Ecological Engineering 118 (2018) 19–30

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Modelling the role of riverbed compartments in the regulation of water quality as an ecological service

Sabine Sauvage[a,*], José-Miguel Sánchez-Pérez[a,*], Philippe Vervier[b], Robert-Joseph Naiman[c], Hugues Alexandre[a], Léonard Bernard-Jannin[a], Stéphanie Boulêtreau[a], Sébastien Delmotte[d], Frédéric Julien[a], Dimitri Peyrard[a], Xiaoling Sun[a], Magali Gerino[a]

[a] EcoLab, Université de Toulouse, CNRS, INPT, UPS, Toulouse, France
[b] Acceptables Avenirs, 815 La Pyrénéenne, Prologue 1, 31670 Labège, France
[c] School of Aquatic and Fishery Sciences, University of Washington, Seattle 98195, USA
[d] MAD-Environnement, 23, rue de la République, 31560 Nailloux, France

ARTICLE INFO

Keywords:
River bed interfaces
Ecological services
Functional compartment
Sediment
Biofilm
Hyporheic zone
Modelling

ABSTRACT

Water quality is strongly related to a river's ecosystem composition at landscape scale. Key water/sediment interfaces, referred to here as functional compartments (FCs), are the epilithic biofilm, the fine sediment at the bottom of the river and the macroporous medium or hyporheic zone, which is primarily located in the active channel where subsurface flow occurs. The function of each FC (consumption or production of organic matter and nitrate) at river reach scale was examined through modelling and calibrated within field measurements to quantify the regulation service for water quality improvement. These functions were tested on a river reach of a dominant interface function (DIF) river, the Garonne River in south-west France. It was found that: a) functions differed between the FCs as a result of biotic (organisms involved) and abiotic (hydrological and morphological) conditions, b) functions varied within each FC over time (measured, but not discussed) and c) FCs acted as transient storage zones and contributed to the development of the river's self-purification capacity. It was concluded that in relation to the concept of river continuum, the upper reaches in the catchment were dominated by epilithic biofilm, where the main function was the production of organic matter (OM) (mean of 0.3 $g{\cdot}m^{-2}{\cdot}d^{-1}$, range from 0.08 to −1.7), the middle course was dominated by the hyporheic zone, where the most important function was to serve as a nitrate sink (−1.25 $g{\cdot}m^{-2}{\cdot}d^{-1}$, range from −45.6 to −0.19), and the downstream parts of the river, whose main function was the degradation of OM within the fine sediment FC (mean of -1000 $g{\cdot}m^{-2}{\cdot}d^{-1}$, range from −960 to −1440). Hence, the morphological heterogeneity of rivers that mimic the natural mosaic of functional compartments with exchanges of water, organic matter and nutrients between compartments could contribute to enhancing their self-purification function and thus to improving water quality and system health. This study is a first step in testing the influence of the different FCs on the water quality regulation service provided by a river reach. The final objective was to be able to upscale the modelling of the different interfaces involved in a watershed's water quality regulation service. The present study demonstrates the need to take the biophysical diversity of reaches into account in order to accurately model this regulation service. Thus the BIODIF concept of BIO-physical (biological and physical) Diversity for rivers Dominated by river-bed Interface Functions (DIF rivers) was investigated for its ability to identify the theoretical relationships between the structure and the function of regulation of a river.

1. Introduction

In the past decade, stream nutrient cycling studies have identified streams to be heterogeneous ecosystems consisting of several compartments with distinct functional influences on water quality. Furthermore, it is widely recognised that in addition to biogeochemical processes in the free surface water, stream ecosystems also include the hyporheic zone, called the saturated subsurface, and riparian and floodplain components (Boulton et al., 1998; Fisher et al., 1998; McClain et al., 2003; Fisher et al., 2004; Lewis et al., 2006; Burt et al., 2010). One of the main challenges in adequately describing the biogeochemical functioning of these heterogeneous ecosystems is to take

* Corresponding author and equivalent first authors.
E-mail addresses: sabine.sauvage@univ-tlse3.fr (S. Sauvage), jose-sanchez@univ-tlse3.fr (J.-M. Sánchez-Pérez).

https://doi.org/10.1016/j.ecoleng.2018.02.018
Received 9 November 2015; Received in revised form 26 January 2018; Accepted 24 February 2018
0925-8574/

into account the many different biophysical compartments that make up the hydrosystem. This challenge raises a number of questions. How does each compartment individually influence biogeochemical river functioning and the resulting water quality? How can the effects and interactions of these different compartments be modelled and included in current models that describe water quality? How are these functional compartments related to water quality regulation services? What are the effects of these compartments, comparing them to those of the riparian zone or periphyton in the stream channel? With the objective of including the heterogeneity of stream compartments in the ecosystem service of regulations in a river section, authors have recently developed suitable mathematical models. Unfortunately, most of these models account for just one of the stream components, with the main focus on the floodplain, riparian zone, hyporheic zone, fine sediments or periphyton individually. This approach means that it is not possible to make relative comparisons between or take into consideration all the components in the same river as a river continuum (Boudreau, 1997, Dent and Henry, 1999; Navel et al., 2012; Graba et al., 2010, 2012).

According to the European Union (EU) Water Framework Directive 2000/60/EC (WFD), quality assessment of water bodies is strongly related to the entire ecosystem, including the diversity of its habitats and their management (European Commission, 2000). This means that all functional compartments (FC), with their relative influence on water quality depending on their surface area, are components of the system structure. The “function” displayed by one compartment is the type of influence exerted by the FC on that water quality, and the water regulation service of the aquatic ecosystem is the sum of all the individual functions performed by each compartment that the water flows through. Furthermore, the WFD views river management from a multidisciplinary systems approach: the integrity of the river ecosystem depends on interactions between ecology, hydrology and geomorphology. However, it is significant that the ecological status of rivers, as classified in Annex V of the WFD, includes both biological elements and the hydromorphological units that support them. Thus, legislation and practices need greater integration of biological, hydrological, and geomorphological influences in both river system management and restoration in order to: 1) maintain ecological services that contribute to improving water quality, and 2) conserve the habitat diversity of riverine ecosystems. When integration of the entire complexity of stream ecosystems determines habitat diversity, it is of prime importance to determine how the diversity of these biophysical compartments contribute to ecosystem service delivery, such as water self-purification within the stream and river corridors. In this context, there is a gap in knowledge about the relationships between the composition of river systems with different hydromorphological units and their capacity to influence water quality status. The approach taken in the present study was based on the assumption that the study of river system integrity in the first instance requires a precise assessment of the specific effects of each compartment on surface water quality. The identification of the properties and related functions of each FC is a first step towards acquiring a better understanding of the functional divergence and heterogeneity of a riverbed at the scale of a large reach or river section comprised of different FCs. The main aim of this paper was to demonstrate the compartments' functional heterogeneity based on biophysical and deterministic models that individually describe the fluxes of nutrients and particulate organic matter (POM) in the water passing through each FC. This perspective corresponds to the concept of system integrity that combines traditional physicochemical qualities with the new “ecological status” of water bodies.

Several studies have highlighted the strong relationship between the hydromorphology of running water and the type of biogeochemical processes taking place in a river reach (Palmer et al., 2005; Clifford et al., 2006; Cardenas et al., 2004; Gooseff et al., 2006; Comin et al., 2017). There have been qualitative demonstrations of the influence of riverbed compartments on the quality of running water and interstitial water with hyporheic sediment (Sánchez-Pérez et al. 2003b, 2009; Weng et al., 2003; Delmotte et al., 2007; Peyrard et al., 2011; Vervier et al., 2009; Marmonier et al., 2012; Yao et al., 2017). These riverbed compartments display different biogeochemical functions in the consumption, production or retention of one or more chemical elements. Each FC is described by its biological and hydromorphological components as the biophysical structure supporting the biogeochemical processes and related fluxes in the compartment and running water. The influence of these FCs on free water quality is greater in dominant interface function (DIF) rivers, where the riverbed compartments control water quality with respect to the influence of biogeochemical processes occurring in the water column. If FCs are defined as the exchange zones between surface water and hyporheic water (from fine to macroporous sediments), several questions emerge. What are the major processes occurring in the different FCs that are able to change water quality in running water? What type of FC is more inclined to reduce or increase a given surface water nutrient and/or contaminant? In the meantime, it is becoming increasingly obvious that biological activity makes a significant contribution to the biogeochemical processes in these FCs. Microbiological activity, primary production and invertebrate communities are known to influence water quality *via* biodegradation, bioturbation and biofilm-grazing processes.

This article presents three examples of FC sub-models with a focus on particulate organic matter and nitrate dynamics using the case of the Garonne River (France) in its middle course (7th order). All the studied FCs are in the same river section in the middle course of the Garonne (more than 70 km in length), and each FC and its related model was investigated in a specific site within this section, where the FCs identified were epilithic biofilm, the hyporheic zone and fine sediments. The aim of this study was to identify and quantify the effect of each FC in terms of exchanged fluxes with the free-flowing water. Based on these results, the various effects of each FC were then compared at reach scale according to their relative surface area on the riverbed. This integration was performed at the scale of the mid-Garonne River case study site. This paper then goes on to discuss the interest in integrating the diversity of the different compartments of a riverbed on a larger scale in the river ecosystem. The concept of biophysical diversity based on the spatial organisation of each FC in a river section and the heterogeneity and complementarity of their functions are explored. Starting from the DIF (dominant interface function) river definition that is particularly suited to this study site, the new concept arising from this discussion will be known as the BIODDIF, as an abbreviation of the BIO-physical Diversity of a DIF river.

2. Methodology

2.1. Dominant interface function rivers

A dominant interface function (DIF) river functions with processes predominantly located at water/sediment interfaces. The hydromorphology of these rivers is characterised by a high Froude number, with large spatial and temporal variations in current velocity and low water depth that favour high-permeability riverbed sediments, mainly pebbles and gravel. The hydromorphological characteristics of this type of river prevent the development of planktonic bacteria and phytoplankton and favour benthic production as biofilms. These biofilms include: a) autotrophic biofilms as benthic algae associated with micro- and macro-organisms in an extracellular polysaccharidic matrix forming complex aggregates (Battin et al., 2003; Lyautet et al., 2005; Boulêtreau et al., 2006; Teissier et al., 2007), and b) heterotrophic biofilms that are attached to river bed sediments (interstitial biofilms in fine and coarse sediments) (Iribar et al., 2008). Therefore biological agents are dominant components of the interfaces that make up the riverbed of a DIF river and represent a major characteristic of such rivers.