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Effects of biofilm on river-bed scour

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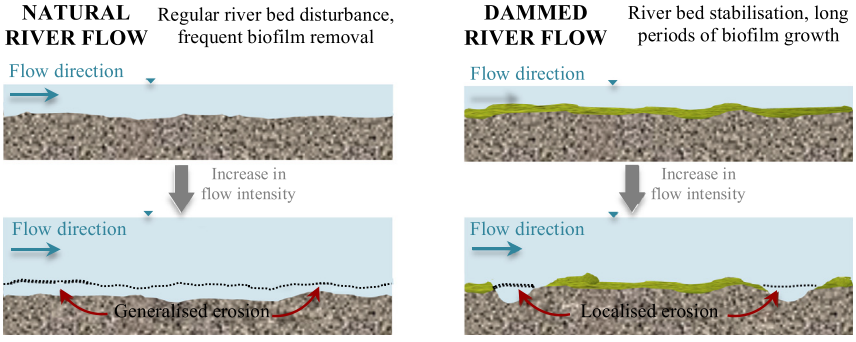
HIGHLIGHTS

- River bed stabilisation by biofilm
- Assessment of the biofilm stabilising capacity by means of indoor channels
- Differences in erosion patterns in biofilm-free and in colonised sediments
- High capacity of biofilm to protect small non-cohesive sediments from flow erosion

GRAPHICAL ABSTRACT



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ABSTRACT

Biofilm acts stabilising river-bed sediments, interfering with particle entrainment and, consequently, preventing bed disturbance. In this paper we present the results of a series of experiments carried out in indoor channels, aimed to understand biofilm alteration of bed material motion and topographic changes in stream channels. We analysed the erosion patterns and bedload rates in non-cohesive sediments in channels colonised by biofilms and compared them to biofilm-free others. All the channels had the same conditions of light irradiance, temperature, slope, and particle size (sand). Discharge and water surface slope were modified to create a range of hydraulic conditions, with pairs of colonised and non-colonised channels subjected to the same flows. We observed that biofilm slightly modified bed roughness and flow hydraulics, but that highly influenced bed disturbance. Biofilm caused bed scour to occur in patches unevenly distributed along the channel length, as a result of localised weaknesses of the biofilm. Once biofilm was ripped up it was transported in chunks, and sand grains were observed attached to these chunks. In non-colonised sediments the erosion was more homogeneous and the formation and movement of bedforms were observed. On average, bedload rates were 5 times lower when biofilm was present. Overall, the protective effect of the biofilm prevented generalised erosion of the channel and delayed the entrainment and transport of sand grains. Results emphasised the important role of biofilm in the incipient motion of bed-material in stream channels; this role may affect the magnitude and frequency of subsequent river bed processes, notably the onset of bedload and associated channel morpho-dynamics.

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1. Introduction

Sediments in river channels constitute a main habitat for biota and, in particular, for those growing on the surface and subsurface zones. Biofilms on sediments are consortia of bacteria, algae, fungi and protozoa within Extracellular Polymeric Substances (EPS, e.g. Romaní et al., 2009). This matrix is composed of polysaccharides and plays a major role in the cohesion of sediment particles and on the adhesion of biofilm to the substratum (e.g. Characklis and Wilderer, 1989). Dade et al. (1990) showed a direct and positive relationship between the polysaccharide content of biofilms and the critical shear velocity needed for bed erosion. Other studies have directly related the biostabilisation capacity in river channels to the presence of EPS (Gerbersdorf et al., 2008). Biofilms are therefore capable of modifying bed roughness and the hydraulic properties of the channel flows (e.g. Salant, 2011; Vignaga, 2012). Biofilms also protect sediments from erosion by developing a sheet onto the bed (e.g. Droppo et al., 2001). These alterations, in turn, may have a direct effect on the magnitude and frequency of bed disturbance, with consequences for a range of other organisms. Other consequences of biofilm development are the clogging of the porous media between sediments, and the modification of hydraulic conductivity (Mauclaire et al., 2006).

Natural river functioning includes a wide range of flow discharges, from low flows to competent floods that affect the entire ecosystem. Floods can be considered disturbances since they represent episodes that alter biological communities but also provide the opportunity to newcomers to set up there (Sousa, 1984). Theory suggests that spatially patchy disturbance which results in heterogeneity in bed conditions may help increase both alpha and beta diversity of biological communities (Buendia et al., 2014). During floods, surface and eventually subsurface sediments are mobilized, causing the detachment of benthic organisms (Gibbins et al., 2007), re-structuring river food webs (Power, 2009), and modifying morpho-sedimentary features (Church, 2006). Episodic mobility of the river bed is therefore an important factor for ecologically diverse and sustainable river functioning (e.g. Baron et al., 2002; Goodwin et al., 2006). Biofilm biomass decreases drastically after a flood (e.g. Power and Stewart, 1987) due to bed scour, particle mobility and bed-material transport, which in turn causes detachment, erosion, transport and burial of the biofilm. The presence and growth of biofilm in river beds may be modified by human actions, such as damming. Dams reduce the magnitude and frequency of floods and alter the sedimentary regime of rivers downstream (e.g. Batalla et al., 2004; Vericat and Batalla, 2006; Vericat et al., 2006). The reduction of flood magnitude and frequency also results in an increase of bed stability due to less competent flows, a fact that typically causes bed armouring in the long-term. This lower degree of fluvial disturbance not only causes loss of biodiversity (Goodwin et al., 2006), but also the simplification of the natural communities expressed in a higher growth of biofilm (Lobera et al., 2016; Ponsatí et al., 2015). River bed stability and the persistence of low flows have been also related to higher benthic biomass (Clausen and Biggs, 1997; Warner et al., 2007); whereas the distribution and consistency of biofilm on a river bed is partly consequence of the frequency and magnitude of sediment transport (Grant et al., 1986; Ponsatí et al., 2015). Thus, the rapid and vigorous growth and development of biofilm downstream from dams is a consequence of the lack of bed disturbance and contributes to further stabilisation of the river bed (Aristi et al., 2014; Ponsatí et al., 2015). Extensive biofilm growth (so-called 'river bed greening') is an increasingly common feature in many rivers, but especially in dammed Mediterranean streams with long-lasting low flows and a lack of competent floods.

Some studies have analysed the bio-physical interactions between sediments and biofilms in relation to river bed stability and particle motion in non-cohesive sediments (e.g. Fang et al., 2013, Vignaga, 2012) as well as in cohesive others (e.g. Fang et al., 2013, Tolhurst et al., 2008). However, patterns of bed scour related to the presence of biofilms are not yet well described. Within this context, a series of experiments were conducted on non-cohesive sediments with the main goal of experimentally assessing topographic changes in colonised and non-colonised biofilm channel beds. Our working hypothesis was that the presence of biofilm affects both internal bed structure (i.e. through clogging and sticking) and surface roughness, with direct effects on flow hydraulics and the associated bed-material processes. Therefore, the main objectives of the study were: i) to analyse how biofilm affects bed roughness, ii) to characterise the patterns of bed scour in biofilm-colonised sediments, and iii) to assess the effects of biofilm on bedload rates. With these experiments we aimed to improve understanding of processes in river reaches experiencing a decrease on hydrodynamics, mimicking those located below dams, where carpet-like biofilm formations are formed as a result of the low hydraulic disturbance and the subsequent channel stabilisation, in a feedback process.

2. Experimental setup

2.1. Experimental channels and treatments

Experiments were carried out at the Experimental Streams Facility located at the Catalan Institute for Water Research (ICRA). The indoor channels ($N = 24$) used for the experiments were made of methacrylate and measured $2 \times 0.1 \times 0.1$ m. A tank with 70 l of water allowed constant water recirculation. Channels could be tilted with slopes ranging from 0.5 to 2%.

To achieve the objective established, pairs of experiments (each time using one channel colonised with biofilm vs. another not colonised) were subjected to similar hydraulic conditions. To simplify the comparison of results, hydraulics were grouped in two classes: low intensity and high intensity flows. In the first stage, biofilm-colonised experiments were carried out (these experiments are labelled *B*, as per Biofilm-colonised, henceforth in the paper). In a second stage, non-colonised experiments were performed (labelled *C*, as per Control, henceforth).

Channels were uniformly filled with small uniform non-cohesive sediments (coarse sand, 0.5–1 mm) to a thickness of 3 cm. A total of 12 channels were seeded with epipsammic biofilm for 5 weeks. During the colonisation period, discharge was kept constant at 30 ml/s and channel slope was set as 0.5% in order to ensure development of a carpet-like biofilm growth on the sediments. For the same reason, temperature was kept between 22 and 24 °C. Water was periodically renewed to maintain this temperature range. Fig. 1a-c illustrate both sets of channels. The 2-meter length of the channels was configured as follows (i.e. in the downstream direction; see Fig. 1d): 1) the first 15 cm were left without sediments; 2) the following 120 cm were filled with sediments, and this reach constituted the section where channel disturbance was assessed and hydraulic measurements were obtained; 3) the following 20 cm were again kept without sediments and used to measure bedload transport by means of a bespoke total bedload trap (for details see Section 2.6); and 4) the lowermost 40 cm of the channel were used to sample the biofilm. The whole experiment was developed in 4 phases:

I) Preparation of the channels: channels were filled with sediment and half of them colonised with biofilm for 5 weeks.
II) Sampling before the experimental runs: channels were carefully emptied of water to take biofilm samples and perform *express* laser scannings. This phase is referred in the text as 'before experiments' or 'pre-experiments'.
III) Experimental runs: period in which bed channels were subjected to higher intense flows than in the colonisation period. Water depth, flow velocity and bedload transport were regularly measured. This phase is referred in the text as 'experiment'.
IV) Sampling after the experimental runs: channels were carefully emptied of water to perform laser scannings. This phase is referred in the text as 'after experiments' or 'post-experiments'.

The duration of the experimental runs varied: 60 min for C1–C9 and B1–B9 channels and 30 min for C10–C15 and B10–B15 channels. In the

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