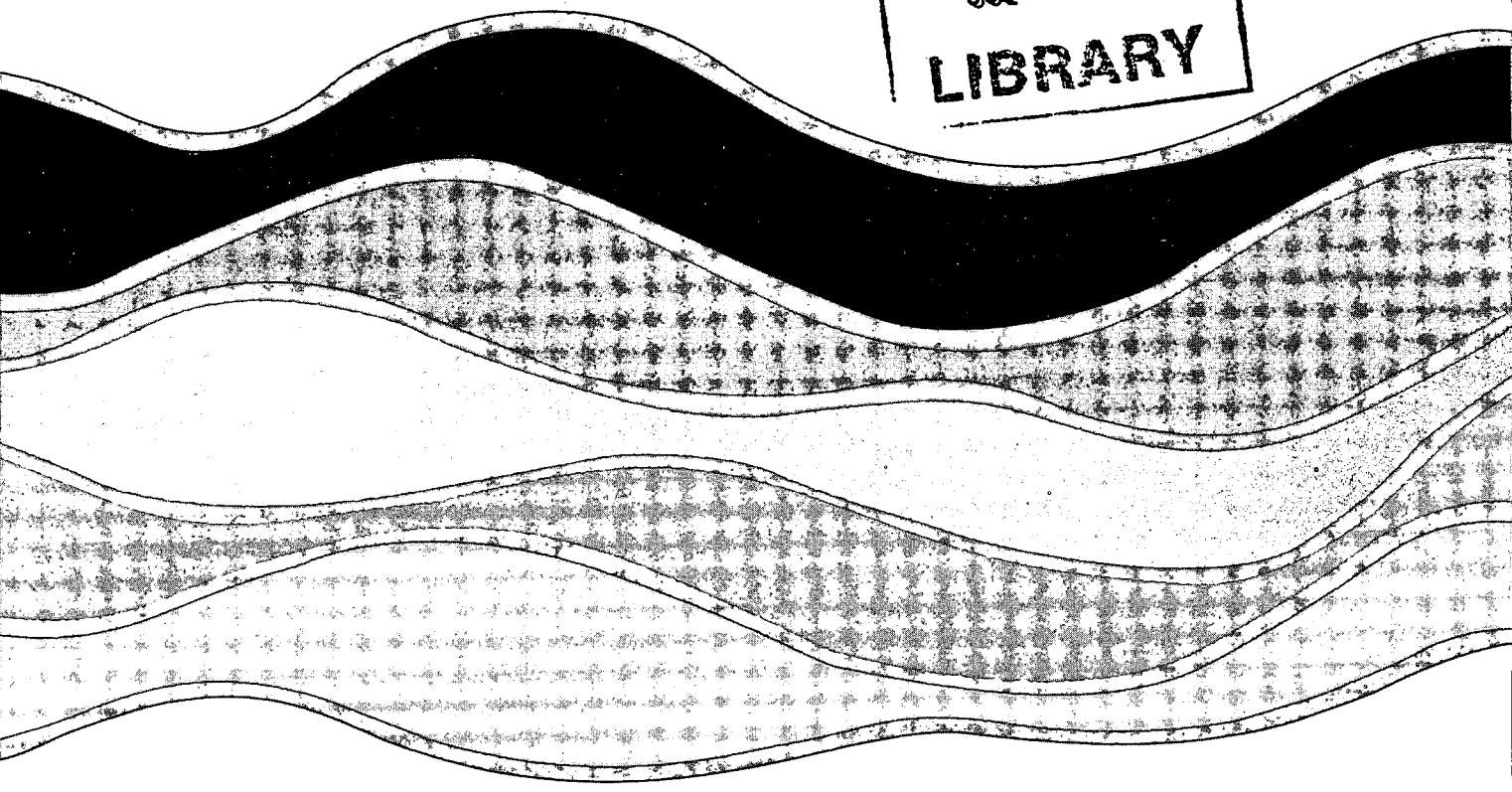
95-63 C1

NATIONAL WATER RESEARCH INSTITUTE

INSTITUT NATIONAL de RECHERCHE sur les EAUX

CCIW
JUL 27 1995
LIBRARY



RELATIVE IMPORTANCE OF MEAN VELOCITY AND BED SHEAR ON BIOFILM ACCUMULATION IN OPEN-CHANNEL FLOWS

Y.L. Lau

NWRI CONTRIBUTION NO. 95-63

TD
226
N87
No. 95-
63
c.1

RELATIVE IMPORTANCE OF MEAN VELOCITY AND BED SHEAR ON BIOFILM ACCUMULATION IN OPEN-CHANNEL FLOWS

Y.L. LAU

National Water Research Institute
867 Lakeshore Road, P.O. Box 5050
Burlington, Ontario, Canada L7R 4A6

NWRI Contribution No. 95-63

MANAGEMENT PERSPECTIVE

Biofilms which grow on the bottom of rivers and streams have the ability to remove biodegradable material from the water column. Many studies have shown that the rate at which environmental contaminants are removed from shallow streams is determined by the growth of biofilms. Thus knowledge of biofilm processes such as growth rate and kinetics are important elements for predicting the fate and pathways of contaminants.

Biofilm growth on the streambed is affected by flow conditions in the stream. Higher velocity and turbulence can increase the metabolism by increasing the transport of nutrients and oxygen from the bulk fluid to the film surface but, at the same time, sloughing of the film may increase because of the higher shear stress. In studies of biofilm growth, the current velocity had always been used as the variable to characterize the flow conditions of the stream. However, from the standpoint of hydrodynamics, the turbulence in a flow is actually better characterized by the bottom shear stress. As there had not been any studies on biofilm growth in which both velocity and shear stress were evaluated, a study was undertaken to compare the relative importance of these two variables by conducting experiments on biofilm growth in two channels simultaneously. The results show that biofilm growth rate is controlled by the flow velocity rather than the bed shear stress. Therefore, studies on the relationship between flow and biofilm processes should continue to use velocity as the governing variable.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Les biofilms qui se forment sur le fond des rivières et autres cours d'eau ont la capacité d'éliminer les matières biodégradables de la colonne d'eau. De nombreuses études ont montré que la vitesse à laquelle les contaminants environnementaux sont éliminés dans les cours d'eau peu profonds est déterminée par la croissance de ces biofilms. Ainsi, la connaissance des processus régissant les biofilms, comme le taux de croissance et la cinétique, représentent des éléments importants pour prévoir le devenir et le cheminement des contaminants.

La croissance du biofilm sur le lit du cours d'eau dépend des conditions d'écoulement dans celui-ci. Une vitesse et une turbulence plus élevées peuvent accroître le métabolisme en augmentant le transport des agents nutritifs et de l'oxygène à partir du liquide vers la surface du film, mais, en même temps, il peut y avoir accroissement de la desquamation en raison d'une plus grande contrainte de cisaillement. Dans les études de croissance du biofilm, c'est toujours la vitesse du courant qui a servi comme variable pour caractériser les conditions d'écoulement du cours d'eau. Cependant, du point de vue hydrodynamique, la turbulence dans un écoulement est en fait mieux définie à l'aide du cisaillement de fond. Étant donné qu'il n'y a eu aucune étude sur la croissance du biofilm, comportant une évaluation à la fois de la vitesse du courant et de la contrainte de cisaillement, des recherches ont été entreprises pour comparer l'importance relative de ces deux variables grâce à des expériences sur la croissance du biofilm conduites simultanément dans deux canaux. Les résultats montrent que la vitesse de croissance du biofilm est régie par la vitesse du courant plutôt que par la contrainte de cisaillement du lit. Les études sur la relation entre l'écoulement et les processus à l'origine du biofilm devraient donc continuer à utiliser la vitesse du courant comme variable déterminante.

ABSTRACT

Experiments on biofilm growth were carried out to investigate whether bottom shear stress or average velocity is more appropriate as a parameter for investigating the effect of flow on biofilm formation in channel flows. The tests were conducted in two identical channels located side by side, using the same water supply. By having different bottom slopes or roughness elements, or both, tests were set up in which the flows in the two channels had equal velocities but different bottom shear stresses or equal bottom shear stresses but different velocities. Porcelain balls were used as bottom roughness elements and the accumulation of biofilm on the balls was monitored. Comparisons of the rates of biofilm accumulation indicate that the average velocity is the more important parameter.

RÉSUMÉ

On a procédé à des expériences sur la croissance du biofilm pour déterminer si c'est la contrainte de fond ou la vitesse moyenne qui constitue le paramètre le plus approprié pour évaluer l'effet de l'écoulement sur la formation du biofilm dans les écoulements canalisés de lits fluviatiles. Des essais ont été effectués dans deux canaux identiques, situés l'un à côté de l'autre, avec la même alimentation en eau. En utilisant des pentes de fond ou des éléments irréguliers différents, ou encore les deux, on a mis sur pied des essais dans lesquels les vitesses du courant dans les deux canaux étaient égales, mais avec des cisaillements de fond différents, et d'autres essais où les cisaillements de fond étaient égaux, mais avec des vitesses différentes. Des balles de porcelaine ont servi comme éléments d'irrégularité; on a mesuré l'accumulation de biofilm sur les balles. La comparaison des vitesses d'accumulation du biofilm montre que la vitesse moyenne est le paramètre le plus important.

INTRODUCTION

Biofilms which are attached to stable surfaces in stream beds can remove chemicals from the water column above the film and can contribute significantly to the purification of the aquatic system. Boyle and Scott (1984) showed that benthic films played a dominant role in the oxygen balance in the River Culm in England, and Srinanthakumar and Amirtharaja (1983) showed that attached biofilms were much more effective in removing organic carbon than the suspended biomass in a swift, shallow stream. It has been shown that biofilm growth can determine the rate at which environmental contaminants are degraded and removed from aquatic systems (Carey *et al.*, 1984; Ganzer *et al.* 1988). Therefore, understanding the growth and development of biofilm is a vital step towards predicting the ultimate fate of chemicals in natural waters.

The formation of biofilm on river beds is affected by the hydrodynamic conditions of the flow. With increasing turbulence in the water, reaeration from the atmosphere and transfer of oxygen and nutrients to the bed level are increased, thus improving conditions for growth. However, excessive turbulence may also inhibit microbial growth, possibly by damaging cell membranes (Toma *et al.*, 1991). In studies of the effects of flow on biofilm, the mean current velocity is most often used as the indicator of the hydraulic conditions and its effect has been demonstrated in a number of cases. Flow velocity has been shown to affect the rate of algal capture (Stevenson, 1983) and the rate of accumulation of periphyton on the substratum (Horner and Welch, 1981). Zimmerman (1961, 1962) found that different species of algae were dominant at different velocities. Other studies have also concentrated on the effects of velocity (McIntire, 1966; Phaup and Gannon, 1967; Rodgers and Harvey, 1976).

Even though it may be the most convenient to use, the mean velocity is actually not the bulk variable which best characterizes the hydrodynamics of a particular flow. Two open-channel flows may have the same mean velocity but very different levels of turbulence because of differences in flow depth, bed slope or bottom roughness. It is the shear between the water and the bottom boundary which generates the turbulence and the most meaningful bulk hydraulic variable for characterizing the turbulence in the flow is the bottom shear stress. However, this variable has seldom, if ever, been used in studying biofilm development. In this study, some tests were carried out to investigate the relative importance of mean velocity and bed shear stress for biofilm growth, to see which is a better variable for studying the relationship between the hydrodynamic properties and biofilm formation in channel flows.

EXPERIMENTAL METHOD

Experiments on biofilm growth were carried out in two flumes located side by side. The flumes were identical, each having a headbox with a smooth contraction which was joined to a straight channel 0.2 m x 0.2 m in cross section and 3 m in length. The flumes were located beside Hamilton Harbour, a large harbour at the western tip of Lake Ontario with a surface area of 2.2×10^7 m^2 and a mean depth of 13 m. Water was pumped from the harbour into a constant-head tank which had two outlets, each supplying water via a pipe into the

flume's headbox. Valves were used to regulate the discharges into the headboxes. Tail-gates at the end of the channels were used to control the flow depth. Water from the channels emptied into a 3 m x 3 m x 1 m high tank from which it was discharged back into the harbour. The discharge went out via a 90^0 V-notch weir which provided measurements of the flow rate. Screwjacks supporting the channels enabled the channel slopes to be adjusted. A sketch of the apparatus is shown in Figure 1.

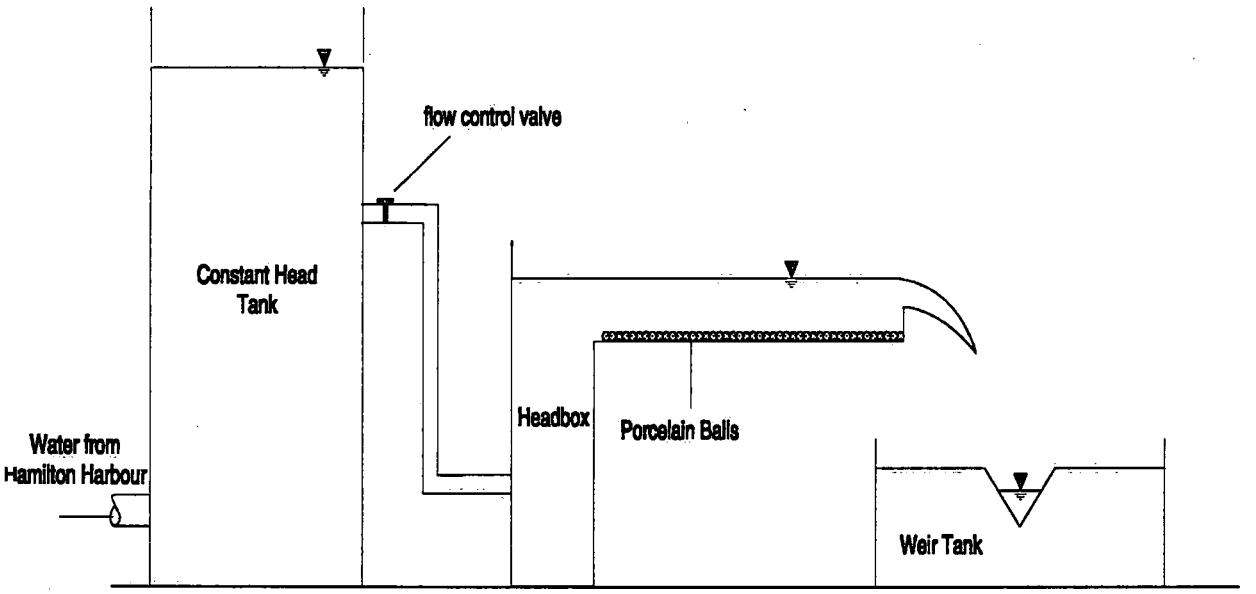


Fig. 1. Sketch of experimental setup.

Porox porcelain balls were used as the substratum for the growth of biofilm. The bottoms of the two channels were each lined with a uniform layer of balls. Channel no. 1 was used as the reference and was always lined with 14.5 mm diameter balls whereas channel no. 2 was either lined with the same size or with larger balls which were 40 mm in diameter. The larger balls provided increased bottom roughness and flow resistance. By giving channel no. 2 a different bottom roughness, or different bed slope, or both, uniform flows could be set up in the two channels with identical velocities but different shear stresses or vice versa. Experiments on biofilm growth could then be carried out in the two flows simultaneously. The bed slopes were measured using a theodolite. Point gauges were used to measure the depths along the channel centreline. The flow depth was taken to be the distance from the water surface down to the level where the bottom would be if the balls were broken down into a uniform slab. As the flows were uniform, the average bed shear stress could be calculated using the slope and the depth. Because the plywood side-walls were much smoother than the bottom, a side-wall correction procedure was used and the shear stress was calculated from the equation

$$T_b = \rho g r_b S \quad (1)$$

in which T_b is the bed shear stress; ρ is the density of water; g is the acceleration due to gravity; r_b is the hydraulic radius of the bed obtained from the procedure proposed by Vanoni and Brooks (1957); and S is the bed slope.

For each set of experiments, a uniform flow was first set up in channel no. 1. A different flow was then set up in channel no. 2 by changing the bed slope and/or the roughness. For instance, when the two channels were given the same volume flow rate while channel no. 2 was lined with the larger balls, the slope for channel no. 2 could be increased until it had the same uniform flow depth as channel no. 1. The flow velocities were then the same in the two channels but channel no.2 had a larger bed shear stress. It was also possible to create a flow in channel no. 2 which had the same shear stress but a smaller velocity than in channel no. 1 by putting a smaller discharge into channel no. 2 and reducing the slope until the flow depths were the same. Once a pair of flows had been set up, the balls in the two flumes were removed and replaced by clean ones to begin the experiment on biofilm growth.

The balls were removed from the channels at various intervals to monitor the accumulation of biofilm. Sampling was usually carried out daily, beginning two to three days following the start of the experiment. At each sampling, three of the large balls and 15 of the small balls were taken. The balls were placed in individual aluminium trays, one for each of the large balls and one for each set of five small balls. They were dried in a drying oven overnight at 80°C and then allowed to cool in a desciccator and weighed. Afterwards, the balls were washed thoroughly to strip off all the biofilm, dried again in their original aluminium trays and weighed. From the difference in mass before and after the cleaning, the biofilm mass on the balls could be calculated.

At the end of an experiment, which lasted between two to four weeks, the balls and the channels were completely cleaned. A new set of flows were then set up for the next experiment. A total of ten experiments were carried out. Tests 1 to 4 were conducted between June and October of 1993 and tests 5 to 10 were conducted between June and September of 1994. The flow conditions are summarized in Table 1.

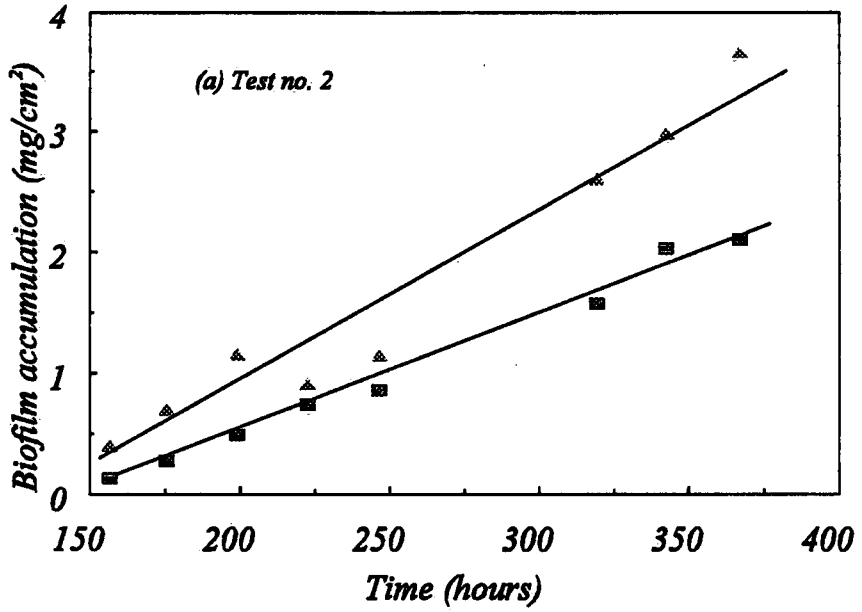
RESULTS AND DISCUSSION

In each test, experiments were conducted simultaneously in the two channels located within a metre of each other, using the same water supply. Therefore, all conditions of water chemistry, temperature and light etc. were identical for the two flows. It is thus reasonable to assume that any difference between the biofilm accumulation rates in the two channels could be attributed to the differences in the hydraulic conditions. By the same token, it would not be meaningful to compare the accumulation rates between different tests as there might have been differences in many of the other parameters which affect biofilm growth.
Results from two of the tests are shown in Figure 2, in which the biofilm accumulation is

TABLE 1. SUMMARY OF TEST CONDITIONS

Test no.	Channel	Bottom material	Discharge (m^3/s)	Slope	Depth (m)	Velocity (m/s)	Bed shear (N/m^2)
1	No. 1	14.5 mm	0.0038	0.00127	0.088	0.216	0.0081
	No. 2	40 mm	0.0038	0.00176	0.092	0.206	0.0127
2	No. 1	14.5 mm	0.0038	0.00127	0.088	0.216	0.0081
	No. 2	40 mm	0.0021	0.00060	0.087	0.121	0.0042
3	No. 1	14.5 mm	0.0016	0.00127	0.049	0.163	0.0050
	No. 2	40 mm	0.0011	0.00150	0.047	0.117	0.0063
4	No. 1	14.5 mm	0.0016	0.00127	0.049	0.163	0.0050
	No. 2	40 mm	0.0015	0.00230	0.050	0.149	0.0102
5	No. 1	14.5 mm	0.0014	0.00141	0.045	0.155	0.0054
	No. 2	40 mm	0.0015	0.00133	0.058	0.128	0.0065
6	No. 1	14.5 mm	0.0015	0.00141	0.046	0.163	0.0054
	No. 2	40 mm	0.0010	0.00131	0.048	0.103	0.0053
7	No. 1	14.5 mm	0.0036	0.00145	0.080	0.225	0.0085
	No. 2	14.5 mm	0.0014	0.00588	0.031	0.224	0.0161
8	No. 1	14.5 mm	0.0035	0.00127	0.079	0.222	0.0072
	No. 2	40 mm	0.0021	0.00587	0.047	0.226	0.0243
9	No. 1	14.5 mm	0.0034	0.00122	0.078	0.216	0.0067
	No. 2	14.5 mm	0.0011	0.00287	0.033	0.166	0.0079
10	No. 1	14.5 mm	0.0034	0.00140	0.078	0.218	0.0081
	No. 2	14.5 mm	0.0009	0.00133	0.036	0.125	0.0042

plotted against time. The biofilm accumulation, in mg/cm^2, was obtained by dividing the total biofilm mass by the surface area of all the balls sampled. In Figure 2a, channel no. 2 had a smaller velocity and a smaller bed shear stress and the data show that the biofilm accumulation increased at a faster rate than in channel no. 1. The rate of accumulation, in $mg/cm^2/day$, was calculated from the slope of line through the data points. Figure 2b is from test no. 8 in which channel no. 2 had the same velocity but a larger bed shear. However, the



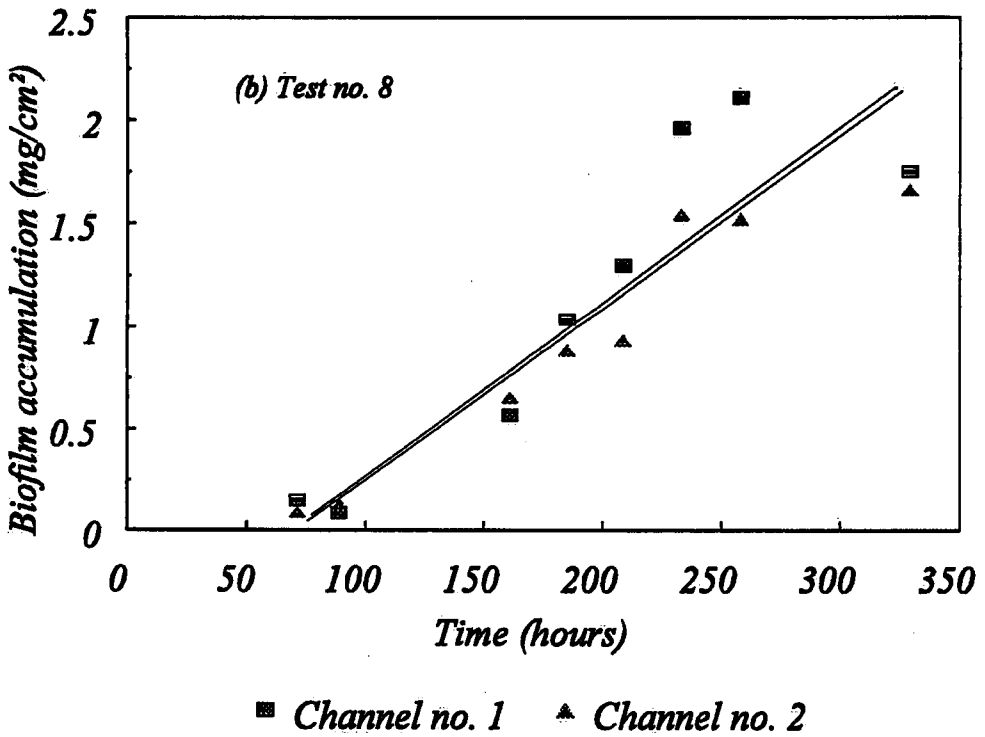


Fig. 2. Increase of biofilm accumulation with time

accumulation rates were practically the same. The comparisons for all ten tests are summarized in Table 2.

TABLE 2. SUMMARY OF BIOFILM ACCUMULATION RATES AND COMPARISON

Test no.	Accumulation rate ($mg/cm^2/day$)		Channel 2 compared with channel 1		
	Channel 1	Channel 2	Velocity	Bed shear	Accumulation
1	0.24	0.24	same	larger	same
2	0.23	0.35	smaller	smaller	larger
3	0.26	0.27	smaller	larger	larger
4	0.06	0.11	smaller	larger	larger
5	0.17	0.24	smaller	larger	larger
6	0.38	0.50	smaller	same	larger
7	0.37	0.37	same	larger	same
8	0.20	0.20	same	larger	same
9	0.19	0.21	smaller	same	larger
10	0.12	0.13	smaller	smaller	larger

From the comparisons given in Table 2, one can see that the accumulation rate is much better correlated with the velocity than with the bed shear. Of the ten tests, there were seven in which the velocity in channel no. 2 was smaller than that in channel no. 1 and three tests in which the velocities were the same. The accumulation rate was larger in all seven tests in which the velocity was smaller. In all three tests in which the velocities were the same, the accumulation rates were the same in the two channels. In three of the six tests in which the shear stress was larger, the accumulation rate was larger, while in the other three the accumulation rate was the same. The accumulation rates were also larger in the two tests in which the shear was smaller and in the two tests in which the shear was the same. Thus it appears that the velocity had a much greater control over the accumulation rate, at least over the range tested. A lower velocity was always accompanied by a larger accumulation rate. The bed shear stress, on the other hand, does not appear to be a very good indicator as larger rates occurred for flows with larger, smaller or equal bed shear.

There is no clear explanation as to why the mean velocity should have so much more influence than the shear stress on the biofilm accumulation rate. Increasing the shear stress or increasing the velocity both increase the turbulent diffusion in the flow which improves the supply of nutrients and oxygen and enhances productivity. However, while the bed shear stress gives an indication of the level of turbulence in the flow field, the mean velocity is a

better representation of the tearing and erosive action which can detach the biofilm and lessen the accumulation on the bottom. It is possible that, in situations where there is sufficient turbulence, the biofilm accumulation is limited more by the horizontal shearing action than by the level of turbulence. Other experiments are required before a more definite reason can be given. However, these experiments have shown that it is probably better to use the flow velocity rather than the shear stress as a variable when studying the effect of hydrodynamics on bottom-attached biofilm in channel flows.

REFERENCES

Boyle J.D., Scott J.A. (1984). The role of benthic films in the oxygen balance in an East Devon river. *Wat. Res. 18*, 1089-1099.

Carey J.H., Fox M.E., Brownlee B.G., Metcalfe J.L., Platford R.F. (1984). Disappearance kinetics of 2,4- and 3,4-dichlorophenol in a fluvial system. *Can. J. Physiol. Pharmacol. 62*, 971-975.

Gantzer, C.J., Kollig, H.P., Rittmann, B.E., Lewis, D.L. (1988). Predicting the rate of trace-organic compound removal by natural streams. *Wat. Res. 22*, 191-200.

Horner R.R., Welch E.B. (1981). Stream periphyton development in relation to current velocity and nutrients. *Can. J. Fish Aquat. Sci. 38*, 449-457.

McIntire, C.D. (1966). Some effects of current velocities on periphyton communities. *Hydobiologia 27*, 559-570.

Phaup, J.D., Gannon, J.D. (1967). Ecology of Spaerotilus in an experimental outdoor channel. *Wat. Res.1*, 523-541.

Rodgers, J.H. Jr., Harvey, R.S. (1976). The effect of current on periphytic productivity as determined using carbon-14. *Wat. Res. Bull. 12*, 1109-1118.

Srinanthakumar S., Amirtharaja A. (1983). Organic carbon decay in streams with biofilm kinetics. *J. Envir. Engng. Div., ASCE, 109*, 102-119.

Stevenson, R.J. (1983). Effects of currents and conditions simulating autogenically changing microhabitats on benthic diatom immigration. *Ecology 64*, 1514-1524.

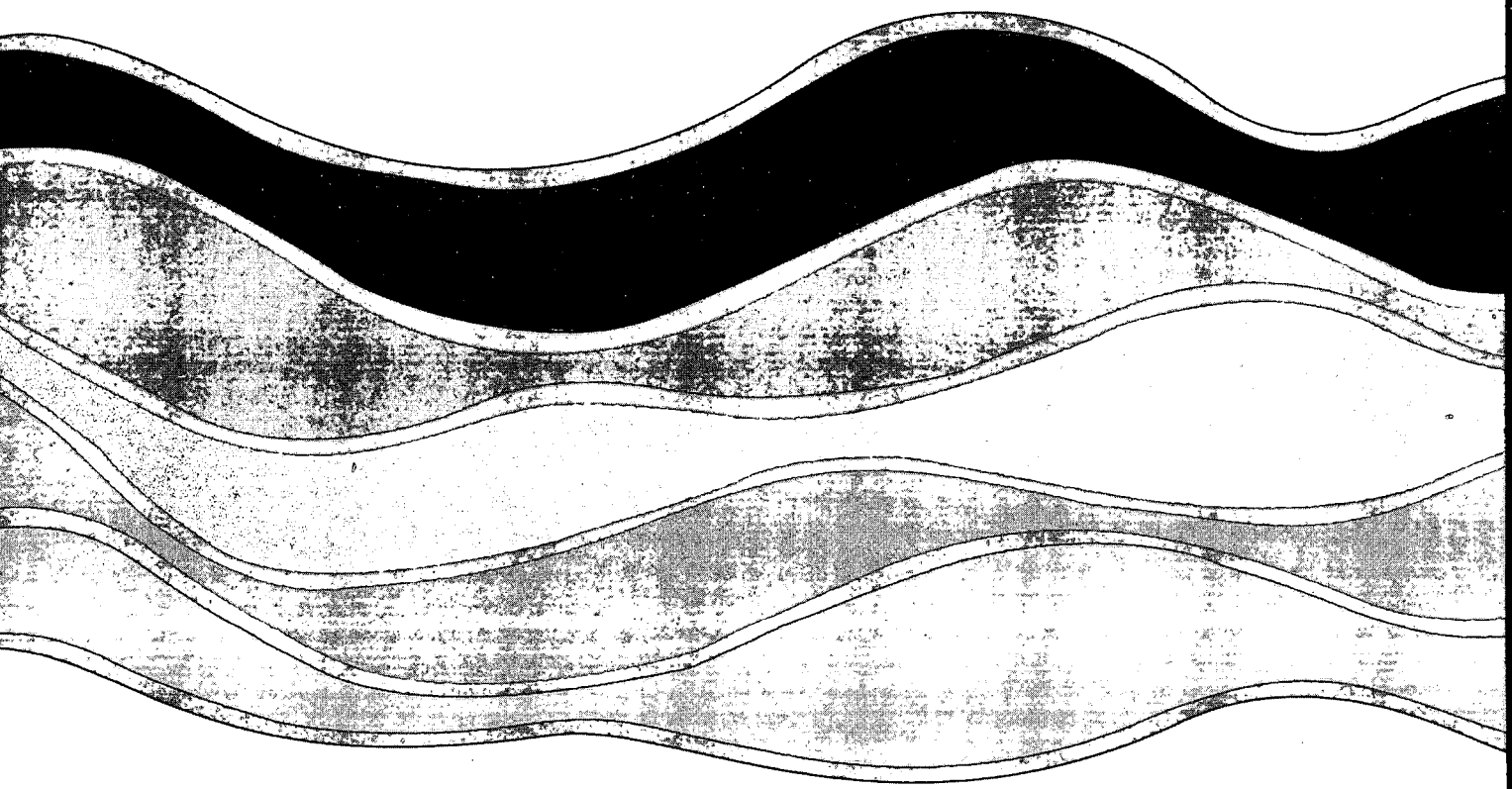
Toma, M.K., Ruklisha, M.P., Vanags, J.J., Zeltina, M.O., Leite, M.P., Galinina, N.I., Viesturs, U.E., Tengerdy, R.P. (1991). Inhibition of microbial growth and metabolism by excess turbulence. *Biotechnology and bioengineering, 38*, 552-556.

Vanoni, V.A. and Brooks, N.H. (1957). Laboratory studies of the roughness and suspended load of alluvial streams. Sedimentation Laboratory Report No. E68, California Institute of Technology, Pasadena, California.

Zimmerman, P. (1961). Experimentelle Untersuchungen über die ökologische Wirkung der Strömgeshwindigkeit auf die Lebensgemeinschaften des fliessenden Wassers. Schweiz. *Z. Hydrol. 23*, 1-81.

Zimmerman, P. (1962). Der Einfluss der Strömung auf die Zusammensetzung der Lebensgemeinschaften im Experiment. Schweiz. *Z. Hydrol. 24*, 408-411.

ENVIRONMENT CANADA LIBRARY, BURLINGTON
3 9055 1016 4675 9



NATIONAL WATER RESEARCH INSTITUTE
P.O. BOX 5050, BURLINGTON, ONTARIO L7R 4A6

Environment Canada Environnement Canada

Canada

INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX
C.P. 5050, BURLINGTON (ONTARIO) L7R 4A6

Think Recycling!

Pensez à recycler !