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A NUMERICAL TOOL TO INTEGRATE BIOPHYSICAL DIVERSITY OF A LARGE REGULATED RIVER: HYDROBIOGEOCHEMICAL BASES. THE CASE OF THE GARONNE RIVER (FRANCE)

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ABSTRACT

This article presents the bases of a hydrobiogeochemical model of the Garonne River (southwest France) which has been developed to integrate physical and biological processes during summer low-water periods. The physical part of this model is composed of a one-dimensional unsteady hydrodynamic model, allowing the resolution of the Saint-Venant equations, and a transport model which simulates downstream changes in solute concentrations. Biogeochemical processes are considered through the definition of functional compartments which make up the channel bed. These different compartments are defined both by the organisms involved in the solute transformation processes and by the physical and hydraulic characteristics of their habitat. Integration of these functional compartments within the model required investigations at different scales. The scale at which biological processes take place ranges from millimetres to metres. The scale of a reach, at which organization of the functional compartments along the river can be linked to hydrodynamic and morphological characteristics, ranges from 500 m to several kilometres. The regional scale is that at which homogeneous reaches can be integrated. A feedback between numerical results and field experiments has allowed improvements to *in situ* measurement to increase modelling accuracy. For example, the model allows estimation of variables, such as fluxes, that are difficult to measure *in situ*. The developed model can integrate various functional compartments and their biogeochemical functioning. Two application examples, focused on dissolved inorganic nitrogen, are presented in order to illustrate the numerical tool functioning: integration of equations on nitrification processes in the water body, and integration of consumption/production terms on epilithic biofilm resulting from *in situ* experimental mean values. The model we have developed constitutes a promising analytical tool that will be able to integrate previous and future studies.

KEY WORDS: river; one-dimensional model; hydraulic; biofilm; nitrogen; biogeochemistry; functional compartments

INTRODUCTION

Over the course of the last thirty years, significant efforts have been made to better understand and attempt to better predict the behaviour of aquatic systems in response to both natural or anthropogenic disturbance. In order to define 'river health', we have to take into account the response of hydrosystems by integrating hydrodynamic, morphological and biological components (Norris and Thoms, 1999). Physical processes are one of the principal factors responsible for the spatial and temporal variability in the distribution of organisms: for example, the alternation between stability phases and vertical mixing controls on the phytoplankton dynamics (Masbernat *et al.*, 1993). Physical processes influence the biogeochemical processes by turbulent and molecular diffusion. Conversely, biological processes can influence physical processes: for example, the periphyton influences the current velocity profile (Godillot *et al.*, 2001). An interdisciplinary approach is therefore necessary to understand river ecosystems (Landers, 1997; Daily and Ehrlich, 1999) and can be accomplished by the construction of a suitable model (Pickett *et al.*, 1999).

The first hydroecological models were concerned mostly with lentic ecosystems in order to tackle eutrophication problems. Most of these models were empirical (Vollenweider, 1968) and failed to integrate physical and biological processes taken as a whole in a spatially heterogeneous environment (Jorgensen, 1976). Subsequently, models became more sophisticated in order to take into account the spatial and temporal variations of organisms and solute concentrations (Salençon and Thébault, 1994).

Since the 1970s, eutrophication problems have become evident in lotic ecosystems as a result of nutrient enrichment. As a consequence, many biophysical models have been developed (e.g. Caussade *et al.*, 1978; Chaussavoine, 1979; Delclaux, 1980; Lung and Paerl, 1988). Nowadays, among the most famous hydroecological models for lotic ecosystems, we can cite QUAL2E (Brown and Barnwell, 1987), PROSE (Even, 1995), KALITO (Lesouef and Andre, 1982) and MONET (Billen *et al.*, 1995) with a few that intend to integrate hydroecological processes at the basin scale: RIVERSTRAHLER (Hannon *et al.*, 1998), PEGASE (Smitz *et al.*, 1998) and AGIRE (Rietjens *et al.*, 1995). The results vary little between the models, but they are more or less satisfactory according to the validity of each model in their application range.

Most of these models focus on processes which occur within the water body. Few models have attempted to integrate other compartments in the river such as the hyporheic zone or the periphyton (Kim *et al.*, 1992; Bencala *et al.*, 1993; Morrice *et al.*, 1997; Uehlinger *et al.*, 1996). Moreover, these models can be applied to small streams since data inputs are given by injecting significant quantities of tracers within the stream. The behaviour of conservative solutes describes the hydrological processes whereas the ratio of reactive to conservative solute concentrations gives an indication of biogeochemical processes. This approach is efficient for small streams but it is not applicable in general for large or complex river systems.

The Garonne is a large gravel-bed river which is characterized by critical low water periods. During low flow periods, knowledge of biogeochemical functioning was necessary to support management of the water resource. The development of a 'hydrobiogeochemical' model has been chosen to integrate knowledge from different scientific disciplines. By combining and stimulating scientific contributions from different specialities, we set up a conceptual framework that links hydrological, geomorphological and biological components of the Garonne river.

The aim of the investigations we present here is to describe and to model the biogeochemical functioning of the Garonne river during low water periods by integrating hydrodynamic, morphological and biological characteristics. In this paper, we present the physical model developed at the IMFT by Siméoni-Sauvage (1999) and the biogeochemical bases of this model which has been set up to integrate the river at the regional scale. We hypothesized that processes which occur at the bottom of the river influence nutrient dynamics.

GARONNE RIVER CHARACTERISTICS

The Garonne river is the principal fluvial axis of southwest France with a stream length of 600 km from its source in the Pyrenean Massif (Spain) to its mouth in the Atlantic Ocean (France) (Figure 1). It is the third longest river in France, and is eighth order at its mouth. It has little hydraulic works for the majority of its course. The hydroelectric dams are located in the upper part of the river (Figure 1).

Compared to other long French rivers, the Garonne has a high overall spatial and temporal heterogeneity in its physical and biological characteristics. Therefore, study of the Garonne river ecosystem, which is large and complex, requires great knowledge of the physical and biological mechanisms involved in a spatially heterogeneous environment which is variable over time. The hydraulic model concerns 200 km from Portet (upstream of Toulouse) to Tonneins (downstream of the confluence with the Lot river). The biophysical model concerns 120 km of the river from Toulouse to Agen (Figure 1).

Hydrological characteristics

The flow regime of the Garonne is pluvio-nival: its tributaries come from the Central Massif (pluvial regime) or from the Pyrenean Massif (nival regime). High variations of the flow of the Garonne river can be observed over time and space.
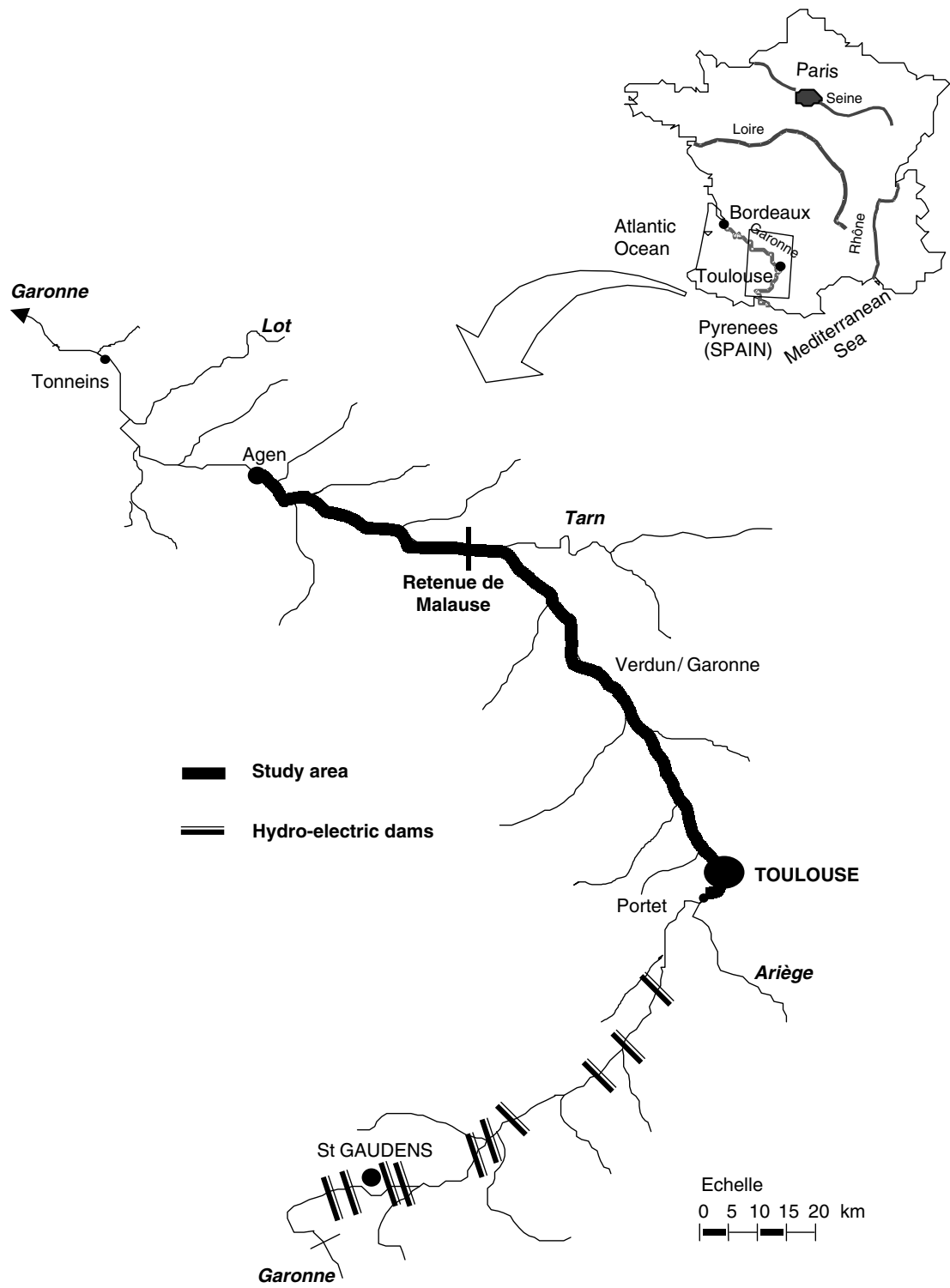
Figure 1. Geographic situation of the Garonne river and the study area

At the hydrologic regime scale, the flow of the river is very variable. This is evident if we compare, for example, the highest discharge (7000 m^3 s^{-1} in 1875) and the discharge during low-water periods (40 m^3 s^{-1}) at Toulouse (for a basin of 9980 km^2 area). We observe a great variation of the Garonne and its tributary flows with high periodic fluctuations (annual, monthly and daily). The annual mean discharge is over 200 m^3 s^{-1} at Toulouse. Most of the year, discharges are maintained by the pluvio-nival regime. For example, during low water periods, the monthly mean discharge of tributaries can contribute 50% of the discharge measured upstream of Toulouse. The low water periods last about three or four months from June to October. The importance of the discharges during this period and the importance of the duration of the low water periods depend on the pluviometry from the previous months (Figure 2). However, from June to October, the natural decrease in the discharge coupled with the important irrigation period produce very low discharges in the Garonne river (from 40 to 30 m^3 s^{-1} downstream Toulouse).

At a daily scale, hydroelectric dams and the dams used to maintain a minimum discharge in the course, located in the upper part of the river, are responsible for the significant fluctuations in discharge. These variations are over 30% and can reach 100% of the daily mean discharge (Figure 3).

Morphological characteristics

The morphology of the river between Toulouse and the confluence with the Tarn river results from modifications due to human activities (Steiger *et al.*, 1998). The morphology of the river bed governs the flow dynamics. The bed slope is around 1‰ in the middle of the course. The Garonne bed is composed of numerous facies (Figure 4). Gravel/pebble beds dominate the composition of the channel bed along the studied sector.
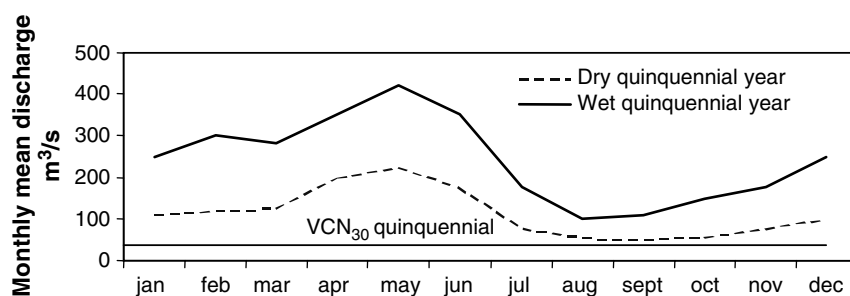

Figure 2. Monthly mean discharges for a dry and a wet quinquennial year. VCN_{30} - the lowest mean discharge for 30 days running
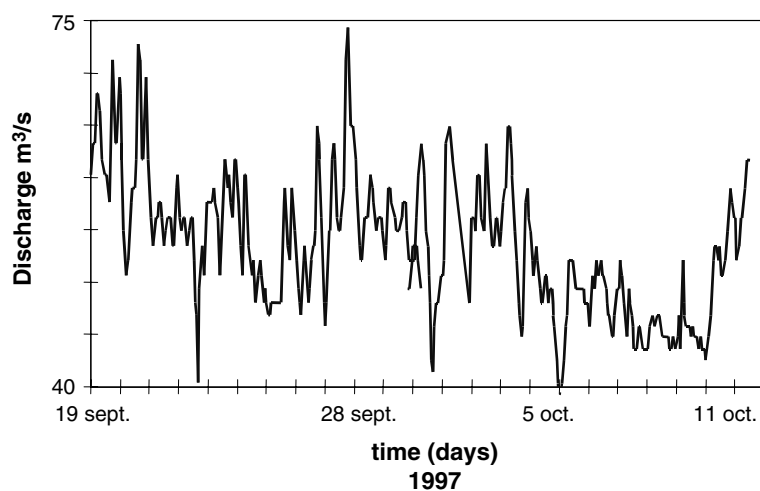

Figure 3. Discharge fluctuations upstream Toulouse due to hydroelectric dams located in the upper part of the Garonne river

Figure 4. Different facies of the minor bed of the Garonne river during low water periods

Bedrock, termed 'molasse', is exposed during low water periods. The molasse is a sedimentary formation deposited in the northern foreland of the Pyrenees, during their Oligo-Miocene development. This bedrock varies in its resistance to erosion, depending on its local composition. When calcareous cement dominates, resistant bedrock rapids provide a local base level (Steiger *et al*., 2001). The pool−riffle sequences create different dynamic flows: for the same discharge, contrasted mean current velocities and water depths can be observed at a scale of some kilometres. For example, during low water periods, over only 3 km downstream of Toulouse, the current velocities vary from 0.05 to 1.2 m s^{-1} and the water depth from 0.4 m to 2.5 m. The Garonne river is therefore characterized by highly heterogeneous flow over space and time.

Biological characteristics

Few studies have been conducted on the Garonne river at a large scale (Cayrou *et al*., 2000; Santoul and Tourenq, 2000; Améziane *et al*., 2000). However, during low water periods, we can observe an important development of epilithic biofilm on gravel beds (Figure 5). The epilithic biofilm constitutes the main primary production in the Garonne river during low water periods.

METHODOLOGICAL APPROACH

The initial study was based on a comparison between ammonium and nitrate data measured in the water body of the Garonne river downstream of Toulouse over a 30 km reach and a transport model of nitrogen based on potential nitrification in the water body developed by Roux *et al*. (1990). The results showed that the model overestimated the ammonium concentrations. The resulting hypothesis was that the processes acting in the river bed are very active in the biogeochemical transformation of the biogenic elements which circulate in the water body.
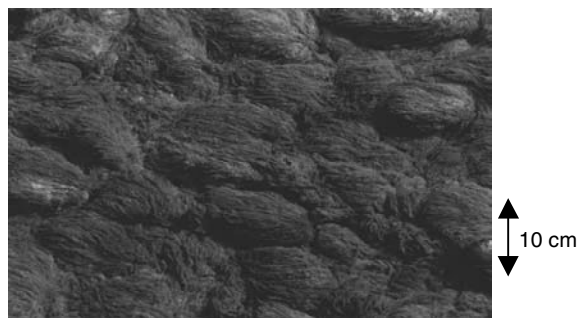

10 cm

Figure 5. Epilithic biofilm covering a gravel bed in the Garonne river during low water periods

In order to model the biogeochemical functioning of the Garonne river during low water periods, by integrating river bed components, we introduce the notion of functional compartments (FCs). A FC is defined both by the organisms involved in the transformation processes of the nutrients and by the physical and hydraulic characteristics of their habitat. Mechanisms which govern exchanges between the FC and the water body, which is the main vector for nutrient transport, are one of the most discriminating parameters. Therefore, the FCs are: (a) the water body (WB) including the phytoplankton and the bacterioplankton, which is characterized by free-flowing water; (b) the epilithic biofilm (EB) which includes the periphyton developing on gravel/pebble beds which is characterized by diffusive exchanges; (c) the fine sediments in the bottom of the river (FS), where exchanges occur mainly through diffusion processes; (d) the macroporous medium, termed hyporheic zone (HZ), located essentially in the active channel where the subsurface flow takes place and is connected with the water body by advective exchanges.

Difficulties exist in evaluating and modelling the exchanges between the water body and the functional compartments composing the river bed, and the dynamics of these compartments at a large scale.

First of all, we developed a physical model composed of a hydrodynamic module and a transport module (Siméoni-Sauvage, 1999).

To complete the integration of physical and biogeochemical components, we stipulate that the hydrodynamic and the morphological characteristics control the organization of the FC and their interactions with the free-flowing surface water. A functional cartography was drawn up in order to specify the organization of the FC in each grid space of the model.

Since we want to take into account biological processes which occur at the habitat scale and at the time of short biological cycles (i.e. algae and bacteria) in a model which attempts to run at the regional scale, we had to face space and time scale changes. We based our approach on the integration of micro-scale studies (study of the processes in the different functional compartments) and at a meso-scale at which nutrient budgets were measured (Vervier *et al*., 1998). To expand to the macro-scale, we proposed to characterize reach studies at the meso-scale and to distribute them at the regional scale (Figure 6).

The 'micro-scale' is necessary for the experimental study and the detailed analysis of fundamental mechanisms. These studies were carried out for the most part *in situ* and were aimed at defining the predominant compartments and their activities.

The 'meso-scale' ranges from gravel beds to sections of the river up to a few kilometres in length. The limits of the spatial units correspond to those morphological zones which were sufficiently homogeneous so that the variables and the parameters used are representative of average ones. The measurements carried out aim at evaluating the influence of activities (production/consumption) according to the morphodynamic characteristics of the sectors.
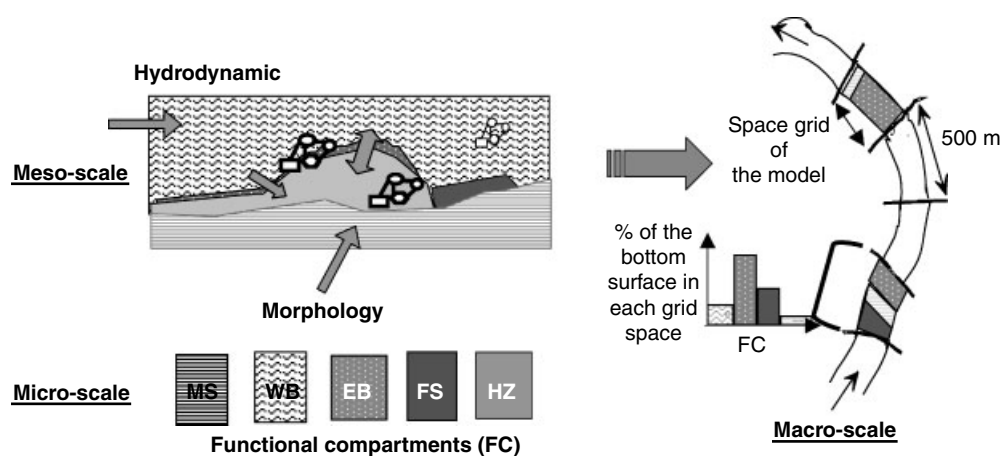

Figure 6. Different scale approaches: from the functional compartments (MS, molassic substratum; WB, water body; EB, epilithic biofilm; FS, fine sediments; HZ, hyporheic zone) to the modelling of a river sector at a regional scale (see text for details)

Finally, the 'macro-scale', a 100 km of the Garonne, is proposed in order to solve the concrete problems of calibration and validation of the hydrodynamic model which has to be coupled with a water quality model.

The integration of the previous data, coupled with a physical model, therefore permits access to a better understanding of this complex system at large spatial and temporal scales.

A BIOPHYSICAL MODEL

General characteristics

The hydraulic model deals with the general characteristics of the flow. In most hydrodynamic models it remains very difficult to model river flow during the low water period. This problem comes from the nature of the flow, characterized by shallow depth and therefore with a significant relative roughness. In these conditions, the river bed has strong heterogeneity such as exposed banks and successions of pools and riffles, which are very difficult to take into account.

The Saint Venant equations in unsteady mode were chosen because they are based on a complete description of the physical processes occurring in the flow at a large spatial scale. Their applications are varied and the calibration is reduced to the friction parameter (Strickler coefficient). The hydraulic model integrates the morphology of the river.

The transport model allows us to simulate transport of conservative constituents by advection and dispersion.

Subsequently, a functional cartography, coupled with the results of the hydraulic model, make it possible to distribute the different FC.

Finally, the biogeochemical module, coupled with the transport module, permits us to simulate the transport and the transformations of the different nutrients by integrating a reaction term in the advection–dispersion equation (Figure 7).

The physical model

The hydraulic model. The hydraulic model solves the Saint Venant equations in one dimension and unsteady mode (Equations 1 and 2) and has been calibrated and validated on a 200 km stretch in the middle of the course from Portet (upstream of Toulouse) to Tonneins (downstream of the confluence with the Lot River).
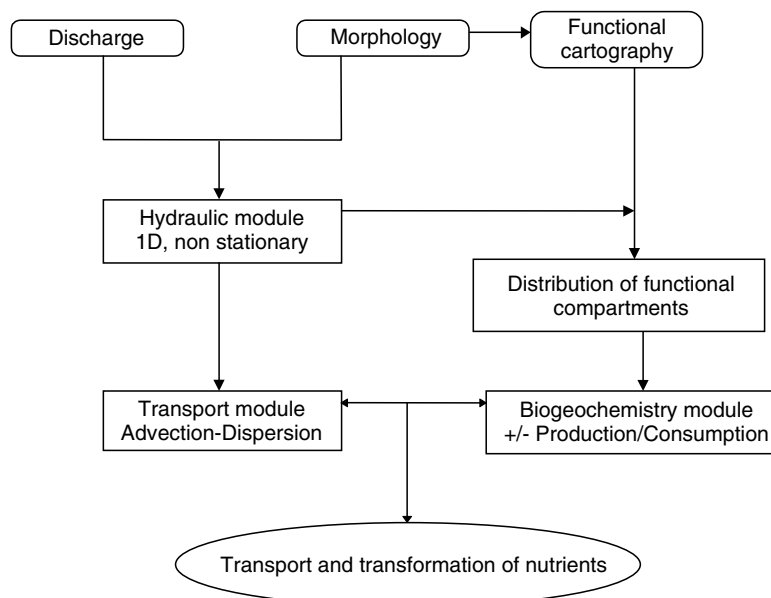

Figure 7. The different modules composing the hydrobiogeochemistry model of the Garonne river

Continuity equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \tag{1}$$

Momentum equation:

$$\underbrace{\frac{1}{A}\frac{\partial Q}{\partial t}}_{\substack{\text{Local} \\ \text{acceleration} \\ \text{term}}} + \underbrace{\frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)}_{\substack{\text{Convective} \\ \text{acceleration} \\ \text{term}}} + \underbrace{g\frac{\partial h}{\partial x}}_{\substack{\text{Pressure} \\ \text{force term}}} - \underbrace{g(S_0}_{\substack{\text{Gravity} \\ \text{force} \\ \text{term}}} - \underbrace{S_f)}_{\substack{\text{Friction} \\ \text{force} \\ \text{term}}} = 0 \tag{2}$$

where Q is the discharge (m^3 s^{-1}); A is the cross-sectional area (m^2); x is the longitudinal space variable (m); t is the temporal variable (s); h is the water depth (m); S_0 is the bed slope (adim); S_f is the friction slope (adim); g is the acceleration due to gravity (m s^{-2}).

The hydraulic model is validated for discharges between 50 and 120 m^3 s^{-1} from upstream of Toulouse to the confluence with the Tarn river, and between 90 and 160 m^3 s^{-1} downstream of this sector. The model is valid for discharges higher than the admissible minimum discharges (defined by legislation on water management) for low water periods which are fixed at 48/52 m^3 s^{-1} upstream of Toulouse, 42 m^3 s^{-1} downstream of Toulouse and 85 m^3 s^{-1} downstream of the Malause reservoir. The model gives very good results on sectors difficult to model because of the longitudinal heterogeneity of the course characterized by variable roughness (Figure 8). Relative errors in the discharge estimation (from 5 to 15% according to discharge) come from the fact that the model simulates mean quantities and from the difficulty in obtaining precise quantitative data.

Flow characteristics during low water periods. The hydraulic model gives different hydraulic characteristics at different cross-sections and over time as the current velocity, the wetted perimeter, the Froude number, the water level and the residence time between two sections (Figure 9).

In the sector of the river studied, the values of the Froude number are more variable from one grid to another than from one sector to another. The mean value is over 0.2 and reaches 0.6 on some riffles.

During low water periods, the characteristics of the flow, when the minor bed is characterized by pool–riffle sequences, can be summed up by the following points (Figures 10 and 11): the values of all the associated variables to the water depth (maximum and mean water depth, hydraulic radius, wetted perimeter) increase crossing a pool and decrease crossing a riffle; the current velocity values and all the associated variables (Froude number) decrease crossing a pool and increase crossing a riffle; in a pool–riffle sequence, the more the discharge increases, the more the relative differences in variables between each section decrease. Moreover, the relative difference of the variables decreases for two different discharges as the discharge
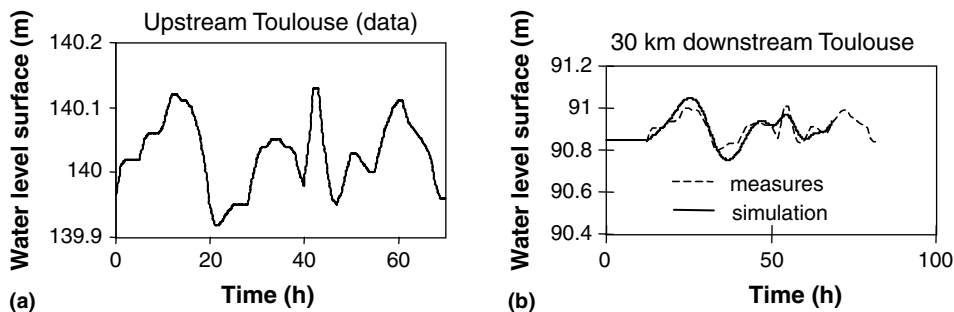

Figure 8. Example of validation of the hydraulic model: comparison between simulated and measured water level surface over 65 hours and for a flow propagations on a 40 km reach. (a) The surface water level upstream of Toulouse (entering the model); (b) comparison between measured and simulated surface water level 40 km further downstream
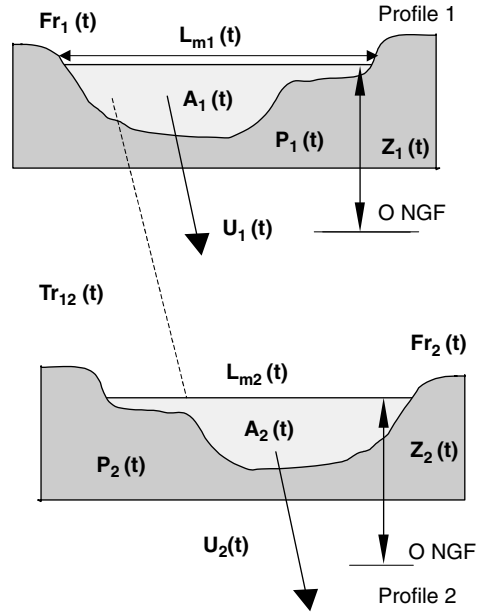
Figure 9. Output variables of the one-dimensional and non-stationary hydraulic model. Fr, Froude number (adim); Lm, width (m); A, cross-sectional area (m^2); P, wetted perimeter (m); Z, water level (m); 0 NGF, mean water level of the Mediterranean Sea at Marseille (southwest of France); U, current velocity (m s^{-1}); Tr, residence time (s)

increases. Relative differences between variables from a pool and a riffle and from two different discharges are all the more important as the discharge is low.

The transport model. The transport model solves the transport equation in one dimension and simulates the transport of a conservative constituent by advection and dispersion. The hydraulic model permits calculation of the mean current velocity U and different flow characteristics (hydraulic radius, friction velocity, etc.) necessary to resolve the advection and dispersion terms.

In the river, the molecular diffusion is insignificant compared to the turbulent diffusion processes. In one dimension, the longitudinal dispersion process is dominated by the dispersion due to differential convection (Simon, 1990; Even, 1995):

$$\frac{\partial C}{\partial t} = \underbrace{-U\frac{\partial C}{\partial x}}_{\text{advection}} + \underbrace{\frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right)}_{\text{dispersion}} \tag{3}$$

where C is the substrate concentration (mg l^{-1}), U is the mean current velocity (m s^{-1}), D is the dispersion coefficient (m^2 s^{-1}).

The transport model is calibrated and validated over 120 km upstream of Toulouse. We used an *in situ* tracing experiment by injecting fluorine within the wastewater treatment plant of Toulouse in order to validate the model. We have simulated the transport of a tracer over 30 km downstream of Toulouse and compared the simulation with the measured data (Figure 12). The results show that the hydraulic model and the transport model (advection and dispersion processes) processes are very well reproduced. Differences in fluorine concentrations are observed in the last section because the mean sampling data (and not instantaneous data) were collected only at that point. The length of mixing is 6 km downstream of Toulouse. The mean dispersion coefficient varied from 2 m^2 s^{-1} in the pool sections to 20 m^2 s^{-1} in the riffle section.

A one-dimensional and unsteady physical model gives interesting results sufficient to integrate biogeochemical components at the scale of 100 km. For example, it reproduces correctly the pool–riffle sequences (Figure 11) and shows the important spatial and temporal hydraulic variations at a scale of some kilometres.
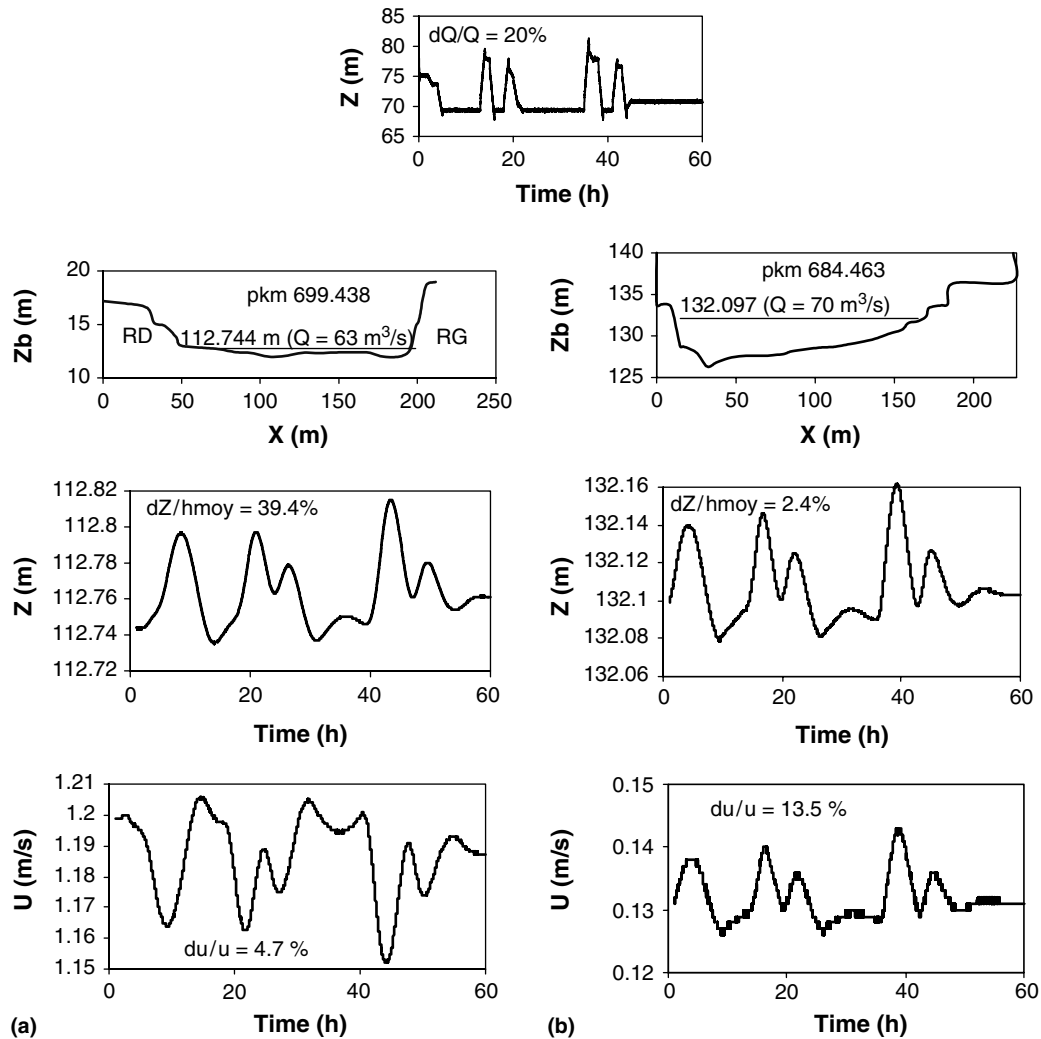
Figure 10. Effect of a typical daily fluctuation of discharge on hydraulic variables (a) on a riffle and (b) on a pool. Q, discharge $(m^3 \ s^{-1})$; Z, water level (m); Zb, bottom level; X, distance from the right edge (m); pkm, kilometric point (km); U, current velocity $(m \ s^{-1})$; hmoy, mean depth (m)

Moreover, it can inform us about the importance of the exchange surface between the WB and the FCs which compose the river bed as, for example, the range zones, on gravel bars, that can be very active during low water periods. The non-stationary model can also give important information about the impact of hourly hydraulic variability on the different FCs which compose the river bed.

The biogeochemical model

General principle. The biogeochemical reactions have been introduced in the transport equation. The *R* term can include:

- solutions of differential equation systems describing biogeochemical processes;
- consumption/production terms resulting from direct measurement.
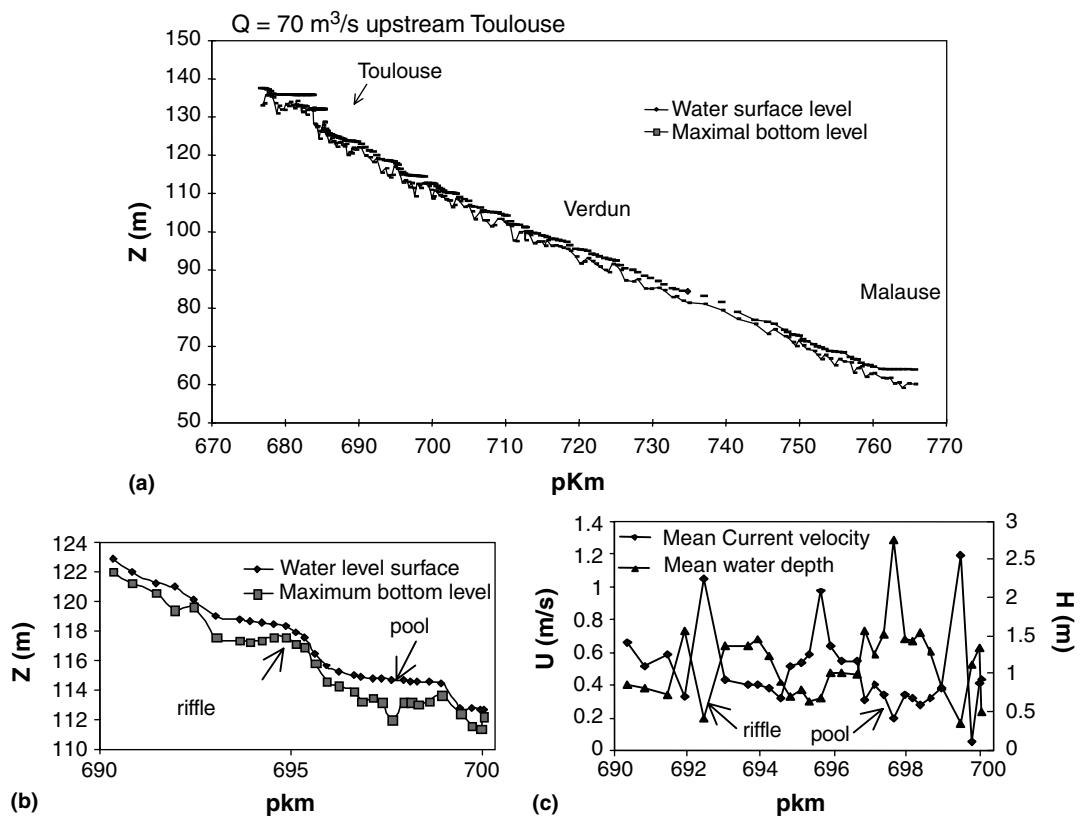
Figure 11. (a) Longitudinal profile of the water surface level over 90 km. (b and c) Mean current velocities and mean water depths crossing pool–riffle sequences on 10 km of the river. Z, water level (m); pKm, kilometric point (km); U, current velocity (m/s); H, water depth (m)
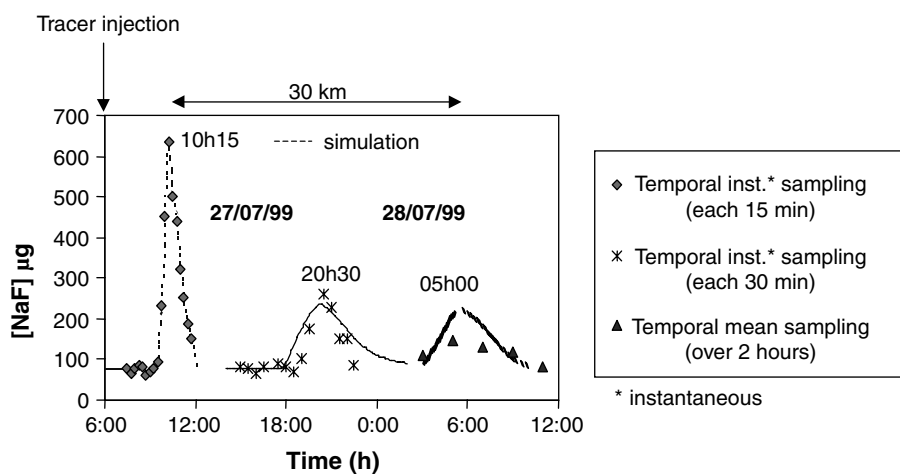

Figure 12. Validation of the transport model by comparison with an *in situ* tracing experiment

The *I/O* term represents the lateral input and output:

$$\frac{\partial c}{\partial t} = -u\frac{\partial c}{\partial x} + D\frac{\partial^2 c}{\partial x^2} + I/O + R \qquad (4)$$

A feedback between numerical results and field experiments allowed *in situ* measurement improvements to increase model accuracy (Sauvage *et al.*, 1999; Vervier *et al.*, 1998): the model defines the processes we have to investigate and permits us to optimize the data collection. It can also determine the range of the parameter values not measured *in situ*.

The main difficulties come from the determination of the different fluxes and exchanges between the different FC components and the extrapolation of the results obtained at the micro-scale to that of the macro-scale. The main idea is that the experiments undertaken at the micro-scale and meso-scale permit the identification of the variables, the parameters and their corresponding parametric laws determining the dynamics of the different biogenic elements and their interactions between the functional compartments. Most of the identified control parameters have to be easily measurable *in situ* or directly calculated by the model in order to extrapolate the functioning of the river at the macro-scale. These parameters have to be common to the different scales. The model, used as a numerical tool to help the research, permits identification and gives a range of values for the parameters not directly measurable *in situ*.

At this stage of the study, the predominant functional compartments and their variables and associated parameters that influence the biogenic elements in the free-flowing water must be identified. Very few studies have been undertaken on the Garonne river till now at a scale of hundreds of kilometres.

The biogeochemical module will first focus on the evolution of DIN (dissolved inorganic nitrogen) in order to estimate the functioning of the river which receives significant allochthonous loads.

The functional cartography. The biogeochemical model is made in order to integrate fluxes from the different FC components in each grid space of the model (500 m in average). The functional cartography shows the distribution of the different FC taking into account:

- the minor bed characteristics defined by a bed cartography and a geomorphological study;
- the hydraulic and transport characteristics (wetted perimeter, current velocity, residence time etc.)

The bed cartography was drawn up after different *in situ* explorations and a comparison with aerial photographs (taken in 1986) of the Garonne river at a discharge of 30 m^3 s^{-1} downstream of Toulouse. This first cartography permitted us to describe the composition of the mean part (120 km long) of the river bottom.

A geomorphological study (Steiger *et al.*, 2000) and the results of the hydraulic and transport model permitted us to identify the pool and riffle zones differentiating:

- the gravel/pebble zones likely to be colonized by epilithic biofilm and where the hyporheic zone can be important;
- the riffles and the shallow pools characterized by the presence of the molasse;
- the deep pools where the processes of sedimentation can be important.

APPLICATION EXAMPLES

Nitrification in the water body functional compartment

The first simulations on the WB have been conducted downstream of Toulouse (between Toulouse and the confluence with the Tarn river) by using data on nitrifying bacteria measured in different points of the Garonne river by the most probable number numeration technique (Teissier *et al.*, 2002). The equation system used to simulate the nitrification process in the water body (Equations 5, 6 and 7) is presented here:

$$\frac{d[Bn]}{dt} = \mu_{\max}e^{\frac{-(t-t_{\mathrm{opt}})^2}{\Delta t^2}} \frac{[\mathrm{N-NH_4}^+]}{[\mathrm{N-NH_4}^+] + \mathrm{K_{N-NH_4^+}}} \frac{[O_2]}{[O_2] + K_{O_2}}[Bn] \qquad (5)$$

$$\frac{d[\text{N} - \text{NH}_4{}^+]}{dt} = -\frac{1}{y}\frac{d[Bn]}{dt} \tag{6}$$

$$\frac{d[N - \text{NO}_3{}^-]}{dt} = -\frac{d[\text{N} - \text{NH}_4{}^+]}{dt} \tag{7}$$

Concentrations of $\text{N} - \text{NH}_4{}^+$ and $\text{N} - \text{NO}_3{}^-$ (mg l^{-1}) and nitrifying bacteria (Bn, mg C l^{-1}) were measured at five sites along the river (from upstream of Toulouse to upstream of the Malause reservoir) during 1998 and 1999 low water periods. The nitrifying bacteria initial concentrations introduced in the model are the mean values. Other terms in the equations are: $\mu_{\max}$, maximal growth rate that can vary from 0.01 and 0.05 s^{-1}; y, substrate–biomass conversion rate, that varies from 0.05 to 0.13; $K_{\text{N}-\text{NH4}}$ varies from 0.4 to 1.28 mg l^{-1}; t_{opt} is taken as 16.5 °C (Edeline, 1993; Brion and Billen, 1998).

pH and oxygen concentration are not limiting factors for the nitrification in the WB of the river Garonne in the studied sector during low water periods. Different studies of sensitivity on parameters and simulation results show that the planktonic nitrification is insignificant in the WB as the ammonium concentrations do not vary significantly along the sector concerned: the ammonium is only transported and not transformed into nitrates. Indeed, concentrations of nitrifying bacteria, which mainly come from urban wastewater of Toulouse, are low and highly diluted in the river and the residence time in the sector of the river (three or four days from downstream of Toulouse to the confluence with the river Tarn) is too short to allow a significant development of those microbial communities.

The research has subsequently focused on the functional compartments which compose the river bed as they seem to be very active in the biogeochemical transformations of nutrients which circulate in the WB.

The epilithic biofilm functional compartment: case of dissolved inorganic nitrogen

The EB is the second FC we investigated. Several studies have been driven (Teissier *et al*., 2002; Améziane *et al*., 2000), parallel to the development of the model (Siméoni-Sauvage, 1999) on epilithic biofilm in the Garonne river in order to evaluate its impact on the DIN that circulate in the free-flowing water.

At the micro-scale. The investigations concerned six sites along the river from upstream of Toulouse to upstream of Agen (Figure 13).
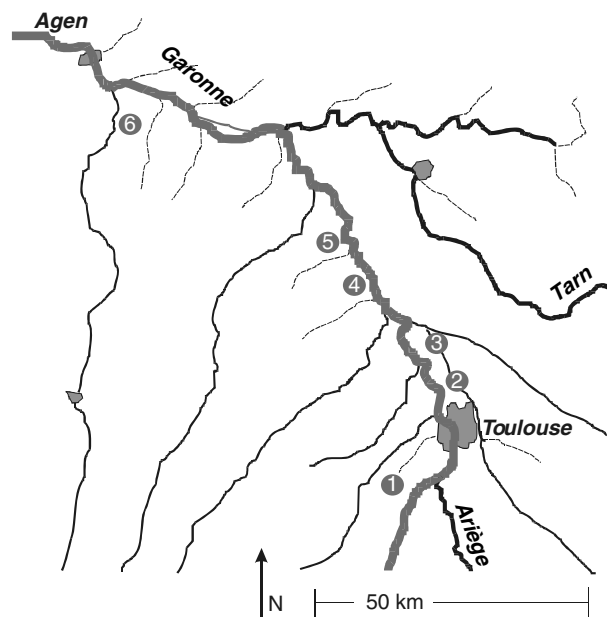

Figure 13. Geographical situation of the sampling sites for the epilithic biofilm activity measurements along the river Garonne

One typical experiment involved four benthic chambers with pebbles colonized by biofilm. Two replicate chambers were incubated in light conditions and two others in dark conditions (chambers covered by a thick black bag) for 5.5 hours in the river at *in situ* temperature.

Time–course kinetics were determined by sampling the water of the chambers each 45 minutes (the first sample being taken after 15 minutes of incubation).

In the laboratory, samples were analysed for NH_4^+ and NO_3^- according to standard methods (APHA, 1991) on filtered (Whatmann GF/F) pre-acidified samples (12.5 µl HCl 1N).

After the experiment, the whole surface of biofilm inside each benthic chamber, estimated by weighing the corresponding surface of aluminium foil, was scraped and suspended in a defined volume of river water.

Dry matter (DM) was determined by weighing dried (80 °C, overnight) an aliquot of biofilm suspension. An aliquot of the dried matter was combusted (500 °C, overnight) for determination of the ash-free dry matter (AFDM).

Six sites were sampled (Figure 13) with a total of 44 chambers during spring in 1998 and during summer low water period in 1998 and 1999.

At the meso-scale. Three *in situ* experiments were conducted during low water periods at different space and time scales (in 1996, 1997 and 1999) between Toulouse and the confluence with the Tarn river. These data will permit (a) an evaluation of the influence of activities (production/consumption) according to the morphodynamic characteristics of the sectors by doing mass balance, and (b) data to be obtained for the calibration and validation of the model.

The mass balance analysis did not permit us to relate the production/consumption of DIN and the hydro-morphology of the sector. Otherwise, the data analysis showed evidence of a relation between phosphorus and the hydromorphology of the sector (Bonvallet *et al.*, 2001).

At the macro-scale. The modelling permits us to approach the functioning of the river at the macro-scale:

- in each grid-space of the model, quantitative and qualitative (NH_4^+ and NO_3^-) inputs (from wastewater treatment plant, industry, tributaries) and outputs (mainly agricultural pumping) are taken into account;
- the functional cartography permits us to distribute the different functional compartments relative to their surface;
- the activity concerning gravels beds and molassic beds corresponds to the measured activity in biofilms.

The surface colonized by the biofilm corresponds to the wetted surface (bottom surface in contact with the water) calculated by the hydraulic model for the mean discharge of the study period and multiplied by 1.2 to take into account the shape of the pebbles.

In order to take into account the biofilm physiology at the macro-scale, we chose a uniform distribution of the biofilm biomass during established summer low water periods: the investigations conducted on the Garonne biofilm distribution during this period by Améziane *et al.* (2000) permitted us to conclude that the Garonne biofilm's mean AFDM could be considered as uniform along the river in the sector concerned by the modelling. The AFDM was chosen as the most adapted descriptive parameter in order to characterize the biofilm's biomass. According to experimental results, the homogeneous biofilm biomass was fixed at 27.4 gAFDM m^{-2} of the colonized surface.

In the study sector, once the biofilm is established (once the biomass is maximum and reaches a plateau), the biofilm biomass is considered as constant in time. We think that at the spatial and temporal scales concerning our study, the abrasion and colonization processes are balanced. Different studies of sensitivity on the AFDM parameter showed that the model is much more sensitive to the fluxes between the epilithic biofilm and the WB.

Interface fluxes between the biofilm and the water body in the R term. At present, we are interested in finding the contribution of the biofilm to the DIN which circulates in the WB during summer low water periods. As the physiology and the dynamics of the biofilm are not modelled at present, interface fluxes are directly integrated in the *R* term.

In the sector concerned by the model, two types of biofilm were identified during low water periods: a nitrifying biofilm near the city of Toulouse and a non-nitrifying biofilm further downstream.

In order to integrate the contribution of the biofilm on the DIN in the WB, mean fluxes of NH_4^+ and NO_3^- (μg N g $AFDM^{-1}$ h^{-1}) were calculated for the two types of biofilm whose AFDM values were greater than 20 g m^{-2} and for day and night conditions (Table I).

Simulations

Several simulations have been done on the 120 km river section and on different sectors, over different years during low water periods by integrating the epilithic biofilm. In all cases, the simulations overestimate the ammonium concentrations and underestimate the nitrate concentrations in comparison with the observed data. Simulations and experimental data obtained during the 1999 low water period (Figure 14) are presented in order to illustrate the general pattern obtained for all the simulations in the 120 km sector. In this figure, different simulations based on different physiologies of the biofilm are presented. The observed differences show that the biofilm compartment, even if it is the principal primary producer of the Garonne river during low water period, is not very influential on the NH_4^+ and NO_3^- concentrations in the WB because of the importance of the water volume circulating on the river and the relatively short residence times (so the exchanges are very limited). The differences between the simulated and measured data could be explained by the following:

(1) concerning NH_4^+ concentrations, NH_3 volatilization could be important and it is not taken into account at present time;
(2) concerning NO_3^- concentrations, a strong hypothesis is that nitrate inputs could come from the exchanges between the river and the underground water of the Garonne river alluvial plain, where intensive agriculture occurs and where the measured concentrations can reach 150–200 mg l^{-1} of NO_3^-;
(3) at the present time, we do not take into account other functional compartments as the investigations have just begun and we do not have sufficient data to be able to describe the functioning of the other compartments in the model.

With these two application examples, we have shown that the model has been developed in order to (1) integrate the bio-physical diversity of a great river and (2) guide future investigations.

CONCLUSION

The model was developed parallel to data acquisition. This model has been developed in order to integrate biophysical diversity. The principal aim is to model the evolution of the different elements (C, N, P) circulating in the WB. So, it is evolutionary (two-dimensional hydrodynamic and transport model for studies in some

Table I. Interface fluxes (μgN g $AFDM^{-1}$ h^{-1}) between the biofilm and the water body for the two types of the biofilm during established summer low water period

	Non-nitrifying established biofilm		Nitrifying established biofilm	
	N-NH_4^+ flux	N-NO_3^- flux	N-NH_4^+ flux	N-NO_3^- flux
Day				
Mean	−31	−366	−68	5
CL ($p = 0.05$)	128	250	42	63
n	5	8	5	6
Night				
Mean	93	−132	29	−14
CL ($p = 0.05$)	51	45	56	39
n	16	24	6	6

Positive values indicate water gain; negative values, water loss CL, confidence limits; n, number of fluxes for the mean flux calculation.
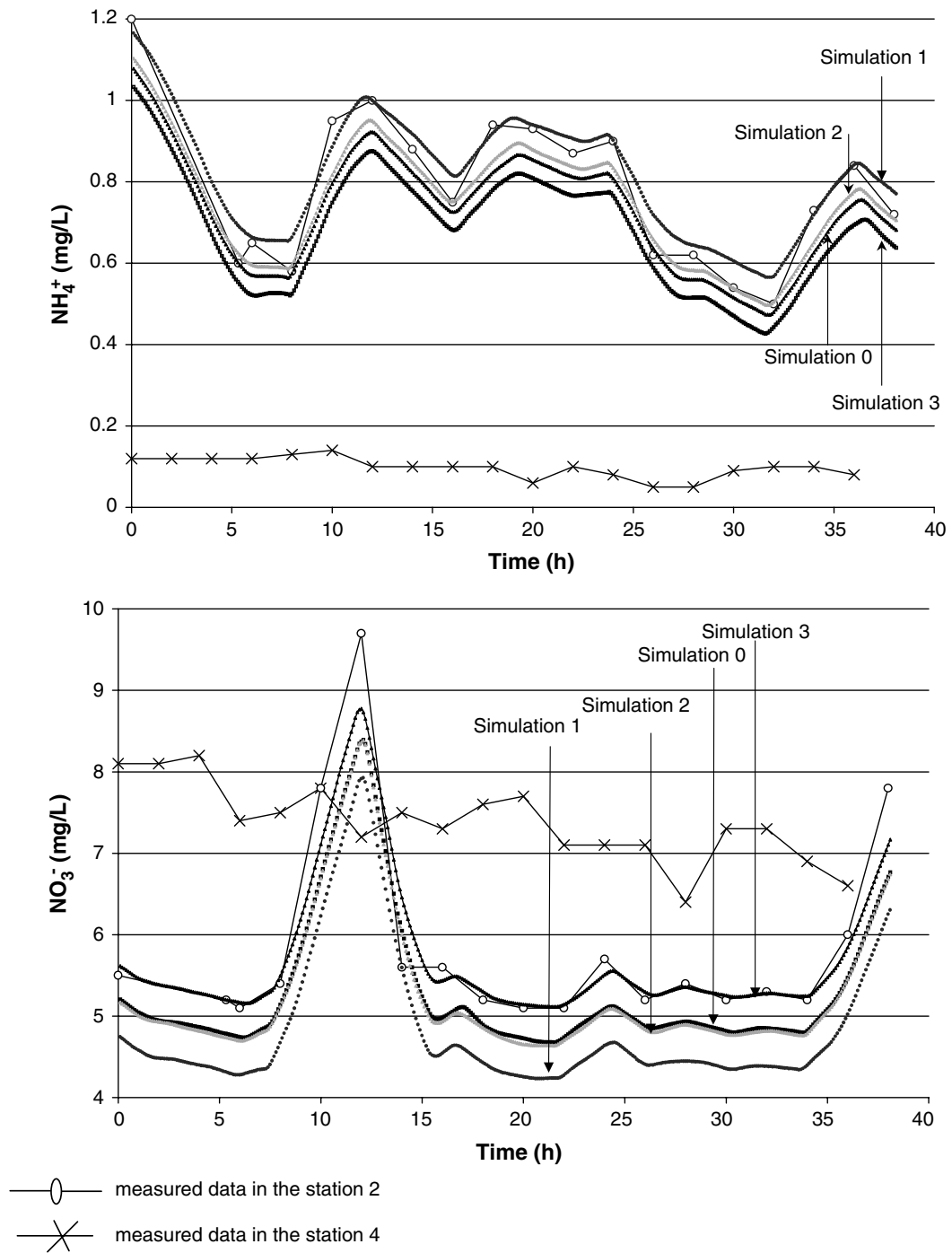
Figure 14. Comparison between measured and simulated concentrations of NH_4^+ and NO_3^- downstream of Toulouse: the measured data from station 2 entered the model. Simulation 0, simulation without biofilm activity; simulation 1, simulation with activity of a biofilm established during summer low water period (Table I); simulation 2, simulation with activity of a biofilm developed during the beginning of the summer low water period; simulation 3, simulation with biofilm maximum activities encountered during *in situ* experiments

particular sectors or for important discharges) and can integrate different data levels in biogeochemistry or in biology acting in different functional compartments.

On one hand, this model constitutes a promising analytical tool able to integrate previous studies and, on the other hand, it allows us to highlight the scientific orientation of the research programme. It is an indispensable tool which can be integrated into any research programme.

It is also a communication tool between scientific researchers and water managers: the physical model has been used to help decisions for water management; for example it permitted us to evaluate the influence zone of the water treatment plant phosphorus outputs on the downstream water course (Bonvallet *et al.*, 2001).

The originality of this model results from several points. The modelling of a large river flow during low water periods remains very difficult to implement and is practically absent in most of the existing hydrodynamic models. Most of them simulate river flows characterized by medium to high discharges. During low water periods, the Garonne river flow is characterized by a high spatial and temporal heterogeneity that creates difficulties for modelling more precisely by increasing the influence of the roughness. However, this model has proved its ability to give very good simulations for discharges above the admissible minimum discharges (defined by legislation on water management) for low water periods. During low water periods, ecosystems are more vulnerable. The functional compartments which compose the minor bed seem to be very active in the Garonne river. Most of the large river studies focus on the lowland sectors where biogeochemical processes occur in the water body. Future research, which will focus on the piedmont part of the large river, have to integrate functioning of the epilithic biofilm, the fine sediments, the hyporheic zone and their interactions with the water body, at the regional scale.

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