Contribution of river-bed interfaces to running water quality by coupling modeling and *in situ* measurements.

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Abstract: Water quality is strongly related to interactions between the structure and function of ecosystem components at landscape scale of a river. Key interfaces as part of these components, identified in our study, are the epilithic biofilm, the fine sediments in the bottom of the river and the macroporous medium or hyporheic zone located essentially in the active channel where subsurface flow takes place. This article presents three examples of interface sub-models where water and elements fluxes exchanged with the surface water are different, with the focus on organic matter and nitrate dynamics for the Garonne river (France) in its middle course (7th order). Each interface on surface quality (e.g. consumption or production of organic matter) at the river reach scale was examined independently through modeling and in field measurements. We found that (i) influences differ between the interfaces and also within each interface over time as a result of biotic (organisms involved) and abiotic (hydrological and morphological) conditions; and (ii) the interface acts as transient storage zones and contributes to emerging self-purification properties of the river. Analysis of biophysical diversity based on spatial distribution of the different interface, their influences and their interactions can contribute to determining the biogeochemical cycle of surface water.

Keywords: hydrosystems, interfaces, biogeochemistry, river-bed, modeling.

1   INTRODUCTION

Several studies have pointed out the strong relationship between the hydro-morphology of running waters and the way they function [Palmer et al. 2005, Clifford et al. 2006]. On the other hand, qualitative demonstrations of the influence of the biogeochemistry of each interface in water quality have been produced [Sánchez-Pérez et al. 2003, Weng et al. 2003, Delmotte et al. 2007]. Nevertheless, there is a gap in our knowledge concerning the quantitative relationships that exist between the hydro-morphological characteristics of river systems and their capacity to influence water quality status. If we define water-sediment interfaces as exchange zones between surface water and sub-surface (from fine to macroporous sediments), several questions emerge: what are the major processes

occurring at the different water-sediment interfaces that are able to change water quality? What type of interface 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 (as microbiological activity, primary production, and invertebrate communities) contributes significantly to processes in this functional compartment.

This work presents three examples of water/river-bed interface sub-models with the focus on organic carbon and nitrate dynamics for the Garonne river (France) in its middle course (7th order). An example of a carbon organic matter and nitrate budget at large scale is presented for the middle course of the Garonne river.

2   METHODOLOGY

2.1   Interface definition

Each interface is described at the interaction between free flowing water and river bed by its biological and physical components. Each interface may influence the biogeochemical processes that occur: an interface is defined both by the organisms involved in the nutrients transformation processes (biological components), and by the morphological and hydraulic characteristics of its habitat (physical components). Mechanisms governing exchanges between the interface and the free-flowing water, which is the main vector for element transport, are very discriminant.

Key interfaces, identified in our study, are the epilithic biofilm that growths on pebbles and gravel beds, the fine sediments in the bottom of the river in lentic zones and the macroporous medium or hyporheic zone located essentially in the active channel where subsurface flow takes place.

Methodology is based on coupling experimental and mechanistic modeling approaches, developed or adapted from existing models.

2.2   The study site: the Garonne river in its middle course

The Garonne is the principal river in south-west France (8th Strahler order at its mouth), with a watershed area of 60,000 km^2 and a length of 600 km. Annual rainfall is about 900 mm but can reach 2000 mm in the upper parts of the basin.

The study site was located in the middle course of the river, downstream of Toulouse city. Compared with other long French rivers, the Garonne has a high overall spatial and temporal heterogeneity in its hydro-morphological characteristics. Strong variations in the flow of the Garonne river can be observed over time and space. In its middle course, the flow regime of the Garonne river is characterized by two hydrological maxima, one in February and one in May, and a low-flow period from August to September. In this sector under study, the mean annual discharge is 200 m^3 s^{-1} and ranges between 17 and 8000 m^3 s^{-1}. The morphology of the river includes numerous facies (pools and riffles). Gravel/pebble beds dominate the composition of the channel bed along the sector studied here. The pool-riffle sequences create different dynamic flows, and thus for the same discharge, contrasting mean current velocities and water depths can be observed on a scale of some kilometers. For example, for low water discharge, current velocity (respectively water depth) can vary from 0.05 to 1.2 m s^{-1} (respectively 0.4 m to 2.5 m) over a 3-kilometer stretch [Sauvage et al. 2003]. The hydro-morphological conditions of the Garonne tend to limit biological and microbiological activities in the free-flowing water. The chlorophyll *a* concentration in the water column is generally low (max = 20 µg l^{-1}) and corresponds to more than 80% of drifted benthic algae coming from epilithic biofilm [Améziane 2000, Améziane et al. 2003]. Other biogeochemical studies on this sector have shown that interfaces can explain up to 22% of total phosphorus retention over a 20-km stretch of the river during the low water period [Bonvallet-Garay et al. 2001].

In the Garonne river, the three identified interfaces are (1) the epilithic biofilm, (2) the fine sediments, and (3) the macroporous medium or hyporheic zone (Figure 1). The scale of a river sector was chosen in order to quantify the role of the functional compartments in element circulation in the free-flowing water. In the three examples, we opted to present the function of each interface in terms of particulate organic matter and nitrogen.
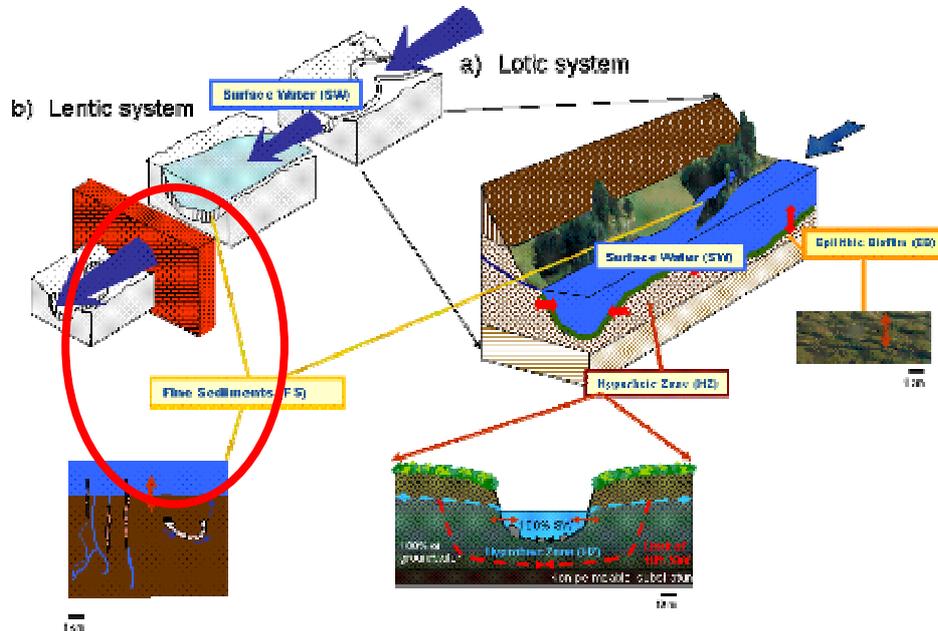

Figure 1. River-bed interfaces involved in biogeochemistry functioning in a fluvial hydrosystem with (a) lotic and (b) lentic zones: the water body (WB) including the phytoplankton and the bacterioplankton, which is characterized by free-flowing water; the epilithic biofilm (EB), including the periphyton (algal and bacteria in polysaccharide matrix) developing on gravel/pebble beds, which is characterized by diffusive exchanges; the fine sediments in the bottom of the river (FS) with bacteria, meiofauna, and macrofauna, where exchanges occur mainly through diffusion processes; and the macroporous medium or hyporheic zone (HZ) including bacteria, meiofauna, and macrofauna, which is located essentially in the active channel where subsurface flow takes place, and which is connected with the water body by advective exchanges. In the HZ there is mixing of surface water and groundwater.

2.3 The epilithic biofilm

In the Garonne river, epilithic biofilm mainly develops on pebbles and gravel banks. Organic matter budget is controlled during the low water period of the Garonne river by production, degradation, recycling, storage and detachment of organic matter from the epilithic biofilm.

Modeling was used to simulate daily epilithic biomass dynamics (expressed as g AFDM m^{-2}) for months covering different hydrological conditions (flood events and low water periods) at the scale of a gravel bank. The main differential equation was composed of one biofilm accrual term representing the phototrophic growth and two biofilm detachment terms, discharge-dependent loss and self-generated detachment due to heterotrophic processes. The model was calibrated on two gravels banks as detailed in Boulêtreau et al. [2006].

Dissolved inorganic N fluxes, including nitrification and denitrification rates, were measured *in situ* under dark and light conditions using epilithic biofilms from a 6th to 8th Strahler order reach of the Garonne river, France [Teissier et al. 2007].

2.4   Fine sediment interface

The fine sediment-water interface is not the most widespread compartment in the river ecosystem, but it can be found where lentic conditions are present (wetlands, pools, reservoirs, etc.). However, it is a compartment of detritic deposition of highly reactive material and bioturbation enhances the material fluxes and reactions. The reactive transport model allowed the influence of this type of interface on the whole river system function to be well described and understood.

We therefore investigated the early diagenesis of organic matter in the fine sediments, focusing on the effects of bioturbation [Delmotte 2007]. Reactive transport models are well suited to this aim, allowing identification and quantification of the intricate processes of (i) physical and biological transports, and (ii) chemical and microbiological reactions.

A reactive transport model was developed that included: (i) biological and physical transports of particles and solutes; and (ii) net reactions that describe primary and secondary reactions involved in the mineralization of organic matter. Hence, application of this model was carried out in a stepwise fashion: (i) Solid and solute transports (physical and biological) was assessed in pseudo *in situ* tracer experiments, to constrain the transport parameters; and (ii) geochemical profiles of carbon and nitrogen were measured in the field, simultaneously with the transport measurements, to validate the model [Delmotte, 2007]. The model was calibrated on fine sediment of a reservoir lake on the mid-Garonne, the Malause reservoir.

2.5   Macroporous medium or hyporheic zone interface

The role of the hyporheic zone (HZ) in stream ecosystem functioning is mainly determined by: (i) the rate of subsurface biogeochemical processes; (ii) the proportion of the stream water flux that exchanges with the HZ and flows through the porous sediments; and (iii) the storage duration of elements in the HZ. Flux exchanges are mostly time-dependent as these are related to the stream discharge, the surface water/groundwater gradient and the physical structure of the interface. The microbial activity of these zones is also conditioned by the geomorphological characteristics of the reaches [Lefebvre et al. 2006].

In order to quantify these fluxes in space and time and to take into account the feedback between groundwater and surface water including the hyporheic zone, a coupled river/aquifer vertically averaged model called 2SWEM (Surface Subsurface Water Exchange Model) has been developed [Peyrard et al., 2008] by coupling 2D St Venant equations for surface water with 2D Darcy-Dupuit for porous media in saturated zone. The dynamic coupling between river and aquifer is provided by continuity of fluxes and water level elevation between the two domains. Equations are solved simultaneously by linking the two hydrological system matrices in a single global matrix in order to ensure the continuity conditions between river and aquifer and to accurately model two-way coupling between these two domains. The model is applied to a large reach (about 36 km²) of the Garonne River (south-western France) and its floodplain, including an instrumented site in a meander. Simulated hydraulic heads are compared with experimental measurements on the Garonne River and aquifer in the floodplain. Model verification includes comparisons for one point sampling date (27 piezometers, 30 March 2000) and for hydraulic heads variations measured continuously over 5 months (5 piezometers, 1 January to 1 June 2000). The model accurately reproduces the strong hydraulic connections between the Garonne River and its aquifer, which are confirmed by the simultaneous variation of the water level in the river and in piezometers located near the river bank. The simulations also confirmed that the model is able to reproduce groundwater flow dynamics during flood events. In addition, each compartment model is coupled to transport/reaction equations. Flow and nitrogen dynamics were simulated in different hydrological conditions and compared with data obtained from a one-year survey. Nitrogen transformation at meso-scale was simulated using a denitrification model adapted from the NEMIS model [Henault and Germon 2000].

2.6 Estimation of the function of the three interfaces at the landscape scale

In the case of the sector studied, Tables 1c and 1d compare flux exchanges between the water column and the interfaces along the 70 km stretch from Toulouse to the Malause reservoir, corresponding to a mean of 13 km² of exchange surface in the lotic part and 80 ha of exchange surface in the reservoir. Each interface is distributed along the sector: hyporheic zone and epilithic biofilm are distributed along the lotic system (47 and 40% of the total exchange surface, respectively), while the fine sediment compartment is distributed on the 80 ha basin (6% of the total exchange surface). On this reach there is another type of interface that does not allow any exchanges, i.e. the impermeable bedrock. This interface surface is not active and is more than 5% of the total surface because in some places two interfaces (epilithic and hyporheic compartments) are superimposed.

3 FIRST RESULTS

3.1 Epilithic biofilm functional compartment: a source of autochthonous particulate organic matter

Model loss terms allowed mean organic matter losses from epilithic biofilm to be quantified during one year. Biofilm losses (g AFDM m^{-2}) were converted to Particulate Organic Carbon (g POC m^{-2}) using a ratio of 50 g POC per g AFDM measured on 28 biofilm samples in the Garonne river (unpublished data). Mean sloughed biomass amounted to 146 g POC m^{-2}, i.e. 0.30 g POC m^{-2} d^{-1} (from 0.08 to 1.70 g POC m^{-2} d^{-1}). Sloughed biomass quantity depends on the development state of the biofilm and on hydrology and temperature.
When 12 h day and 12 h night were applied to the values of AFDM simulated daily for the period, the results showed that on average, the epilithic biofilm represents a nitrate sink of around 5.7 mg m^{-2} d^{-1}.

3.2 Fine sediment functional interface: the bioturbation effects on biogeochemical processes

The model produced an integrated mean for fine sediments of 4.25 g m^{-2} d^{-1} of POC, with 0.41 g m^{-2} d^{-1} of labile POC (around 10%) and 3.83 g m^{-2} d^{-1} of refractory POC (around 80%). Similarly, nitrates that are consumed in the sediments showed entry fluxes from 14 to 110 µmol cm^{-2} yr^{-1} , so that the mean nitrate sink was 6.8 10^{-2} g m^{-2} d^{-1} (Table 1a, 1b).

3.3 Macroporous medium or hyporheic zone (HZ) interface: a transient storage zone for processes to be activated

The simulation results showed for example that at the scale of a meander of 6 km long 30 km downstream Toulouse city the hyporheic zone acts mainly as a sink for nitrogen in surface water (mean concentration around 1 g m^{-2} d^{-1}, with a maximum of around 45 g m^{-2} d^{-1}), but it can also act as a source for surface water, with a maximum of 9 g m^{-2} d^{-1} during flood events (Table 1a, 1b).

3.4 Estimation of the function of the three interfaces at the landscape scale

These results correspond to an estimation of retention budget at the scale of a reach, estimated from the sum of the exchanged fluxes, weighted by their relative surface.

The results show that the hyporheic zone is the most efficient compartment at the scale studied here for NO_3 retention (coming from water surface and agricultural practices from the aquifer). The epilithic biofilm is a source of POC and the fine sediment is a sink of POC.

Table 1. "+" for production rate, "-" for retention rate: a) and b) Mean, minimum and maximum daily fluxes (g m^{-2} d^{-1}) of Particulate Organic Carbon (POC) and Nitrates (NO_3^-) exchanged between surface water and each functional compartment (epilithic biofilm, hyporheic zone, and fine sediment) c) and d) Mean, minimum, and maximum annual fluxes (t yr^{-1}) of Particulate Organic Carbon and nitrates at the reach scale considering only the effect of the related functional compartments along 80 km stream (70 km of the course and 10 km of the reservoir with 13.8 km² of exchange interface).

a)

POC in g m^{-2} d^{-1}	Mean	Min	Max
Epilithic biofilm	+ 0.30	+ 0.08	+ 1.70
Fine Sediment	- 4.25	-3.29	- 4.93
Hyporheic zone	**n.a.**	**n.a.**	**n.a.**

b)

NO_3^- in g m^{-2} d^{-1}	Mean	Min	Max
Epilithic biofilm	- 5.7 10^{-2}	-1.1 10^{-1}	- 7.8 10^{-4}
Fine Sediment	- 6.8 10^{-2}	-2.38.10^{-2}	- 0.19
Hyporheic zone	- 1.25	- 45.6	+ 8.55

c)

POC in t yr^{-1} Garonne (70 km stream long and 13 km² of exchange interface)	Mean	Min	Max	% of the interface repartition
Epilithic biofilm	+ 697	+ 186	+ 3952	47
Fine Sediment	-1000	-960	-1440	6
Hyporheic zone	**n.a.**	**n.a.**	**n.a.**	40

d)

NO_3^- in t yr^{-1} Garonne (70 km stream long and 13 km² of exchange interface)	Mean	Min	Max	% of the interface repartition
Epilithic biofilm	- 133	- 256	- 2	47
Fine Sediment	- 20	- 7	- 55	6
Hyporheic zone	- 2491	- 90876	+ 17039	40

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4   DISCUSSION

Exchanges of water and elements between surface water and interfaces are very complex and depend on the typology of the river, i.e. on hydrological and local morphological conditions.

The dominant influence of hydro-morphology in nutrient retention has been emphasized in several cross-site studies. For example, Alexander et al. [2000] showed that nitrogen retention was inversely related to mean stream depth. When this finding was coupled with the well-known relationship of increasing stream depth with distance downstream, Alexander et al. [2000] demonstrated that headwater streams were more effective at retaining nitrogen than downstream reaches. These authors attributed this pattern to systematic hydrogeomorphical variations in watersheds. Similarly, uptake length is often correlated with discharge across a range of stream sizes [Butturini and Sabater 1998, Peterson et al. 2001, Doyle et al. 2003]. An earlier synthesis of nutrient retention literature suggested that channel morphology could dominate uptake processes [Stream Solute Workshop, 1990, p. 113].

Now that we know that river-bed interfaces contribute differently to water quality, investigations on the spatial organization of these interfaces and their inter-relationships are possible to optimize their contributions at the hydrosystem scale. An example of budget at large scale in the middle course of the Garonne river allows the influence of each interface to be quantified according to its *in situ* surface area. This estimated budget should be compared with *in situ* measurements of retention capacity of the same reach at the landscape scale. Comparisons between the calculated and the measured budget should give an idea of the influence of the spatial organization. The spatial distribution at the landscape scale of the different interfaces may influence the function of each interface because it controls organic matter fluxes and physical-chemical context. If different (whatever the sign), this shows that the function of each interface depends on its position in the system.

5   CONCLUSION

These first studies on the processes taking place in river-bed interfaces confirm the importance of hydrological and morphological conditions in the global biogeochemical functioning of a fluvial hydrosystem. Modeling how each interface influences POM and DOM transported in the surface water revealed the diversity of the processes that act in the benthic boundary layer. It demonstrated that each FC has its own biogeochemical process that is more efficient in production or retention of a given element. This heterogeneity is a source of a wide range of metabolic pathways that may interact in the river continuum. Even if the quantitative coupling of these interfaces has not yet been accomplished, this first step of modeling has already supplied information on the respective contribution of each interface in the organic carbon and nitrate being transported in the surface water.

REFERENCES

Alexander RB, Smith RA, Schwarz GE. (2000), Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico. *Nature* 403:758–61.

Améziane T., 2000. Développement des micro-organismes phytoplanctoniques et périphytiques en période d'étiage estival dans le fleuve Garonne. *Thèse de troisième cycle*. Université Paul Sabatier, Toulouse III. 116 p.

Améziane T, Garabétian F., Dalger D., Sauvage S., Dauta A., Capblancq J. (2003), Epilithic biomass in a large gravel-bed river (the Garonne, France): a manifestation of eutrophication. *River Research and Applications* 18: 343–354.

Bonvallet-Garay S., Sauvage S., Vervier P. (2001), Hydromorphological control of phosphorus dynamic in a large regulated gravel bed river: the Garonne river (France). *Regulated Rivers: Ressources and Managment* 17: 461-472.

Boulêtreau S., Garabétian F., Sauvage S., Sanchez-Perez J. M. (2006), Assessing the importance of self-generated detachment process in river biofilm models. *Freshwater Biology* 51: 901–912.

Butturini A, Sabater F. 1999. Importance of transient storage zone for ammonium and phosphate retention in a sandy-bottom Mediterranean stream, *Freshwater Biology* 41: 593–603.

Clifford N.J., Harmard O.P., Harvey G., Petts J.E. (2006), Physical habitat, eco-hydraulics and river design: a review and re-evaluation of some popular concepts and methods. *Aquatic Conservation: Marine and Freshwater Ecosystems* 16: 389–408.

Delmotte S., Meysman F.J.R, Ciutat A., Sauvage S., Boudou A., Gerino M. (2007), Cadmium transport in sediments by tubificid bioturbation: an assessment of model complexity. *Geochimica et Cosmochimica Acta*, 71 : 844-862.

Delmotte S., 2007. Rôle de la bioturbation dans le fonctionnement biogéochimique de l'interface eau-sédiment: Modélisation de la diversité des transports biologiques et effets sur la diagenèse précoce des sédiments d'une retenue. Thèse de Doctorat de l'Université de Toulouse III, 282 p.

Doyle M.W., Stanley E.S., Harbor J.M. (2003), Hydrogeomorphic controls on phosphorus retention in streams. *Water Resources Research* 39 (6): 1-17.

Henault C., Germon J. (2000). NEMIS, a predictive model of denitrification on the field scale. *European Journal of Soil Science* 512: 257-270.

Lefebvre S., Marmonier P., Peiry J.L. (2006), Nitrogen dynamics in rural streams: differences between geomorphologic units*. International Journal of Limnology* 42 (1): 43-52.

Palmer M.A., Bernhardt E.S., Allan J. D., Lake P.S., Alexander G., Brooks S., Carr J., Clayton S., Dahm C. N., Follstad S. J., Galat D. L., Loss S. G., Goodwin P., Hart D.D., Hassett B., Jenkinson R., Kondolf G.M., Lave R., Meyer J.L., O'donnell T.K., Pagano L., Sudduth E. (2005), Standards for ecologically successful river restoration. *Journal of Applied Ecology* 42 (2): 208-217.

Peterson BJ, Wollheim WM, Mulholland PJ, Webster JR, Meyer JL, Tank JL, Marti E, Bowden WB, Valett HM, Hershey AE, McDowell WH, Dodds WK, Hamilton SK, Gregory S, Morrall DJ. (2001), Control of nitrogen export from watersheds by headwater streams. *Science* 292: 86–90.

Peyrard D., Sauvage S., Vervier P., Sanchez-Perez J.M., Quintard M. (2008), A coupled vertically integrated model to describe lateral exchanges between surface and subsurface in large alluvial floodplains with a fully penetrating river. *Hydrological Processes* 22**:** 4257-4273.

Sánchez-Pérez JM, Vervier P, Garabetian F, Sauvage S, Loubet M, Rols JL, Bariac T, Weng P. (2003), Nitrogen dynamics in the shallow groundwater of a riparian wetland zone of the Garonne, Southwestern France: Nitrate inputs, bacterial densities, organic matter supply and denitrification measurements. *Hydrology and Earth System Sciences* 7(1): 97-107.

Sauvage S., Teissier S., Vervier P., Améziane T., Garabetian F., Delmas F., Caussade B. (2003), A numerical tool to integrate bio-physical diversity of a large regulated river : hydro-biogeochemical bases ; the case of the Garonne River (France) – *River Research and Application* 19: 181-198.

Teissier S, Torre M, Delmas F, Garabétian F. (2007), Detailing biogeochemical N budgets in riverine epilithic biofilms. *Journal of the North American Benthological Society* 26 (2): 178-190.

Weng, P., Sánchez-Pérez J.M., Sauvage, S., Vervier, P., Giraud, F. (2003), Assessment of the quantitative and qualitative buffer function of an alluvial wetland: Hydrological modelling of a large floodplain (Garonne River, France). *Hydrological Processes* 17: 2375-2393.