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An innovative modelling concept for integrated water resources management linking hydrological functioning and socio-economic behaviour - The Hérault catchment case study, south of France

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Abstract : This paper presents a conceptual modelling framework for integrated water resources management at the scale of the river basin. A simulator was developed using Matlab/Simulink software to ensure the numerical formulation of the conceptual model. The simulator is problem-solving oriented allowing to investigate the responses of the hydrosystem according to various scenarios defined by the stakeholders of the basin. The simulator is mid-way between full-determinist models which are data- and time-consuming, although more accurate in terms of quantitative outputs, and full-lumped models which are too simplistic to account for hydrogeological heterogeneity and realistic impacts of economic development scenarios, although easy to implement and time-saving. After having described the key hydrological processes and economic rules at the watershed scale, the simulator has been used to compute groundwater and river flows, according to a set of economic scenarios which are likely to occur in a very near future. The simulator has been tested on the Hérault floodplain (100 km²) where the major conflicts occur.

Keywords : watershed, conceptual model, hydrology, economic scenarios, integrated assessment

1. INTRODUCTION

In Europe, changes of economic environment resulting in increased water demand along with evolution of societal attitude towards water resources have led to an escalation of local conflicts over water use and conservation in which a growing number of users and citizen groups are progressively being involved. In response to this situation, a number of European countries, and more recently the European Union, have promoted participatory approaches to design water management policies and have established institutions where such disputes can theoretically be discussed by stakeholders and solved through negotiation processes. In practice, such negotiation processes have not been successful. For instance, in France, only 3 out of 42 negotiated local water management plans projects (SAGE) started before 1997 had been agreed and signed by February 2001. These difficulties can partly be attributed to the fact that stakeholders generally do not have at their disposal any interactive tool to investigate and compare the impact of various water management scenarios. Due to the strong emphasis recently put by decision-makers and politicians on integrated (i.e., large scale) and sustainable (i.e, long term) water resources management, integrated assessment and modelling techniques, decision-support systems being a part of those, showed a marked increase since the mid 1990's even though not entirely new (Jamieson and Fedra [1996]; Dunn et al., [1996], Reitsma [1996], Andreu et al. [1996], Parker et al., [2002].

The research presented in this paper aims at developing an integrated model likely to be used as a simulation tool by a group of stakeholders involved in water management planning at the watershed level. The methodology and the computer prototype were developed for the alluvial aquifer of the Hérault watershed in South of France. The Hérault River Basin is a Mediterranean watershed of 2500 km² located in the Languedoc Region, 150 km north-east of the Spanish border. The study area, which extends over 100 km² in the alluvial plain of the watershed, is characterised by a raising competition for water use. Irrigation, which is the most ancient water use, still represents today more than 70% of the total water abstraction in the study area. However, agriculture increasingly competes with tourism activities, which used to be concentrated along the seashore but are now developing inland. The river leisure activities like swimming, fishing and canoeing are attracting a growing number of regional, national and foreign tourists. As a result, there is an increasing demand for in-stream water preservation (quantity and quality) along the Hérault river. Water quality has now become vital to the local tourism economy. Almost simultaneously to the development of tourism, the rapid economic growth of the city of Montpellier, which is outside from the Hérault catchment, has induced an intensive urbanisation of the alluvial Hérault valley. A number of villages and small cities located along the new highway which connects them to Montpellier are facing population growth rates ranging between 5 to 10% per year. Furthermore, since every new house built comprises a swimming pool and a garden, the demand for domestic water has increased tremendously, compelling the municipalities to rethink their water supply strategy in order to be able to satisfy the peak of demand. In order to solve the emerging new conflicts over water use, the local authorities have initiated a local water management plan project (SAGE).

In a first section, the paper presents the different steps of the methodology developed in this interdisciplinary research project. Then, it focuses on the integrated model development and its computational implementation using the Matlab-Simulink© software. Validation of the model is presented in the third section and a proposed set of simulations are discussed in the concluding section.

2. MODELLING CONCEPT AND METHODOLOGY

The modelling approach consists in five major steps which are presented below:

Stakeholder analysis. Seventy semi-structured individual interviews (on average 2 hours) were conducted in 2001 with local stakeholders [Garin et al., 2001]. The stakeholders were selected to cover all water uses (farming, drinking water, tourism, fishing activity, environmental protection) though privileging institutional representatives (elected officials, professional organisations, territorial bodies, associations, Government services, contractors, consumers). The geographic distribution of interests in the watershed was considered as well. The analysis of the information collected through these interviews lead to *(i)* the identification of the key actors depending on (or having an impact on) the functioning of the hydrosystem; *(ii)* the specification of their decision rules for all the actions which have an impact on the status of the hydrosystem; *(iii)* the identification of the variables which determine the level of satisfaction of each actor; and *(iv)* the identification of the existing and anticipated conflicts over water use and conservation.

Hydrological modelling. The objective was to represent the key hydrological processes that are likely to be impacted, over space or time, by the behavioural rules of economic actors. Based on the multidisciplinary expertise gained by the water department, BRGM, on the Hérault catchment in the field of geology, hydrogeology, geochemistry hydraulics and modelling from Fuchey and Lestrat [2001] and Weng et al. [2001], a simplified hydrological model of the Hérault alluvial aquifer was built up. The integrated model identified three key hydraulic entities which store and transfer water over the catchment : *(i)* the Hérault river itself, *(ii)* the Gignac irrigation canal, *(iii)* the hydrogeological units. All the three hydrological entities are closely interconnected because the excess of irrigation water returns to the river either directly through overflow at the outlets of irrigation furrows or through the aquifer which is recharged by seepage losses within the irrigation network or soil infiltration, and ultimately is drained by the river. Water may flow from the aquifer towards the river or the opposite depending upon the evolution of the hydraulic head between the river and the aquifer over space and time. The hydrological model has to be considered as a quasi-distributed model because each of the hydrogeological units corresponds to a well-delineated area of the aquifer which has specific hydrogeological properties (thickness, permeability and storage coefficient), soil type and support given irrigation practices.

Formulation of the conceptual model. This step consists in linking hydrological processes and behavioural rules in a simple but dynamic representation of the hydrosystem defined as a complex system. The model accounts for feedback loops existing between the economic and hydraulic entities of the complex system (e.g., direct relationships between hydraulic entities, impact of actor's action on water quantity and quality, completion of actor's satisfaction criteria depending on the status of water resources). For instance, behavioural rules of actors are evaluated weekly according to the status of water resources at the previous time steps, which is computed on a daily basis.

Development of the simulator. The simulator is the computer encoding of the conceptual model. The simulator was developed and implemented with the commercial software Matlab/Simulink © (version 5.3). Matlab/Simulink © is very powerful to built up such a simulator because of its user-friendly graphic interface, graphical language programming ability, and modularity which allowed easy plug-in or plug-out of modules. The simulator links numerically the three socio-economic modules with the three hydrological modules. The simulator was validated against the fully-distributed hydrodynamic model of the area (2798 computing cells of 200 x 200 m) developed by Petit et al. [2001] and Weng et al. [2001] with the finite difference software MARTHE © [Thiéry, 1993].

Definition of scenario and simulations. Information collected through interviews described above was complemented by a review of regional planning documents to define scenario of change in water use patterns in the medium and long term (2010 and 2020). The scenarios include potential increase of water demand, exploitation of karst aquifer to supply growing urban areas, reduction of water use by agriculture, etc. These scenarios are translated into new behavioural rules which can be incorporated in the integrated model; their impact on the status of the hydrosystem and on the satisfaction of other actors can then be simulated using the simulator.

3. INTEGRATED MODEL OF THE HERAULT ALLUVIAL AQUIFER

The integrated model (Figure 1) is composed of three interconnected hydrological modules representing the river, the aquifer and the soil simulating water transfers from one to the others. Rainfall and/or irrigation water enter the soil module that transfer water downwards to the aquifer module, which in turns exchange water with the river module. The **three hydrological modules** are :

- **the river module** is a storage-type model, based on the equation of mass conservation and the storage law of Muskingum that allows to compute discharge in the river. The river is divided in four reaches, each being defined by an upstream and downstream node that correspond to hydraulic discontinuities such as channel junctions (downstream node of reach 2) and singular head loss (reaches 1, 3 and 4).
- **the aquifer module** is based on the Darcy's law to compute groundwater discharge exchanged between adjacent hydrogeological units (north, south, east and west) and/or the river. The simulated area of alluvial aquifer (100 km²) is represented by six hydrogeological units : two units represent the recent alluvial aquifer (alluvial 1 and 2, 2.0 and 3.3 km^2 respectively) while four others represent the terrace aquifers corresponding to ancient alluvial formations (terraces 1 to 4, from 4 to 9 km^2). The groundwater module delivers outputs at the scale of the six hydrogeological units.
- **the soil module** computes a classical water budget from two types of inputs (rainfall and irrigation) and three types of outputs (actual evapotranspiration based upon available soil water capacity and crop coefficient; runoff and infiltration) for three types of soil (gravel cultivated soil, alluvial cultivated soil, and bare soil). The total amount of water supplied by irrigation is driven by the decision rules of each category of farmer which all depend on rainfall amount and soil type.

Economic actors have their own strategies supported by behavioural rules that enable them to modify both water quantity and quality of surface and ground waters. At the current stage of model development, **three behavioural modules** are integrated to portray key water users within the area : the manager of the irrigation canal (actor A), the two categories of farmers (actors B1 and B2) and the canoe renter (actor C).

The irrigation canal manager module (actor A) depicts management rules of the Gignac irrigation canal. The amount of water diverted from the Hérault river is determined by the amount of rainfall of the previous week, the collective requirement of the different categories of farmers and the administrative constraints requiring by law to let a minimum discharge in the river downstream of the canal inlet. Since the irrigation period starts, water uptake is managed under three different rates from 0 (inlet is closed), average rate ($Q=2.5$ m^3/s) and maximum rate ($Q=3.5$ m^3/s).

The farmer module (actor B) considers two types of farmers regarding irrigation practices. Irrigation rules were established through interviews by Augustin [2000]. Farmers B1 irrigate depending on the soil type and the amount of rainfall during the previous week (soil type 1) or one week out of two whatever the amount of rainfall was (soil type 2). Farmers B1 irrigate at a rate of 630 m^3/ha/week and represent 80% of the cropped area. Farmers B2 use low pression pipe systems and irrigate at a rate of only 112 m^3/ha/week whatever the soil type is. Farmers located within the irrigation area have direct access to water irrigation. Farmers located outside the irrigation area may withdraw water directly from the alluvial aquifer and/or from the Hérault river. Irrigation period usually lasts from mid-June to mid-August but may be brought forward whenever soil water content available for crops drops below a given threshold (defined by farmers as part of behavioural rules) and the water gate allowing uptake of water from the Hérault river into the irrigation canal is open. For simulation runs, it is assumed, first that discharge of the irrigation canal is large enough over the irrigation period to fulfil farmer requirements, and second that groundwater is not limited in access for farmers outside the irrigation area.

The canoe renter module (actor C) is based on a criteria of satisfaction, set up by the actor himself, that depends only on the river discharge expressed as a minimum and maximum discharge threshold over the period from June to September that permits to practice canoeing. However, definition of the discharge thresholds is highly subjective and questionable even though estimated by the actor himself because it is more empirical than measured. Actor C solely relies on the water resource without having the possibility to modify it unlike actors A and B.

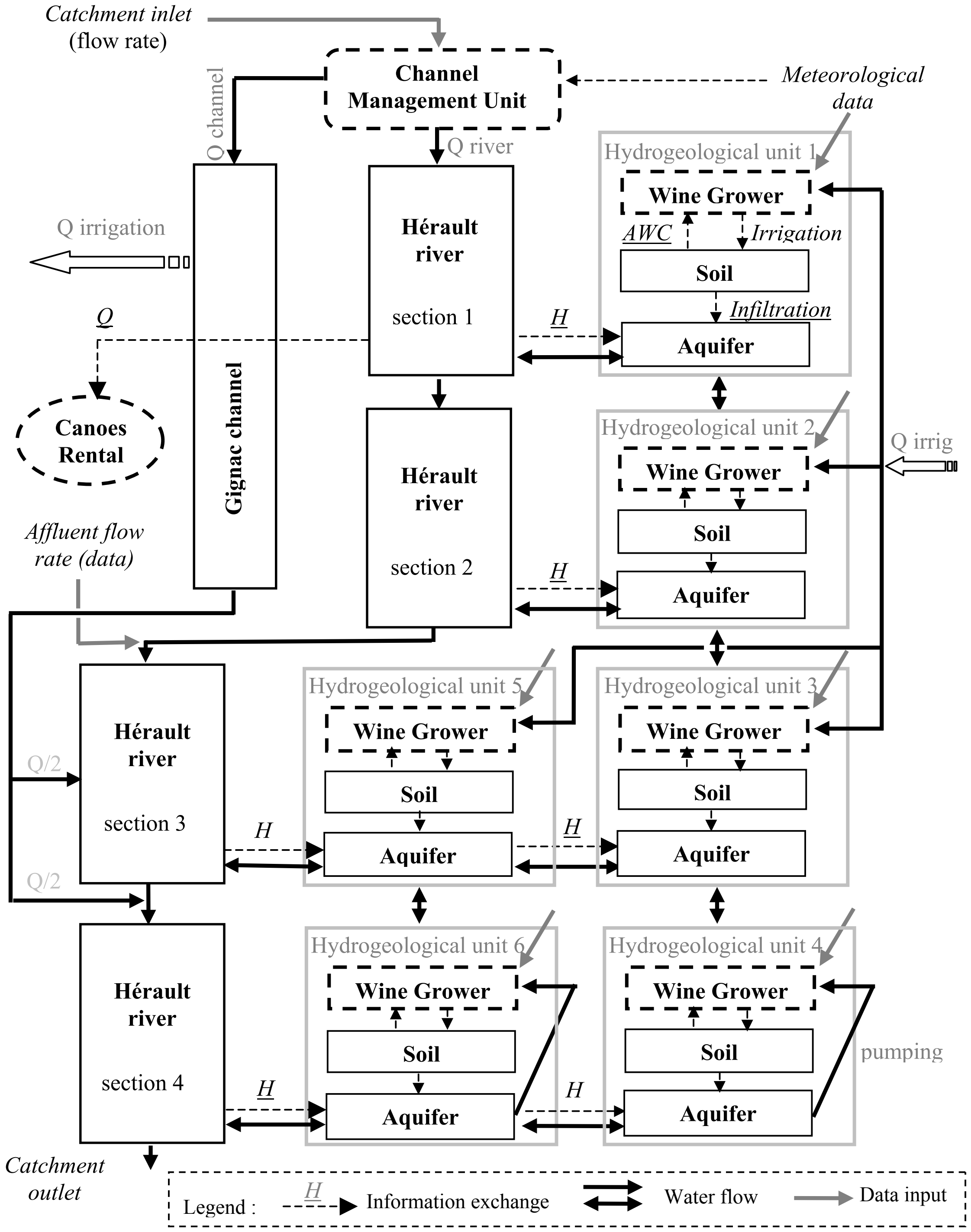

Figure 1. Conceptual diagram of the integrated model of the Hérault alluvial aquifer.

4. NUMERICAL COMPUTATION

4.1. Calibration and validation

Simulations require to set up numerical values of 10 parameters : Muskingum parameters α and k, mean width of the reach and crest elevation of hydraulic structures for the river module; thickness, permeability and storage coefficient for the groundwater module; runoff coefficient, crop coefficient, and maximum available soil water capacity for the soil module. Only the two first parameters, α and k, were calibrated according to El Idrissi and Persoons [1995]. Values of the other parameters have been previously set up either as part of field data collection (i.e., width of river reach, crest elevation) or previous modelling works. Boundary conditions of the model correspond to the river inflow (m^3/s) in reach 1 of the river module; rainfall and PET in each soil module of all hydrogeological units. Initial conditions correspond to the water level in each reach of the river module, groundwater level in each hydrogeological unit of the groundwater module, and the value of the available soil water capacity in each soil module.

First validation of the Matlab simulator is made by calculating the water balance which reaches 0.5% at the end of the simulation period, which corresponds to the current hydrological context and behavioural rules for actors.

The second validation is made by comparing trends of change of piezometric heads computed by the Matlab simulator (in hydrogeological units 1 and 6 as an example) against the finite difference (FD) hydrodynamic model MARTHE. Therefore, outputs of the FD model are set to be the reference data sets (i.e, observed data sets) as the model has been previously calibrated. The hydrogeological unit 1 and 6 correspond to one computing cell of 9,0 km^2 and 3,3 km^2, respectively, while they correspond to 225 and 83 computing cells of the FD model, respectively. Despite the simplified representation of the hydrological units and processes, piezometric heads simulated by the Matlab simulator, which represent the change of average piezometric head over the whole hydrogeological unit at each time step, are on the same trends as the ones computed by the FD model at one or two chosen computing cells.

The third validation is made by comparing river discharge computed by the Matlab simulator and the FD model at the model outlet, that corresponds to the downstream node of river reach 4. Change of river discharge at the model is considered to be a very good indicator of the goodness of fit between the Matlab simulator and the FD model because it integrates several hydrological processes generated far upstream such as flow routing along the three river reaches, river-aquifer flow exchange and lateral inflows caused by excess irrigation water. Again, change of discharge simulated by the Matlab simulator at the model outlet is in good agreement with the simulated discharges from the FD model, resulting in a difference of less than 16 % over the one year-simulation period.

4.2. Scenario simulation

Cumulative impacts of current water resource management (i.e., business as usual scenario) can be explored using the Matlab simulator. Change of inflow rate into the Gignac irrigation canal is compared to the change of water requirements for vineyard irrigation. The latter results from the behavioural rules of farmers as they express themselves during the interviews stage of the study. Computation clearly shows that much more water is diverted from the Hérault river to the canal than required for irrigation practices as they are currently operated by farmers. Indeed, farmers effectively use about 1 m^3/s for irrigation while 2 to 3.5 m^3/s are entering the irrigation canal. The remaining discharge, which varies from 1 to 2.5 m^3/s and is no longer available to the river downstream of the irrigation uptake, may be of the same order of magnitude as the discharge that should be left by law downstream of the canal uptake to ensure environmental functions such as dilution of organic pollution produced by water treatment plants or habitat of good ecological quality for fishes.

Furthermore, such an excessive water uptake despoils other actors such as canoe renter and tourism sector of a natural resource which is providing a growing economic activity at the regional scale. This is of major interest for water resource management of the area because deep rooted conflict already exists related to the sharing of water between farmers, tourism activities and environmentalists. Such an issue would have never been possible to explore in a quantitative way with usual hydrological modelling tools because they do not manage numerically hydrological processes and behavioural rules in an integrated way.

5. CONCLUSION

Compared to simulated outputs of the FD hydrodynamical model MARTHE, results obtained from the Matlab simulator are convincing regarding simulated piezometric heads and river discharges in spite of the quite simple representation of the hydrosystem functioning. On the other hand, the simulator allowed to easily explore economic and social consequences of scenarios (i.e., excessive uptake for irrigation practices) based on behavioural rules depicted by the farmers themselves and numerically translated in the simulator. In that sense, the simulator is seen as a powerful modelling concept to assess correct understanding and mathematical coding of key hydrological processes and behavioural rules of economic actors.

The study demonstrates the great advantages of such an integrated socio-hydrological simulator to explore long-term trends of change within the catchment due to alternative scenarios of economic development or societal expectation. Nevertheless, it is not designed nor used as a deterministic model to predict values with a great spatial and temporal accuracy. Whenever greater accuracy is requested, either in terms of absolute value or location, determinist models may be plugged into the Matlab simulator to refine a given hydrological process or even a whole hydrological module such as river, aquifer or soil module. This would be one of the next steps of the Matlab simulator development along with integration of new actors including environment protection NGO's that may not have quantitative behavioural rules but rather qualitative expectations. Handling quantitative and qualitative variables within the same integrated model architecture is considered as a computational challenge.

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7. REFERENCES

Andreu, J., J. Capilla, and E. Sanchès, AQUATOOL, a generalized decision-support system for water-resources planning and operational management. Jl Hydrol, 269-291, 1996.

Augustin, S., Demande en eau et problématique de modernisation de la rive droite du canal de Gignac : étude de cas sur Gaste fer, StGenies et Tressan. Rapport CEMAGREF, Irrigation R&E N° 2000-19, Montpellier, 66 p, 2000.

Dunn, S.M., R. Mackay, R. Adams, and D.R. Oglethorpe, The hydrological component of the NELUP decision-support system. Jl Hydrol, 213-236, 1996

Fuchey, Y., and P. Lestrat, Modélisation géologique des dépôts plio-quaternaires de la basses vallée de l'Hérault. Rapport BRGM-RP-50770-FR, 2001.

Garin, P., J.D. Rinaudo, and J. Ruhlmann, Linking expert evaluations with public consultation
to design water policy at the watershed level. Second World Water Congress, Berlin, Germany, 15-18 October, 2001.

El Idrissi, A., and E. Persoons, MHM : le modèle hydrologique maillé. Actes de l'Atelier International « Télédétection et Ressources en Eau », 30 nov.-1 déc. 1995, Montpellier, 1995.

Jamieson, D.G., and K. Fedra, The "WaterWare" decision-support system for river-basin planning. Jl Hydrol, 163-213, 1996.

Lanini, S., J.D. Rinaudo, and V. Petit, Modèle socio-hydrologique global de la moyenne vallée de l'Hérault. Rapport BRGM/RP-50872-FR, 56 p., 2001.

Parker, P., R. Letcher, A. Jakeman, M.B. Beck, G. Harris, R.M. Argent, M. Hare, and C. Pahl-Wostl, Progress in integrated assessment and modelling. Env. Modelling and Software, 17 : 209-217, 2002.

Reitsma, R.F., Structure and support of water-resources management and decision-making. Jl Hydrol, 253-268, 1996.

Rinaudo, J.D., V. Petit, F. Giraud, and N. Courtois, A methodology to explore alternative water management scenarios : example of the middle Hérault valley. Rapport BRGM/RP--FR. Orléans, 2002 (in press).

Thiéry, D., Manuel d'utilisation du logiciel MARTHE, Vol. 1. BRGM R 32210, 1993.

Weng, P., E. Petelet-Giraud, A. David, H. Mathieu, L. Aquilina, B. Ladouche, F. Giraud, J. Cubizolles, and J.L. Izac, Couplage des outils hydrologiques et géochimiques appliqué à l'étude du fonctionnement de la plaine alluviale de l'Hérault. Contrat de Plan Etat-Région 1994-1998. Rapport BRGM RP-51126.FR, 127 p., 2001