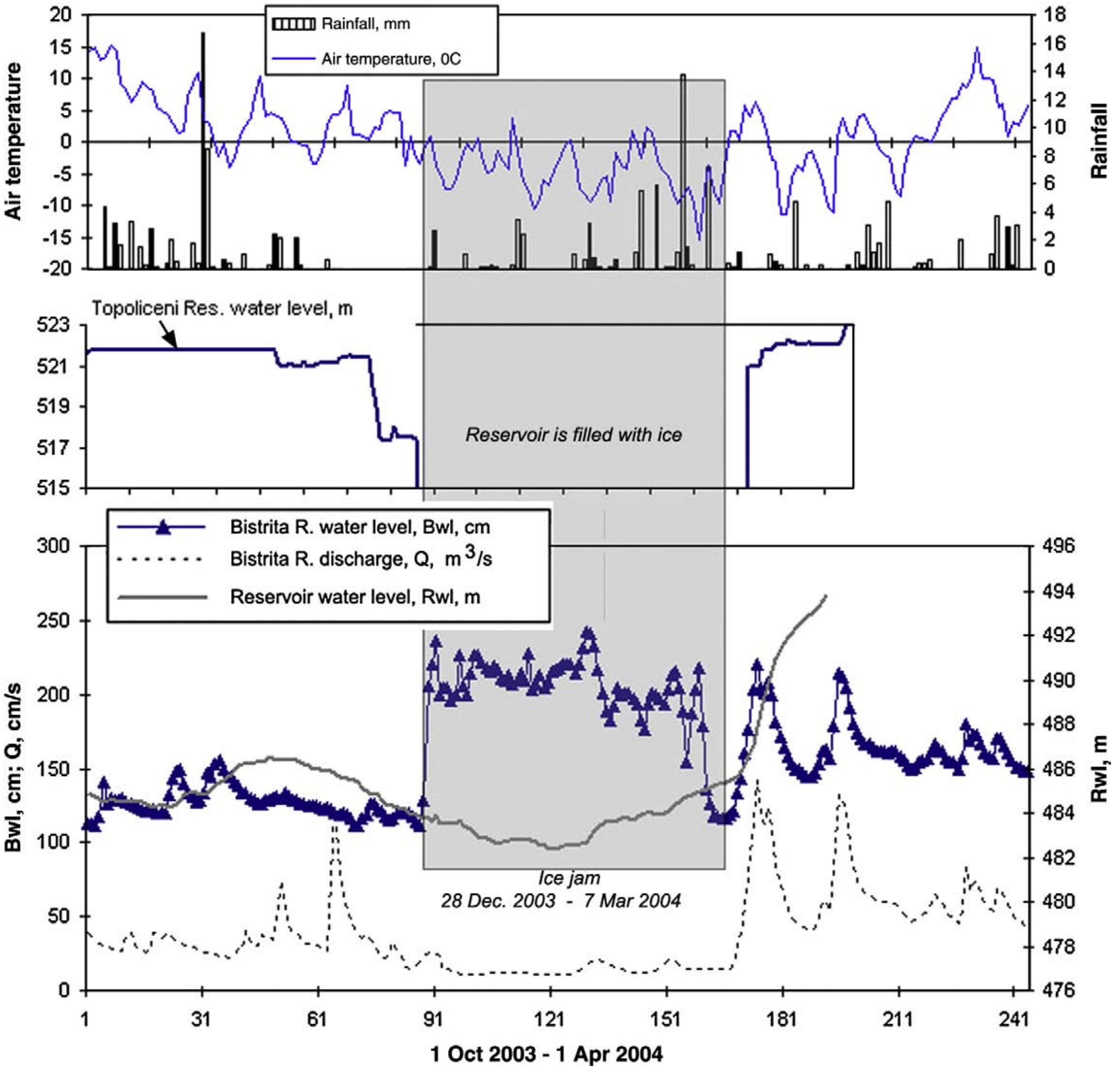

Fig. 11. Variation of the controlling factors of the ice jam at Frumosu station, Bistrita River in 2003–2004 (when the Topoliceni Reservoir was put to use). Other comments are in the text.

Table 2
Summary of the hydro-meteorological conditions of ice jam formation upstream of Izvoru Muntelui Reservoir.

Year	Analysed period, days	*T* air, °C	Rainfall, mm	River water level, cm	*Q*, m^3/s	Reservoir water level, m	Observations
1976	14.01 ÷ 20.01	− 5.0 ÷ − 12.8	2.8 ÷ 0.7	110 ÷ 104	12.5 ÷ 10.0	496 ÷ 493	No ice jam
	6.02 ÷ 13.02	− 8.3 ÷ − 17.3	No	106 ÷ 103	9.66 ÷ 7.38	489 ÷ 487	No ice jam
1982	8.01 ÷ 28.01	− 13.6 ÷ − 19.1	1.8 ÷ 3.1	146 ÷ 340	32.0 ÷ 23.0	499 ÷ 498	+ 195 cm water level determined by ice blockage
1998	2.12 ÷ 12.12	− 6.9 ÷ − 11.7	0.1 ÷ 0.8	124 ÷ 317	20.0 ÷ 19.5	500 ÷ 499	+ 193 cm water level determined by ice blockage
	19.12 ÷ 29.12	− 7.5 ÷ − 18.7	0.2 ÷ 2.8	165 ÷ 278	18.3 ÷ 18.9	498 ÷ 496	+ 113 cm water level determined by ice blockage
1999	23.01 ÷ 6.02	− 8.0 ÷ − 13.4	0.1 ÷ 8.3	182 ÷ 186	14.3 ÷ 15.4	502 ÷ 498	No ice jam
2000	22.12 ÷ 26.12	− 5.0 ÷ − 12.6	3.1	119 ÷ 124	9.4 ÷ 6.25	496 ÷ 495	No ice jam
	3.01 ÷ 28.01	− 7.7 ÷ − 15.7	0.1 ÷ 1.3	119 ÷ 126	12.9 ÷ 16.4	496 ÷ 491	No ice jam
2001	13.01 ÷ 24.01	− 5.4 ÷ − 10.8	0.2 ÷ 2.1	102 ÷ 146	5.1 ÷ 6.8	508 ÷ 500	+ 44 cm water level determined by ice blockage
2002	8.12 ÷ 13.12	− 9.4 ÷ − 13.8	No	116 ÷ 277	15.5 ÷ 18.0	509 ÷ 504	+ 161 cm water level determined by ice blockage
2003	7.01 ÷ 21.01	− 7.0 ÷ − 13.3	0.1 ÷ 6.1	124 ÷ 282	÷	507 ÷ 502	+ 158 cm water level determined by ice blockage
2003	2.02 ÷ 6.03	− 4.4 ÷ − 12.2	0.1 ÷ 13.9	127 ÷ 293	12.7 ÷ 13.0	501 ÷ 496	+ 166 cm water level determined by ice blockage
2003–2004	26.12.2003 ÷ 8.03.2004	− 4.3 ÷ − 15.4	0.6 ÷ 13.7	111 ÷ 236	14.5 ÷ 25.5	Topoliceni Res. filled with ice	+ 125 cm water level determined by ice blockage
2007–2008	16.12.2007 ÷ 10.02.2008	− 4.9 ÷ − 15.4		108 ÷ 250		Topoliceni Res. filled with ice	+ 142 cm water level determined by ice blockage

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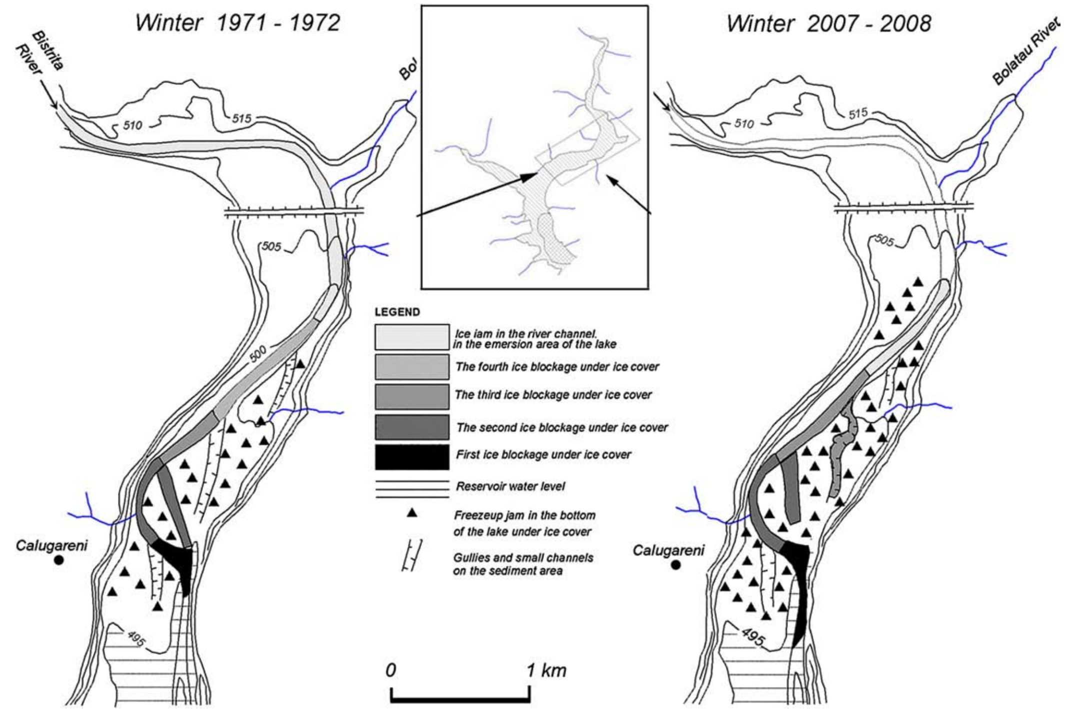

Fig. 12. The mapping of the winter phenomena on the Bistrita river channel in the Izvoru Muntelui Reservoir area; this is former area of ice jam formation and its upstream migration.

Fig. 13. Ice obstruction of the Bistrita river channel induced a change in the course of the river (Calugareni area in the emersion area of the Izvoru Muntelui Reservoir): March 1972 (photo: I Miron); March 2008 (photo: N. Rădoane).

have reached thicknesses of 5–7 m. Monitoring of winter phenomena between 1996 and 2005 has shown that flows of frazil slush, ice cover, ice jams, and ice flows happen on an average of 94 days each year. Analysis of the hydroclimatic and morphological conditions of the riverbed has revealed that a certain combination of their temporal variations is favourable to ice jam formation. The hydraulic geometry of the Bistrita river bed is favourable to the flow of frazil slush, frazil pans, and ice floes while the air temperature is below −7 °C and the water level of the Izvoru Muntelui Reservoir is below 500 m. Above this level, ice jams block the river bed, and this blockage advances upstream at velocities of several hundred meters per day.

The appearance in 2003 of the Topoliceni Reservoir, 4 km upstream of the Izvoru Muntelui Reservoir, has complicated the evolution of these winter phenomena, with the lake itself acting as an accumulation pool for ice from upstream. This development has led to damages and inconveniences in canals and at the entrances to power plants, spillways, outlet works, and other hydraulic structures.

The local community, seriously affected by the consequences, was alarmed by the fact that before the appearance of the Izvoru Muntelui Reservoir, no ice jam phenomena had been reported in the area. During the winter, the press campaigns violently against the local authorities, who are incapable of viable solutions. The issues we raise in this paper indicate that the human factor is the main cause of the persistence and the magnitude of this natural phenomenon. That is why we appreciate the initiative of the Hydroelectrical Company to support research in order to find a balance between attenuation measures and minimum effects of the social, economical and ecological level.

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