MONITORING TOOLS AND PROGRAM FOR MODELLING SUBSURFACE FLOWS THROUGH THE BED OF A STREAM RECEIVING URBAN STORM-WATER RUNOFFS

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ABSTRACT
In order to better understand the self-purification processes in a suburban small stream impacted by a combined sewer overflow, it appears that a key-factor to be quantified is the water fluxes through the substrata (the hyporheic zone). These fluxes could play a role by storage or dilution and cleaning effect on organic matters. Several methods and tools were used in order to find the most relevant and convenient way to measure the hyporheic exchanges of water in our study site.
Tracer-based methods failed mostly because of the difficulties to pump water or to inject tracer in the hyporheic zone without disturbance. Significant head gradients, conversely, were easily measured in the first layers of the streambed. At the end of such an exploratory phase, a method was chosen, based on continuous measurements of head in two sites, using piezometers and multilevel probe, at the local scale of a riffle/pool sequence. This data acquisition will be completed by regular surface tracer experiments, in order to survey the evolution of the transient storage parameters at the reach scale.

KEYWORDS
Hyporheic zone, instrumentation design, surface-water ground-water interactions

INTRODUCTION
The restoration ecology of aquatic ecosystem is now one of the challenges of the future. Nevertheless, it is difficult to propose restoration rules, including limitations on polluted inputs, without focusing on the study of aquatic ecosystem functioning (Lafont, 2001). Self-purification processes must be considered in the management of aquatic systems, particularly in the context of the UE Directive which emphasises the conservation or restoration of good ecological quality. The main problem comes from the difficulty of research about aquatic ecosystem functioning, because of multiple and complex interactions between physical, chemical and biological factors.
The research presented here deals with the assessment of the physical conditions (hydraulics, hydrogeology, geomorphology, etc.) that favour the self purification capacity of a small river with low dilution capacities, and receiving urban storm-water runoffs discharged through Combined Sewer Overflows (CSOs). Final aim is to produce an assessment tool of the self-purification capacity of small rivers by means of efficient measurement protocol and modelling.
First step for modelling self-purification processes is to be able to model hydric exchanges between surface and groundwater. Pathways through the streambed actually determine driving, removal, retention and uptake of particulate or dissolved matters like nutrients discharged through CSO. Much of these exchanges take place in the saturated sediments below the surface and the banks, at the interface between water column and groundwater (Boulton *et al.*, 1998). This zone is termed the hyporheic zone.
The flows through hyporheic zone occur within a variable depth of sediment and in the three space directions: vertically and laterally through the bed and the river banks depending of head gradients between the water table and the free surface water, as well as longitudinally across some geomorphological units like pool-riffle-pool sequences or natural steps, with series of downwelling and upwelling (Harvey & Bencala, 1993; Harvey & Wagner, 2000; Sophocleous, 2001).

Quantitative data of water discharges through these zones are needed as well as information about pathways (direction of flows, duration, etc.) (Findlay, 1995).
This research focuses on the study of a 1.5 km long reach of the Chaudanne river, an intermittent stream located in the district of Grézieu-la-Varenne, a town of the western part of the Lyon's agglomeration. The particular study site (cf. fig.1) is a reach of the Chaudanne river, that takes place from 150 m upstream a CSO device, to 150 m downstream the CSO.

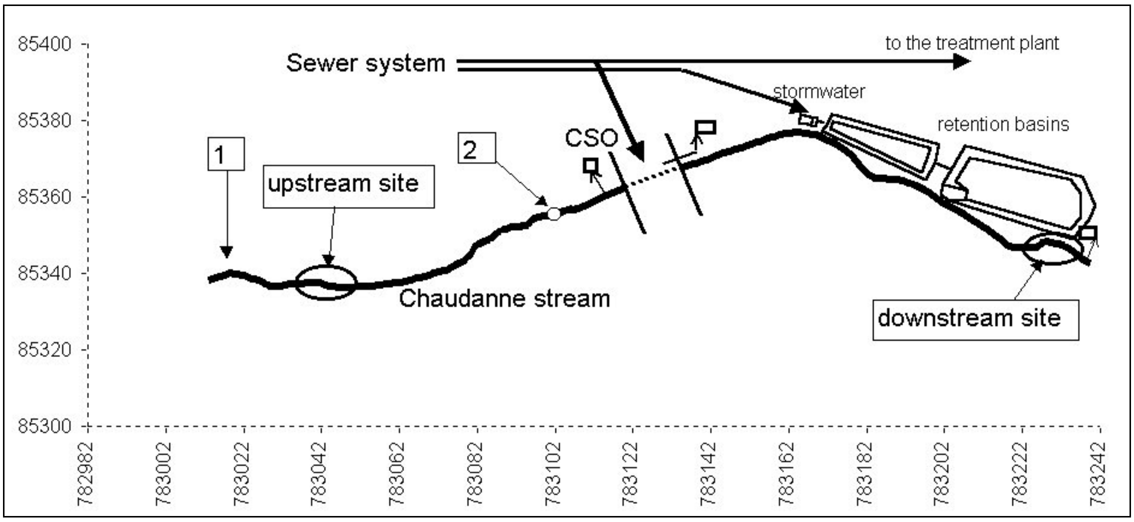

Figure 1: schematic map of the study site, river and basins from topographic survey in Lambert II coordinates. Solid curve shows the Chaudanne river. The rectangles connected to the river show the automatic sampling devices. Other descriptions are done in the text.

The upstream part of the reach is considered as a quite natural site and can be used as a control site, while the part of the reach below the CSO is impacted by the urban storm-water runoffs. In addition, the groundwater in the left bank of the downstream part might be modified by the two basins used for storage and infiltration of storm water.
Previous studies of oligochaete and crustacean assemblages (Lafont *et al*, 2000; Ruysschaert *et al.*, 2002) showed that hydric exchanges in the hyporheic system might have a purification effect on the river impacted by polluted water from CSO. The hypothesis was a) that downwelling surface water increased the storage of organic pollution in the hyporheic layer ("storage effect") and b) conversely, that upwelling groundwater had a beneficial effect on the ecological quality ("dilution and cleaning effects"). In addition, samples of water for isotopic measurements ($\delta^{18}O$) were collected from 13 surface and 9 hyporheic points along the stream (Gnouma, 2002). Results indicate that even if the average evolution of $\delta^{18}O$ in the stream and in the hyporheic zone are very similar, some singular samples show local zones of upwelling (when the value of $\delta^{18}O$ in the stream is the same than in the hyporheic zone) or conversely zones of downwelling.
In this context, according to these biological and isotopic indications of the existence of hydric exchanges in the hyporheic zone of the Chaudanne river, our objective is to investigate these hyporheic flows in order to model them. This presentation deals with the exploratory phase of the study, whose purpose is to define the relevant monitoring program to be settled in order to provide useful data for modelling. During this first phase, several various experiments were carried out. Because the storm-water retention basins were excavated during 2002-2003, our investigations took place in the upstream part of the reach. Tracers were used in surface water to assess global influence of the hyporheic zone on the transport of solutes. A prototype of multilevel probe was developed in order to sample hyporheic water at different depth on the same vertical line. This probe was used during tracer experiments carried out both in surface water and hyporheic zone. In addition we measured head gradients and hydraulic conductivity by mean of piezometers in the bank and micro-piezometers in the streambed.

MATERIEL AND METHODS

Surface tracer experiments: During surface tracer experiments, the tracer (1 L) was injected in the stream either quasi instantaneously or at a constant rate. Constant rate injection was obtained by means of a Mariotte's bottle, in the upstream part of the reach (point 1 on fig. 1), just before channel steps, which ensure that the tracer is well mixed. We used a solution of sodium chloride as a conservative tracer. Electrical conductivity was measured in surface water in four cross sections between the injection point and the CSO. We translated electrical conductivity on solute concentration thanks to the calibration curves established for each conductivity meter used.
The data collected were used to run the OTIS (One-dimensional Transport with Inflow and Storage) model, which simulates the transport of solute taking into account the concept of transient storage. Zones of transient storage are parts of the stream where solute is stored for a short time before being released (Bencala and Walters, 1983). The hyporheic zone, as well as dead zones, can be a transient storage zone, so its influence can contribute to the modification of the solute cloud form along the stream. Two indicators of the transient storage are used in OTIS: the cross-section area of transient storage zone and the exchange coefficient between transient storage zone and surface water. The STARPAC module of OTIS (Runkel, 1998) was used for auto-calibration of the dispersion coefficient, the storage zone area and the exchange coefficient in order to assess globally the importance of transient storage in the Chaudanne river, at the reach scale. Nevertheless, a significant existence of transient storage doesn't mean that hydric exchanges in the hyporheic zone are active because this phenomenon can be due to dead zone in surface water, but conversely if no transient storage is observed in the stream, we can suppose that exchanges in hyporheic zone are very weak.

Hyporheic sampler: We developed a prototype of a three-depth hyporheic water sampler. The aim was to use the less as possible destructive protocol in order to sample a small volume of water and to increase the number of measurement points. The sampler was constituted by a 3-cm diameter external stainless steel tube with three zones of strum at 10 cm, 30 cm and 50 cm below a reference, in order to allow water to flow into the tube only at these depths. A sampling chamber was created at each level: a series of washers was fixed across a vertical threaded rod put inside the external tube in order to ensure the sealing between the sampling chambers. Three capillary tubes coming from the top of the tube passed through the washers. Each capillary tube stops inside a sampling chamber and allows sampling of water from a zone around the corresponding strum by mean of a peristaltic pump connected to it. The pump we used was equipped by three ways allowing sampling in three chambers at the same time.
The multilevel sampler, equipped with a solid point, was pushed into the streambed by hammer. The reference of the strums levels was positioned close to the surface of the bed. Thus, sampling hyporheic water from depth of 10, 30 and 50 cm along the same vertical line was possible.
Two prototypes were put in a riffle (located on point 2 in fig.1), the second about one meter downstream the first. Two kinds of experiment were carried out using this sampler: During surface tracer experiments, sampling was carried out once before the tracer injection to know the initial conditions and several times after the cloud was passed over the riffle. In the hyporheic zone, a salted and coloured solution was made with NaCl and rhodamine or fluorescein and was injected 30 cm deep on the upstream sampler. Water was sampled the days after at the others levels both in the upstream sampler and the downstream one. The presence of coloured tracer in the samples was visually controlled and electrical conductivity was measured too.

Piezometers and micro-piezometers: At the upstream site (localisation shown in fig. 1) some piezometers have been installed on the banks. Three micro-piezometers (*i.e.* 3-cm diameter external stainless steel tube with strum and point at the bottom) were put into the streambed. Piezometers are

equipped with pressure transducers connected to a data logger. Level in the micro-piezometer was measured by hand using an electrical probe.
Slug tests were carried out in these two kinds of piezometer in order to measure the hydraulic conductivity of the porous media both in the banks and at different depth in the streambed, using the Bouwer and Rice method (Bouwer and Rice, 1976; Butler, 1998).
Vertical hydraulic gradients (VHG) were measured in the streambed as the difference of water level inside and outside a micro-piezometer divided by the distance between the strum and the surface of the streambed. Distances are measured from the top of the tube in each case. The water level inside corresponds to the head in the substrata at the deep of the strum and the level outside is the head in the stream.

RESULTS AND DISSCUSSION

Transient storage: Calibration of the parameters of transient storage was performed with the data of tracer experiment carried out the 02/06/03, when stream-flow discharge was about 75 l/s. The selection of the parameter of dispersion only, without any transient storage taken into account, allows a well auto-calibration. No relevant calibration was possible of the transient storage parameters with the data used. This result seems to indicate that during the period of the tracer experiment at least, *i.e.* with these hydraulic conditions of water table level, water level in the stream and stream-flow discharge, no significant transient storage, and then no significant hyporheic flows can occur.

Electrical conductivity of the hyporheic zone: The natural electrical conductivity of hyporheic water was measured at different date by mean of the two sampler put in the riffle. The results shown in figure 2 clearly indicate that gradients of electrical conductivity exist both in a vertical and in a longitudinal direction, but are quite variable in time.
The vertical gradient is increasing, so it reveals a progressive mixing of surface water and groundwater, which is more mineralized then show greater value of electrical conductivity. But values on 09/20/02 and 12/04/02 show that surface water and hyporheic water at 10 and 30 cm deep are quite the same at the upstream point and at 10 cm deep on 09/20/02 at the downstream point. For each date, conversely, at 50 cm deep in the downstream point the water have high electrical conductivity. This variable pattern could be explained by the variations of intensity of a downwelling of surface water at the upstream part of the riffle, even at the downstream part sometime (09/20/02), mixing with groundwater within the hyporheic zone: more surface water appears to be driven into the hyporheic zone at the upstream part of the riffle - and deeper - than at the downstream part.
During the 12/04/02 and 02/06/03 tracer experiments, hyporheic water was sampled just after the salt tracer passed over the multilevel samplers in the riffle. Electrical conductivity of the samples on the 12/04/02 is presented on figure 3.
The first peak of electrical conductivity in the river was 490 µS/cm and the second 398 µS/cm. Electrical conductivity briefly increase in the 10-cm deep hyporheic zone both upstream and downstream, after the first peak in surface water only, not after the second one, but later downstream than upstream. No evolution occurs in the 30-cm deep upstream samples but variations in the 30-cm deep downstream ones are significant only after the second peak in surface water. A hypothesis could be that this increase is due to a lag-time because of the movement of tracer from the 10-cm deep both upstream and downstream to the 30-cm deep downstream hyporheic zone. But the accuracy of the measurement is about more or less 5 µS/cm, so that every increase of hyporheic electrical conductivity is poorly significant: every peak of hyporheic electrical conductivity is close to this limit.

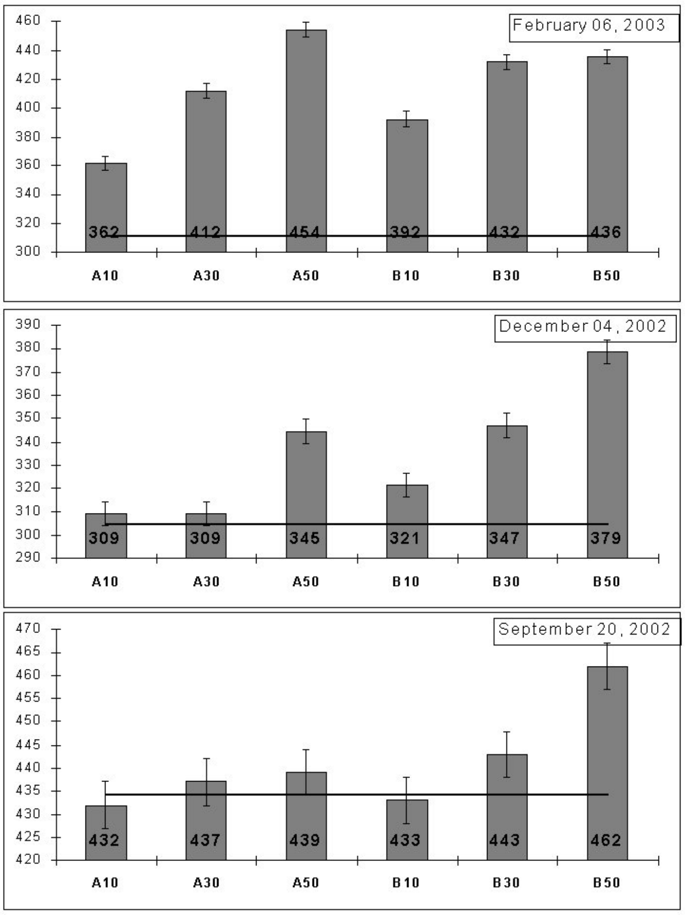

Figure 2: Natural electrical conductivity of the surface water (solid line) and the three depths of the hyporheic zone. Samples are labelled by A for the upstream sampler, B the downstream one, followed by the depth in centimetre.

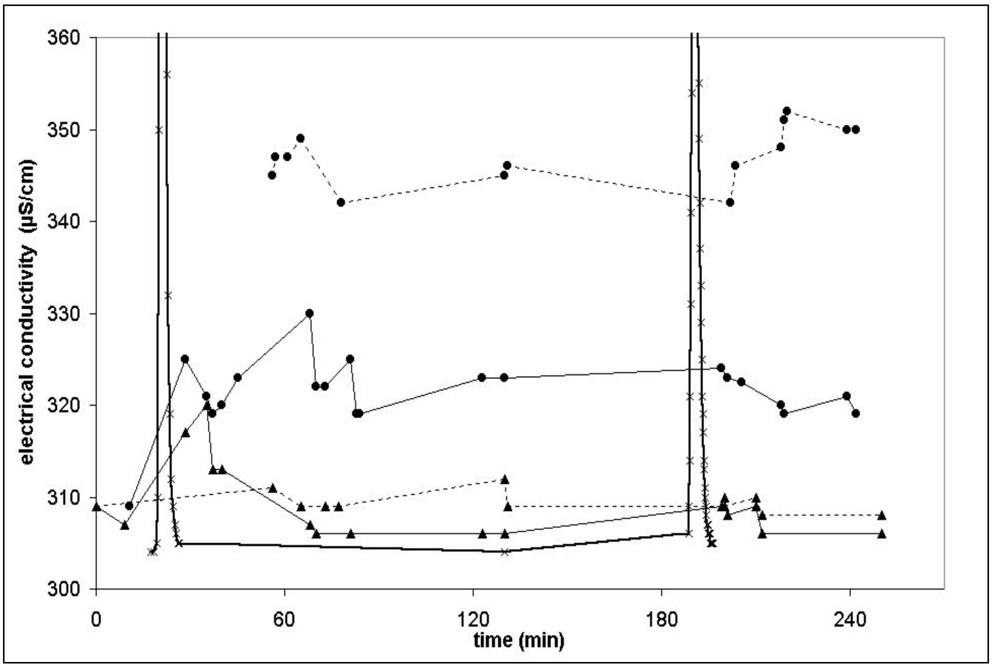

Figure 3: Evolution of the electrical conductivity of surface (solid line with crosses) and hyporheic water pumped in the upstream sampler (triangles) and the downstream one (circles) at depths of 10 cm (solid lines) and 30 cm (broken lines) during the 12/04/02 tracer experiment

Sampling was repeated on 02/06/03, but only the first sample at 10 cm deep in the upstream prototype showed an significant increase of electrical conductivity (15 µS/cm), before water came back to the mean natural value. Others places of sampled hyporheic zone did not show any variations. Nevertheless, this single increase could be due to an artificial mixing of hyporheic and surface water, occurring during the sampling while the cloud of tracer was not completely passed, but this bias does not appear in the other sampler. Last, only a 370-µS/cm peak of electrical conductivity in surface water was obtained over the riffle, which could be a too low value to make sensitive any movement of tracer from the surface to the hyporheic zone.
These results indicate that water may be driven into the first centimetres of the substrata, but this exchange is probably insignificant and anyway difficult to measure because of the duration of the pumping for a single sample and because of the probable dilution of the small part of the tracer driven into the hyporheic zone. In order to increase the visibility of the exchanges by mean of tracer, other system should be designed, which could produce higher increase in surface water electrical conductivity with higher duration.
Tracer experiments carried out in the hyporheic zone produce also ambiguous results: tracer injected the 09/20/03 at 30 cm deep in the upstream sampler was visually observed the days after in the 50 cm deep chamber of the downstream sampler (about one meter downstream) and very dilute in the 30 cm deep chamber of this sampler ten days after the injection, but without significant increase of electrical conductivity when taking into account the natural increase of the electrical conductivity of the surface water. Furthermore, immediate contamination of the 50 cm deep chamber of the upstream sampler by the tracer injected in the 30 cm deep chamber was observed, indicating that sealing is not ensured in the prototype when a pressure (by pumping or injection) is imposed to the sampling chambers.
In order to minimize the pressure imposed to the washers, we would have to pump at the most low rate but that leads to use very long time step. In particular for the deepest chamber (50 cm), the time of pumping was prohibitive enough, without real insurance that there is no mixing of water coming from different depth anyway.

<u>Pattern of hydraulic conductivity:</u> Observations and slug tests allow us to describe briefly the characteristics of the porous media in the upstream site. In the banks and below the riverbed, the soil is composed of two main layers. The first one from the surface to about 1.50 m deep is a sandy gravelled media whose hydraulic conductivity is about 10^{-6} m/s. Above the fractured bedrock is a layer of clay, whose hydraulic conductivity is about 10^{-8} m/s. The left bank shows a low slope, and the right bank is closed by a steeper part of the fractured bedrock that appears in several places.
Slug tests in the first tens of centimetres of the streambed showed a decreasing gradient of hydraulic conductivity, starting with value of 8.10^{-5} m/s at 20 cm deep, then 2.10^{-5} m/s at 35 cm deep, and finally 4.10^{-6} m/s at 45 cm deep, like in the banks. Such a structure of the porous media leads to think that a more intensive flow could occur within a layer about 40 cm thick just below the streambed than through the bank.

<u>Vertical hydraulic gradients:</u> The vertical hydraulic gradients we observed in the micro-piezometers put in the streambed confirm this idea. The measurements are presented on the figure 4 with indicative value of average stream-flow discharge during the same period.
Positive gradients in this figure indicate conventionally a downwelling and inversely negative values show an upwelling. A downwelling occurs in the pool-to-riffle transition whereas upwellings exist both in the riffle-to-pool transition and in the pool close to the bank. These gradients are strong in relation with the horizontal ones between two piezometers in the banks but they occur in a layer of the streambed thick of about 40 cm only. We can notice that the distance between the downwelling and the upwelling zone is the riffle length only *i.e.* few meters. No correlation seems exist between the existence of the head gradients and the value of the stream-flow discharge except that the upwelling seems to decrease as the mean discharge increase.

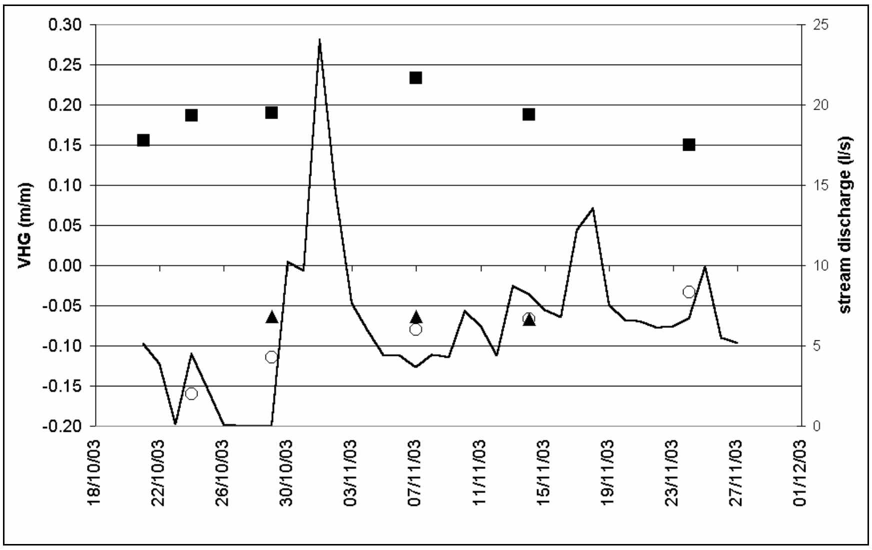

Figure 4: vertical hydraulic gradients at different dates in the micro-piezometers: in the pool close to the right bank (black triangles), in the transition pool/riffle in the centre of the cross section of the bed (black square) and in the transition riffle/pool in the centre of the cross section of the bed (circles). The solid line indicates the stream discharge values during the period.

These trials of various experiments lead us to conclude that: (1) analysis of surface tracer indicates that the transient storage was negligible at the reach scale the day we tested it; (2) hyporheic tracer needs to be perfected by adapting both the injection system and the multilevel sampling tool in order to use this method to assess any hydric exchange; (3) nevertheless there is a electrical conductivity gradient which is variable in time and space within the 50-cm deep hyporheic zone and indicates that mixing of surface and groundwater may occur and be variable in space; (4) in addition, this 40 or 50-cm deep layer of streambed have quite high hydraulic conductivity that may favour hyporheic flows inside; (5) hyporheic head gradients, that drive subsurface flows, at least along the vertical direction in the streambed, are strong enough to be measured and confirm that geomorphologic units like riffle/pool generate downwellings and upwellings at a local scale.

As a result we have chosen to develop a monitoring program of two local sites, one upstream the CSO and the second downstream (surrounded on fig. 1). These sites (about 10-m long and 5-m large) cover geomorphological units: one pool/rifle/pool sequence and one meander. Each of them was equipped by several piezometers (with pressure transducer) in the banks, one tensimeter (less accurate than pressure transducer but offering a more rapid response to the variation) at each bank close to the streambed, and three multilevel probes adapted from the prototype of sampler already used. All of these transducers have been connected to data loggers in order to provide continuous measurements.

The new prototype of multilevel probe can be equipped with micro-transducer: three differential pressure transducers between the three levels within the hyporheic zone and surface level in order to measure head gradients, and one relative pressure transducer in order to measure free surface water level. In addition, some micro-electrical conductivity transducers could be installed in the different levels of the multilevel probe. So we will favour *in situ* measurements against pumping way.

Three multilevel probes at least will be put in the streambed: one at the pool-to-riffle transition, the second in the riffle, and the third in the riffle-to-pool transition. Data collected at the local scale are expected to be useful for very fine 2 or 3-dimensionnal modelling.

In order to assess the global importance of the processes whose observation is expected at the local scale, we will continue to carry out regular surface tracer measurements. These reach-scaled data will be analysed by mean of the OTIS model to control the evolution of the transient storage parameters, that may become significant during low flow.

CONCLUSION

Various experiments (surface and hyporheic tracer approach, natural electrical conductivity measurements, slug-tests, VHG measurements) were applied to the Chaudanne river. The ambiguous results tend to indicate that even if hyporheic flows could exist in this stream, these processes should be very variable in space and time and so be difficult to observe and describe. The main flows may occur in the first 50-cm deep layer of the streambed. The trial of different ways to investigate them leads us to design the instrumentation of two sites at the local scale of geomorphological units, allowing *in situ* and continuous measurements of head and if possible electrical conductivity. A tentative of fine modelling of the hyporheic flows at this scale is expected thanks to the data that will be collected. At the reach scale, the evolution of the effects of these hyporheic flows will be controlled by assessment of the transient storage empirical parameters using the OTIS model.

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