STREAM LEVEL STABILIZATION BY ALGAE OF THE GENUS *CLADOPHORA**

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Investigations in the Pryský brook experimental catchment revealed that the vegetation of the stream channel stabilizes water level depth in the measured profile. The explored brook has been heavily overgrown by algae of the genus *Cladophora* due to a strong pollution by nitrates. It seems that if the algae average length exceeds the midsize of the stones paving the bed (ca. 30 ± ٧ cm in diameter, escribed circle to pentagon or heptagon), the water level stagnates in the flowrate range of 60–180 l s^{-1}. This totally blocks the streamflow daily oscillation (in summer months in a purely stone bed reaching up to 15%, along with tidal phenomena). The article analyzes one of possible explanations of this effect due to the dependence of the algae thickness layer modifying the channel bed cross-section on the speed of flowing water.

catchment parameters, water level, algae of the genus *Cladophora*, daily fluctuation of discharge

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INTRODUCTION

It seems that hydrological parameters, such as flow velocity or turbulence in the flow, impact not only formation of a channel bed, but also the species composition of riparian vegetation. For example, flow velocity is suspected to considerably modify the spreading possibilities of certain plant species in the direction of the brook fall line. We consider the possibility that even the water level oscillation can play a role as well. These parameters may impact the occurrence of certain species and their spreading. We consider the probability that some species are able to endure the periodic soaking more easily than others, which, however, are capable of replacing them in the case of such oscillation failures. Periodic irrigation causes the occurrence of specific flora of flood-plain forests (Molles, 2008). Even short-term periodic flooding results in the change of riparian vegetation (Raffaelli, Hawkins, 1999). For this reason, we decided to put into practice monitoring of the Pryský brook oscillation. Since 2012, hydrological measurements have been carried out in the catchment of the Pryský brook with the closing profile at the lower border of Horní Prysk village. Description of the watershed is given in Table 1. The stream level is being scanned every second by a submersible sensor. On this stream, as well as on our other experimental catchments of Teplý and Starosuchdolský brooks, daily oscillations of the flow rates are commonly observed, as was discussed in detail in previous papers (Dvorakova et al., 2012; Dvorakova, Zeman, 2014). A similar approach practised on other catchments is described in Burt et al. (2010). To determine the stream velocity profile, a new float method has been developed (Dvorakova, Zeman, 2013).

During the summer of 2013, the Pryský brook was gradually invaded by algae of the genus *Cladophora*,

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probably due to a solid discharge of animal waste on the territory of the Prysk village. This resulted in a complete stagnation of the stream level in January through June 2014. In this period the algae not ever occurring at the measurement point, reached the average length of ca. 40 cm here. The complete stagnation of water level height occurred with an accuracy of 0.2 mm, while the repeated measurements with a hydrometric propeller indicated that the velocity profile of the stream remained unchanged. Only a reduction of the active cross-section of the channel could be observed. After a mechanical removal of the algae, daily oscillations reappeared suddenly 5 m ahead of the measured profile and 3 m behind it, as well as fluctuations following weak precipitation.

As in the summer months under favourable conditions the daily oscillations of the stream water level exceed 10 mm, we are of the opinion that the observed absence of the stream water level fluctuation is caused just by the algae (not by changing roughness of the riverbed which would change the velocity profile) and their ability to partially block the bed and thus reduce the active flow area.

This article also deals with the mathematical description of algae behaviour, which can cause the water level stabilization in the mentioned range.

The study by Chow-Fraser et al. (1998) follows the influence of flow on vegetation and formulates the results even with the help of mathematical relations. However, they are not based on the Manning's equation and so it illustrates only the existence of the described phenomenon. Mattas (2014) thoroughly depicts the relation between flow rate and the condition of a riverbed. Our hydrological-mathematical apparatus builds on this work. Cardinale et al. (2002) get a bit farther, incorporating kinetic energy into the calculation. However, the effect of riverbed roughness on the flow is not considered. Reiter (1986) gets the closest in describing the influence of algae on the flow. He does not use any mathematical apparatus to formulate the results – they are only tabulated in the article for different situations, the same as the coefficients of the Manning's model.

The objective of this paper is to explain the absence of daily fluctuation of water level of the stream the bottom of which is strongly covered by algae on the basis of designing a function formula for the efficient intersection provided the constancy of the Manning's coefficient with the flow rate. Our measurements clearly show that in a given range of flow rates the elimination of the oscillations indeed occurs. It can be expected that in the Czech Republic, where the precipitations have been accumulated in recent years, the decline of the median of flow in water flows will continue. This fact together with the increasing pollution of surface waters (which goes hand in hand with the mentioned water level decrease and a constant amount of pollutants) implies overgrowing of the stream channels by algae. For this reason, a gradual disappearance of daily oscillations on a majority of small water flows with all its consequences can be assumed.

Table 1. Characteristics of the Pryský brook catchment

P	catchment area	8.53	km^2
P_L	catchment area of left slope	5.21	km^2
P_R	catchment area of right slope	3.32	km^2
L_{th}	length of thalweg	6.64	km
L_{main}	length of the main stream	6.43	km
L_{all}	length of all streams	10.59	km
o	perimeter of divide	15.5	km
B	mean width of catchment	1.28	km
α	shape of catchment	0.19	–
I_{th}	average slope of thalweg	4.51	%
I_{SR}	average slope of right slope catchment	21.44	%
I_{SL}	average slope of left slope catchment	18.35	%
I_S	average catchment slope	19.55	%
$H_{max.}$	maximum elevation thalweg	644.4	m
$H_{min.}$	minimum elevation thalweg	345	m
ΔH	difference of elevations	299.4	m

MATERIAL AND METHODS

The Pryský brook discharge was determined by two experimental methods, in the closing profile with coordinates 50° 47' 36.629" N, 14° 29' 13.440" E. Both measurements took place on April 24, 2013. The stream channel is paved with basalt blocks and is slightly overgrown by grass. The slope of the stream channel in the place of the measured profile is about 3.5%, therefore the brook falls into the category of torrents. The cross-section is approximately trapezoidal (see Fig. 1).

The water level of this brook is at the point of 50° 47' 36.629" N, 14° 29' 13.440" E, i.e. approximately at the 3.5th km of the streamflow, every second recorded by a submersible level gauge Vegawell 52.

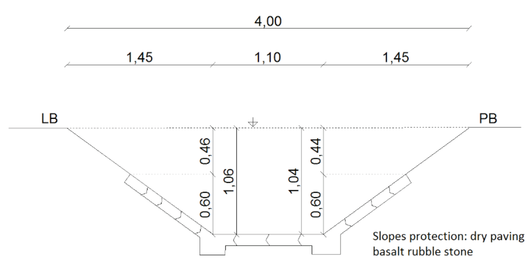

Fig. 1. Cross-section profile of the Pryský brook (values in m)

The level gauge is firmly fixed to the basalt block at the bottom of the stream channel. Useful resolution of this level gauge is 1/10 mm. The measurement started on June 10, 2012, and is still in progress. In addition to the stream level height, the ground temperature as well as soil moisture at a depth of 30 cm are recorded and also the amount of precipitation using a shuttle pluviometer.

Since the summer of 2013 sharp increases in nitrate have been recorded several times a week by emptying of a 10 m^3 gulley sucker tank about 300 m up the stream, which is accompanied by intensive odour. We suspect that this rapid nutrient enrichment triggered the sharp development of the Pryský brook flora. Within several months its entire immersed surface was covered by multiplying algae of the genus *Cladophora*. In the stream channel the calibration using a ball thrower was performed (Dvorakova, Zeman, 2013) and the velocity profile of the channel was determined. We also established the relationship between the discharge and the water level height.

The Chézy equation (1) (Bauer et al., 2004; Mattas, 2014) was applied to the measured data. To calculate the velocity coefficient C, the Manning's equation (2) was used. From this comparison the fair value of the roughness coefficient n = 0.135 was obtained. This value can be explained by turbulences, which proceed in the channel very intensively.

The equations are as follows:

$$v = C\sqrt{RI} \qquad (1)$$

where:
v = mean velocity (m s^{-1})
C = Chézy coefficient ($m^{1/2}$ s^{-1})
I = bottom slope (m/m)

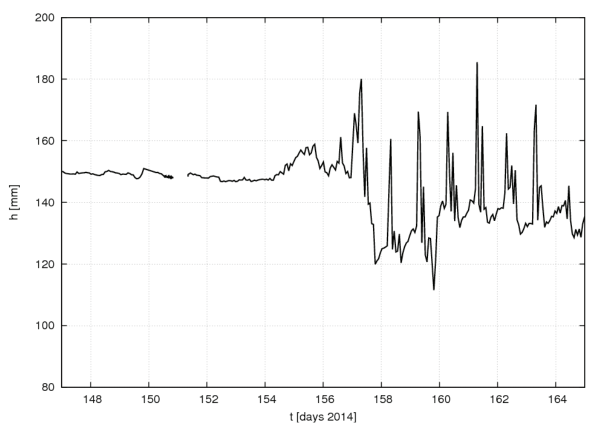

Fig. 2. Water level fluctuation of the Pryský brook before and after the algae layer removal (on the 155th day of the year, i.e. on June 4th, 2014). After using the formula for flow rate (Q = S v) and data from the velocity profile measurement using balls (Dvorakova, Zeman, 2013) we found that the median level for this measured episode corresponds to 80 ± 6 l s^{-1}

R = hydraulic radius (~ water depth) calculated as $R=S/o$ (m)
where:
S = cross-section area (m^2)
o = wetted perimeter (m)

$$C = \frac{1}{n} y^{\frac{1}{6}} \qquad (2)$$

where:
n = Manning's roughness coefficient (s $m^{1/3}$)
y = water depth (m)

RESULTS

Having found out that the stream channel overgrown by algae of the genus *Cladophora* showed in the course of several months no water level fluctuation usual in the Pryský brook before the massive algae layer formation around the wetted surface of the channel, in April 2014 we decided to mechanically remove the algae from the stream channel. The algae are about 60 ± 15 cm long in the untreated channel and they grow back to this length within a month when treated to the length of 3 ± 2 cm. We assume that this happens due to the water pollution by nitrates. The algae length was measured by a ruler directly in the water flow. As expected, in consequence of this step the periodic evapotranspirational fluctuations were restored. The whole process is illustrated in Fig. 2. After removing the algae from the channel we could see that the process returned to the similar oscillations observable at other brooks (Burt, 1979; Zeman, Dvorakova, 2013).

In Fig. 3 we can see that the presence of algae in a certain range of flow stabilizes the height of the stream level. Due to this effect, we can make the following calculation, in which we assume that at different discharges the stream channel roughness does not alter, only the flow area and wetted circuit change, as the algae open with increasing the discharge. Therefore we introduce the following parameters:
h = water depth (m)
y = reduced water depth (m)

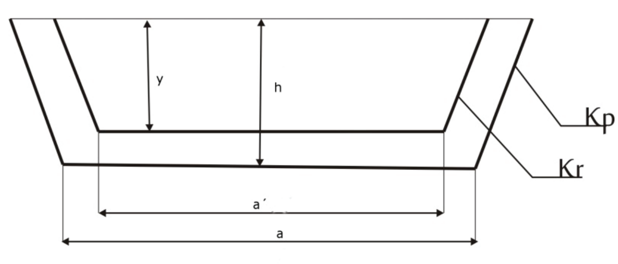

Fig. 3. Scheme of the channel with the algae layer
Kp = original channel, Kr = channel with reduced discharge

a = width of the channel (m)
a' = width of reduced channel (m)
α = shore slope

We get eq. (3) for wetted perimeter and eq. (4) for flow area.

$$o = 2\frac{y}{\cos\alpha} + a - 2(h-y)tg(45° - \frac{\alpha}{2}) \quad (3)$$

$$S = y(a + ytg\alpha - (h-y)tg(45° - \frac{\alpha}{2})) \quad (4)$$

These equations we substitute to equations (1) and (2). Our goal is to determine the height of the algae, depending on the flow speed or discharge. From this assignment it is possible to obtain eq. (5), but the explicit expression of the roots of this complicated polynomial equation of the 4th degree is hardly practicable.

$$v = \frac{1}{n}y^{\frac{1}{6}}\sqrt{\frac{y(a + ytg\alpha - (h-y)tg\left(45° - \frac{\alpha}{2}\right))}{2\frac{y}{\cos\alpha} + a - 2(h-y)tg(45° - \frac{\alpha}{2})}I} \quad (5)$$

For this reason, we can try an approximate calculation, the solution of which can be made either directly, or it can be analytically estimated. We will perform two levels of approximation. One rough, in which we assume that the flow area has a rectangular shape and the wetted circumference is determined only by eq. (6).

$$o = a - 2(h-y) = a' \quad (6)$$

In this case we assume that the width of the channel is much greater then water depth. It is therefore eq. (7) and after substituting into eq. (1) and eq. (2) we get eq. (8). This is the first and the roughest estimate of the relationship between algae height and velocity of flowing water.

$$S = ya', o = a' \quad (7)$$

$$v = \frac{1}{n}y^{\frac{1}{6}}\sqrt{yI} \rightarrow (\frac{vn}{\sqrt{I}})^6 = y^4 \quad (8)$$

We will now try to make this result more exact, namely by taking into account double height of the drain layer to the wetted perimeter. In principle we just reduce a trapezoidal profile to the rectangular. Now, therefore, we obtain eq. (9).

$$S = ya', o = a' + 2y \quad (9)$$

After substituting to eq. (1) and eq. (2) we have eq. (10).

$$v = \frac{1}{n}y^{\frac{1}{6}}\sqrt{\frac{ya'}{a'+2y}I} \rightarrow (\frac{vn}{\sqrt{I}})^6 =$$

$$= y(\frac{ya'}{a'+2y})^3 = \frac{y^4a'^3}{(a'+2y)^3} \quad (10)$$

$$b = (\frac{vn}{\sqrt{I}})^6 \quad (11)$$

$$b(a'^3 + 6a'^2y + 6a'y^2 + 8y^3) = y^4a'^3 \quad (12)$$

It is also possible to write this equation (after the substitution of eq. (11)) in the form of eq. (12). Due to the channel geometry the size of the terms in brackets is significantly declining. If we neglected the last three terms, we would get the previous case, i.e. eq. (8). However, we will try to take into account also the second term, hence to solve the eq. (13).

$$b(a'^3 + 6a'^2y) = y^4a'^3 \rightarrow ba' + 6by = y^4a' \quad (13)$$

Although we cannot determine the root of this equation analytically, we can, however, approximate it. We can see that the left side of the equation represents (with respect to y) the line given by eq. (14). The right side of the equation is the equation of parabola (15) (see Fig. 4).

$$z_1(y) = ba' + 6by \quad (14)$$

$$z_2(y) = y^4a' \quad (15)$$

In Fig. 4 the real values of I, a, n, and v for our catchment are considered. Due to the fact that all of the coefficients of eq. (14) are positive, the function is increasing. For this reason, the value of the point of intersection of the line (14) and the parabola (15) must lie above the value of the ba', in which the line intersects the axis z. We can construct the tangent line in point A, the functional value of which is ba' (M o s n a , 2013). The equation of this tangent is as follows (16)

$$t: z = 4a'b^{\frac{3}{4}}y - 3a'b \quad (16)$$

$$y_v = \frac{2a'}{2a'b^{-\frac{1}{4}} - 3} \quad (17)$$

Of course, we are able to calculate the point of intersection of the line eq. (14) and the tangent eq. (16). The y-coordinate value of this point of intersection is

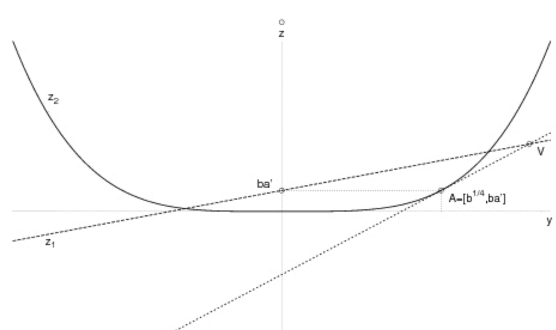

Fig. 4. Chart showing the gradual approximation of the intersection of the function z_2 and the line z_1. The first approximation is the point A, the second is the point V

eq. (17). From Fig. 4 it is obvious that this value will be slightly overestimated.

This solution can be recalculated for two extreme cases:

First, Eq. (18): the channel is so wide that its narrowing by algae is negligible and this leads only to the drain layer height reduction. Then eq. (17) can be written in the form of eq. (19).

Second, Eq. (20): the channel is narrowed from both sides by the whole depth of the channel. This is the situation when the drain layer is already very slim. Equation (17) then has the form of eq. (21).

$$a' = a \tag{18}$$

$$y_v = \frac{2a}{2ab^{-\frac{1}{4}} - 3} \tag{19}$$

$$a' = a - 2h \tag{20}$$

$$y_v = \frac{2(a-2h)}{2(a-2h)b^{-\frac{1}{4}} - 3} \tag{21}$$

The graph in Fig. 5 compares the numerically calculated exact trapezoidal solution of eq. (5) with the exact numerical solution of the rectangular approximation of eq. (12) and with the values of the approximate analytical formulas of the rough solution of eq. (8) and the finer solution of eqs (19) and (21).

DISCUSSION

Provided that the Manning's coefficient is independent on algae length, we managed to express the height of the algae which bind the stream channel depending on the velocity of flow through the water channel by variously accurate approximations. This derivation stems from the observed fact that the flow through the channel bed overgrown by long algae does not cause any change of the water level. If there is a change in the flow rate and not in the water level, there must be a change in the profile and velocity of the water flow. Assuming that the character of the flow (Manning's coefficient) does not change, the well-known dependence is between the cross-section of the channel and the velocity of the flow. It is therefore possible to create a graph of the dependence of flow velocity and algae height corresponding to these velocities which could be used e.g. for experimental verification of our justification for stopping the fluctuation by algae. The current layer of algae could be monitored e.g. by a camera. Then it would be for example possible to determine the current flow velocity from the algae layer thickness. The resulting dependence coming from our model is presented in the graph in Fig. 5. Here it is clearly seen that even the simplest form of equation which we considered, i.e. eq. (8), basically fairly describes the expected behaviour of algae. However, for all considered speeds at which our basic assumption seems to be true, the values of the algae layer thickness are overestimated by approximately 1 cm compared to other more accurate solutions. Interestingly, the most accurate solution by eq. (5), taking into account the trapezoidal shape of the channel, differs from that in eq. (19), counting with the simplest rectangular shape in the entire course, only by less than 2 mm. Taking into account the fact that eq. (19) is an analytical expression, while eq. (5) is solvable only numerically and still with difficulty, for channels like the Pryský brook eq. (19) seems to be more suitable, giving a result that will be probably in practice experimentally hardly distinguishable from the exact solution of eq. (5).

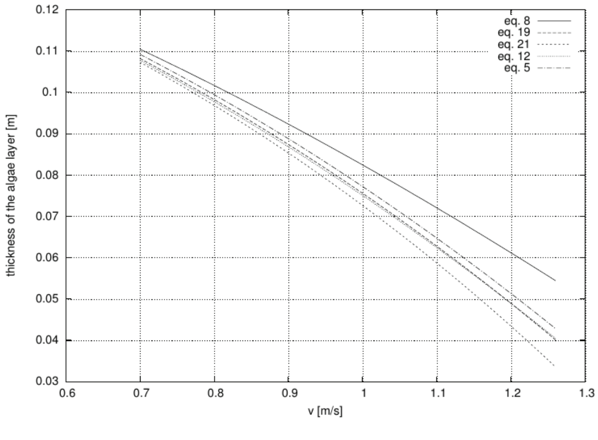

Fig. 5. Comparison of various functions depicting the dependence of the algae layer thickness on the velocity of water flow in the Pryský brook channel. The results obtained by the equations (12) and (19) are very similar. Their functions (curves) nearly overlap in the graph.

To what extent our assumptions about the permanence of the Manning's roughness coefficient (according to Reiter (1986)) in a slightly changing discharge are fulfilled and algae therefore behave according to the listed equations can be verified only by a direct measurement. It would probably require an ultrasound Doppler speed sensor and a specially adapted immerse camera sensing the thickness of the algae layer. The Doppler sensor of the flow rate works on the principle of the sound wavelength differences in flowing and stagnant water and it is then possible to determine the exact flow rate without the use of relations between slope, roughness, and flow. Measuring the speed by a hydrometric propeller in fast-flowing water with very long strings of algae of the genus *Cladophora* is much more difficult because the algae gradually completely block the propeller rotation.

For our purposes, this method was used only three times, and according to these findings the Manning's coefficient did not change, what is in accordance with formulas by Mattas (2014).

We may speculate on what else can play a role in the thickness of the algae layer. The turbulence and the physical dimension of the algae themselves has the effect on this parameter.

CONCLUSION

Our measurements clearly show the stabilizing effect of algae of the genus *Cladophora* on the water level of the flow at different discharges. This effect can be explained by spacing of algae under the greater velocity of the flowing water. Assuming that the riverbed roughness at this algae spacing did not change, it was possible to derive eq. (5) and thus predict the relationship between the variables of flow velocity and algae height. The prescription of eq. (5) is very complicated for routine use. Its solution, however, completely explains the water level behaviour under the assumption of the Manning's coefficient. It is possible to simplify eq. (5) under certain assumptions and thus to obtain a solution similar to the exact one which is, however, much simpler – it is represented by eq. (19). This stabilizing effect may have a secondary influence on the potential biodiversity in the floodplain of the stream, since the occurrence of algae of the genus *Cladophora* can avert regular spilling of water from the stream, on which some species may be dependent. The proposed functional dependence (eq. 5) could be used firstly in theoretical model biology and hydrology, and also to design concrete arrangements with the aim to revitalize the floodplain of the stream.

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