RESEARCHES ON THE ICE JAM FORMATION IN THE UPSTREAM OF IZVORU MUNTELUI RESERVOIR

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Key words: frazil slush, ice jam, hydraulic geometry, hydroclimatical conditions, reservoirs, Bistrița River.
Cuvinte cheie: năboi, zăpor, geometrie hidraulică, condiții hidrometeorologice, lacuri de acumulare, râul Bistrița

Abstract. The current work provides a description of the ice jam phenomena along the river of Bistrita, which has the longest mountainous course in Romania (216km). During the cold season of the year, in the upstream of the Izvoru Muntelui Reservoir over a length of 25-30 km, there are generated with a almost yearly frequency ice blocks accumulations known as ice jams. Analysis of the hidroclimatical and morphological conditions of the river bed has revealed that they are favorable to formation of ice jam provided there is present a certain combination of their temporal variations. Hidraulic geometry of the Bistrita river bed is favorable to flow of frazil slush, frazil pans and ice floes while the air temperature is -7 oC as long as the level of Izvoru Muntelui Reservoir is below 500 m. Over this level, the river bed is blocked with ice jam during the submerse phase of the lake and this blockage advances upstream with velocities of several hudreds of meters per day. The most dramatic phenomena has been recorded during the winter of 2002-2003 when the thickness of the ice was of 6 meters and it caused floods that provoked damages and claimed human lives. Aparition in 2003 of the Topoliceni Reservoir, placed 6 km upstream of the Izvoru Muntelui Reservoir, has complicated the evolution of the phenomena, the lake itself acting as an accumulation pool for the ices in the upstream.

1. Introduction

Aglomerations or ice dams that form on rivers during winter seasons are an usual manifestation in temperate regions. An ice season can last more than 100 days for most of the rivers from Scandinavia, Russia and Canada and it can reach latitudes of 420 şi 300N in North America and Asia (Bates, Bilelo, 1966). Also knowns as ice jam (in Romanian zapor, in Russian zator, in French embâcle, in German as Eisbarre according to Savin, 1966) these ice aglomerations block the flow of the river (usually reduced during this time of the year) and cause large floods. By their effect, ice jams are considered as the most hazardous winter phenomena on the rivers (Ashtn, 1986). With this reason in mind the scientists have long time been focused on the understanding of this phenomenon, establishing the cause and mostly to finding solutions for the attenuation of the negative effects. Numerous examples of damages and loses of human lives have been signaled during winter time on rivers in Canada and U.S.A., Russia, scandinavian countries, Island, Japan and China etc. which were thoroughly commented in a long series of studies by the well known canadian scientist Beltaos (2007, 2008) and his team (Prowse, Conly, 1998; Prowse, Beltaos, 2002; Prwose, Bonsal, 2004). Also, there were published inventorying catalogues for the Siberian rivers (Korytny, Kichigina, 2006), large paperworks, inventories and specialized web sites (we're mentioning here the site US Army Corps of Engineering, the Cold Regions Research and Engineering Laboratory - http://www.crrel.usace.army.mil/icejams/ - which presents some of the most complex informations regarding the ice dams phenomena, ice jams, and in general analysis of causes, sistematics of the phenomena, field and laboratory experiments, effects upon the other components of the environment and the whole range of attenuation measures).

In Romania, interest in reasearching winter phenomena on rivers date back since '60s, when it started the developement of the national network of observation of hidrological phenomena on rivers (Semenescu, 1960; Constantinescu, 1964; Ciaglic, 1965; Ciaglic, 1985; Ciaglic, Vornicu, 1966, Ciaglic et al, 1975). Winter floods on the mountain rivers in our country (Moldavian Bistrita, Transilvanian Bistrita, the Mures, the Danube etc.) have captured the interest of climatologists, hidrologists, geomorfologists but also for specialists in river engineering, which has resulted into PhD thesis and numerous articles and book chapters (Miță, 1977; Musteţea, 1996; Păvăleanu, 2003; Romanescu, 2005; Surdeanu et al., 2005; Ştefanache, 2007).

Winter phenomena with dangerous effects have in the riverbed and the valley of Bistrita upstream of the Izvoru Muntelui Reservoir have caused a series of investigations in studies and analysis of the phenomena, mostly from the Hidroelectrica Company, office of Piatra Neamt (1997, 1998); most of the current paperwork has resulted from such collaboration and financial support from the formentioned company.

As for our interdisciplinary team of hidrology and geomorphology, we have focused on the analysis of the ice jam phenomena on the Bistrita riverbed upstream of Izvoru Muntelui Reservoir, with a special look on the sector placed between the tail of the lake and the Topoliceni dam. The analysis was made on the basis of the latest progresses in researching the phenomena, our own experience in the region of study and on the basis of detailed observations during the cold season 2007 - 2008. The main targets of our study are the following: a) presentation of the region of study with a closure look over the dynamics of Bistrita's riverbed in the upstream of Izvoru Muntelui Reservoir; b) the hidraulic geometry of Bistrita's riverbed in free conditions and in ice jam conditions; c) analysis of the climatic and hidrologic processes favourable to formation of iced jam; d) considerations over the causes of ice jam formation in the upstream of Izvoru Muntelui Reservoir.

2. The zone of study

Bistrita is the river with the longest mountaineous course in Romania, with a total length in the Carpathian Mountains of 216 km. From Vatra Dornei to Piatra Neamt, the valley of Bistrita is a narrow lane with steep mountain sides on its sides and in which the riverbed is winding. On one side and the other there are two mountain chains with altitudes of 1859 m (peak Budacu in the Bistrita Mountains) and of 1529 m (peak Bivolul in the Stanisoara Mountains). The valley of Bistrita is a creation of the river itself, in such way that the most important genetic outline is the fluvial outline composed of the riverbed, the floodplain and the fluvial terraces. Their altitude varies from 0,5 - 4 m to a maximum of 280 m in the flysch area (Călugăreni, Izvoru Alb ş.a.). The terraces and some floodplain steps from the valley of Bistrita are the fields that are the most favourable to developement of human activities. Along the valley there are cities and villages, the railroad and most of the road that accompanies the river. From a climatic point of view the mountaineous valley is characterized by the general temperate-continental with different nuances depending on the altitude and the shape of the outline, and the particularities of the atmosphere's dynamics.

In figure 1 it is shown the longitudinal profile of the river, the position of the dams, positions of the confluences and mostly it is specified the sector of formation for ice jam. On this profile there are located the dam (with a height of 127 m) and lake Izvoru Muntelui (which was put in function in 1960, with a volume of 1,23 billions cubic meters and a length of the lake of 33 km) and the dam (height of 15,5 m) and the lake of Topoliceni (put in function in 2003, with a volume of 800 000 cubic meters and a length of 3,6 km).

The winter phenomena of the ice jam kind happen almost yearly on the Golden Bistrita, upstream of the Dorna confluence, on the River Dorna itself, in the upstream of Bistrita's confluence and on the Bistrita itself, between Vatra Dornei and Poiana Teiului. The sector in which this phenomen manifests most ample is the one in the upstream of Poiana Teiului on a distance of 25 - 30 km, ice jams have reached thickness of 5 - 7 m. Monitorization of the winter phenomena between 1996 and 2005 (Ştefanache, 2007) have shown a medium presence of 94 days each year there are flows of frazil slush, ice cover, ice jam and ice flows. The longest period of manifestation of ice jam in this sector was between 2002 - 2003, respectively, in 84 days from 106 days with winter phenomena.

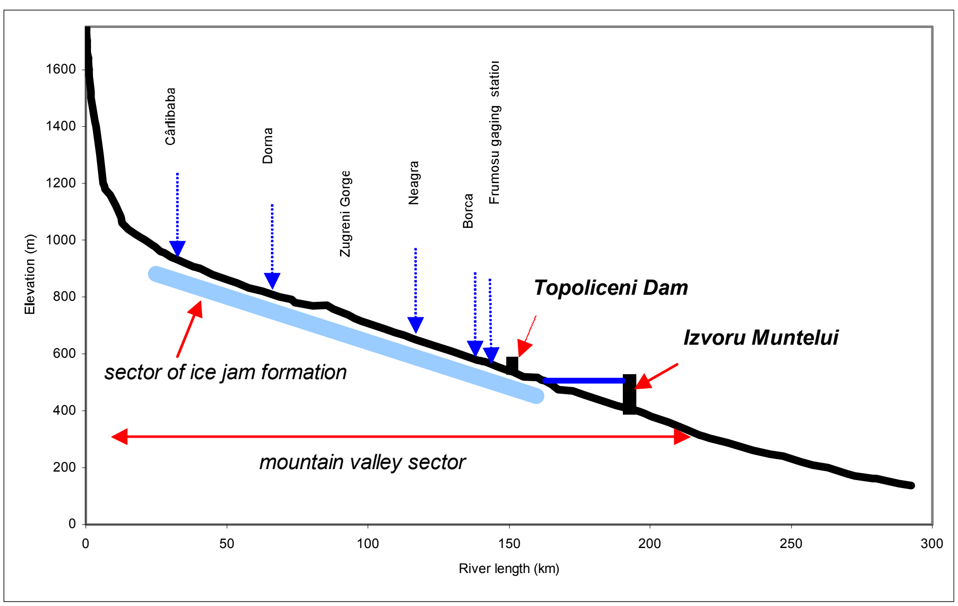

Fig. 1. Longitudinal profile of the Bistrita River, with the research location.

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

It is well known that even though aluvial riverbeds present great mobility there is always the oportunity to define a certain stability in relationship with them. This is called dinamic stability or in other words put, it is a dynamic in which relations between different variables which compose the system keep themselves in terms with low change rates. This phenomenon is best described by the parameters of the at-a-station hidraulic geometry. The most used descriptors of the riverbeds are shown in figure 2 of which B is the channel width, P is the wet perimeter, A is the channel cross-section area, H is the depth of the riverbed and S is the slope or the difference of level between two points e1 şi e2, along the riverbed.

Studies on large populations of riverbed cross-sections have shown approximately two types of outlines with great stabilty in nature: a large parabola shape in riverbeds with a perimeter of homogenic noncohesive sands; a rectangular trapezoidal shape in riverbeds with a perimeter of clay-siltous deposits of great cohesion. For the BIstrita riverbed, the Frumosu section has a parabola shape, with very well outlined banks, with sandy materials in its superior side and blocks and gravels in the inferior one (figure 2). The latter material advances in the riverbed which becomes rougher towards the thalweg line. Also, the ratio between depth and width varies between 20 and 80, which results in an wide and shallow riverbed, which is another characteristic for rivers cut into noncohesive deposits.

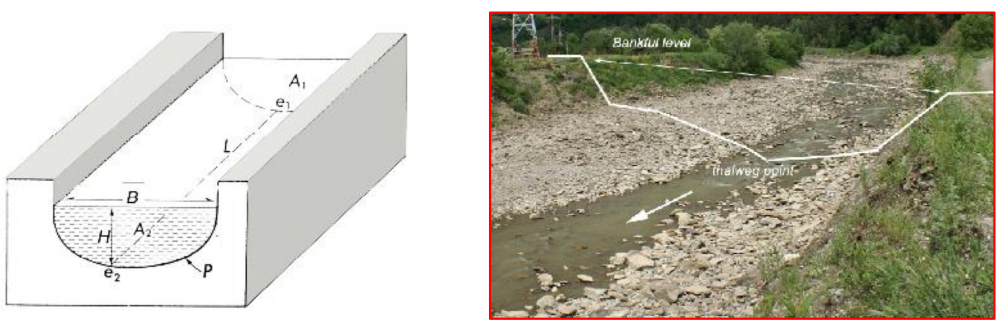

Fig. 2. Dimensional elements used in at-a-station hydraulic geometry determination (Bistrita River at Frumosu cross section).

The properties of selforganization and identity as a process-response system of the section are manifested through adjusting its variables as a function of the flow, which is the most important factor of determining of the riverbeds dimensions. These relations which make cohesion between the morfological system and the water-sediment cascade form what Leopold and Maddock (1953) have named it hidraulic geometry. In this way it has been established that the description of the riverbed's geometry considers the following three fundamental relations: for the width of the riverbed (B), B =ABQb, for the medium depth of the riverbed (H), H =AH Qf and for the flow velocity (V), V =AV Qm. At a closure look, the product of the dependent variables give a measure expression of the flow.

B . H . V = Q (m3/s).

This is the most clear proof of the existence of an adjustment between these variables. From this axiom which describes the continuity of the movement, the multiplication coefficients (AV. AB, AH) and their exponents (b,f,m) must comply to the following conditions:

AB . AH . AV = 1

b + m + f =1

For stable parabola-like sections the three exponents are approximately equal b=m=f=0,33 while in rectangular sections the exponent of the width is usualy lower(0.05). Measurements made on 139 rivers by Park(1977) and 587 rivers by Rhodes (1977) have found the following ranges of the three exponents:

$b \approx 0,00 = 0,84$, $f \approx 0,01= 0,84$, $m \approx 0,03 = 0,99$

Knowledge of the hidraulic geometry is important, on its basis one could identify from a dynamic point of view the stable sections, so 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 this adjustment.

To evaluate the hidraulic geometry of Bistrita's riverbed, in open-channel conditions and constrained by ices, hidrometric 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 - 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, is done by using correlation graphs function of the discharge, Q, mc/s. In figure 3 are shown the variations of the three parameters in open-channel conditions and in ice jam, ice cover and frazil slush.

In open-channel conditions, the hidraulic geometry of the Frumosu section is described by the following equations(figure 3):

B = 41.91 Q0,04

Vm = 0,217 Q0,43

Hm = 0,105 Q0,53

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 varies from 0,38 m/s to 2,58 m/s and its depth grows from 0,38 m to 2,30 m while the discharge varies from 6,5 m3/s la 320 m3/s. The sum of the exponents 0,04 + 0,43 + 0,53 = 1,00, which confirms a quasi-uniform flow condition.

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 hidraulic 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 riverbed 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 correlation slope for the flow velocity is much higher than in the case of the open channel (0,719 as to 0,430).

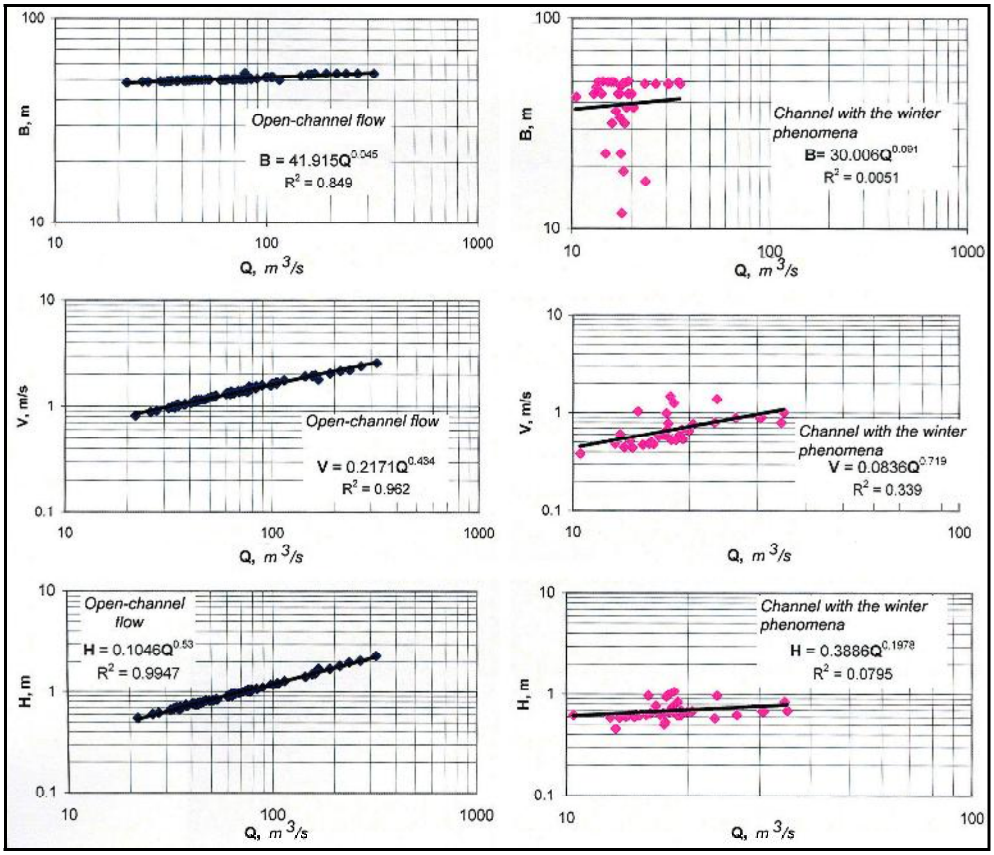

Fig. 3. The at-a-station hydraulic geometry for Bistrita River for two conditions: open-channel flow and channel with the winter phenomena (frazil ice flow, anchor ice, border ice, ice jam).

Fig. 4. Bistrita river channel downstream Topoliceni bridge filled by freezeup jam (February 6, 2008) and almost open (March 8, 2008).

The conclusion that we draw from the analysis of the hidraulic geometry is the following: flow in the riverbed section must be maintained by any interventional costs. No matter how much the flow space is reduced, the river adjusts ints parameters such that the transport process is not interrupted; total block of this space produces floods and damages. This is suggested by the compared images in fig. 4 on the riverbed of Bistrita is completely filled with freezeup jam and incapable to maintain flow of the river and the same riverbed in open-channel conditions.

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

The evaluation of the correlations between the parameters of the air and the water of the river Bistrița has been done according to the measurements at the same hydrometric station Frumosu, on the river Bistrița, upstream the Topoliceni Reservoir. The parameters taken into consideration have been the daily values of air temperature, the atmospheric precipitations, the water level of the Izvoru Muntelui Reservoir, the water level of the Topoliceni Reservoir, the water level of the river Bistrița, the discharge of the river Bistrița. The period analyzed have been the cold seasons of the years 1975-1976, 1981-1982, 1998 – 1999, 1999 – 2000, 2000 – 2001, 2001 – 2002, 2002 – 2003, 2003 - 2004. The correlations have been analysed on the basis of the diagrams of the type of time series presented in cascade (temperature →precipitațtions→the water level of the Izvoru Muntelui Reservoir and of the Topoliceni Reservoir → the water level of the river Bistrița → the discharge of the river) from which we extracted only a few examples (figures 5, 6).

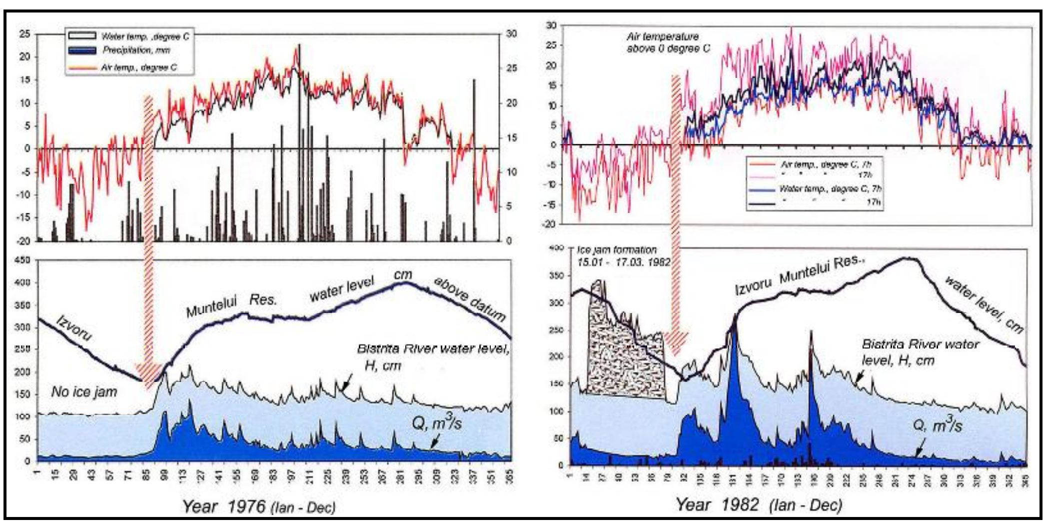

Fig. 5. Variation of the controlling factors of the ice jam at Frumosu station, Bistrita River in 1976 and 1982. Other comments in the text.

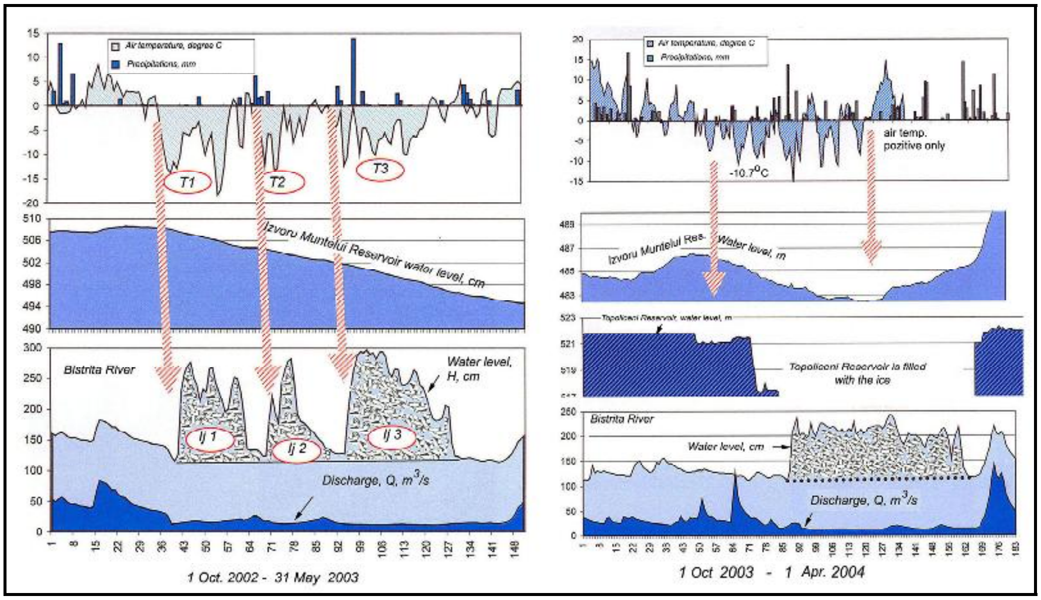

Fig. 6. Variation of the controlling factors of the ice jam at Frumosu station, Bistrita River in 2002 –2003 (when the dangerest ice jam occured) and 2003 – 2004 (when Topoliceni Reservoir has been set working). Other comments in the text.

For the years 1976 and 1982 we analyzed the variation of the hydro-meteorological factors for all the 365 days (figure 5). There have been years when from the climatic point of view there were conditions of ice on the rivers, especially air temperature values below –100C. The effect of these conditions appear evident in the variation of the water level of the river Bistrița. Comparing the two situations (1976 cu 1982) we noticed that in the winter of the year 1976 the water level of Bistrița maintained around the value of 100 cm, while in the winter of 1982 the value rose at about 350 cm (on the 15th of January 1982). Which was the cause that determined this situation that favoured the apparition of ice jam in 1982 in comparison with 1976?

Drawing a comparison between the hydro-meteorological elements that generated the winter phenomena on the river Bistrița, the only one that differs is the position of the water level of the Izvoru Muntelui Reservoir. In this period the Topoliceni Reservoir did not exist, so the recordings from hydrometric station Frumosu could be influenced directly by the Izvoru Muntelui Reservoir. In both cases, the months January- March record a decrease of the water level of the lake, the difference consisting in the fact that in December 1981 and january 1982, the value was higher with about 1 m as compared with 1976.

Although this situation may appear insignificant, the research carried out have proved that the reduction of the flow section and the shutting of the ice jam spreads upstream with an important speed of about several tens and hundreds of meters a day. (She, Hicks, 2006). As we can see, the effect of the rise in the water level has an immediate response. For some rivers, such as Athabasca in Canada, the rise of the level was of 4.4 m in 15 minutes (Kowalckyk, Hicks, 2003).

Another pair of charts that we comment upon are those presenting the situation of the ice jam formation in the cold seasons 2002 – 2003 and 2003 – 2004 (figure 6).

In the winter 2002 - 2003 the winter phenomena on the Bistrița river had one of the most complex and extended stage of evolution, their effects proving to be disastrous for the inhabitants of the villages on Valea Muntelui (3 dead persons and 98 destroyed houses). The ice blockages from the tail of the Izvoru Muntelui Reservoir lay upstream on 21 km, with maximum thickness of 6 m (Surdeanu et al., 2005; Ştefanache, 2007). Between the 2nd of December 2002 and the 7th of March 2003 the daily average temperature values were almost permanently negative except for two short periods of temperature rise with 3– 5 degrees over zero. The ice and the blockages broke and cumulating those they encountered on their way, increased the pressure upon the downstream ice jam, causing the biggest water discharge, with the most important damage. It is important to remark the fact that during all this time of accumulation and overlapping of the ice blocks, the level of the Izvoru Muntelui Reservoir was maintained 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 is started decreasing very slowly, yet without influencing the massivity of the upstream ice blockage on the river. The most compact ice jam appeared between the 3rd of February – the 6th of March 2003, period when the flood level was 3 m thick.

The above presented situation has to be compared with that in the following cold season (2003 – 2004), the element of new that appeared in the meantime being the functioning of the Topoliceni accumulation that created a new level basis on the river Bistrița, a new interruption of the flow. The winter started rather mild, with daily average values of the temperature of around –10C , - 30C, culminating with –10,70C on the 26yh of December 2003, when the activity of the Topoliceni plant stops because the accumulation is filled with ice from upstream. Two days later, on the 28th of December 2003, at la Frumosu upstream the Topoliceni Reservoir, the water level of Bistrița rises suddenly with about 1 m and remains so until the 7th of March 2004. In this moment the blockages disappear and the Topoliceni Reservoir comes back to its normal water level of retention. In all this time the water level of the Izvoru Muntelui Reservoir remained at small values, below 487 m and even below 483 m, but for the hydrological activity in the Frumosu section this fact was not influential at all. This time, the effect of the Topoliceni Reservoir and the role of accumulation basin of the ice prevail.

Out of the presented facts results a general and commonsensical observation: the causality of the ice jam formation on the river Bistrița is not a simplist one or generating of absolute truth. We insisted upon the description of a contradictory situation, just to avoid making the mistake of imposing a supreme cause. For example, we noticed the fact that the decrease of the temperature value below –150C did not automatically cause ice jam apparition (in 1976, but also in 1999-2000 – fig. no. 7 - or 2000–2001), in exchange, milder temperature values generated such phenomena. The explanation could be that the ice accumulated on the sector of the tail of the Izvoru Muntelui Reservoir – Farcaşa and that will appear upstream the Topoliceni Topoliceni does not originate in this place. Their source is somewhere much more upstream, where the climactic conditions are more severe. According to one of the authors (V. Ciaglic), this source is on the Bisțrița river, in the area Rusca – Crucea – Cotârgași. We plan to bring arguments in our future research.

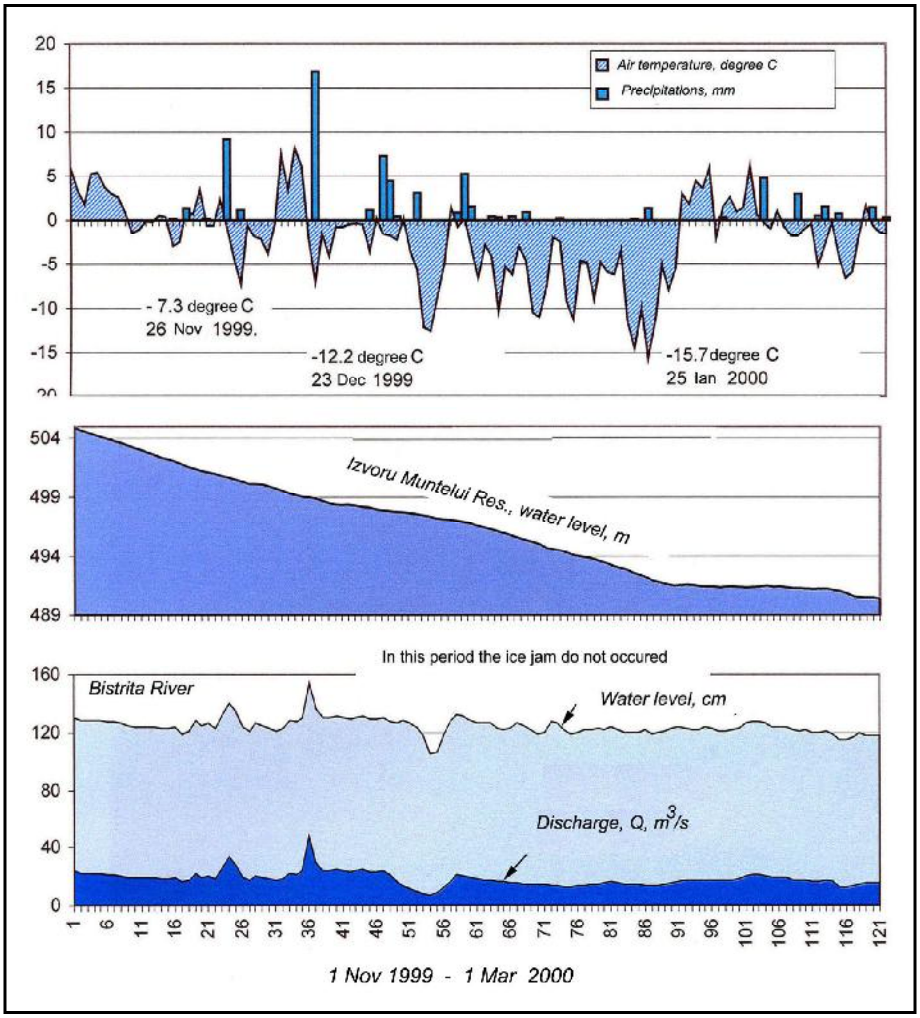

Fig. 7. Variation of the controlling factors of the ice jam at Frumosu station, Bistrita River in 1999-2000. Maximum favorability for ice jam, but this do not occured.

Another puzzling situation was the role of the Izvorului Muntelui Reservoir. No doubt, the effect of basis level with all the implicated hydraulic mechanisms is generally accepted as a primordial cause. But the mechanism of the water level oscillation and its optimal position in order to avoid ice jam formation is less understood. In our work we will offer a hypothesis. Until then let us remark the variation of the hydro-meteorological parameters in the winter 1999-2000 when the air temperature decreased below –150C several times at Frumosu (with even lower upstream values), and yet on the river there did not appear ice blockages. Should the cause be the water level of the reservoir that was below 499 m? Maybe yes, because in 2001 – 2002, 2002 – 2003, at the same values of the air temperature, but at lake level values of over 508 m, there appeared blockages on the river Bistrița and they lasted between 50 and 108 days with all the unwanted effects.

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

The first information we have regarding ice jam formation on the Bistrita River, upstream of Izvoru Muntelui Reservoir, appears in a study of the clogging in the tail area of the lake. The study was performed by the Hidrological Station Piatra Neamt in 1973, and was published in 1975 (V. Ciaglic et al). THe authors of the study have drawn the conclusion that the 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 sink. To be more exact, the first blockade of the riverbed appeard under the ice cover in the Calugareni area, near the left shore of the lake, where the river holds a very tight curve. On the opposite shore of the lake there are a small church and the cemetery of the Calugareni village and the marker of the 28th topografical profile (according to the topografical measurment in 1972, figure 8).

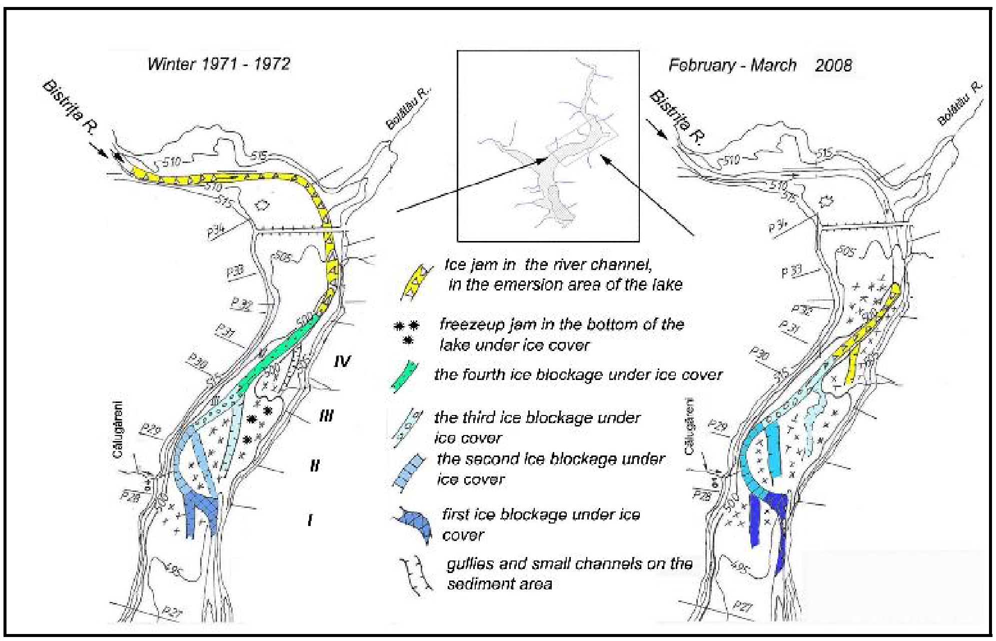

Fig. 8. The mapping of the winter phenomena on the Bistrita river channel in the Izvoru Muntelui Reservoir area; this is former area of ice jam formation and its upstream migration.

This observation was based on the presence in the site of rills and ephemeral gullies starting from the riverbed which suggests that the water coming through the riverbed was forced by the blocking of the riverbed to find itself a new way to the interior of the lake. The same paperwork signals the fact that the blockade of the riverbed produced while the level of the lake was slowly but continously dropping.

The transparency of the water at the confluence was very reduced, 15-30 cm, while towards the interior of the lake this was over 200 cm. This unusual phenomena was produced while, considering the very low flows inside the river, turbidity was also reduced at the entrance in the lake, between 0,005 - 0,144 kg/m3. Hence the increase of the turbidity and consequently the high decrease of the transparency in the tail area of the lake appears as a paradox. Following comes the explanation: while the level of the lake was dropping and the river was resuming its gravitational flow, by the force of the current, particles deposited during the former submerse epoch were put into motion.

The authors suppositions regarding the fact that the first blockade (ice jam) starts inside the lake under the ice cover and then gradualy extends to the upstream were confirmed by our observation during february-march 2008. Once the ice cover from the lake's tail area has melted it was revealed that the entire course of the Bistrita River, from Calugareni to the Topoliceni dam, the riverbed was fully filled with freezeup jam clogged with deposits and covered with sediment layer of about 10 - 15 cm, on top of which there were still some ice areas formed over the surface of the lake in a advanced stage of melting (figure 9).

Fig. 9. Ice obturation of the Bistrita river channel determined a river course change (Calugăreni area in the emerse area of the Iyvoru Muntelui Reservoir): 1972 (foto I. Miron); March 2008 (foto N. Rădoane).

The mechanism of formation of the first blockade comprizes two stages: the submerse stage of development of spogious ice (frazil ice) following a slower evolution and the emerse stage when the process moves into the riverbed and advances into the upstream with high velocity. From this moment onward the evolution of the hidrometheorological summed with the charachteristics of the horizontal plane of the riverbed (bottlenecks, windings, sudden changes of movement) and in vertical plane (alternations of segments with broken slopes, segments with high slopes and steps, blocks in the riverbed) can produce hardly controlable situations.

In conclusion, our analysis on the ice jam phenomena on the Bistrita valley searches to prove that the process is normal and deterministic in the valley of Bistrita and not at all "unique in Europe" or even "in the whole world" as it was characterized by some local media (Monitorul de Neamț, 9th january 2008). Also, we want to show that any intervention over the riverbed and over the control factors has to be preceded by a minimal investment into knowledge of the phenomena in its entire complexity. The question marks we raised in this paperwork shows that there is still need for research and experiments. The Hidroelectrica initiative is salutary and we are convinced that it will result in a synchronization of the attenuation measures needed with minimal effects in social, economical and ecological dimensions.

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