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WATER LEVEL VARIATION DUE TO BRIDGES OR OTHER RIVERS CONSTRICTION

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Abstract

At the construction of a bridge in the riverbed, the water flow section is usually reduced due to the placement of the piles and abutments of the bridge between the banks. How the water flow change depend on the flow regime (fast-supercritical or slow-subcritical) existing in the river in the absence of the bridge. Of interest is the change of the water level in the section of the bridge and upstream of the bridge. The water level may rise or fall depending on the flow regime (slow or fast) and the size of the channel narrowing.
Romanian hydraulic bridge calculation standard states that the water level upstream of the bridge increases under any conditions. Other technical prescriptions distinguish between different changes in water level at bridges depending on the flow regime existing on the river before the bridge is placed. The frequent situation in which the flow regime on the river is slow is of great interest because they are the most common. The calculation schemes that describe this situation have the premise that the water level upstream of the bridge increases. In most situations this is what happens but not in any situation. The article aims to identify situations where, in a slow flow regime, the water level upstream of a bridge does not increase but decreases, even if the presence of the bridge means the narrowing of the water flow section. This clarification is very important for the agencies that issue the bridge construction permits, for which the specifications in the regulations are important landmarks. The same situation can be encountered in the case of levees that obstruct the major riverbed. And in this case the water level may decrease or increase under the narrowing of the riverbed.

Keywords: afflux at bridges, backwater, calculation standard, construction permit, river constriction

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1. Introduction

The nature of flow through constrictions is described by Chow (1959). A constriction in a open channel constitutes a reach of sudden reduction in the channel cross section. The effect of a constriction on the flow depends mainly on the boundary geometry, the discharge and the state of flow. The phenomenon is ussually so complicated that the resulting flow pattern is not readily subject to any analytical solution (Chow 1959). A practical solution is possible. In subcritical flow, a backwater (or "afflux" of Hamill 2004) region it can be created, in which the flow depth is greater than it would be under unconstricted conditions. When the flow is supercritical the constriction (bridge) will disturb only the water surface that is adjacent to the upstream side of the constriction and will not extend the effect farther upstream. The case usually encountered in practical problems is that the flow through constriction is subcritical. When an area constriction is introduced in an uniform flow, channel, a backwater profile is first developed upstream from the constriction (Fig. 1).

The diagram (Fig. 1) suggests a large section reduction in the bridge area. In this situation the phenomenon is described exactly. But if the variation of the section is smaller, what happens? And how small (or large) can the narrowing be? This approach is also found in other authors (*e.g.* Hamill 2004). Besides that, if water flows through a constriction, the water level increases upstream of the constriction compared with natural channel condiction. The water depth at the upstream end of the structure increases above the normal water level and this is known as backwater (Atabay et al., 2018, Mantz, 2007). In more recent research it is shown that the typical impact of bridge constriction on the water surface profile under the subcritical flow condition, can cause increases of the water depth at the upstream end of the structure, by increasing the water level (Atabay et al., 2018).

In the Romanian technical literature (Bartha et al., 2004, Mateescu, 1961) the variation of water level at bridges is described (for the slow flow regime) in the same terms (by increasing the water level). As a result of the practical design needs, standard of hydraulic calculation of the bridges appeared. The Romanian standard (PD 95, 2002) stipulates that, when the bridges are located on the rivers, the water flow section is usually reduced due to the presence of piles and abutments. It also establishes the computation relation of the level superelevation (remuu) in the river section in which a bridge was built (Eq. 1):

$$\Delta z = \frac{v_{mp}^2 - v_m^2}{2g} \quad (1)$$

where: Δz = afflux (backwater) [m]; v_{mp} = the average water speed in the bridge section [m/s]; v_m = the average water speed in the same section without a bridge [m/s]; g = gravity acceleration [m/s^2].

Upon other authors, the hydraulic calculation of bridges is initiated in the same terms - in the subcritical flow condition, which can cause increases of the water depth at the upstream end of the structure (Barnard et al., 2013, Bradley, 1978; USACE, 1995; 2016, Zevenbergen et al., 2012). It was established that, in subcritical flow, a backwater region is created, in which the flow depth is greater than it would be under unconstricted conditions. The location where the backwater effect is the greatest is considered to be the upstream end of the contraction reach (USACE, 1995).

So, the objective of this paper is to show that in some situations, even in slow flow, the water level decreases in the riverbed narrowed by bridges or other works. These findings can be useful to designers, who are asking for permits to build bridges, levees and who can be declined based on existing standards.

2. Material and methods

Most bridge hydraulic studies employ one-dimensional analysis methods (Zevenbergen et al., 2012). This method considers as a basic parameter and the calculation of bridge opening ratio (M), Eq. (2):

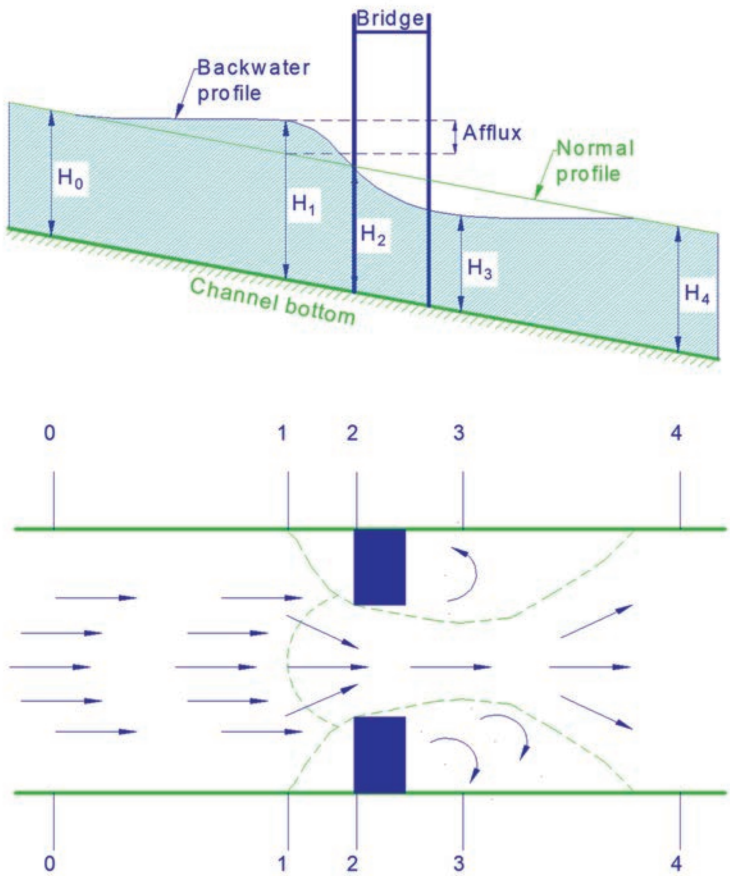

Fig. 1. Definition schetch of flow through constriction
(adapted upon Atabay et.al., 2018; Bradley, 1978; Chow, 1959; Hamill, 2004)

$$M = \frac{Q_b}{Q} \tag{2}$$

where: Q_b = discharge that can pass through the bridge without redirection by the encroaching road embankments or abutments; Q = total cross section discharge.

In this method of calculation, the bridge opening ratio (M) is assumed to be proper fraction. Can there be situations in which $Q_b = Q$? This possibility must be investigated. We will do it for a real case.

The calculation of the water level at bridges depends first and foremost on the flow regime in the riverbed. It can be slow or fast. The critical flow regime is a theoretical hypothesis difficult to meet in practice (Chanson, 2004). Once critical depth is reached, the water surface upstream from the constriction is no longer influenced by conditions downstream. Theoretically there is no backwater produced by supercritical flow if the flow regime is kept under the bridge (Bradley, 1978). The most common situation is the one in which the flow regime in the river before the construction is slow (subcritical).

The variation of water level produced by a reduction in the channel width is treated by Chaudhry (2008) and Kay (2008). The water depth decreases when the width decreases if the upstream flow is subcritical and it increases if the flow upstream of the constriction is supercritical. There is an upper limit by which the channel width may be contracted. We may reduce the channel width until critical flow is produced at the constriction. A further reduction in the channel width either reduces the unit discharge or raises the upstream water level (Chaudhry, 2008). This is not so easy to believe. But it follows from the energy equation and it actually happens in practice (Kay, 2008) (Fig. 2).

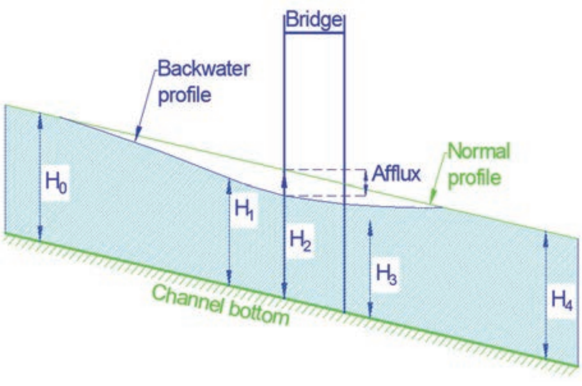

Fig. 2. Alternative definition sketch of flow through constriction, for slow flow in river bed

The most common situation is the one in which the flow regime is slow (subcritical) upstream of the bridge, downstream of the bridge, and throughout the bridge waterway. Fig. 1 illustrates the most commonly used schema. But after calculating the level of water upstream of the bridge may be lower, not higher than the initial one (Fig. 2).

We thus have two approaches: a practical one that describes the water flow with the increase of the level, and a theoretical one in which the effect of the narrowing of the section can be associated with both the increase and the lowering of the water level. Given these considerations, the inconsistency between the provisions of the norms and the theoretical considerations we will verify the two approaches. To verify the approaches we will calculate the level of the river water for two situations in which the designed works produce narrowing of the riverbed:

- flow section narrowing on the Bahlui River, in Iasi, Romania due to the bridge abutments located in the riverbed; Bahlui River is located in the northeastern part of Romania and has the following parameters in the calculation section (Iasi city): surface of the river basin = 1,967 km^2; length = 119 km.

- flow section narrowing on the Siret River in Adjud, Romania by placing a longitudinal levee. The Siret river basin is located in the east - north - east part of the country, being the largest river basin in the territory of Romania. Siret River is the most important tributary of the Danube, having an average multiannual flow, at discharge, of about 250 m^3/s. The basin of Siret River has a total area of 44,811 km^2 of which 42,890 km^2 on the territory of Romania and the rest on the territory of Ukraine, where the spring is. The surface of the river basin related to the calculation section is 20,385 km^2.

2.1. Determination of the flow regime in the riverbed

To identify the flow conditions below the bridge, we have calculated the flow regime in riverbed (slow-fast). For this it is necessary to calculate the critical depth of the water in the river at the calculation flow rate. The critical depth is influenced only by the discharge per unit width *q*. It has nothing to do with the slope or the normal depth (Kay 2008). The discharge is maximum when the flow is critical for a given specific energy (Chaudhry, 2008).

For the calculation of the critical depth, in the case of some irregular sections, the common method is the Bernoulli equation (Eq. 3) (Bartha et al., 2004; Kay 2008):

$$E = h + \frac{\alpha v^2}{2g} = h + \frac{\alpha Q^2}{2gA^2} \tag{3}$$

where: E = hydraulic energy in section [m]; $Q = A \cdot v$, is the calculation flow rate [m^3/s]; A = the water flow section at depth h measured on the transverse profile; h = water depth; B = river width; α = energy coefficient.

The hydraulic energy is minimum for $h = h_{cr}$ so from the first derivative we find h_{cr} (Eq. 4).

$$\frac{dE}{dh}=1+\frac{\alpha Q^2}{2g}\frac{d}{dh}\left(\frac{1}{A^2}\right)=1-\frac{\alpha Q^2}{2g}\frac{1}{A^4}\frac{dA^2}{dh}=1-\frac{\alpha Q^2}{2g}\frac{1}{A^4}\frac{2AdA}{dh}=1-\frac{\alpha Q^2}{gA^3}\frac{dA}{dh}=1-\frac{\alpha Q^2 B}{gA^3}=0 \quad (4)$$

Grouping the terms, we find Eq. (5):

$$\frac{A^3}{B}=\frac{Q^2}{g} \quad (5)$$

and a function is obtained by Eq. (6):

$$f(h)=A^3/B \quad (6)$$

where in the second term of the equation (Q^2/g, known), allows to locate h_{cr}.

The application of the Bernoulli equation is valid only within the range of assumptions (i.e. steady frictionless flow of incompressible fluid). For *short and smooth transitions* the energy losses are negligible and the Bernoulli equation may be applied quite successfully (Chanson, 2004).

2.2. Calculation of water depth in the section of the bridge with and without constriction

After calculating the critical depth, the normal depth of the water in the section at the calculation flow rate is determined based on the function represented by Eqs. (7-9):

$$Q=f(h) \quad (7)$$

where:

$$Q=AC\sqrt{RS} \quad (8)$$

A = flow section [m^2]; $C=\frac{1}{n}R^y$ Chezy coefficient;

n = channel roughness;

$$y=2.5\sqrt{n_e}-0.13-0.75\sqrt{R}\left(\sqrt{n_e}-0.1\right) \quad (9)$$

For irregular sections the equivalent roughness is used. Equivalent roughness coefficient n_e has been determined by Eq. (10):

$$n_e=\left(\frac{\sum P_i n_i^{3/2}}{\sum P_i}\right)^{2/3} \quad (10)$$

$R=\frac{A}{P}$ = hydraulic radius; P = wetted perimeter; S = the slope of the river.

If the water depth is greater than the critical depth, the flow rate is slow (subcritical); if it is smaller, then the flow rate is fast (supercritical). The situation of interest is the one in which the flow regime is slow in the unconstricted section. In this case, there is no increase of the water level upstream. If the flow regime in the constricted section is supercritical, the water level increases upstream.

3. Results and discussion

3.1. Bridge on Bahlui River

The abutments of the bridge over Bahlui River narrow the riverbed. In this context we have to calculate the effect of the bridge on the flow of water in the river at the calculation flow rate. The calculation flow is the one attenuated, according to the accumulations upstream (Boariu et al., 2013). The riverbed section is trapezoidal with horizontal berms halfway through (Fig. 3).

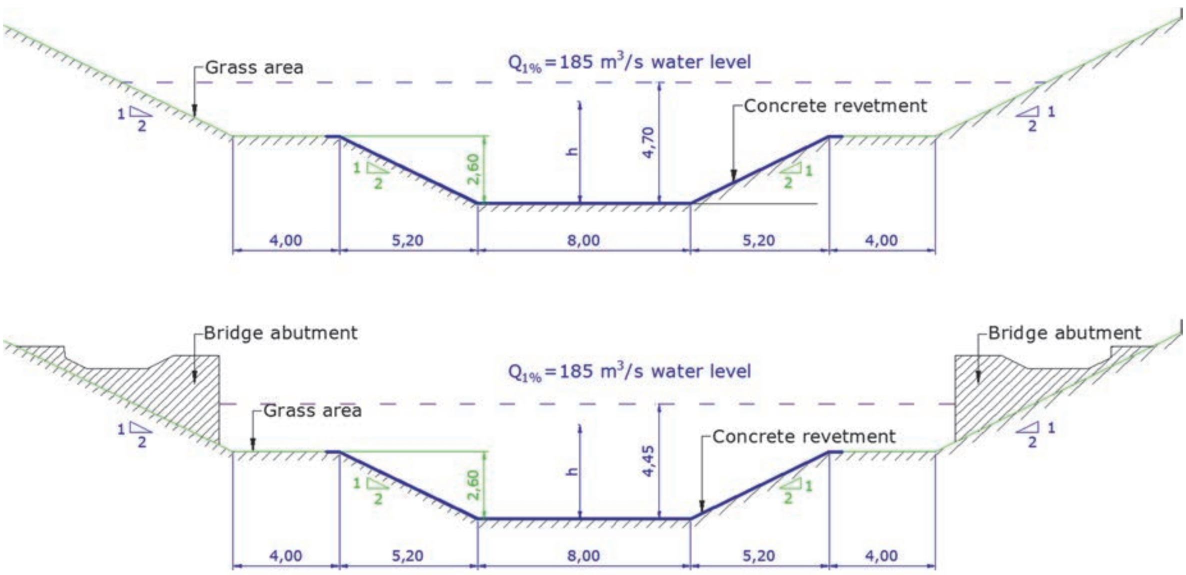

Fig. 3. Bahlui River sections

Calculation results give: Q = 185 m^3/s; S = 0.00045; n_1 = 0.014 for the concrete area; n_2 = 0.03 for the grassy area.

3.1.1. Calculation of critical depth in the river

The critical depth is found by constructing the graph defined by the Eq. 5 and 6 (Fig. 4). The value entered in the graph on the A^3/B axis is 3.489.

h_{cr} = 3.04 m for section without bridge;

h_{cr} = 3.02 m for secton with bridge.

3.1.2. Calculation of the normal depth in the river

The normal depth is found by constructing the graph defined by the Eqs. 9 and 10 (Fig. 5). The result is h = 4.70m in river bed without bridge. It results that the river bed regime is slow because the water depth is greater than the critical depth. The depth of water is then calculated, at the flow rate for river bed, with construction. This may be higher or lower than the depth before. From Fig. 5, the dash line curve provides the depth of water: h= 4.45m in river bed with bridge. These calculations show that the water level in the bridge section does not increase but decreases 25 cm.

3.1.3. Calculation of backwater with one-dimensional analysis methods

The result of the calculation performed with this method is a negative value, i.e. there is a decrease in the water level. Bridge opening ratio (M), which represents the degree of constriction of the waterway is M = 1 because Q = Q_b (Zevenbergen et al., 2012).

This result is obtained because the narrowing of the section is small. A first conclusion may be that under conditions where the water flow through the narrow section is greater or equal to the flow through the section without construction, the water level does not increase upstream.

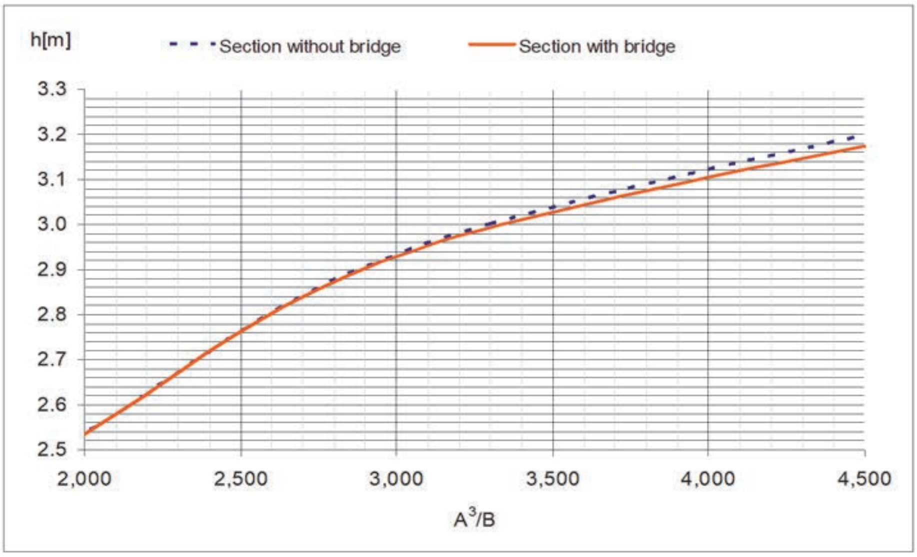

Fig. 4. Graph for calculating of the critical depth

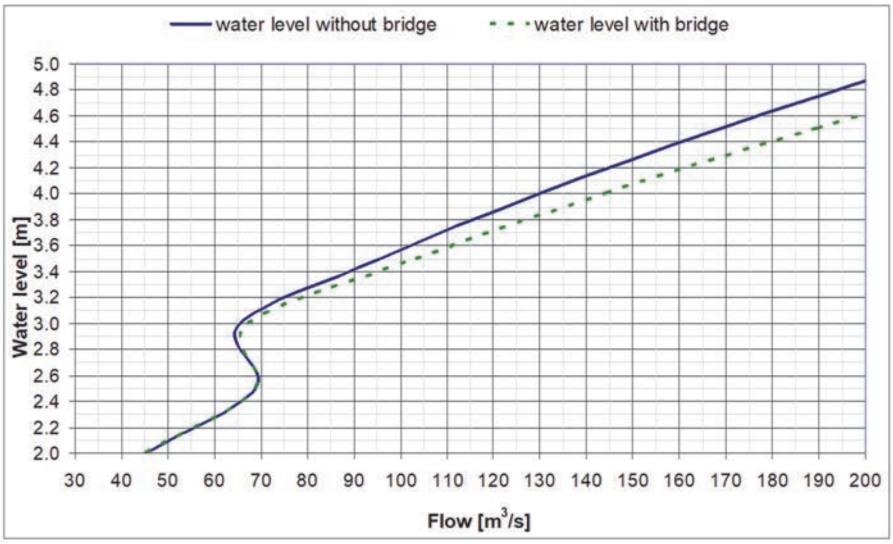

Fig. 5. Graph for calculating of the normal depth in the river

3.1.4. Calculation of backwater

By applying Eq. (1) it results in an increase in water level by 6 cm that is false: in reality the water level decreases 25 cm (Eq. 11).

$$\Delta z = \frac{v_{mp}^2 - v_m^2}{2g} = \frac{2.17^2 - 1.88^2}{2 \cdot 9.81} = 0.06\text{m} \qquad (11)$$

3.2. Levee on Siret River

A construction project near the Siret river bed provides for a longitudinal levee into the major bed of the river (Fig. 6). How the water level in the riverbed is changed after the construction of the levee is shown in Fig.6, in which the water level is calculated for the same flow $Q_{1\%}$= 3.420 m^3/s.

3.2.1. Calculation of critical depth in the Siret River

Calculation values are: $Q_{1\%}$ = 3.420 m^3/s; S = 0.00051; n_1 = 0.025 for the minor bed; n_2 = 0.045 for the major bed. The critical depth is found by constructing the graph defined by Eq. 7 and 8 (Fig. 7).

The value entered in the graph on the A^3/B axis is 1,192,294. The critical depth obtained from the graph is h_{cr}= 3.70m (80.08m in altitude value). The critical depth is the same for the normal section and for the narrow section, because the levee is located in the major bed over the water level, at the critical depth.

3.2.2. Calculation of the normal depth in the river

The normal depth is found by constructing the graph defined by the Eqs. 9 and 10 (Fig. 8).

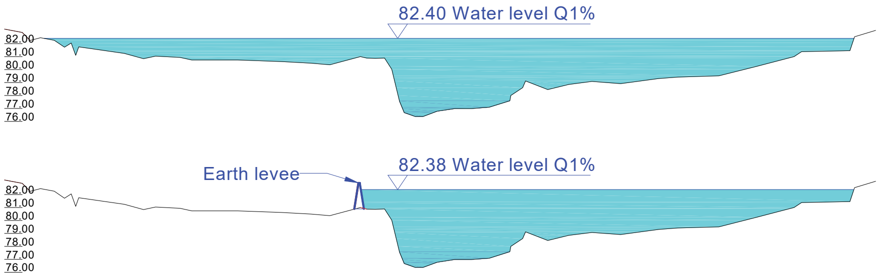

Fig. 6. Siret River sections (level is altitude in m - above Black Sea)

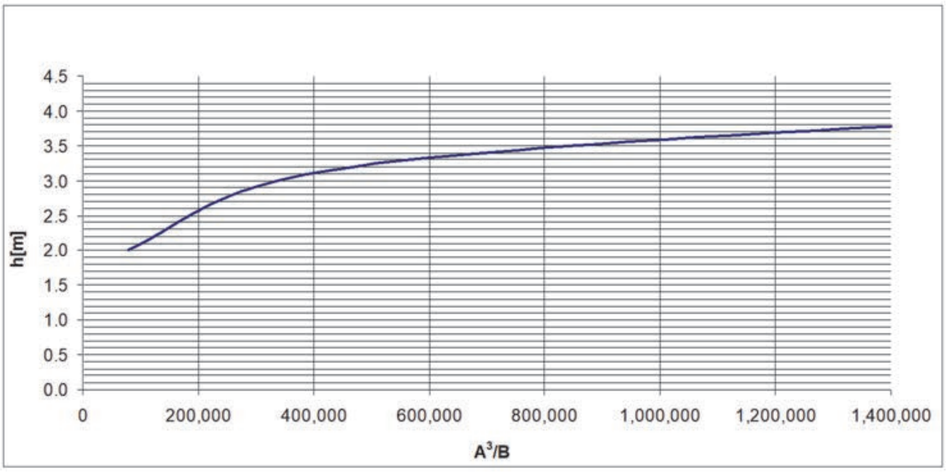

Fig. 7. Graph for calculating of the critical depth in Siret River

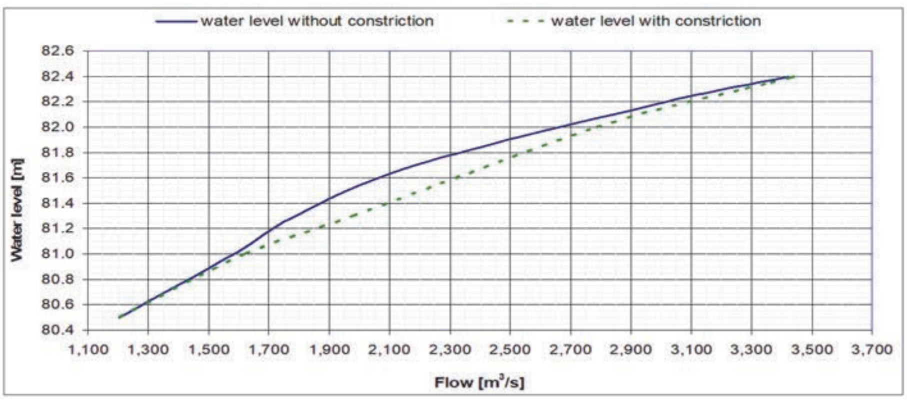

Fig. 8. Normal water depth calculation in Siret River

It results that the water level decreases in the narrow river bed. From the physical point of view the explanation may be the increase of the hydraulic radius, by reducing the wetted perimeter in case of narrowing the river bed. The condition is that the decrease of the wetted perimeter is greater than the decrease of the flow section. In other conditions, if the narrowing of the river bed was higher, the water level could increase. So, both situations can be encountered: a drop in water level if the narrowing is small enough or an increase in the water level in the riverbed if the narrowing is sufficiently large.

4. Conclusions

The calculation methods and principles used in this article are known approaches. The results obtained by applying these calculation methods show that:

- although all computation schemes in the literature and standards for the slow flow regime illustrate an increase in the water level upstream, we showed that the water level does not always rise when the river bed is narrowing

- the calculation made according to some standards, although they have an inaccurate scheme, give accurate results

- the calculation made according to the Romanian standard may have wholly erroneous results.

Other standards are incomplete; computational relationships are correct, but the approach is unilateral, the calculation scheme induces the idea that there is always an increase in water level, that is incorrect.

If the bed of a river, in which the water flow is slow (subcritical), is narrowed by the construction of a bridge or a levee, the level of water upstream of constriction has the following the evolution:

▪ until in the constricted zone does not reach rapid flow (supercritical), the level of upstream water drops;

▪ a further reduction in the channel width either reduces the unit discharge or raises the upstream water level.

Considering the presented results, the definition of backwater (afflux) should be changed accordingly: the water depth at the upstream end of the structure increases or *decreases* above the normal water level and is known as backwater. The difference between the water surface elevation at the upstream section before and after the construction of the bridge is known as afflux. The current regulations implicitly consider the case illustrated in the paper. To help with the approval of the design documentation, in standards and manuals, the sketch presented in diagrams should also be entered.

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