MoGIRE: A Model for Integrated Water Management

Arnaud Reynaud[*] and Delphine Leenhardt[†]

April 15, 2008

Abstract

In a context of water scarcity where competition for water allocation is increasing, modelers are often asked to move from specific water use models (either agricultural, industrial or residential) toward more integrated frameworks including an explicit representation off water users relationships. This is the main objective of MoGIRE ("**Mo**dèle pour la **G**estion **I**ntégrée de la **R**essource en **E**au") which is a model for integrated water management at the river basin level, allowing to optimize water use under several possible scenarios (agronomic, climatic or economic). MoGIRE includes a nodal representation of the water network. Agricultural, urban and environmental water uses are also represented in MoGIRE using mathematical programming and econometric approaches. The model then optimizes at each date the allocation of water across agricultural and urban water demands in order to maximize the social surplus derived from water consumption given the constraints imposed by the water network. An application of the model is proposed for the Neste system located in South-West of France.

Keywords : Integrated water management, optimization-simulation model, agronomic-economic modeling, river basin.

---

[*] Toulouse School of Economics, LERNA-INRA, areynaud@toulouse.inra.fr

[†] UMR1248 INRA-INSAT AGIR, Delphine.Burger-Leenhardt@toulouse.inra.fr

1 Introduction

Climate change and growing water needs have resulted in many parts of the world in water scarcity problems that must by managed by public authorities. Hence, policy-makers are more and more often asked to define and to implement water allocation rules between competitive users. This requires to develop new tools aiming at designing those rules for various scenarios of context (climatic, agronomic, economic). Models have been developed for each type of water use (see for instance Dalhuisen, Florax, deGroot, and Nijkamp (2003) for a survey of residential water demand models or Couture and Bontemps (2002) for a model of agricultural water demand). However, very few models link these different uses in the context of a particular area, while such an integrated approach is a relevant stake for designing regional water and land policies.

The lack of such integrated models can be explained by the difficulty of integrating models developed by very different disciplines and by the problem of scale change (collecting data on large area, arbitrate between the computational tractability of models and their level of aggregation). However, modelers are more and more asked to deal with large basin scales while analyzing some policy impacts at very high detailed levels. These contradicting objectives require to develop new modeling tools. The CALVIN economically-driven optimization model developed for managing water in California is a good example of this type of framework, Draper, Jenkins, Kirby, Lund, , and Howitt (2003). Cai, McKinney, and Lasdon (2002) and Cai, McKinney, and Lasdon (2003) propose another integrated water management model for the Syr Darya Basin (Central Asia). Recent reviews of the literature on integrated water management at the basin level include Cai, Rosegrant, and Ringler (2003), Letcher, Croke, and Jakeman (2007) or Cai (2008).

We present here an original framework for integrated water management at the river basin scale called MoGIRE ("**Mo**dèle pour la **G**estion **I**ntégrée de la **R**essource en **E**au"). MoGIRE is an integrated framework, currently under development by an interdisciplinary team within the APPEAU project (2007-2010) funded by the French National Research Agency within the "Agriculture and Sustainable Development" program. It is intended to optimize water use at the river basin level and to evaluate scenarios (agronomic, climatic or economic) for a better planning of agricultural and non-agricultural water use. In specific contexts such as in South-West France, water scarcity occurs during the summer when agricultural water needs and urban needs are maximum. Besides, water demand greatly varies within the water basin, with sub regions having competitive uses. Consequently MoGIRE accounts for such intra-annual conflicts and for the spatial heterogeneity of the water basin.

The remaining of the paper is organized as follows. In the next section, we present the integrated river basin model and we describe its main components. In the following section, we provide an empirical application to the Neste system (South-West of France). We conclude by summarizing our findings.

2 Architecture of MoGIRE

MoGIRE may be viewed as a multi-use water allocation model with an explicit representation of the water network at the river basin level.

2.1 Representation of the river basin

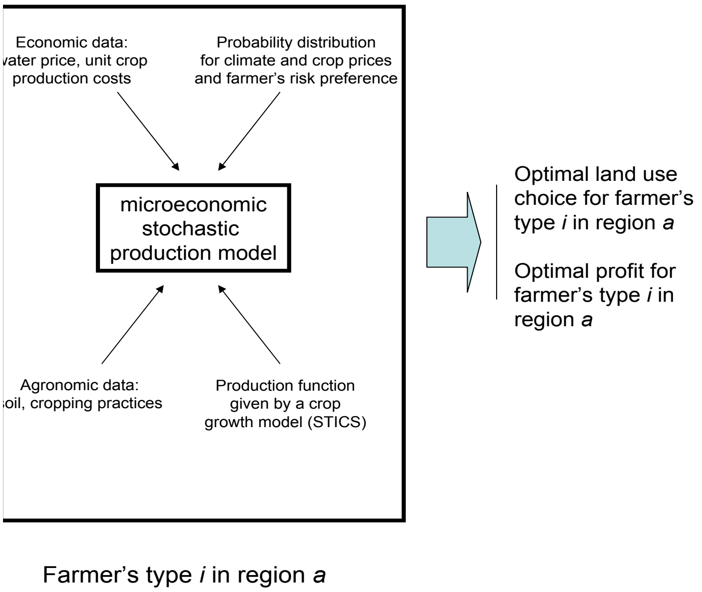
A river basin includes the network of the river and its tributaries, the land of the river catchment, and all related land and water users. Because the river basin is large and the users are numerous, we need a simplified representation of this complex system. Following Cai, Rosegrant, and Ringler (2003) or Cai, McKinney, and Lasdon (2003), it is possible to view the water network as network objects (reservoirs, pumping nodes and confluence nodes) connected by some links (rivers, canals). This nodal network representation is a common framework for considering water allocation in river basins, Letcher, Croke, and Jakeman (2007). In this type of representation, water users interact with the stream system in two ways, Letcher, Croke, and Jakeman (2007). First, they may affect the generation of runoff and thus the volume of water reaching the stream. Second, they may involve direct extraction or use of water once it has reached the stream. We mainly focus here on this second type of interaction between water uses and the water network.

We used a nodal representation of the river network with a division of the catchment area into regions (see Figure 3 for a presentation of the Neste river basin where the model has been implemented). In rural areas, agriculture is the main water user. This is why we identified the regions using soil, climate and hydrological criteria. The methodology is fully described in Clavel and Leenhardt (2008) and resulted in A regions indexed by $a = 1, \ldots, A$. In these regions, water uses (agricultural, domestic and industrial) must then be modeled.

2.2 Representation of agricultural water demands

The first step of the analysis has been to characterize farmers located within each region $a = 1, \ldots, A$. Some GIS regional data on soil, climate and hydrology have been used. Agricultural regions are then characterized by specific cropping systems, climate conditions, soil characteristics, economic conditions (available agricultural area (in ha), number of farmers, crop prices,

Figure 1: Agricultural production model for farmer's type i in region a



etc.). Moreover, each agricultural region is connected to the water network through one or several nodes. Water allocated to any agricultural region allows to produce crops which generates a net profit that will be optimized by the social planner.

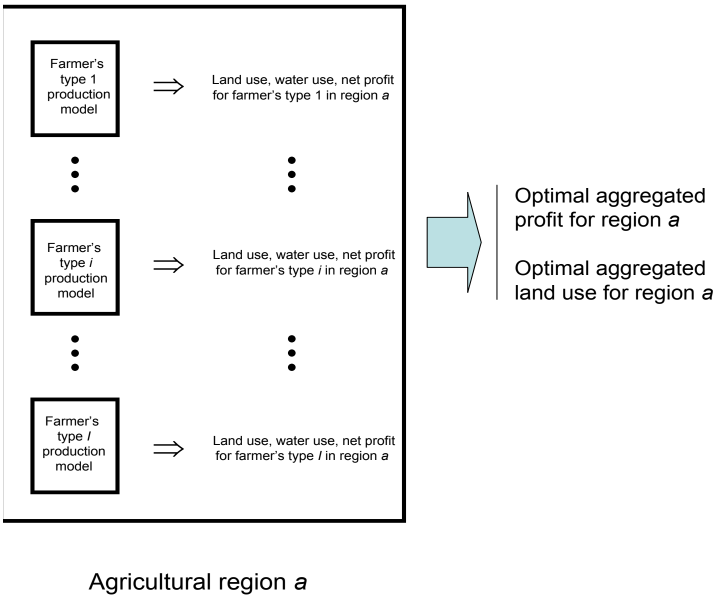
The second step of the analysis has been to build for each region an agricultural production model allowing to derive the net profit from water use.

- Since Maton, Leenhardt, Goulard, and J.-E. (2005) and Maton, Leenhardt, and J.-E. (2007) have shown that, at a regional scale, easily accessible farm characteristics could be good indicators of farmers' practices, we first have build, for the whole area, a typology of farmers. Following Clavel and Leenhardt (2008), the typology is based on farm size, cropping systems and irrigation intensity. This typology has allowed us to identify I farmer types we will index by $i = 1, \ldots, I$.

- Second, statistical agricultural databases gave us the number of farmers of each type in each region. The number of farmers of type i in region a is denoted by n_{ai}.

- Third, we have developed an individual production model in order to represent the behavior each farmer type i in each region a, see Figure 1. This individual model incorporates a risk linked to climate uncertainty and impacting land use decisions of farmers. These decisions are : allocating the available land across all possible crops (land use choices), choosing a sowing date for each crop (sowing date choices) and finally allocating for each crop at

Figure 2: Agricultural production model for region a



each date of the growing season the available water (water use choices). We assume that a farmer takes these decisions in order to maximize its expected utility of profit. This individual production model is presented in details in Reynaud (2008). Notice that the agricultural production functions used in the model are derived from the STICS biophysical model of crop growth, see Brisson, Mary, Ripoche, Jeuffroy, Ruget, Nicoullaud, Gate, Devienne-Barret, Antonioletti, Durr, Richard, Beaudoin, Recous, Tayot, Plenet, Cellier, Machet, Meynarda, and Delécolle (1998). This crop growth model allows to characterize the relationships between agricultural water use and crop yields.

– Lastly, using the number of farmers n_{ai}, we aggregated the production outcome for all types of farmer within a given region to get regional land uses and regional net profit, see Figure 2.

2.3 Representation of urban water demands

The first step of the analysis has been to characterize urban water consumers (domestic and industrial users) located within each region $a = 1, \ldots, A$. The characterization of urban water consumers is based on socioeconomic data from various sources including population census and water agency files. Those regions are defined, in particular, by their size (number of households) and by the socioeconomic characteristics of households (income, age, housings, etc). All the urban water demands are connected to the water network through one or several nodes.

Economists have developed frameworks for estimating the value for urban water consumption. Typically, this value corresponds to the marshallian surplus which can be derived from the urban water demand function. Hence, estimating the value for urban water consumption in each region requires first to estimate urban water demand functions, see Garcia and Reynaud (2004). Dalhuisen, Florax, deGroot, and Nijkamp (2003) have conducted a meta-analysis on residential water demand based on 51 published articles. They report that 20 articles provide estimates of price and income elasticities based on a logarithmic demand function (either semi or double logarithmic). Following this previous literature (see also Nauges and Thomas (2000)), we assume that the water demand function in a given urban region can be approximated by a log-log form. Denoting by $\hat{Y}_a$ the daily water consumption of the representative residential water user in region a, we have:

$$\ln \hat{Y}_a = C_a + \sum_l \alpha_l \cdot \ln \mathbf{X}_{la} + \beta \cdot \ln p_a \tag{1}$$

where C_a is a constant, $\mathbf{X}_{la}$ represents a vector characterizing the residential water users and determining the water consumption (characteristics of households, income, housings, climate, etc), p_a is the peak period unit water price and β is the price elasticity of the urban water demand which is assumed to be negative. To estimate the parameters of the urban water demand function (Equation 1), we used various sources of data including population census and water agency files.

Having estimated the urban water demand function, we can compute the daily consumer surplus (CS_a) resulting from water consumption in region a. Then, we can compute the variation in urban consumer surplus due to a change in the water price from p to p' in region a. We denote it by $\Delta CS_a(p, p')$. Since the consumer's surplus is, by definition, measured by the area under the Marshallian demand curve, the change in daily consumer surplus following a change in the water price from p to p' is given by (see Strand and Walker (2003)):

$$\Delta CS_a(p, p') = \frac{1}{1+\beta} p' \hat{Y}_a(p') \Big[\Big(\frac{p}{p'} \Big)^{1+\beta_p} - 1 \Big]. \tag{2}$$

2.4 Representation of environmental water demands

Freshwater ecosystems need certain water flow regimes to sustain their animal and plant communities. This environmental water demand, allowing for instance to provide critical habitat for endangered species, increases the competition for water among users especially during the summer season. There is however no consensus on the economic value to be attributed to the environmental water demands. As a result, we have decided to introduce the use of water for environmental purpose as a set of flow constraints that must be satisfied at specific nodes of the water network and at specific periods (typically during the summer). This approach allows us to get the dual variables associated to these flow constraints. In other words, this approach allows us to measure the social cost for all water users from imposing these environmental water flows constraints.

2.5 The river basin water allocation problem

The model, including the representation of the water network, has been coded using the algebraic modeling language GAMS, see Rosenthal (2008). GAMS is a high-level modeling system for mathematical programming and optimization. MoGIRE then allocates water across uses within a region and across competitive regions. The water is allocated to maximize the agricultural and urban economic value resulting from water use at each time within the year. This pursuit of economic objectives (aggregated social surplus resulting from water consumption) is then limited by water availability, water network characteristics, and minimum flow constraints.

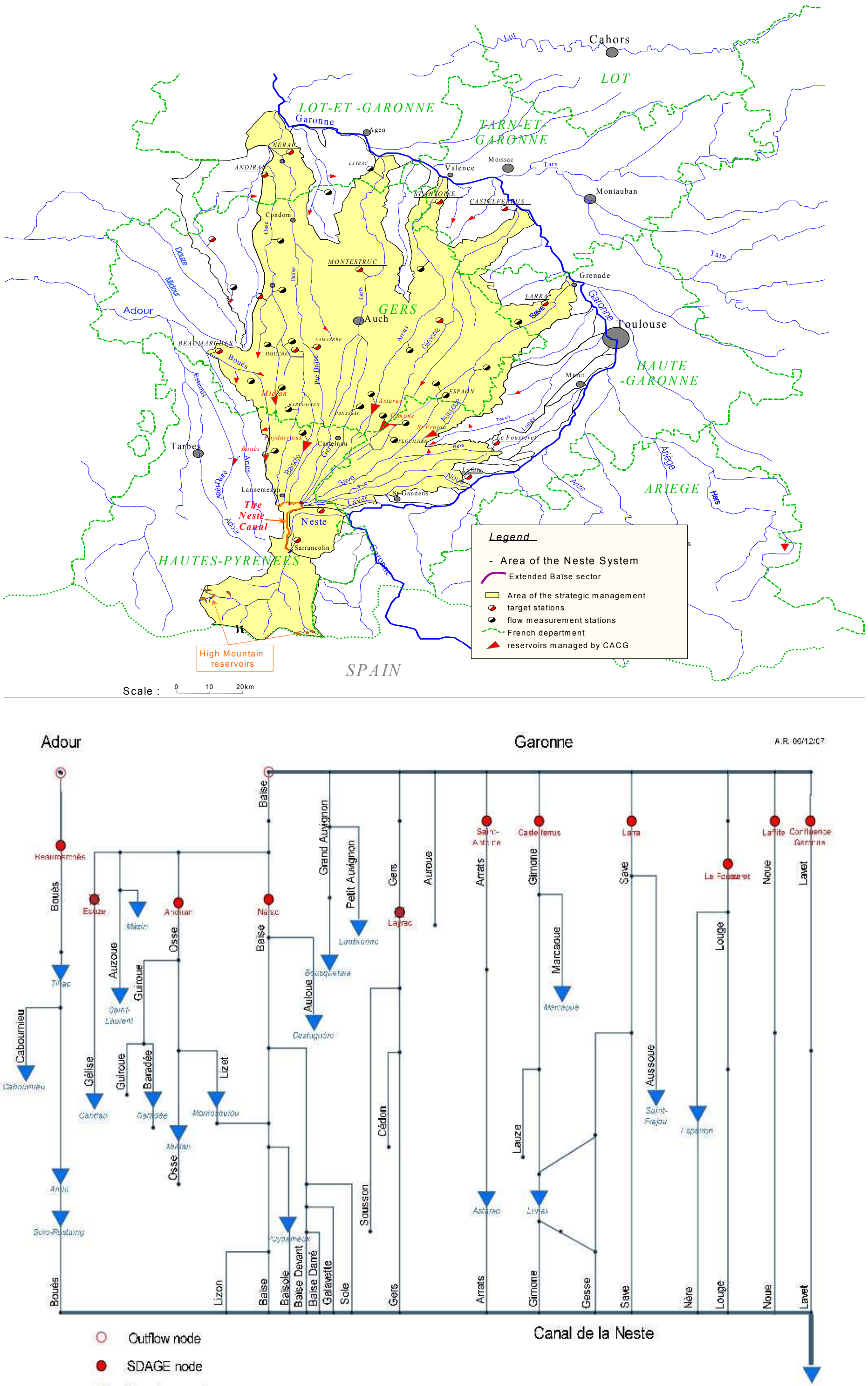
3 Application of MoGIRE to the Neste System (France)

3.1 The Neste system

Within the APPEAU project, MoGIRE is currently applied on the Neste system located in South-West of France, see Figure 3. The Neste system is a system of rivers artificially recharged by upstream reservoirs located in the Pyrenees mountain through a single canal, the Neste canal. The Neste system covers 800,000 ha area and gathers the catchment areas of 14 main rivers. The land is mainly dedicated to agriculture (500,000 ha are cultivated from which 50,000 ha are irrigated).

This system has been chosen for application of MoGIRE first because it is managed by a single operator, the Compagnie d'Aménagement des Coteaux de Gascogne (CACG) and second, since there are significant water scarcity issues in that area that make the development of an integrated water management model relevant. For instance, the relationship between the CACG and farmers is defined by a contract. This contract specifies first, a discharge rate and second, a quota associated to each unit of discharge rate (l/s) subscribed by a farmer. Given the current price for the discharge rate, the demand of discharge rates by farmers exceeds the flow capacity of the system. The CACG must then manage a waiting list for quota allocation.

Figure 3: The Neste system (France) and its nodal representation

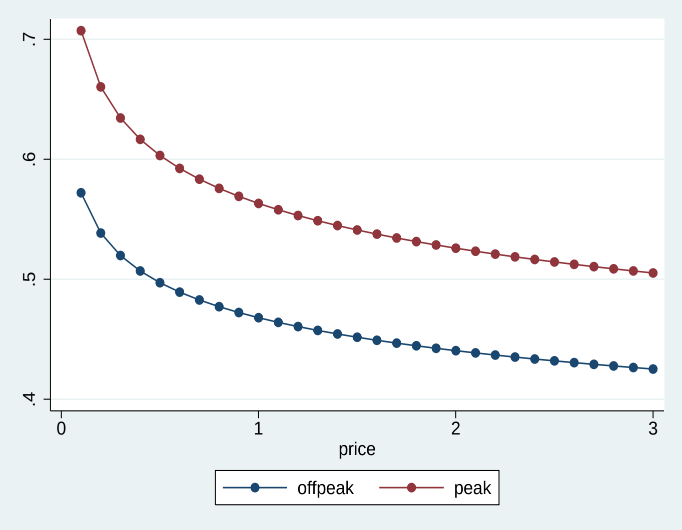


3.2 The representation of water demands

The regions have been defined as the intersection between CACG management units and Small Agricultural Regions (SAR), Clavel and Leenhardt (2008). CACG management units are used by the operational water manager to optimize water releases between different rivers. The SARs, defined by the National Institute for Statistics and Economic Studies, are mainly based on a soil and climatic conditions homogeneity criterion. As a result, 67 regions have been identified in the Neste system. Those regions are characterized by specific cropping systems, specific climate and soil characteristics and by their connections to the water network.

601 local communities are located within the Neste system. The local communities have been aggregated in order to represent urban water consumers in each of the 67 region. Data used for estimating the residential water demands come from various sources including population census and water agency files based on local communities declarations. The dataset we have used covers 3 years, 1998, 2001 and 2004. In Figure 4, we have represented the estimated daily urban water demand functions for the peak (summer) and the off-peak seasons from which residential water surplus have been computed.

Figure 4: Estimated water demand function in m^3 day^{-1} for peak and off-peak seasons (average urban user)



Concerning the environmental water demands, we have made the distinction between two minimum flow levels: the Crisis Minimum Flow (CMF) and the Target Minimum Flow (TMF). The CMF (in French, débit de crise) defines the minimum flow under which biological life is not possible. When the water flow is lower than CMF, no irrigation is allowed. The TMF (in French, débit objectif d'étiage) defines the water flow level above which biological life is not constrained. When the water flow is greater than TMF, irrigation is not limited.

The model then optimizes at each date the allocation of water across agricultural and urban water demands in order to maximize the social surplus derived from water consumption. MoGIRE also allows to simulate various agronomic, climatic or economic scenarios on the Neste system.

4 Conclusion

We have presented an original framework for integrated water management at the river basin. This model, called MoGIRE, includes a nodal representation of the water network. Agricultural, urban and environmental water uses have been modeled using mathematical programming and econometric approaches. MoGIRE then optimizes water use at the river basin level and allows to evaluate scenarios (agronomic, climatic or economic) for a better planning of agricultural and non-agricultural water use.

The model has been applied to the Neste system in Southwest of France. All the agricultural and the urban water demands have been identified and the whole model, including the nodal representation of the water network, has been coded using the algebraic modeling language GAMS. We are currently analyzing the robustness of the approach through scenario testing. The next step of the analysis will be to characterize the optimal allocation of water across competitive water users at each point of the network and at each date of the year.

Finally, we plan to evaluate several scenarios using MoGIRE (agronomic, climatic or economic). For instance, a relevant economic scenario could be a move toward peak-load pricing. The rational for implementing peak-load water pricing in an integrated river basin framework is that the value of water is likely to vary according the period of the year. In particular, it is likely that the social value is higher during the summer where the high competition across water users might result in scarcity rents. Peak-load pricing could then be used by the water network operator in order to send scarcity signals to water consumers. Agronomic scenarios may include the introduction of new crop varieties more resistant to water stress or the introduction of new cropping practices (e.g. early sowing of early maize varieties Lorgeou, Bouthier, Renoux, and Cloute. (2006), replacing maize by sorghum (Amigues, Debaeke, Itier, Lemaire, Seguin, Tardieu, and Thomas (2006)), etc.). Lastly, since weather conditions are introduced as determinants of agricultural and urban water demand models, some scenarios of climate change may be tested (e.g. SRES scenarios (Terray and Braconnot (2007)). Agronomic scenarios may include the introduction of new crop varieties more resistant to hydric stress or the introduction of new cropping practices. Lastly, since weather conditions are introduced as determinants of agricultural and urban water demand models, some scenarios of climate change may be tested.

Acknowledgments

This work is a part of the project APPEAU funded by the program "Agriculture and Développement Durable" from the Agence Nationale pour la Recherche (ANR). The authors gratefully acknowledge support from the ANR grant that has made this work possible. We also thank the French Water Agency Adour-Garonne for making available water data.

References

Amigues, J.-P., P. Debaeke, B. Itier, G. Lemaire, B. Seguin, F. Tardieu, and A. Thomas (2006): “Sécheresse et agriculture. Réduire la vulnérabilité de l’agriculture à un risque accru de manque d’eau. Expertise scientifique collective,” Expertise scientifique collective, Rapport, INRA (France), 380 pages + annexes.

Brisson, N., B. Mary, D. Ripoche, M. H. Jeuffroy, F. Ruget, B. Nicoullaud, P. Gate, F. Devienne-Barret, R. Antonioletti, C. Durr, G. Richard, N. Beaudoin, S. Recous, X. Tayot, D. Plenet, P. Cellier, J.-M. Machet, J. M. Meynarda, and R. Delécolle (1998): “STICS: a generic model for the simulation of crops and their water and nitrogen balances. 1. Theory and parameterization applied to wheat and corn,” *Agronomie*, 18, 311–346.

Cai, X. (2008): “Implementation of holistic water resources-economic optimization models for river basin management - Reflective experiences,” *Environ. Model. Softw.*, 23(1), 2–18.

Cai, X., D. McKinney, and L. Lasdon (2003): “An Integrated Hydrologic-Agronomic-Economic Model for River Basin Management,” *Journal of Water Resources Planning and Management*, 129(1), 4–17.

Cai, X., D. C. McKinney, and L. S. Lasdon (2002): “A framework for sustainability analysis in water resources management and application to the Syr Darya Basin,” *Water Resources Research*, 38, 21–1.

Cai, X., M. Rosegrant, and C. Ringler (2003): “Physical and Economic Efficiency of Water Use in the River Basin: Implications for Efficient Water Management,” *Water Resources Research*, 39(1), 1013.

Clavel, L., and D. Leenhardt (2008): “Development of matrices to build scenarios of cropping systems distribution for integrated catchment assessment. A proposition for an irrigated area in south-western France,” Mimeo, UMR1248 INRA-INSAT AGIR.

Couture, S., and C. Bontemps (2002): “Irrigation water demand for the decision maker,” *Environment and Development Economics*, (7), 643–657.

Dalhuisen, J., R. Florax, H. deGroot, and P. Nijkamp (2003): “Price and Income Elasticities of Residential Water Demand: A Meta-Analysis,” *Land Economics*, 79, 292–308.

Draper, A., M. Jenkins, K. Kirby, J. Lund, , and R. Howitt (2003): “Economic-Engineering Optimization for California Water Management,” *Journal of Water Resources Planning and Management*, 129(3), 155–164.

Garcia, S., and A. Reynaud (2004): “Estimating the Benefits of Efficient Water Pricing in France,” *Resource and Energy Economics*, 26(1), 1–25.

Letcher, R. A., B. F. W. Croke, and A. J. Jakeman (2007): “Integrated assessment modelling for water resource allocation and management: A generalised conceptual framework,” *Environ. Model. Softw.*, 22(5), 733–742.

Lorgeou, J., A. Bouthier, J.-P. Renoux, and G. Cloute. (2006): “Stratégie d’évitement en maïs grain dans le Centre ouest. Adapter le cycle aux contraintes hydriques par la précocité?,” *Perspectives agricoles*, mars, 62–67.

Maton, L., Leenhardt, and B. J.-E. (2007): “Geo-referenced indicators of maize sowing and cultivar choice for better water management,” *Agronomy for Sustainable Development*, 27(3), 377–386.

Maton, L., D. Leenhardt, M. Goulard, and B. J.-E. (2005): “Assessing the irrigation strategies over a wide geographical area from structural data about farming systems,” *Agricultural Systems*, 86, 293–311.

Nauges, C., and A. Thomas (2000): “Privately-operated Water Utilities, Municipal Price Negotiation, and Estimation of Residential Water Demand: The Case of France,” *Land Economics*, 76(1), 68–85.

Reynaud, A. (2008): "Agricultural land allocation and intra-annual optimization of agricultural water use under climate and price uncertainty," Mimeo, LERNA-INRA, University Toulouse 1.

Rosenthal, R. E. (2008): *GAMS: A user's guide.* GAMS Development Corporation, Washington DC, USA.

Strand, J., and I. Walker (2003): "The value of water connections in Central American cities: A revealed preference study," Discussion paper, University of Oslo, http://folk.uio.no/jostrand/watervaluepaper.pdf.

Terray, L., and P. Braconnot (2007): "Livre Blanc ESCRIME. étude des Scénarios Climatiques Réalisés par l'IPSL et Météo-France," Miméo IPSL and Météo-France, 70 pages.