Coupling groundwater modeling with biology to identify strategic water resources

Didier Graillot, Frédéric Paran, Djamel Mimoun, Gudrun Bornette, Janine Gibert, Laurent Cacilhac

Coupling Groundwater Modeling with Biology to Identify Strategic Water Resources

Didier Graillot[1], Frederic Paran[1], Djamel Mimoun[1], Gudrun Bornette[2], Janine Gibert[2], L. Cadilhac[3]
[1]*Saint-Etienne School of Mines, mimoun@emse.fr, Saint-Etienne, FRA*
[2] *UMR CNRS 5023 "Ecology of Fluvial Hydrosystems", University Cl. Bernard Lyon 1, Villeurbanne, FRA*
[3] *Water Agency of Rhône Méditerranée Corse RMC, Lyon, FRA*

ABSTRACT

The identification of hydraulic interactions between rivers and groundwater is part and parcel of assessing the capabilities of aquifers in response to the constraints induced by anthropic activities and climate changes on water management. On the extensive Rhône river basin in France, lack of measurements hinders groundwater modeling everywhere and simulating water management scenarios in every place. This work focuses on the advantages of coupling groundwater modeling with biological markers i.e. micro- and meso- invertebrates and aquatic vegetation on very well instrumented areas. A correlative analysis between hydraulic and biological properties of the aquifer provides a better understanding of the transfer of groundwater into or from the surface waters. This analysis makes the adjustment of boundary conditions easier and the calibration of groundwater models more efficient. Finally our approach enables to identify the conditions under which it could be possible to substitute biological indicators in lieu of a large field of piezometric measurements. This work proposes an interdisciplinary approach for the quantitative and qualitative characterisation of hydraulic interactions between rivers and shallow aquifers. Integration in a future decision support system should help water agencies to consider appropriate long term water policies like preservation of groundwater for potable water supplying and/or mitigation of pollutions risks.

INTRODUCTION

The assessment of interactions between the rivers and their floodplain via groundwater represents a relevant issue for the water resources management in the long term and for the preservation of biodiversity. This is accomplished by characterizing hydraulic exchanges existing between i) the Rhône River in France, its river branches and tributaries, ii) channels and diversion canal iii) alluvial watersheds and other connected aquifers. For this, new methodologies are required to provide watershed managers with decision support systems able to identify strategic reserves and their scope for water uses.

PURPOSE AND SCOPE

This research program is designed to estimate the groundwater recharge to the Rhône River and to identify their origin. It will be possible to delineate the sections of the aquifers which are the most influenced by the river and most threatened by a potential pollution in the river. It will be possible to identify those areas of surface water and the wetlands which are strongly affected by groundwater flows.

This is an interdisciplinary approach which is based on hydraulics, groundwater mechanics and biology to characterize and assess potential or existing hydraulic interactions between the Rhône River and the connected aquifers from the Leman Lake in Switzerland all the way downstream to the Mediterranean Sea. Anthropic water use is considered as potable water supplying, irrigation and industrial water needs. Our methodology should contribute to the preservation of groundwater, often considered as an invisible resource as well as provide more generally to the preservation of water resources and biodiversity throughout the entire Rhône River basin.

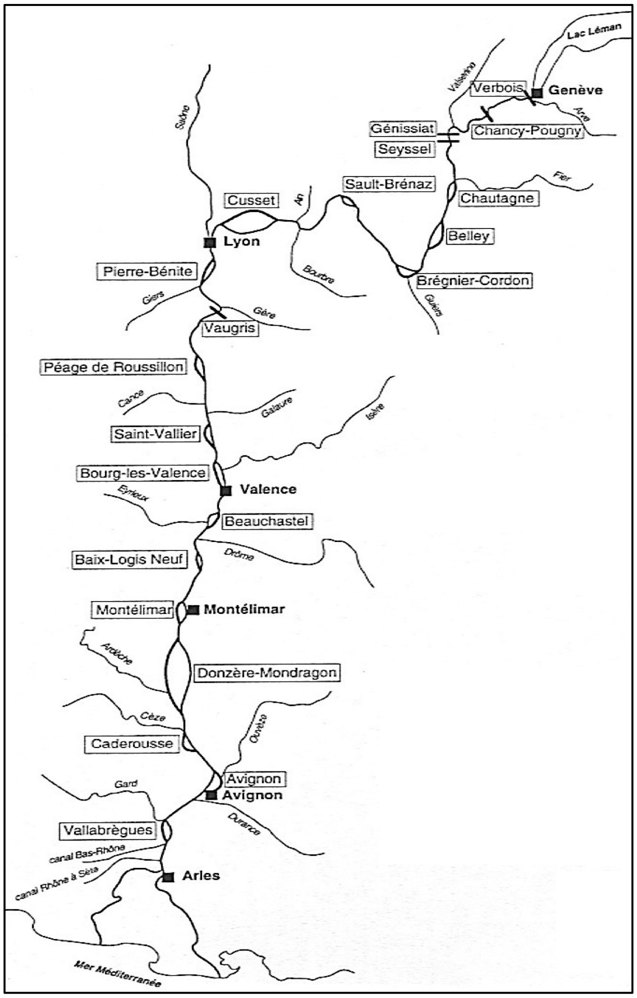

Figure 1 : Rhône River Basin (Coulet 1997)
545 kilometers from Geneva to the Mediterranean sea

SITE LOCATION AND DESCRIPTION

The Rhône River flows from southwestern Switzerland in the Alps to the Mediterranean Sea along 545 kilometers in France. The surface of the drainage area is about 5 220 square kilometers. The land covering is composed of rocks and glaciers (38%), forest and pasture (46%), agricultural land (16%). The Rhône River crosses 3 administrative regions, 11 counties, 213 municipalities and 48 hydrographic zones (Figure 1). Along this river many different watersheds exist:
- Free and confine sedimentary aquifers: limestone, alluvial aquifers with sand and gravel, glacial tills and deposits, Pliocene formations, Miocene molasses, glacial complex formations,
- Impervious geological formations which can produce very small aquifers: silt and alluvium, limestone, marl and sandstones.
- Aquifers in the fissured bedrock (granite and schist).

As many rivers, the Rhône is supplied by rain and run-off. The Rhone River also receives snowmelt upstream in the Alps and groundwater from the aquifers along the river. Groundwater influences strongly surface waters.

Many man-made structures have been built along this river downstream from the metropolis of Lyon. The water supply of the entire urban area depends on groundwater from the alluvial aquifer close to the city. The wells are exploited up to an average of 350 000 m^3 per day using bank filtration from 3 tracts of the Rhône river. Direct recharge by the river can reach 95%. About 40 dams have been built to produce hydroelectric power, prevent floods, enhance navigation and provide water for irrigation. A diversion canal has been dug along the river with 300 kilometers of embankments. All these engineering works have a strong influence on the hydraulic interaction between the river, slow flowing former channels and aquifers. The average flow upstream Lyon is about 423 m^3/s and varies from 160 m^3/s to 1900 m^3/s. Downstream, the average flow reaches 177 m^3/s and varies from 540 m^3/s to 9600 m^3/s.

The European Water Framework Directive has defined quality objectives for ground and surface waters which have to be reached and satisfied in 2015 so that decision makers and water authorities have an obligation to protect rivers, aquifers and ecosystems along the Rhône River.

METHODS FOR ESTIMATING GAINS AND LOSSES OF WATER

This novel approach associates the well known physical methods i.e. groundwater modeling, geochemical and isotopic analysis with biological methods based on the sampling of micro-invertebrates and on aquatic plants (Paran, Graillot, 2006; Bornette *et al.* 2007).

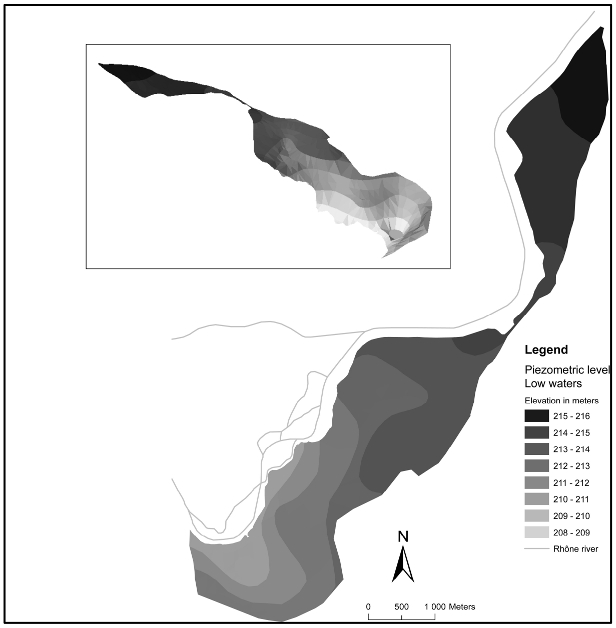

Figure 2: Mapping of the piezometric level in the alluvial aquifer

Hydraulic Diagnosis

Hydraulic interactions between the alluvium and the river are preliminarily estimated from gradients which are calculated from digitalized piezometric maps (Figure 2). Bank filtration is calculated with a Darcy's law considering the cross section in the river and the permeability of the aquifer. This estimation is weighted by a clogging factor to take into account the impervious banks on each side of the river. Sometimes channel drawdowns the groundwater flow on each side of the river so that the contribution of the aquifer to the river is removed at downstream.

Comparison with Biological Markers

This first diagnosis of the hydraulic exchanges (outflow, inflow, equilibrium) is compared to the population of micro- and meso -invertebrates which have been sampled from the river, into the wells drilled in the aquifer and into canals and channels. Obligate groundwater-dwelling species (i.e. stygobionts) as certain oligochaetes are especially influenced by phreatic conditions and significant of groundwater infiltration. A spatial analysis of the distribution of hyporheic microfauna and of stygobionts helps to determine the nature, the origin and the intensity of the flow circulating into sediments at the bottom of a river. The spatial distribution of the ecological groups: stygobionts, stygophiles (ubiquitous species) or stygoxenes (epigean species) should obtain a relevant description of hydrological exchanges.

A comparison with sampled aquatic vegetation is also made. Aquatic vegetation indicates the trophic degree of the rivers (oligotrophic, mesotrophic, eutrophic). The analysis of ecological successions and of particular vegetal species as macrophytes can help to determine groundwater infiltration. There is a correlation between the intensity of groundwater infiltration and the thermal variability of surface water in which vegetal species grow. However, these correlations are not always available at different latitudes. Other physical parameters such as conductivity and temperature can be used to check the coherence of the hydraulic exchanges which have been formerly calculated.

Finally, the study of the hydraulic exchanges is made in two steps. A first correlative analysis is made at the scale one single sampling station to identify the correlations between the different metrics. The second step tries to apply them to other cases study to validate these correlations or to identify others.

Comparison with Groundwater Modeling Results

A limited case study in the Rhône River basin has produced results which can be visualized by GIS mapping with geological hydrological and biological metrics. A comparison was performed with the results given by finite differences 2D models implemented with Modflow on this river section. The infiltration flow from the aquifer into the river is generally represented by a Cauchy condition in the model (de Lange 1999) [1]. A cross validation of each method (biologic and hydraulic gradients) improves the convergence of the calculated flow discharge between the aquifer and the river.

Q (m³/s): infiltration flow
Hsw (m): surface water level
Hgw(m): groundwater level
C(s/m²): resistance of the bank

$$Q = \frac{(Hsw - Hgw)}{C} \quad [1]$$

RESULTS AND DISCUSSION

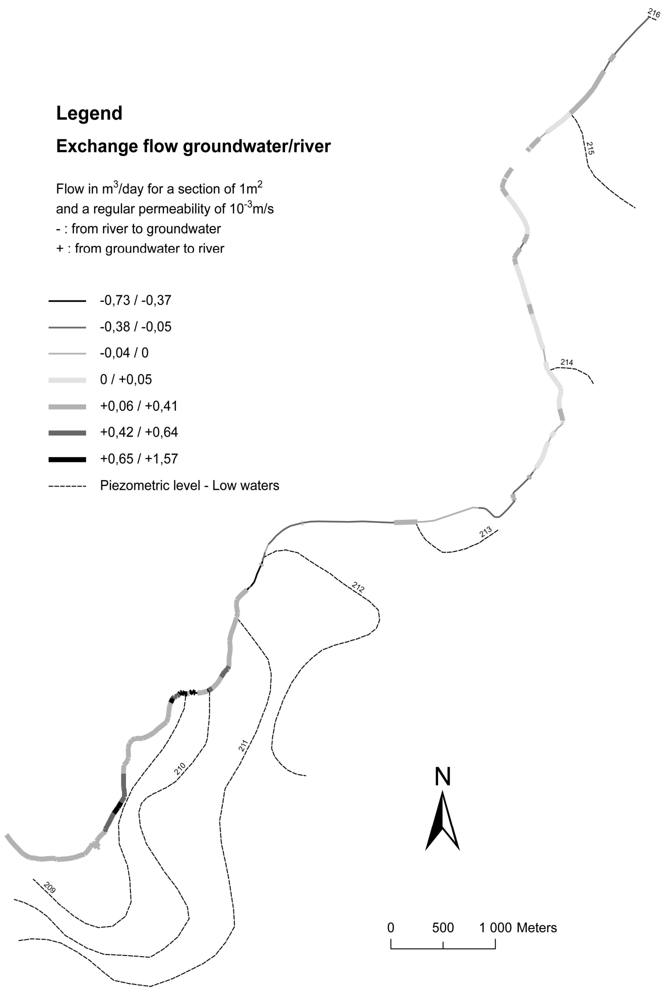

Figure 3: Mapping of the hydraulic exchanges between the river and the alluvial aquifer

From a hydrogeological view point the case study shows that the groundwater discharge is limited to 100 l/s and per kilometer (350l/s along 7.5 km) into the river. These very weak values mean that the aquifer doesn't represent a strategic reserve of groundwater (Figure 3). It is not possible to extend the catchment areas to dig other wells to supply water for irrigation or potable water use. Downstream of this section, the results show that the groundwater flows into the channel beneath the river are higher (660 l/s).

The biological assessment of micro-meso-invertebrates and aquatic vegetation sampling leads to confirm a phreatic influence of the alluvial plain in this section. They bring more information about the origin and the role of groundwater flows on the eutrophication process in the river and in the aquatic medium (Paran *et al*. 2004). A first comparison between the hydraulic and biological metrics on this case study shows the interest of such an interdisciplinary approach. Complementary isotopic analysis and environmental tracers measurements (Cl^-, $\delta^{18}O$ and $\delta^{2}H$) should be made to confirm these results (Fette *et al.* 2005). Several already-existing groundwater models have been applied on at least 3 main river sections. The results given by these very precise and documented models will be compared with biological and geochemical measurements and the calculation of the hydraulic interactions. This could lead to a new global modeling approach at the scale of such a river where it would be too prohibitive (in cost and time) to implement a gridded model.

METHOD LIMITATION AND ACCURACY

The accuracy of the results given by the method is different for each metric. In hydrogeology, we find the traditional sources of errors such as the depth of the aquifer, inhomogeneities in the alluvial aquifer, errors in the measurement of groundwater level and conductivity. In hydraulics, the depth of the channels has been estimated up to 5 meters depending on the data quality provided by the National Company of Rhône. The possible clogging of the banks has been estimated from the results given by models when available. Errors induced by the biological field sampling procedures may also arise even if identification of fauna and aquatic vegetation seems to be more deterministic. A spatial analysis of uncertainties has been achieved for each metric so that it could be possible to propose uncertainty mapping with a confidence interval for each calculation of flow exchanges.

FUTURE RESEARCH

The spatial correlation found between these different metrics has to be validated on another case study to take into account diverse latitude, climate, geological context and anthropic conditions. Transient conditions remain to be studied since GW/SW interactions can be modified during the fall low-flow period. Another field of research should be developed to predict the modification of these hydraulic exchanges induced by climate changes. The resulting thermal modification could have rough repercussions on the nuclear power plants which would need more and more stenothermal groundwater. Other rivers have been studied in the world and especially to identify hydraulic interactions with aquifers: Danube, Murray River, Snake River. Very few only have been studied with an integrated biological and physical approach.

CONCLUSIONS

Numerical modeling of groundwater/surface-water interactions is not always efficient for a large scale river basin. On very well instrumented areas the gains and losses between groundwater and surface-water can be calculated from spatial analysis of piezometric gradients. They can be validated by results given by groundwater models which have been implemented at a local scale. The biological markers which are influenced or not by the phreatic conditions and the discharge fluctuations can also confirm these GW/SW interactions. This novel approach has been applied on two sections of the Rhône River and shows correlations between hydraulics and biology which permits under specific conditions to avoid extensive groundwater modeling on similar sections. Results will provide decision makers with relevant hydrological and biological information to identify by sight strategic reserves of groundwater.

ACKNOWLEDGMENT

This research program is supported by the French Water Agency of Rhône-Méditerranée-Corse with the help of the National Company of Rhône for providing hydraulic data.

REFERENCES

Bornette G., Dechomets R., Ferreira D., Germain A., Gibert J., Graillot D., Lafont M., Paran F. Puijalon S. (2007) Evaluation des échanges nappes rivières et des apports souterrains dans l'alimentation des eaux de surface. Application au Rhône et à ses aquifères superficiels. Research report, ZABR n°A11, Phase 1, Agence de l'Eau RMC, 167 p.

de Lange W.J. (1999) A Cauchy boundary condition for the lumped interaction between an arbitrary number of surface waters and a regional aquifer.J. of Hydrology, 226, 250–261.

Fette M.W., Kipfer R., Schubert C.J., Hoehn E., Wehrli B. (2005) Assessing river-groundwater exchange in the regulated Rhone River (Switzerland) using stable isotopes and geochemical tracers. Applied Geochemistry, 20, 701-712.

Paran F., Graillot D., (2006) Un territoire en 3 dimensions (T3D) et un acteur en 4 dimensions (A4D) pour une argumentation spatiale adaptée. In : Aide à la décision pour l'aménagement du territoire, D., Graillot, J-P, Waaub, Traité IGAT, Hermès-Lavoisier,181-212.

Paran F., Malard F., Mathieu J., Lafont M., Galassi D. Marmonier P. (2004) Distribution of groundwater invertebrates along an environmental gradient in a shallow water-table aquifer, In: Proceedings of an International Symposium on World Subterranean Biodiversity (Ed. J. Gibert), pp. 99-105, Villeurbanne, France, 8-10 December. University of Lyon, France.