

Interplay between turbulence and periphyton in rough open-channel flow

Interactions entre turbulence et périphyton dans un écoulement rugueux en canal

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ABSTRACT

During the low flow period, important development of periphyton occur in rivers. The understanding of the mutual 'periphyton-flow' influences have induced, through recent studies, conflicting conclusions which underlined the particular complexity of these interactions. An experimental flume has been built to show that the near-bed regime (which depends on the water discharge, the nature and form of the substrate, the presence or absence of blowing, ...) and the development of the periphyton are strongly dependent on each other. Indeed, different experiments show that the periphytic characteristics differ depending on the hydrodynamic conditions and that the flow properties are modified by the presence of the periphytic matrix. The periphyton induces a smoothing of the roughness of the bottom which is significant depending on the thickness of the periphytic matrix. This thickness has been taken into account in terms of a gap of the y -axis in the interpretation of measurements of the hydrodynamic parameters, contrary to recent papers.

RÉSUMÉ

En période d'étiage, on observe une croissance de périphyton très forte dans les rivières. La compréhension des influences mutuelles 'périphyton-écoulement' a conduit, lors d'études récentes, à des conclusions contradictoires qui ont permis surtout de souligner la complexité de ces interactions. Un canal expérimental a été construit de façon à mettre en évidence que le régime près de la paroi du fond (qui dépend du débit, de la nature et de la forme des substrats de colonisation, de la présence ou non de remontées d'eau,...) et le développement d'un périphyton dépendent fortement l'un de l'autre. En effet, différentes expériences nous ont permis de montrer que les caractéristiques du périphyton diffèrent suivant les conditions hydrodynamiques et que les propriétés de l'écoulement sont modifiées par la présence du bioderme. La présence du périphyton induit un lissage de la rugosité de la paroi plus ou moins marqué suivant l'épaisseur de la matrice périphytique. Celle-ci a été prise en compte en terme de décalage de l'origine de l'axe des y dans l'interprétation des mesures des paramètres hydrodynamiques, contrairement à des travaux très récents.

1 Introduction

The turbulence characteristics of stream flows are of great interest in hydraulic engineering but also in ecological engineering (see Morin et al. 2000).

Several processes are linked together, such as the flow over rough beds, the growth (or the erosion) of biofilms (which influence the flow) or the exchanges, during the low flow periods, between groundwater (generally enriched in nutrients) and surface water. This is why it is important to analyse (i) the change in velocity and turbulence intensity distributions and in turbulent shear stress, in the presence of an increasing layer of periphyton, (ii) the dynamics of the biofilm in relation with the evolution of dynamic parameters, (iii) the influence of a boundary seepage on these parameters.

Considering that it is almost impossible to study these phenomena in details in natural rivers, the best way is to perform experiments in a laboratory channel. Moreover, this type of experimental device allows investigation of large range of values of the main hydrodynamical parameters, as well as the aspect ratio of the flow and the relative roughness of the substrate. It allows simulation of possible seepage through the substrate, to study the influence of the rate of blowing or suction¹ on the main stream flow and, in

association with the supply of nitrogen, on the dynamics of the periphyton.

Experimental studies of the mean flow and the turbulence structure of uniform open channel flow have been performed extensively – see Nezu and Nakagawa (1993). However, the majority of these studies has dealt with smooth beds and the knowledge of the turbulence structure over rough beds remains incomplete, until the work of Kironoto and Graf (1994) where the authors have drawn several important conclusions (based upon experimental results on the mean velocity and turbulence profiles for large relative roughness).

These conclusions will serve as a reference for our own results. Moreover, the formation of extensive mats in streams by periphyton, if occurring, can have major consequences on stream environments (Nikora et al. 1997). Recent studies have been devoted to understand the mutual influences between the periphyton and the stream flow. Reiter (1989a, 1989b) has shown that the friction velocity u_* increases as the periphytic bioderm grows and, in the same way, the measurements of Nikora et al. (1997, 1998) have revealed that the bed is rougher with periphyton than without. On the contrary, Biggs and Hickey (1994) have assumed that the periphyton smoothes the roughness of the substrate. Beyond these contradictions, these works have underlined the complexity

1. There can be a flow normal to the substrate at the interface, named 'transpiration', which could be into the surface or out of it. The terms 'blowing' (upward direction) and 'suction' (downward direction) are used to denote the direction of the flow at the interface.

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of periphyton-flow interactions.

Concerning the exchanges between surface water and groundwater, it is necessary to have in mind that they can be very important during low flow periods. For instance, it has been shown that, in the summer, the Garonne river (one of the most important river in France) receives one third of its flow discharge from groundwater (Danneville 1995). In fluid mechanics, the transpired boundary layer began to attract attention in the early 1950s, and work in that area rapidly developed (Phordoy 1992). However, bibliographical researches into transpired boundary layers in the presence of periphyton seem to indicate that the subject has not received any attention.

It is clear that studies devoted to this type of flow involve a significant amount of multidisciplinary work. In an other way, it is very important that the nature of the benthic boundary layer be well explained by hydrodynamicists to hydrobiologists, to help them in the choice of parameters for benthic ecology and also to prevent possible misinterpretation. Concerning this last point, it is interesting to recall to the reader (after Carling 1992) that Ambuhl published in 1959 a paper in which he drew ecologists' attention to the presence of a *laminar flow layer*, adjacent to the bed in a turbulent stream flow, *in which invertebrates might be able to maintain station*. This interpretation, readily accepted at the time and during some decades by ecologists, is based upon a confusion of terminology as this has been well explained by Carling (1992).

Faced with these problems, our objectives were to adequately quantify and parameterize, at the laboratory scale, the mutual influences between the hydrodynamic regime and the development of the periphyton, considering that the near-bed regime depends on the water discharge but also on the presence or lack of a transpiration through the substrate. These influences were evaluated by measuring both physical and biological parameters. First of all, it seems to us necessary to perform physical measurements within the inner region near the gravel bed (where the logarithmic velocity distribution is valid), to determine clearly the position of the reference level (the hypothetical point in the substrate at which the velocity 'goes to zero'), with and without periphyton, in order to evaluate correctly and with a good accuracy k_s , the equivalent sand roughness of the gravel bed (with or without periphytic mats) and u_* , the friction velocity. These parameters, as well as the shear stress (τ_w) exerted by the flow on the bed and linked directly to the friction velocity, are necessary to compare and discuss the results. Their knowledge and correct evaluation are fundamental for benthic ecology (Carling 1992), but also to correctly simulate hydrodynamic conditions in natural rivers, above all during low flow periods, since it is well known that this type of model is particularly sensitive to the resistance coefficient of the river bed.

2. Materials and methods

2.1 The experimental flume

The open-channel flow experiments are conducted in a horizontal laboratory flume built at the I.M.F.T. The layout of the experi-

mental installation is shown on Fig. 1. The flume is 11.0 m long, 0.5 m wide and 0.2 m deep, with Plexiglass sides (10 mm thick) and PVC bottom (20 mm thick) on which the different roughness were applied. Two test sections, including a recess of 2 m long and 0.4 m wide, are respectively located at 4 m (section 1) and 7 m (section 2) measured from the flume entrance and at a distance where the flow is fully developed. The hydraulic circuit of the flume is a closed system; the downstream (3300 litres) and upstream (1500 litres) tanks are connected with a 100 mm main. The water discharge is measured with a flow meter and regulated with a sluice and a by-pass. The pump allows a maximum discharge of 20 l/s, i.e. a maximum velocity near to 50 cm/s which is the maximum velocity at which more periphytic loss than accumulation occurs for an unenriched flow and artificial substrate (Horner and Welch 1990). A fraction of the water is renewed every week. Several guiding and stabilizing devices (grid and convergent) are placed at the entrance of the flume to ensure a quasi-uniform entrance flow. A valve at the end of the channel is used to regulate the depth of the water. Two different types of roughness are available: a rough plate outside (downstream, upstream or between) the test sections and a gravel bed of different thickness inside the test sections. In section 1, where the bed elevation is 0.05 m, this gravel bed is used to simulate a hyporheic process (very low circulation of water). In section 2, where the bed elevation is 0.2 m, it is used to simulate exchanges between the surface water and the groundwater by means of an upward seepage applied from the bottom of the recess by a small pump; the rate of wall transpiration (the ratio between the blowing velocity and the mean longitudinal velocity of the mean flow) is very small ($\sim 10^{-2}/10^{-3}$).

Illumination is supplied by a rack of 4 neon tubes above each test section to simulate the cycle of sunlight (total of $200 \mu\text{E}/\text{m}^2/\text{s}$). At the beginning of each experiment, periphyton taken from the Garonne river (the main river of south-west France) and periphyton grown on artificial substrate in the laboratory are used to seed the flume. Proportions and methods are strictly controlled (Godillot 1996) in colonizing the flume before each set of experiments which last several weeks (4 to 6). In order to limit the development of the bioderm outside in the test sections, an opaque rooftop has been placed on the channel and the side walls have been made opaque to daylight.

The choice of the substrate of colonization has been one of the first problems to which we have been confronted at the beginning of this study. First, we have realized tests of colonization followed by physical and biological measurements on PVC sticks (diameter of 8 and 10 mm) arranged side by side and perpendicu-

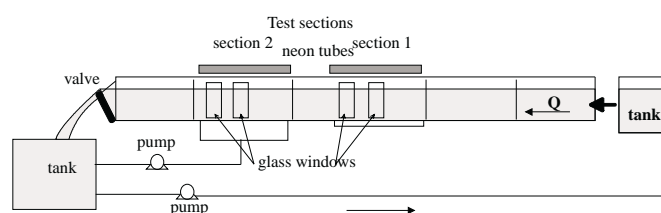


Fig. 1. Schematic diagram of the experimental flume

larly to the side walls of the channel (Godillot 1997), and on 6.3-10 mm quasi-uniform gravels. The sticks represent two-dimensional roughness so it seems that the interpretation of the physical measurements would be easier. However, the thickness of the bioderm appearing on the sticks is very thin compared to those obtained on the gravels during the same growing period due to the nature of the surface. This is the reason why we have chosen to use gravels. It is interesting to notice that the presence of two test sections have enabled the study of two sizes of gravels with the same hydraulic conditions. The first granulometry is made of gravels with a diameter of 6.3/10 mm (roughness 1, denoted R1), the second of gravels with a diameter of 14/20 mm (roughness 2, denoted R2). It is also important to underline that this kind of substrate looks like the rough beds of natural streams. To ensure a fully developed flow before the entry of the first test section, we have disposed the gravels starting from the entrance of the channel. In the case where both sizes of gravel are used together, the smallest gravels are located at the entrance of the flume and in the first test section, the largest gravels in the other parts of the flume. For the experiments with transpiration, both recesses are filled up with gravels. In the first test section (Fig. 2-a), we have put only the smallest gravels (6.3/10 mm). In the second test section (Fig. 2-b), we have placed large size gravels at the bottom (more than 20 mm) and, under, layers of gravels of smaller size until a last layer of smallest gravels (6.3/10 mm). Finally, a single layer of glass marbles (diameter 16 mm) is glued to the original floor of the flume and arranged over the gravel beds of the test sections, this kind of roughness being more regular than the gravels. That way, we have the possibility to control the difficulties due to the irregularities of the gravels. Table 1 summarizes the experimental conditions and the corresponding Reynolds and Froude numbers.

2.2 Measurements of velocity structure

The velocity measurements are carried out with a non intrusive high resolution device: the velocimeter or Laser-Doppler Anemometer (LDA) which produces a single green line ($\lambda = 514.5$ nm) for one component measurement. Four glass windows (4 mm thick) located on each side wall at 0.8 m and 1.6 m from the en-

trance of each test section allow measurements very close to the wall. The transmitting and receiving parts of the LDA are placed on supports on both sides of the flume, which allow horizontal and vertical movement (Fig. 3). The vertical displacements are located with a cathetometer with accuracy of few tenths of a millimetre. The photomultiplier (receiving part) signals are processed by a Burst System Acquisition (BSA) and a computer. This non intrusive method allows the measurement of the longitudinal velocity U , and the root-mean-square (RMS) values u . By rotating the transmitting optics by $+45^\circ$ and -45° , the shear stress is evaluated from the RMS values u_{+45° and u_{-45° . The vertical profiles of longitudinal velocity, of longitudinal turbulence intensities and of Reynolds stress are measured at each station in the centreline of the flume in order to limit the possible side walls effects. The measurements, carried out at different flows, are repeated weekly with and without periphyton. The measuring positions in the flume are located at $x = 5.6$ m (station 1) and $x = 8.2$ m (station 2) from the flume entrance. Without periphyton, we obtain measurements less than 1 millimetre above the gravels, but, with the periphyton, it is more difficult. First, the periphytic communities create particles in the water and their size is often so significant that the measurements with the Laser become very difficult. Indeed, the Laser is used to measure the velocity of the particles in the water and these particles have to be small enough to perfectly follow the flow. In this case, their velocities are the same as the water velocity. If the particles are too big, they do not follow the flow perfectly and the measurements are erroneous. Second, the periphyton is sometime composed of filaments which cross the laser beams when we try to measure near the periphytic communities. This presence in the beams makes the measurements difficult or impossible because it is necessary that both beams meet each other. Indeed, measurements are made at this point, and the consequences of this presence on the quality of the signal is unknown. The longer the filaments are, the more difficult the measurements near the periphyton.

2.3 Biological measurements

The periphyton is sampled weekly during each experiment by scraping gravel with a knife blade and a toothbrush in a measured

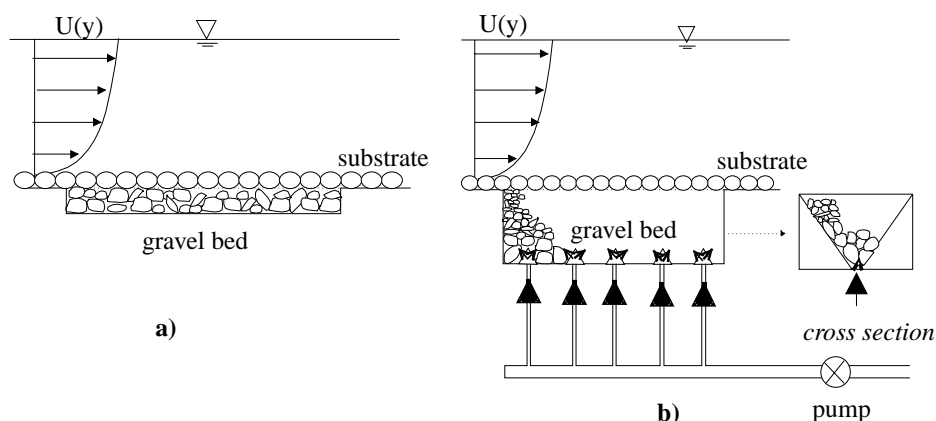


Fig. 2. The test sections: a) section 1; b) section 2

Table 1. Experimental conditions

Runs	velocity U	blowing	Substrate	water depth H	aspect ratio D/H	Fr	Re
1	33 cm/s	/	gravel	12.2 cm	4.1	0.38	34700
2	8 cm/s	/	gravel	12.2 cm	4.1	0.1	8860
3	16 cm/s	/	gravel	12.2 cm	4.1	0.19	18300
4	42 cm/s	/	gravel	9.5 cm	5.3	0.6	38300
5	16 cm/s	0.4 mm/s	marbles	12.2 cm	4.1	0.16	15000

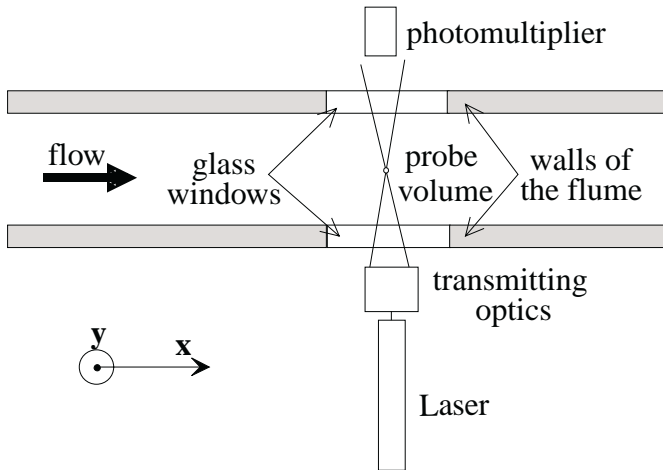


Fig. 3. The Laser Doppler Anemometry (upper view of the flume)

volume of water. In this way the “periphytic suspended solution” is obtained. Aliquot fractions of each periphytic suspended solution are collected to determine the quantity of dry mass (DM), ash free dry mass (AFDM, a measure of total organic matter) and chlorophyll-a in triplicats. The colonized surfaces of the gravels are determined by trace and weight. After each sampling, a similar and clean gravel is put in the place of each colonized gravel which has been taken out of the flume. Aliquot fractions are filtered on fibreglass filters (Wathmann GF/C). After filtration, the filters are dried at 80 °C for 24 hours and then weighed (DM). The same filters are reduced to ashes at 505 °C for 3h. The AFDM is obtained from the difference between the weights. Chlorophyll-a (chl.a) in material retained on fibreglass filters (Whatmann GF/C) is extracted in 90 % ethanol at 75 °C. The extinction of extracts is measured at 750 nm and 665 nm before and after adding HCl (phaeopigments concentration). The content of chlorophyll-a is calculated according to Marker et al. (1980). An aliquot fraction is preserved in glutaraldehyde (0.5%) to identified and enumerated algae using the Utermohl method (Lund et al., 1958). Identification is allocated to a functional group (Diatoms, Chlorophytes and Cyanophytes), using monographs by Bourrelly (1972, 1981, 1985, 1988) and Germain (1981). Results are expressed as percentage abundances. The interpretation of the results requires the knowledge of some other parameters which have been observed, measured or determined during the progress of all the experiments: light intensity, temperature of the water, pH, dissolved oxygen, nitrates (NO₃) and dissolved organic carbon (DOC) concentrations.

3. Results and discussion

Measurements with the Laser are first taken without periphyton in order to evaluate the initial hydrodynamic parameters. Then, the periphytic solution is introduced in the flume and physical and biological measurements are carried out weekly as explained above.

3.1 Velocity distribution without periphytic bioderm

The choice of gravels as substrate of colonization has induced a delicate problem from the hydrodynamic point of view. Indeed, as it is stressed in recent scientific literature (Wang et al. 1993, Kironoto and Graf 1994, Wilcock 1996, among others), the knowledge about the turbulence structure over rough beds remains incomplete, even if everything seems to be quite clear for the mean longitudinal velocities, in opposition to the case of smooth bed. Furthermore, the smooth bed relations can nevertheless be applied to flow over rough beds affected by wall roughness. It is perhaps here that we can find the reasons of some incoherences observed in the analysis of the measurements with periphyton. Above such a rough surface we suppose that the regime is “fully rough”, so that the velocity profiles have to satisfy in the inner (or wall) region, near the rough bed, where the logarithmic velocity distribution is valid ($(y-y_0)/H < 0.2$) :

$$\frac{U}{u_*} = \frac{1}{\kappa} \ln \left(\frac{y - y_0}{k_s} \right) + Br \quad (1)$$

where U(y) is the mean point velocity at a distance (y-y₀) measured from the reference level (y=y₀).

From this formula and the velocity measurements it is possible to estimate u_{*} and k_s. However, uncertainties exist about the choice of the y-axis origin and about the value of k_s, which is a measurement of the linear dimension of the roughness elements (Chow 1959). The origin of this axis is the theoretical point where U = 0 and in the case of gravels, this point is located under their crests (between 0.15 k_s and 0.3 k_s) (Fig. 4). A problem in determining the parameters of the equation may arise if an inappropriate “zero-datum” is chosen (Jackson 1981). Since long ago, this question is debated by scientific people. It is important to underline here that y₀ is affected by the changing of roughness caused by the periphyton mat. This is why it is necessary to explain the manner in which this problem has been solved.

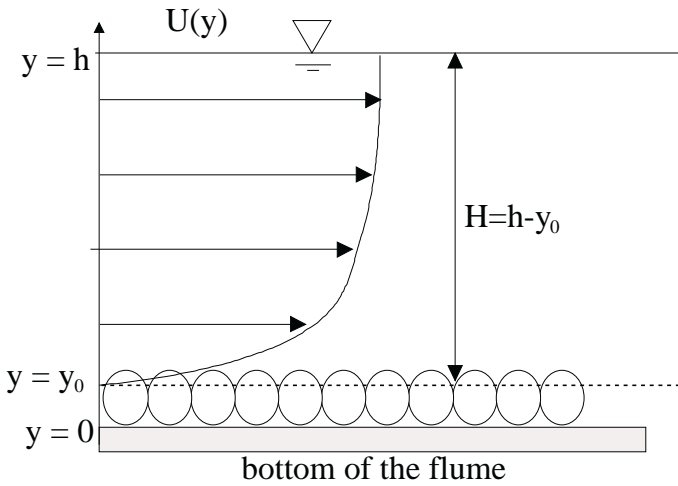


Fig. 4. Schematic description of flow over rough beds

In order to determine the y-axis origin, it is necessary to answer the question: what kind of parameter should be used to represent the size of roughness elements? In agreement with Nikuradse for rough beds composed of uniform gravels, we have chosen $k_s = 8.15$ mm for R1 (i.e. $0.067 < k_s/H < 0.086$) and $k_s = 17$ mm for R2 (i.e. $0.14 < k_s/H < 0.18$), these values being the respective median grain diameter of the gravels. We have then determined the location of the theoretical wall level y_0 , where $U = 0$, such that the friction velocity deduced from the velocity profile and from the shear stress profile are equal. We have also verified that the value of the constant Br corresponds to the values of the literature (Br = $8.5 \pm 15\%$, Reynolds 1974). Indeed, the shear stress is a marker of the turbulence, its evolution shows modifications of the nature of the wall and, subsequently, modifications of the turbulence production. However, the shear stress measurements are very difficult to perform. For example they are strongly sensitive to an error of one or two degrees in the rotations of the optics. Furthermore, the use of one component Laser anemometer induces a time shift between the $\pm 45^\circ$ profiles.

The components of stress tensor determine the transport of momentum by turbulent velocity fluctuations. After Kironoto and Graf (1994) and Nikora et al. (1997) we expect that for stream hydraulics and stream ecology the most important component is τ_{xy} because it describes the vertical transfer of the momentum of the fluid to the bottom. In the case of the uniform 2D flow (see Nezu et Nakagawa 1993):

$$\frac{\tau_{xy}}{\rho} = -\overline{uv} + v \frac{\partial U}{\partial y} = \frac{\tau_w}{\rho} \left(1 - \frac{y-y_0}{H}\right) \quad (2)$$

where

$$\tau_w = \rho u_*^2 \quad (3)$$

is the shear at the bottom. Thus:

$$-\overline{uv} + v \frac{\partial U}{\partial y} = u_*^2 \left(1 - \frac{y-y_0}{H}\right) \quad (4)$$

In the logarithmic zone, the viscous effects disappear in the case of completely rough beds because the roughness elements penetrate the fully turbulent logarithmic layer. Thus:

$$-\overline{uv} = u_*^2 \left(1 - \frac{y-y_0}{H}\right) \quad (5)$$

Despite some experimental scatter, our measurements (i.e. Fig. 5) show a reasonable agreement with this linear stress distribution. We can evaluate u_* from the value of the shear at the reference level, obtained by extrapolating the linear profile to y_0 : $-\overline{uv}_{(y-y_0)/H=0} = u_*^2$. Ligrani and Moffat 1986 have underlined that the most appropriate representation to show differences between the hydraulically smooth, intermediate and completely rough regimes is the profiles $U_+ = f(y_+)$. For the rough regime:

$$U_+ = \frac{U}{u_*} = \frac{1}{\kappa} \ln \left(\frac{(y-y_0) u_*}{\nu} \right) + \frac{1}{\kappa} \ln \left(\frac{\nu}{k_s u_*} \right) + Br \quad (6)$$

Table 2, with u_{*1} the friction velocity deduced from the velocity profile and u_{*2} the friction velocity deduced from the shear stress profile, summarizes the flow parameters for all the experiments with gravels and for marbles without blowing.

Fig. 6 shows the velocity profile at 8 and 33 cm/s above the smallest gravels (R1) using the inner region data. As we can see, the velocity profile at 33 cm/s is rougher than those at 8 cm/s: indeed $k_s^+_{33\text{cm/s}} > k_s^+_{8\text{cm/s}}$ i.e. $u_{*33\text{cm/s}} > u_{*8\text{cm/s}}$. The values of k_s^+ show that the hypothesis of the “fully rough” regime is justified because $k_s^+ > 55$ (Hinze 1975 quoting Nikuradse’s works 1942, Ligrani and Moffat 1986) for all the experiments. But it seems that the critical values of k_s^+ vary slightly between observers: i.e. the flow is completely rough turbulent flow as $k_s^+ > 70$ (Schlichting 1979), $k_s^+ > 68$ (reported by Carling 1992). In the present case, our first run ($U = 8$ cm/s over R1) seems “incompletely rough” near the boundary with completely rough flow. As expected, our results are coherent with those of the literature and justify our choices of k_s and in determining the origin of the y-axis. So, these values will be used as references for the measurements with periphyton.

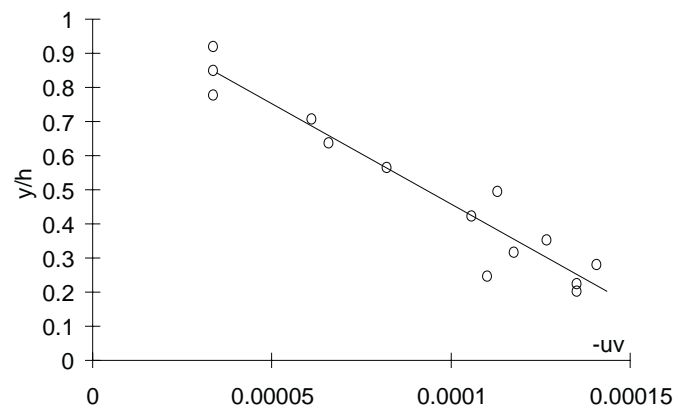


Fig. 5. Reynolds stress profile above marbles (o measured values, — fitted linear law)

Table 2 Hydrodynamic parameters

Velocity (cm/s)	substrate	u_{*1}	u_{*2}	k_s^+	Br
8	R1	0.65	0.68	56	8.72
	R2	0.82	0.82	140	8.95
16	R1	1.38	1.22	112	8.95
	R2	1.42	1.37	242	9.82
32	R1	2.7	2.9	220	6.85
	R2	2.7	2.6	460	9.96
42	R1	3.5	3.5	285	9.05
	R2	4.34	3.9	738	9.24
16	marbles	1.27	1.27	127	7.62

3.2 Velocity distribution with periphyton

3.2.1 The periphyton

The biological measurements have to show possible differences in the periphytic accumulation for different flows and substrate. Ghosh and Gaur (1998) show an inverse relationship between the periphytic accumulation and an increasing of the current velocity: they have observed the maximum accumulation on substrata kept in a pool. Several reports (McIntire 1966, Steinman and McIntire 1986, ...) reveal that, during the period of colonization, higher velocities show greater biomass accumulation even if there is a greater biomass accumulation at lower velocities during the initial stages of colonization.

In our cases, we have first observed different appearances of the periphyton according to the different velocities.

Quantitatively, the chlorophyll-a concentration measurements ($\mu\text{g}/\text{dm}^2$) as a function of the age (on the gravels) are presented on Fig. 7. These measurements represent the evolution of the living autotrophic organic fraction. These results have been obtained on the gravels R1 and for all the flow velocities. However, the tendencies are the same concerning the measurements realized on the gravels R2. First, we can underline that the maximal biomass is reached between 20 and 30 days-old, which justifies that the duration of the experiments will not be over 35 days.

Then, we observe (as seen in Fig. 9) that, for flow velocities between 16 and 42 cm/s, the chlorophyll-a quantity decreases when the flow velocity increases, whereas, between 8 and 16 cm/s, the

chlorophyll-a quantity increases when the flow velocity increases. This means that there is, in our experimental conditions, a critical velocity (near 16 cm/s). Horner et Welch (1981) have also observed that with a low phosphate concentration (as in this study) the increase in current velocity seems to reduce the development of periphyton. The higher water velocity delays the attachment of the algal cells as it is underlined by Lock (1981). But we do not observe, as he does, that this barrier disappears after 3 weeks.

Therefore, we believe that the appearances of the bioderm and the way in which the periphyton is attached to the substrate can be considered as indicators of the water velocity.

We now consider the chlorophyll-a quantities measured on the marbles with and without blowing and we compare these quantities with those measured on the gravels at the same flow velocity (Fig. 8). We first observe that in the presence of blowing, the development of the periphyton seems to be slower than without blowing during the first 3 weeks. After the 4th week of development, the chlorophyll-a quantity becomes more important in presence of blowing whereas it begins to decrease in the absence of blowing. Even if we could not realize measurement after 28 days of development, we can conclude that the next experiments with blowing will have to be more than 28 days long in order to attain the maximum chlorophyll-a quantity.

Moreover, we can see that the chlorophyll-a quantities measured on R1 at the same flow velocity are clearly more significant than those measured on the marbles when the size of the substrates is quite similar. This means that the micro-structure of the substrate is very important in the development of the periphyton, as under-

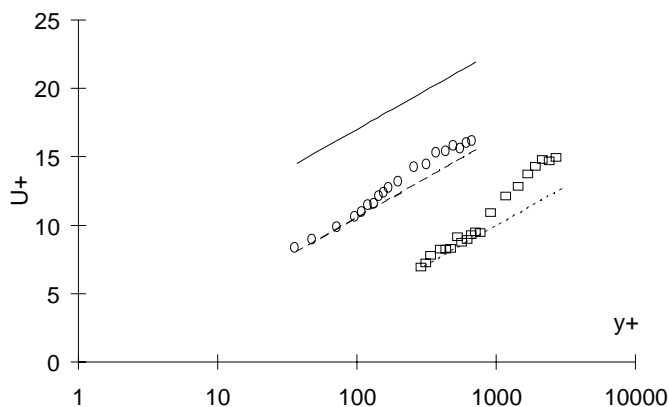


Fig. 6. Velocity profiles above R1, in dimensionless coordinates (\square 33 cm/s; \circ 8 cm/s; — smooth logarithmic formula; - - logarithmic formula (8 cm/s) see eq. 6; --- logarithmic formula (33 cm/s) see eq. 6)

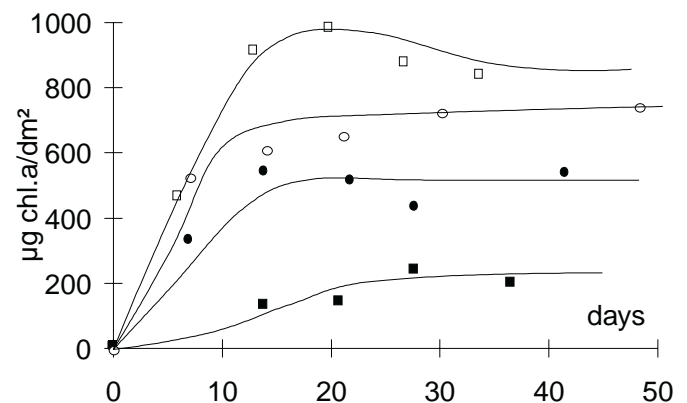


Fig. 7. Chlorophyll-a (chl.a) quantities measured on the gravels (R1) versus time (in days) \blacksquare at 42 cm/s; \bullet at 33 cm/s; \square at 16 cm/s; \circ at 8 cm/s

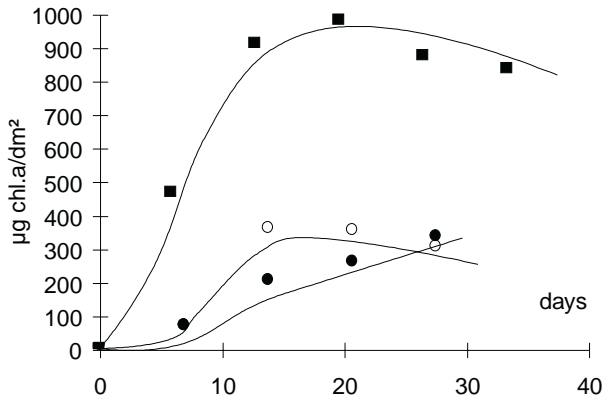


Fig. 8. Chlorophyll-a (chl-a) quantities measured at 16 cm/s on R1 (■), on the marbles with blowing (●) and without blowing (○)



Photo 1. Periphytic aspect at 8 cm/s after 4 weeks of development

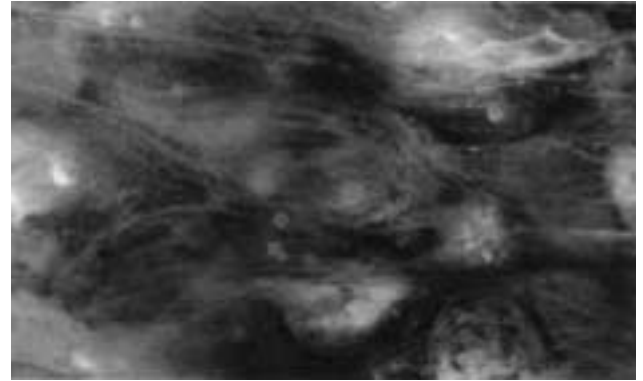


Photo 2 Upper view at 8 cm/s after 4 weeks of development

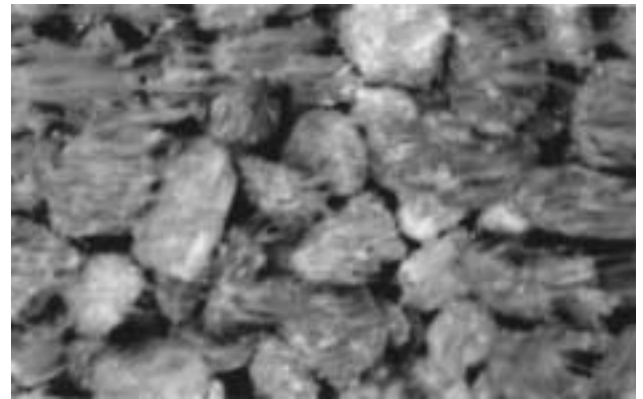


Photo 3 Upper view at 33 cm/s after 4 weeks of development

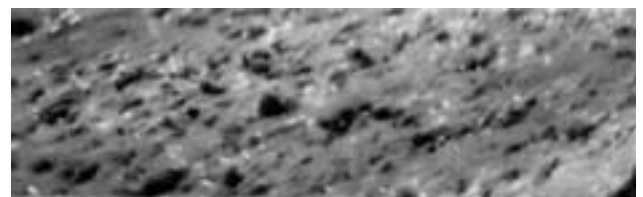


Photo 4 Periphytic aspect at 33 cm/s after 4 weeks of development

lined by DeNicola and McIntire (1990).

All the properties of the periphyton (thickness, structure, ...) will have consequences on the interpretation of the physical measurements above the bioderm.

It is possible to relate biological and hydrodynamical parameters such as the chlorophyll-a, DM and AFDM quantities measured after 4 weeks of development on R2 for example and the Reynolds numbers (Fig. 9). We observe that there is a critical value of the Reynolds number near $22 \cdot 10^3$: above this value the chlorophyll-a, DM and AFDM quantities decrease when Re increases whereas below this value the chlorophyll-a, DM and AFDM quantities increase with Re. This observation is only valid in our flume and our experimental conditions and it is necessary to confirm it because it could be very useful for the future work. Generally, papers rarely speak about appearances of the bioderm which is characterized through different biological measurements such as quantities of chlorophyll-a or others pigments, AFDM, ... Here, the differences in the appearance are clear: at 8 cm/s, after one week of colonization, periphyton appears on few gravels as small parcels. The periphytic aspect is cottony with a small density. After several weeks of development, the periphytic bioderm seems to be a tangle of very thin filaments (Photo 1) with filaments at the top which flap in the flow. The periphyton covers all the gravels with a significant thickness (more than 1 cm) but with always a low density because it is possible to see the gravels through the bioderm on the upper pictures (Photo 2). This means that, in spite of the thickness, the matrix has a high 'porosity'

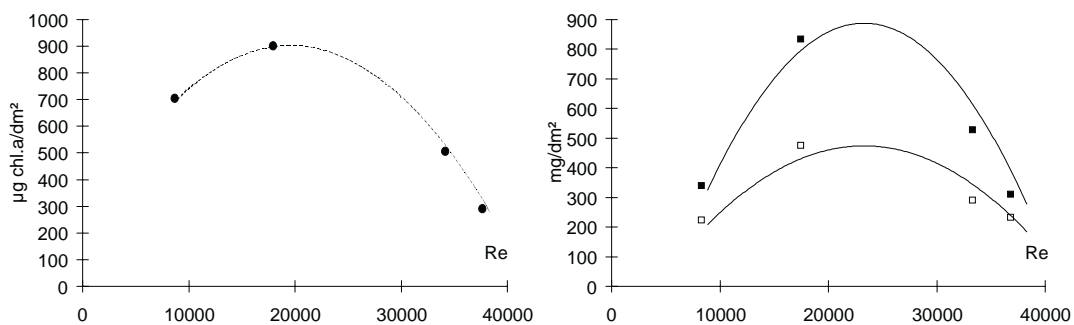


Fig. 9. Correlation between the Reynolds number and a) the chl.a quantities and b) the DM (■) and AM (○) quantities measured on R2 after 30 days of development

with a lot of voids. Filaments are at the top of the bioderm at 33 cm/s, after one week of development, small green peaks appear on the gravels. On the upper pictures, even after several weeks of development, the bioderm does not cover all the surface of the gravels (Photo 3). After the third week, some filaments attain important dimension, more than 10 cm, whereas the others filaments are smaller (not more than 1 or 2 cm) and seem to be directly attached to the gravels. Both types of filaments flap in the flow at 8 cm/s. The thickness of this periphytic bioderm is thinner (few millimetres, Photo 4) than those at 8 cm/s and we observe an important quantity of bubbles of oxygen, phenomenon not observed at 8 cm/s. These qualitative observations do not show differences between the two sizes of gravels.

When we have determined the algal composition of the biofilm, we have seen that, under any current velocity, the Diatoms are the main component of a 7 days aged periphyton (Fig. 10). It is the classic growth of biofilm with an important colonization by Diatoms during the 1-2 first weeks (Stock et Ward 1989). However, after 3 weeks, the level of the current velocity seems to cause a selection in benthic algae (Fig. 11). Indeed, Diatoms are dominant (> 60 %) at 8 and 16 cm/s and they represent less than 30% to 33 and 42 cm/s whereas Cyanophytes become dominant (> 60 %) at these current velocities.

Picture 1 shows a tangle of Diatoms represented mainly by filaments of *Melosira varians* Aguard, and the pictures 3 and 4 show a tangle of filaments of Cyanophytes (*Lyngbya sp.*).

These results confirm that current velocity is a factor which has an influence on the species repartition and structure of periphytic communities as shown, for example, by Marker (1976) and Horner et Welch (1981).

3.2.2 Physical measurements

Fig.12 shows longitudinal velocity measurements above gravels R1 after 4 weeks of periphytic development at 42 cm/s and after 1 and 4 weeks of development at 8 cm/s. They have been compared with measurements obtained without periphytic mat.

At 42 cm/s, the thickness of the periphytic bioderm after 4 weeks of development is small and the differences between the velocity profiles become practically invisible (Fig.12a). However, at 8 cm/s differences already appeared after just one week of develop-

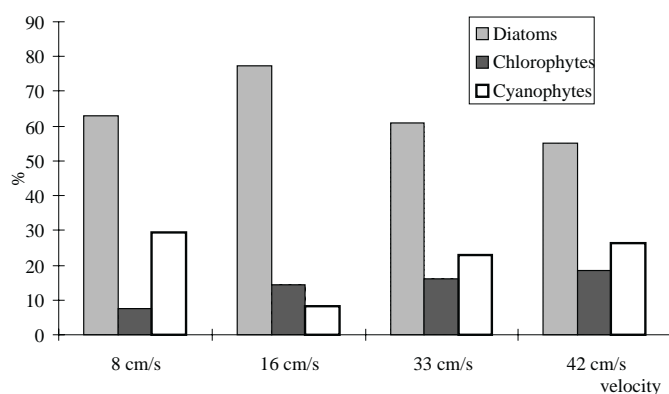


Fig. 10. Algal composition for a 7 days aged periphyton depending on the flow velocity (relative abundance percent)

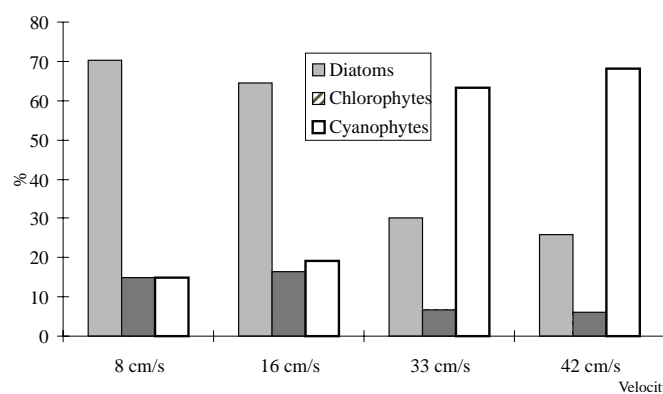


Fig. 11. Algal composition for a 3 weeks aged periphyton depending on the flow velocity (relative abundance percent)

ment (Fig.12b). This phenomenon increases with the development of the periphytic mat (Fig.12c). We can observe that the position of the first measured values above the periphyton is shifted vertically: due to an important increase of the thickness of the layer of periphytic mats we have an significant zone of the flow where it is impossible to obtain any information. According to the preceding description of the periphyton after several weeks of development, it is quite reasonable to think that the essential effect of the periphytic bioderm is to strongly slow down the flow in the region that it occupies, i.e. just above the substrate. In effect, it is quite reasonable to postulate that the periphytic mat can be compared to a porous medium. So, there exists a permeable boundary between the free-flowing surface water and the biofilm. Therefore, we are in the presence of two parallel flows with a strong mean velocity contrast. In these conditions, the first measurement points realized above the periphyton are situated in the upper zone of a shear flow. When the thickness of the periphytic mat is significant enough to induce differences between the profiles, the velocity profile is close to the curve presented on Fig.13a. This theory allows us to present, on Fig.13b, possible extrapolations of the measurements in this zone. This hypothesis has been proposed, but without any conviction, by Nikora et al. (1998) and it can be supported by works presenting certain similarities and which concern air flow near the earth in presence of vegetation as short grass or cereals (corn in particular) – see Guyot (1997). In the absence of direct velocity measurements, the numerical simulation seems to be a possible way to propose a velocity profile very close to the reality and also to support our hypothesis. Fig.12c shows, in presence of the periphyton, a strong acceleration of the mean longitudinal velocity which is very perceptible from the upper half-part of the flow (U increases of 15 % for R1). This is in good agreement with the formulated hypothesis as the flow ‘adjusts’ to allow the passage of the imposed discharge at the entrance of the flume. It is clear that the flows without and with periphytic bioderm present different properties for the mean values of the velocity. The thickness of the periphytic mat (at the IMFT) can be so important that after some weeks of development it strongly changes the flow and correlatively induces modifications to the turbulent parameters such as turbulent intensities, and Reynolds stress. Data for turbulence intensities for rough beds are limited and were obtained by Grass (1971) and

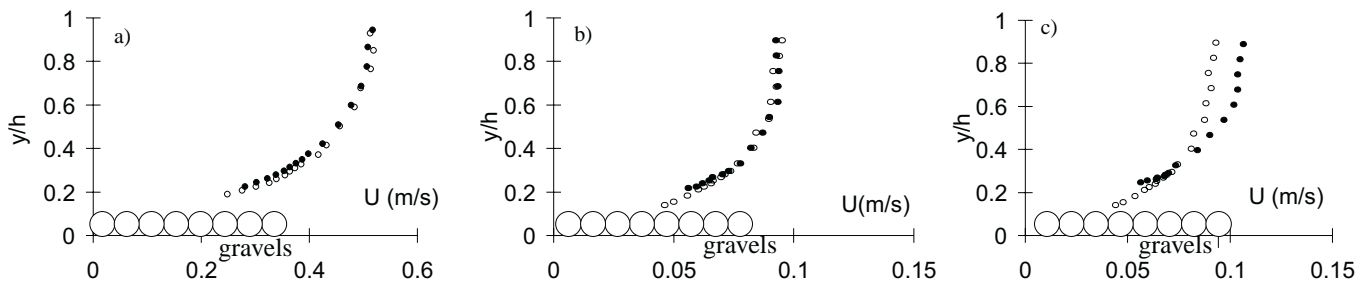


Fig. 12. Influence of the periphyton on the velocity profile at 42 cm/s after 4 weeks of development (a); at 8 cm/s after 1 week (b) and 4 weeks (c) of development (O without periphyton, ● with periphyton)

Nezu (1977a). They have shown the following results: (i) if y/h is larger than 0.3, the roughness has no effect on turbulence intensities; (ii) near the wall, $y/h < 0.3$, the value of u/u_* decreases gradually with increasing k_s^+ . Nevertheless, if the data show important differences between an hydraulically smooth bed ($k_s^+ < 5$) and a completely rough bed ($k_s^+ > 55$), the differences are very slight between an incompletely rough bed and a completely rough bed (see Nezu and Nakagawa 1993, p.57). Our measurements without periphyton, when $56 < k_s^+ < 738$, show the same tendencies (see Godillot 1998), that is to say: when $y/h < 0.3$, data are well fitted by the law $u/u_* = 2.3 \exp(-y/h)$ proposed by Nezu (1977b) and independant of the roughness; near the wall we observe a damping of the values correlatively with increasing k_s^+ . With periphyton these tendencies are found again but with some differences due to the nature of the 'wall' which is not a solid rough boundary (see Fig. 14). First, it is impossible to perform measurements very near the interface of the periphytic mats (this has been previously underlined). But, although an important decrease of the values is clearly observed near the interface, it is impossible to have a good evaluation of the maximum value of u . Second, the influence of the roughness is significant until $y/h \sim 0.5$; this is an interesting observation and is due to the expansion of the periphytic mats which can be observed for small mean velocities. As this has been underlined previously by Nikora et al. (1998) and confirmed by Magné (2000), periphytic mats are often buoyant due to oxygen bubbles produced during photosynthesis and trapped in the mat or attached to filaments. It is difficult to confirm because the gravels capped with a layer of periphytic mats are a special case of roughness boundary with properties which fluctuate due to environmental conditions.

To evaluate the dimensionless hydrodynamic parameter, we are

confronted with a more complicated problem than is the case without periphytic mats. As a matter of fact, the roughness of the substrate changes continuously during the growth of the periphyton. At the outset of each experiment and whatever the flow velocity and the type of substrate, it is clear that it is impossible to discriminate between the flow over gravels and the flow over gravels recently colonized by periphyton. On the other hand, as it is described in Godillot (1998), the top and the rear part of each gravel are progressively colonized and, after some weeks, and as a function of hydrodynamic parameters, the periphytic mats can look like a real cover over the bed of gravels. Consequently, three typical situations are to be considered : (1) bare- gravels (including the period of first colonization), (2) each gravel is capped with a layer of periphyton, (3) the bed of gravels is capped with a cover of periphyton. We are concerned here with the two last cases. Case (2) can be analysed by considering that the only (but possibly important) difference between a bare-gravel and a gravel capped with a layer of periphyton is that the surface roughness of the gravel is modified. So, the global roughness of the bed seems to be unchanged or a little altered. In this case, it seems pertinent to apply the same procedure as without periphyton to evaluate k_s and u_* . Case (3) corresponds to a new global roughness of the bed because the gaps between the gravels have been occupied by periphytic mats. In this case, the nature of the substrate is completely different and it seems realistic that the presence of the gravels must be forgotten; but these are insufficient observations or analytical models to evaluate the equivalent roughness of this type of bed. Thus, situations (1) and (2) can be studied implementing the same procedure as the one previously presented (without periphyton); case (3) needs an other approach. To support this theory, we have evaluated the dimensionless hy-

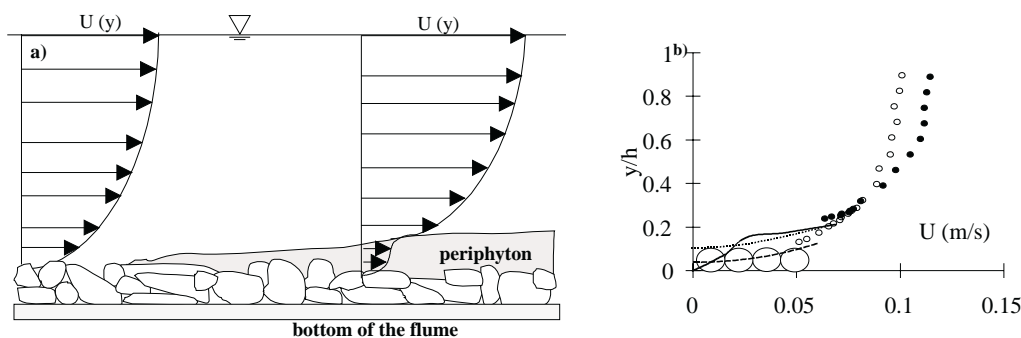


Fig. 13. Velocity profile above and in the periphyton a) hypothesis; b) -- velocity profile without periphyton, --- logarithmic velocity profile above periphyton, — hypothesis with a sub-flow in the periphyton

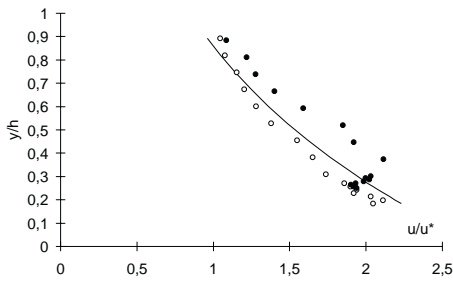


Fig. 14. Turbulent intensities without (O) and with (●) periphyton — fitted law

hydrodynamic parameters when the gravel bed is colonized by a 4 weeks old bioderm (that is to say corresponding to case (3)) taking into account the layer of bioderm in terms of displacement of the reference level (y'_0). We have determined y'_0 and the friction velocity u_* from the shear stress profile and the velocity profile (Godillot 1998). Then, we have supposed that the longitudinal velocity profile follows a logarithmic law similar to (1). As underlined in Table 3, if we chose similar roughness heights with and without periphyton, the values of Br are not coherent with those of the literature. Then, the only possibility is to impose $Br = 8.5 \pm 15\%$ and to determine the value of k_s : Table 4 presents hydrodynamic parameters with and without periphyton evaluated for the gravels R2.

We observe that the differences between the friction velocities with and without periphyton are very small even if it seems that, in presence of periphyton, u_* decreases. Concerning the values of the roughness heights it is clear that the periphyton induces a decrease of k_s and/or k_s^+ and also a smoothing of the roughness of the wall which is greater since the thickness of the periphytic matrix is significant.

Moreover, we can see, on Fig.15, that even if the periphytic ma-

trix is thin (Fig.15a) the velocity profile is smoother than those without. When the thickness is great (Fig.15b), we observe that the velocity profile is very close to the smooth logarithmic law and that the value of k_s^+ (for R1) is closer of the values of the smooth regime than those of the rough regime.

It is also very interesting to consider the influence of the periphyton on a more global parameter interpreting the resistance of river bed such as the Chezy coefficient currently used in hydrodynamic models of Saint Venant or shallow water types. The Chezy coefficient is defined as:

$$C = \sqrt{8g} \frac{1}{\sqrt{f}} = \sqrt{g} \left(\frac{U}{u_*} \right) \quad (7)$$

Table 5 presents the values of C with and without periphyton: we observe that the periphyton induces, for all the flow velocities, an increase of C. This means that the periphyton smoothes the roughness of the bottom. However, the influence of the periphyton depends on the thickness of the periphytic matrix. At 42 cm/s the periphyton is very thin and the difference between the values of C evaluated with and without periphyton is not great, whereas at 8 cm/s the periphytic thickness is significant as the difference between the both C. This confirms the previous interpretation and proves that growing of periphyton on a river bed smoothes the natural roughness.

4 Conclusion

The experimental flume described in this paper has allowed us to undertake experiments in hydrodynamically controlled conditions. One of the originalities of this work is to present both biological and physical measurements.

Table 3 Values of Br in presence of periphyton if k_s (with periphyton) = k_s (without periphyton)

velocity	Substrate	k_s (mm)	k_s^+	Br
42 cm/s	R1	8.15 mm	275	9.46
	R2	17 mm	669	11.02
33 cm/s	R1	8.15 mm	138	15.2
	R2	17 mm	421	12.27
16 cm/s	R1	8.15 mm	97	12.54
	R2	17 mm	216	12.65
8 cm/s	R1	8.15 mm	44	13.89
	R2	17 mm	122	10.20

Table 4 Comparison between friction velocities and roughness heights measured above R2

velocity	With periphyton		Without periphyton	
	u_*	k_s (mm) and k_s^+	u_*	k_s (mm) and k_s^+ evaluated with $Br = 8.5 \pm 15\%$
42 cm/s	4.34 cm/s	17 738	3.93 cm/s	$3.72 < k_s < 10.31$ $146 < k_s^+ < 406$
33 cm/s	2.7 cm/s	17 460	2.48 cm/s	$2.26 < k_s < 6.26$ $56 < k_s^+ < 156$
16 cm/s	1.42 cm/s	17 242	1.27 cm/s	$1.94 < k_s < 5.38$ $25 < k_s^+ < 70$
8 cm/s	0.82 cm/s	17 140	0.72 cm/s	$5.18 < k_s < 14.38$ $37 < k_s^+ < 104$

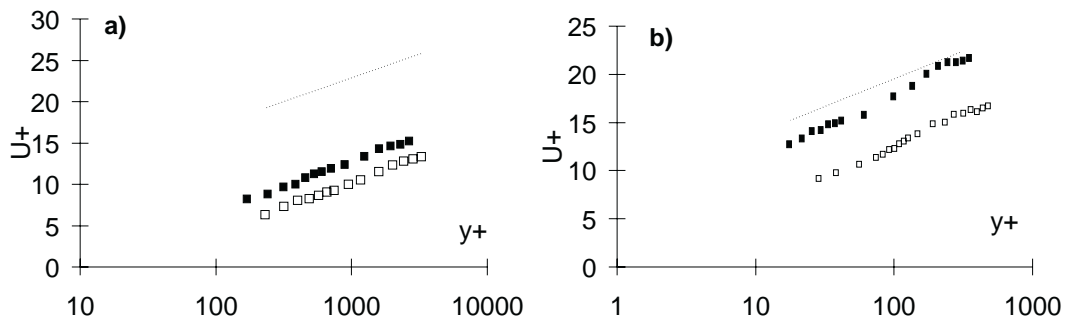


Fig. 15. Influence of the periphyton on the dimensionless velocity profiles: a) at 42 cm/s above R2; b) at 8 cm/s above R1; \square without periphyton; \blacksquare with periphyton; -- smooth logarithmic law

Table 5 Influence of the periphyton on the Chezy coefficient

velocity	substrate	without periphyton	with periphyton
8 cm/s	R1	C = 38,53	C = 47,8
	R2	C = 33,01	C = 38,5
16 cm/s	R1	C = 35,93	C = 45,36
	R2	C = 34,55	C = 43,3
33 cm/s	R1	C = 33,88	C = 62,29
	R2	C = 36,01	C = 43,03
42 cm/s	R1	C = 35,73	C = 38,62
	R2	C = 32,78	C = 36,84

Through the biological results presented here, we have observed that the flow velocity and the substrate of colonization induce the development and the composition of the bioderm.

Moreover, we have been able to show that, in presence of periphyton, the modifications of the mean flow are very significant. Indeed, measurements with the Laser Doppler Anemometer suggest the presence of a shear flow due to the strong decrease of velocity near the bioderm. They also indicate that the evolution of the turbulent parameters, turbulent intensities and Reynolds stress are the signs of hydrodynamic changes in the benthic zone, due to the important thickness of the periphytic mats. By evaluating the dimensionless hydrodynamic parameters and more global parameters such as the Chezy coefficient, we have underlined that the roughness of the bottom is smoothed by the periphyton. The fact that we have chosen to take into account the thickness of the periphytic matrix in terms of a gap in the logarithmic law followed by the mean longitudinal velocity profile is a very important difference compared the interpretation of Nikora et al. (1997, 1998). Had we not considered this gap, the conclusions would have been that periphyton created an increase in the roughness of the wall. On the contrary, the thickness of the periphytic matrix can be so great that it is impossible to omit it in the interpretation of the results, hence stressing the necessity of describing the periphyton.

Consequently, these experimental results impose a revision, under a new scope, of the hydroecological models of the rivers

Acknowledgements

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Symbols

Br constant of integration of the log law ($Br \approx 8.5$)
 C Chezy coefficient
 D channel width ($D = 0.5$ m)
 f Colebrook coefficient
 Fr Froude number ($Fr = \frac{U_{max}}{\sqrt{gH}}$)
 g acceleration due to gravity
 h water depth measured from the bottom of the channel
 H water depth measured from the reference level
 k_s Nikuradse's equivalent sand-grain roughness
 k_s^+ roughness Reynolds number ($k_s^+ = \frac{k_s u_*}{\nu}$)
 Re Reynolds number ($Re = R_h U/\nu$)

R_h hydraulic radius
 U local mean velocity
 u turbulent intensity in the longitudinal direction
 U^+ dimensionless velocity ($U^+ = U/u_*$)
 u_* friction velocity
 $-\overline{uv}$ Reynolds stress
 v turbulent intensity in the vertical direction
 x longitudinal axis
 y vertical axis and distance from the bottom of the channel
 $y^+ = (y-y_0) u_* / \nu$
 y_0 reference level without periphyton
 y'_0 reference level with periphyton
 κ Von Karman's universal constant ($\kappa \approx 0.4$)
 ν kinematic viscosity of the water
 ρ fluid density
 τ_{xy} shear stress
 τ_w wall shear stress