Critical multi-level governance issues of integrated modelling: An example of low-water management in the Adour-Garonne basin (France)

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SUMMARY

This paper presents the experience gained related to the development of an integrated simulation model of water policy. Within this context, we analyze particular difficulties raised by the inclusion of multi-level governance that assigns the responsibility of individual or collective decision-making to a variety of actors, regarding measures of which the implementation has significant effects toward the sustainability of socio-hydrosystems. Multi-level governance procedures are compared with the potential of model-based impact assessment. Our discussion is illustrated on the basis of the exploitation of the multi-agent platform MAELIA dedicated to the simulation of social, economic and environmental impacts of low-water management in a context of climate and regulatory changes. We focus on three major decision-making processes occurring in the Adour-Garonne basin, France: (i) the participatory development of the *Master Scheme for Water Planning and Management* (SDAGE) under the auspices of the Water Agency; (ii) the publication of water use restrictions in situations of water scarcity; and (iii) the determination of the abstraction volumes for irrigation and their allocation. The MAELIA platform explicitly takes into account the mode of decision-making when it is framed by a procedure set beforehand, focusing on the actors' participation and on the nature and parameters of the measures to be implemented. It is observed that in some water organizations decision-making follows patterns that can be represented as rule-based actions triggered by thresholds of resource states. When decisions are resulting from individual choice, endowing virtual agents with bounded rationality allows us to reproduce (*in silico*) their behavior and decisions in a reliable way. However, the negotiation processes taking place during the period of time simulated by the models in arenas of collective choices are not all reproducible. Outcomes of some collective decisions are very little or not at all predictable. The development and simulation of *a priori* policy scenarios capturing the most plausible or interesting outcomes of such collective decisions on measures for low-water management allows these difficulties to be overcome. The building of these kind of scenarios requires close collaboration between researchers and stakeholders involved in arenas of collective choice, and implies the integration of the production of model and the analysis of scenarios as one component of the polycentric political process of water management.

1. Introduction

Current water governance practices are challenged by a growing number of pressures suffered by socio-hydrosystems. Among these, we could point out: (a) current and potential impacts of climate change on the availability and accessibility of water resources (Arnell, 2004; Bates et al., 2008; Frederick 2001; Vörösmarty et al., 2000); (b) impacts of land use and land use changes on the water

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cycle (Bhaduri et al., 2000; Elfert and Bormann, 2010; Hulse et al., 2004; IAASTD, 2009; Narcy, 2004); (c) human pressure, especially when dealing with increased water withdrawals for competing uses (Berndes, 2002; Murray-Hudson et al., 2006; Rosenzweig et al., 2004; Strzepek and Boehlert, 2010; Weiß et al., 2009); (d) implementation of public policies for protection or restoration of aquatic ecosystems (Haasnoot et al., 2011); and (e) the emergence and strengthening of participatory modes of management of public goods (Huitema et al., 2009). Even if climate change is a key driver in the availability of water resources, in some regions, socio-demographic, economic or technological changes can have a larger effect (Vörösmarty et al., 2000; Strzepek and Boehlert, 2010; Moss et al., 2010). With the increased risk of drought and water shortage, the development of structural measures used to support low-water management has grown in recent decades.

To design and implement water policy, demands for integrated and adaptive water resource management are progressively raised (Engle et al., 2011; Pahl-Wostl, 2007). Integrated modelling can simultaneously take into account most of the dimensions related to the issues of resource management (Jakeman et al., 2006). Integrated models that simulate the quantitative aspects of water system dynamics can be implemented as decision-support tools for policy building and managing natural resources within river basins by assessing various societal, hydrological and environmental effects of different scenario-based alternatives (Alcamo et al., 2000; Mahmoud et al., 2009; March et al., 2012). However, the modelling of water management presents a series of difficulties, especially related to the understanding and formalization of the decision-making process in multi-level governance systems (Pahl-Wostl et al., 2010). Following the pioneering analysis of Rittel and Webber (1973) concerning "*wicked problems*" of planning and governance in open social systems, we adopt a critical posture in our analysis and modelling practices as they deal with complex issues involving high stakes, with a high degree of uncertainty and with diverging perspectives on values and facts (Funtowicz and Ravetz, 1993).

With this in mind, the goal of this paper is to tackle the challenges of integrating various kinds of decision-making processes related to multi-level governance in water management modelling. As a starting point (Section 2), the organization of multi-level governance for low-water management in France is described, using the Adour-Garonne basin (South-West of France) as a case study. In Section 3 we discuss the potential of integrated modelling as means to deal with water management issues. Key studies based on modelling performed in the Adour-Garonne basin are briefly introduced and the modelling of two contrasting types of decisions is illustrated: (a) decisions that are akin to actions based on rules; and (b) decisions that involve bounded rationality of virtual agents. Section 4 highlights the importance of the negotiation processes occurring within collective-choice arenas in the effectiveness of water management in France. Then, we discuss critical issues and limits of integrated modelling to represent the collective decision-making processes induced by multi-level governance. Next, in Section 5, we describe how to deal with these limits, endorsing the use of policy scenarios to capture *a priori* non-predictable outcomes of several participatory decision-making processes. Finally, the main precautions that we think need to be taken in order to exploit integrated modelling as a component of decision-making processes for water management are briefly discussed in Section 6, at the risk of 'opening Pandora's box' of persistent controversies. Conclusions are drawn in Section 7.

2. Low-water multi-level governance in France

Several syntheses presenting the legal and administrative organization of water policy in France have been produced recently (Council of State, 2010; Gazzaniga et al., 2011) as well as evaluation reports of various aspects of water management (financing of water policy: Commissioner-General for Sustainable Development, 2011; instruments for the sustainable management of water: Court of Auditors, 2010; public services of water management and sanitation: Barucq et al., 2010, etc.). Table 1 provides an overview of the main legal instruments involved in the quantitative management of water in France. Each governance level relies on a specific variety of actors that may include end-users, managers of infrastructures, public and private companies, State services, associations, and local authorities (county, municipality). These actors are involved in management procedures of particular events, such as scarcity or "low-water" and floods, and in other issues such as water pricing, construction or maintenance of reservoirs.

In France, since the so-called "second law on water" in 1992, water management strategies and policies are designed at prime-order river basin level through participatory procedures. In these river basins, three main institutional levels and corresponding low-water management policies exist, as explained below.

2.1. Basin or sub-basin level: structural measures for low-water management

The Adour-Garonne basin is the basin with the largest water structural deficit in France. This river basin encompasses numerous irrigated farming systems that consume up to 80% of the total anthropic water consumption during the low-water period. In France, the Master Scheme for Water Planning and Management (SDAGE[1]) of each basin, approved by the Basin Committee and enacted at the basin level in the case of the Adour Garonne by the Adour Garonne Water Agency (SDAGE AGB, 2010), defines the general rules to manage water deficit within sub-basins and the main policy measures to pursue sustainable water management (e.g. premiums for increasing water use efficiency; construction of dams, financial resources for supporting studies about hydrosystems functioning, etc.) and ensuring that 60% of water masses will reach the objective of good water status by 2015 in accordance with the European Water Framework Directive (EU WFD) (2000) and the *Loi sur l'eau et les milieux aquatiques* (Law on water and aquatic environments) (LEMA, 2006). The SDAGE is endowed with a strong legal power to impose that any program or administrative decision to be compatible with its provisions in the field of water (Environmental Code, art. L212-1), and in policy domains impacting water resources (territorial coherence schemes, local urban planning, agricultural policy, etc.). Regarding low water management it defines the general orientations for the management of water resources and water demands. More particularly, it fixes, for a given number of strategic hydrological sites (64 sites in the Adour-Garonne basin) two regulatory flow levels: the *objective low-water flow* (DOE[2]) corresponding to the minimum flow that ensures locally the good functioning of aquatic environment and should be respected 8 years out of 10, and the *crisis flow* (DCR[3]) corresponding to the level under which the supply of drinking water for basic needs and the survival of the aquatic species are in danger.

The SDAGE AGB (2010) was developed in a participatory manner by seeking the opinions of a wide variety of actors: in 2008 a public consultation of citizens was conducted to gather their opinions on the draft adopted by the Basin Committee in 2007 and previously developed since 2002 by the Adour-Garonne Planning Commission assisted by various territorial commissions, local technical secretariats, local water forums, and the Technical Secretariat

[1] SDAGE: Schéma Directeur d'Aménagement et de Gestion de l'Eau.
[2] DOE: Débit d'objectif d'étiage.
[3] DCR: Débit de crise.

Table 1
Main instruments of the legal system of water management in France.

Short name	Identification [scale of application]	Main focus
WFD 2000	Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy *[European]*	Good status for all waters to be achieved by Member States in 2015. Introduces the principle of preserving aquatic environments as part of the resource management by Member States. Transposed into French law by Law No. 2004-338 of 21 April 2004
	Law No. 64-1245 of 16 December 1964 *[National]*	Rules and the distribution of water and the fight against pollution. Organizes water management at the level of river basins
	Law No. 92-3 of 3 January 1992 on water *[National]*	Balanced management of water resources taking into account the various uses and their impacts, the development, protection and distribution of this economic resource. Ensures the preservation of aquatic environments and wetlands
LEMA (2006)	Law No. 2006-1772 of 30 December 2006 on water and aquatic environments *[National]*	Combines the balanced management with the resource sustainability, including consideration of risks posed by climate change. Modifies the procedure for allocation of water available for irrigation
SDAGE	Master Scheme for Water Planning and Management *[Basin-scale]*	Guidelines for the 5-year management of water. In the AGB, the SDAGE AGB (2010) includes provisions relative to the management of low-water given the importance of this issue for the farmers and for the managers of dams. It is accompanied by a program of measures which establishes the use of financial resources for the operational implementation of priority actions
SAGE	Water Planning and Management Schemes *[Sub-basin scale]*	Takes into account local specific priority issues for implementation of the SADGE
PGE	Low-Water Management Plans *[Sub-basin or local scale]*	They specify how to keep or reach again the objective low-water flows. The content of such a plan describes in an operational way the balance between aquatic environments and uses, and clarifies the management rules and the commitments of involved partners

of the basin. The opinion of the institutional partners – nearly 2300 people or structures were consulted: Regions, Departments, economic and social councils, Chambers of Commerce, Public Territorial Basin Institutions, major cities, geographical commission members, mayors, etc. – already sought in 2004, was asked for again in 2009 and led to the final version of the document (currently in force) adopted by the Basin Committee on November 16, 2009. However, this presentation of the procedure only partially reflects the number of actors involved in the setting of related measures, complementary programs and other institutional arrangements (river contracts, etc.) federated by the SDAGE for the achievement of common goals and shared in various territories (down to the watershed level).

At the sub-basin level *Low-water Management Plans* (PGE[4]) define strategies and public policies to manage, in the medium term, imbalances between water resources and demands during periods of low-water at the sub-basin level. In recent years, the design of such Low-water Management Plans strives to promote a better use of the existing stored resources (e.g. optimization of water releases to sustain river flows), to adjust the levies to the available resources (e.g. optimization of irrigation practice, reduction of water network leaks) or to create new water reservoirs. A Low-water Management Plan formalizes an agreement between different organizations representing the main stakeholders of the quantitative water management. It is elaborated through multi-year (about 3–4 to 8–10 years) social negotiation processes where the logic of resource management (creation of reservoirs) opposes with the logic of demand management (reduction of water withdrawals).

2.2. Local administrative level: the operational water management

Regulatory measures to face droughts are implemented at departmental level (administrative district similar to a county) through two key regulatory systems. First, a multiannual interdepartmental State decree defines general rules that departmental State services have to use to implement measures of water use restriction when required. These rules are based on the use of three regulatory reference flow levels at *nodal points*: the *alarm flow* (QA = 80% of the DOE), the *reinforced alarm flow* (QAR = DCR + 1/3[DOE − DCR]) and the *crisis flow* DCR (as defined by the SDAGE). They define three levels of water use restriction according to the value of the daily mean flow (QMJ): (a) Level 1 of restriction when QA < QMJ < DOE: irrigation is forbidden 1 or 2 days a week; (b) Level 2 of restriction when QAR < QMJ < QA: irrigation is forbidden 3 or 4 days a week; (c) Level 3 of restriction when QMJ < DCR: irrigation is forbidden 7 days a week. The implementation of these regulatory restriction is based on a principle of progressivity of measures (along time), a principle of upstream–downstream solidarity (not allowing a difference of more than one degree of restriction between adjacent areas along a river course) and coordination of inter-department management continuity.

Second, during the low-water period, when the QMJ decreases below the reference thresholds, State services (Departmental Directorates of Territories – DDT) are supposed to ask the Prefect the enactment of suitable restriction decrees (or Drought Decree). In order to take decisions the DDT and Prefect rely on a large amount of empirical knowledge and data (e.g. evaluation of the current state of the water reserves,[5] weather forecast, estimated current and future agricultural water needs, likeliness of actors' non-compliance with the regulatory flow levels). In some departments, decisions to trigger restrictions are taken by DDT alone. In some other departments the Prefect's decision is taken only after consultation with the *Drought Cell* of the department. According to department, the Drought Cell includes a more or less wide spectrum of stakeholders including the DDT, the Water Agency, the Chamber of Agriculture (Agricultural Advisory Services), the Joint Association for the Study and Development of the Garonne (SMEAG), Electricity of France EDF and other dam managers, local representatives of irrigators, even environmental associations and consumer associations, etc. According to the departmental authorities, the Drought Cell meets more or less systematically when problems occur. It is a participatory arena where the members share information, debate to reach a common representation and assessment of the situation.

[4] PGE: Plan de Gestion d'Etiage.

[5] Important volumes of water are purchased to the operators of upstream dams and lakes, intended to be released for the river stream replenishment in case of needs.

They may negotiate about the most relevant level of water withdrawal restriction to implement in the coming weeks. In some department, the debates of the Drought Cell most often conclude with the adoption of the restriction level proposed by the DDT and which corresponds to the implementation of the general rules defined in the multiannual inter-departmental State decree. In such cases, the Drought Cell seems to serve as an instrument to ensure that the decision taken is accepted as peacefully as possible or at least is understood by everyone after having being able to hear the other's point of view. In other department, the general rules are less systematically applied or even strongly distorted in order to preserve social peace (Debril and Therond, 2012). In such case, the drought decree appears as the result of a process in which the departmental State services find the way to reconcile stakeholders' desires with the regulatory framework imposed by the State.

2.3. Watershed level: authorized abstraction volumes (for irrigation)

Departmental State services also deliver annual authorizations of water withdrawal to water users including individual and collective irrigators. They should deliver these authorizations in order to ensure balance between water resources and the withdrawals at the watershed level. However many watersheds in the Adour-Garonne basin present chronic shortages of water resources with regard to the needs. This is linked to the fact that in order to avoid conflicts with farmers and local or regional agriculture representatives, State services provide agricultural water users, year after year, with annual withdrawals authorizations that largely exceed the available resources (Debril and Therond, 2012). In turn, this implies that State services are forced to regulate each year these unbalances between supply and demand through recurrent and sometimes numerous Drought Decrees. As a response to overcome these dysfunctions the water law LEMA (2006) imposes the obligation to determine the volumes actually available for human uses per *reference watershed* (defined as a consistent perimeter for water management). These *Abstraction Volumes* are defined to ensure that the low-water flow objective (DOE) is respected on average four out of five years without having to resort to restriction decrees.

In the Adour-Garonne basin, as agriculture represents up to 80% of water consumption during the low-water period, the LEMA also supports the objective to estimate more specifically Abstraction Volumes *for irrigation* to be allocated to individual irrigators and managed by so-called *Single Organizations for Collective Management* (presently under creation; Lafitte et al., 2008). Accordingly, the Regional Directorate of Environment, Planning and Housing (DREAL) and the Adour-Garonne Water Agency estimated *Initial Abstraction Volumes* for the 143 reference watersheds under their jurisdiction through the estimation of resources available for irrigation, in the driest year out of five years, given the estimation of the priority needs for domestic and industrial uses and the compliance with the objective low-water flow. However, as discussed in Section 4, these volumes had to be renegotiated and revised under pressure from the farm lobby, leading to unforseen results.

3. Integrated assessment and modelling of water management

Integrated assessment approaches are interdisciplinary, and possibly participatory processes, of combining, interpreting and communicating knowledge from diverse sources to allow a better understanding of complex phenomena (Rotmans and Asselt, 1996). They assemble the needed knowledge and information from a wide range of scientific disciplines and put them into a policy oriented context (Toth and Hizsnyik, 1998). These approaches are extensively applied to water management taking into account economic effectiveness, social cohesion and ecological balance, putting sustainable development at the heart of policy design. The special issue coordinated by Pahl-Wostl and Borowski (2007) contains many examples of integrated and participatory approaches focusing on water management issues.

3.1. The potential of water management modelling

Integrated Assessment and Modelling (IAM) describes the causal relationships and the interactions between several quantitative models of multi-level system components into a framework for integrated assessment (Jakeman and Letcher, 2003; Parker et al., 2002). Many authors (Sterk et al., 2009; McIntosh et al., 2007; Jakeman et al., 2006; Oxley et al., 2004) claim that the potential of model-based methods is well-established for handling natural resources management and policy problems. The role of models in participatory assessment has been analyzed in-depth (Sterk et al., 2009; Horlitz, 2007; Oxley et al., 2004). A wide-range of integrated water resource assessment models is available (see Pahl-Wostl and Borowski, 2007; Letcher et al., 2007).

One of the most interesting applications of these models, lies within the possibility to compare *in silico* and *ex ante* direct or indirect, intended or unintended (Merton, 1936) effects of various policy or normative alternatives of water management and governance considering, if required, global changes (e.g. demography, land cover dynamics, climate change). These models allow the projection of the likely evolution of a socio-hydrosystem subject to these policy or normative options over periods of several decades. The analysis of sets of trajectories corresponding to various scenarios, allows the tracing and quantification of the interdependence of causes and the conjunction of effects induced by the combination of policy or normative options. Their inter-comparison produces reasonable and revisable arguments for supporting the selection of particular management options or making certain decisions with regard to criteria that are set up explicitly in models. Such scenario approaches allow the comparison of environmental and socio-economic impacts of policies and management strategies based, on one hand on "command-and-control" and "supply-side management" logics (Del Moral Ituarte and Giansante, 2000; Kallis and Coccossis, 2003) and, on the other hand on participatory approaches and territorial cohesion concerns that strongly link land use with water management issues (EEA, 2012; Narcy and Mermet, 2003).

3.2. Water management modelling in the Adour-Garonne basin

For several years the Adour Garonne Water Agency has been supporting and coordinating several integrated assessment studies such as the scenario exercise on the water needs and resources across the Garonne basin (Garonne 2050, http://www.garonne2050.fr/), the Imagine 2030 Project (Hendrickx and Sauquet, 2013) that assesses the impacts of climate change on water resources in two main sub-basins of the Garonne and on the management of reservoirs at the horizon of 2030, and the Adapteau Project (http://www.adapteau.fr/) that contributes to the integrated assessment of impacts and adaptation to global changes in the Garonne basin. State services responsible for low-water management, dam managers, water agencies and local authorities in charge of designing the *Master Scheme for Water Planning and Management* and the *Low-water Management Plans* and *Single Organizations* in charge of designing allocation plans of withdrawal authorizations are expecting models to assist them in the design of their respective strategies, regulations and policies. They ask for tools that will help them foresee the likely consequences of their decisions and also anticipate local impacts of global changes

(Debril and Therond, 2012; March et al., 2012; Balestrat and Therond, 2014).

To illustrate the nature and potential of integrated modelling of water management to fulfill expectations like the ones of Adour-Garonne stakeholders we briefly introduce the multi-agent platform MAELIA. This platform is dedicated to support decision-making of organizations involved in the management of low-water. Its design methodology, its modelling architecture and components, the calibration methods used, the performance of the simulations, the way scenarios are built, and examples of application are described in several articles (Sibertin-Blanc et al., 2011; Mazzega et al., 2013; Gaudou et al., 2014; Lardy et al., 2014; Therond et al., 2014; Murgue et al., 2014). What matters for our illustrative purposes here is to draw the framework within which this platform works and indicators it produces.

Key processes and human activities modelled at different spatial and temporal resolutions and evolving interactions are listed in Table 2. MAELIA allows the simulation of the evolution of the socio-hydrosystem over a few decades, following the hypotheses given by diverse scenarios of interest. Various indicators are assessed to evaluate and compare the results of these scenarios (see Table 3). Following Alcamo's (2001) typology, we develop two baseline (i.e. no new policy intervention) and two policy quantitative scenarios, simulated over the 2000–2030 period with a daily time-step. One baseline scenario assumes the continuation of observed trend of climate change impact on the quantity and spatio-temporal distribution of rainfall (business as usual scenario); the other one is consistent with a hypothesis of increasing resource scarcity during low-water periods (Pagé and Terray, 2010). The two policy scenarios are based respectively on the management of water by abstraction volumes (as provided by the LEMA, 2006), and on an adaptive management based on continuous flow monitoring, as desired by the agriculture profession.

Fig. 1 illustrates key agronomic and hydrologic indicators over the period 2002–2008, showing in particular the impact of the dry year 2003 and to a less extent of the year 2004 on some irrigated and rain-fed crops and on the crossing of objective low-water flow (DOE) and crisis flow (DCR) thresholds. Let us emphasize that the performance of agricultural production does not depend on the state of water resources only, but also on the management options taken at various levels. In particular the relatively frequent publication of drought decrees prohibiting certain water uses (including agricultural irrigation) leads to irrigation practices that are at best sub-optimal both for agriculture and for the environment. For example, based on empirical observations, expert knowledge and farm surveys, the MAELIA platform reproduces an increased frequency of irrigation turns in farm fields, inducing an increase of withdrawal intensities, when water use restrictions apply on 1 or 2 days a week. In turn this practice often leads to an acceleration of the degradation of the river flow.

3.3. Modelling of actors' decisions

Human decision-making plays a key role in the multi-agent modelling of natural resource management. In the MAELIA platform several decision-making processes are modelled, like farmers' decisions on crop allocation and management (including irrigation), farmers' decisions relative to the management of private hill reservoirs[6], dam managers' decisions about water releases to support low-flow, State services' decisions to enact restrictions of water uses, farmers' decisions to comply or not to the restrictions. These decisions are made by virtual agents in relative autonomy. The effects of their decisions are mainly conveyed to other stakeholders *via* the impact they have on shared resources. With the objective to properly gauge the specific obstacles to modelling the decision-making process taking place in arenas of collective choice (next section), we briefly present some approaches we use for various virtual agents. These agents represent individuals or organizations whose behavior can be reduced to that of a nominal actor whose intentions do not change with respect to issues to be addressed during the period of simulated time. These agents are endowed with more or less sophisticated computational capabilities depending on the nature of the decisions they have to make and on the diversity of information they have to deal with. Consider two contrasted examples.

As observed in most departments, the decision of the competent State services regarding the publication of temporary restrictions on water use means following the procedure described in Section 2.2, given the regulatory flow thresholds and state of stream flow at nodal points, the nature of the restriction of use is selected and the decree published. Geographical expansion is decided by an equally predictable pattern based on the location of the point where the flow deficit is measured, and on the constraints of upstream–downstream solidarity and continuity of restrictions between connected hydrological zones. The nominal virtual agent (here called "State services") makes decisions autonomously when needed, depending on the simulated evolution of the state of the resource and on observations of monitoring sites (nodal points). So without being endowed with a sophisticated rationality, this virtual agent undertakes actions based on rules (Mayor et al., 2012). This simple approach correctly reproduces most water use restrictions published in the basin in the past years.

As a second example, we consider the farmers' decisions regarding the annual choice of crop rotation. The model used is the Dempster–Schaeffer's model (Dempster, 1967; Shafer, 1976) only briefly summarized here (details can be found in Taillandier et al., 2012). This model produces the decision about choosing one of the predefined plans of crop rotation on the basis of the description of the agent's beliefs, desires and intentions. Field surveys (Dury et al., 2010) lead to the identification of the following main desires: (a) maximize profit; (b) minimize the variability of income; (c) minimize workload (to maximize the number of free days for other activities); (d) minimize the changes from the choice of previous years. The belief functions primarily capture the empirical knowledge of farmers on the functioning and on the response of agricultural systems. They combine the performances expected by farmers in terms of profits, income securing, free time and keeping of already tested choices, with the possible alternatives of crop rotation. The statistical combination of these information elements and related uncertainties, leads each virtual farmer to choose a plan of crop rotation within a set of predefined plans, given the specific nature of his agricultural exploitation and the prevailing environmental conditions.

What matters for our purpose is that such approaches – a rule-based logic on one hand, and a model of bounded rationality on the other hand – can be used and produce very satisfactory outputs because one necessary condition is fulfilled: we observed regularities in the actors' behaviors. In our case, the development of models of key actors' decision-making processes is relying on techniques of knowledge engineering and methods of mental representation elicitation (Therond et al., 2014). Note also that the association of a nominal actor to a composite entity (such as for example the "State services") is conditioned by the empirical observation of a pattern of behavior and by the possibility of reducing the choices made in a kind of weighting of various predetermined criteria and actualized information. These cases are in stark contrast to the process of decision-making in the arenas of collective choice.

[6] It is generally accepted that the management of the 15,000 hill reservoirs and small dams in the Adour-Garonne basin totaling approximately 290 Mm^3 (to be compared to the 300 Mm^3 in dams of more than 2 million m^3 dedicated to supporting low water) has an effect on the elongation of low water periods.

Table 2
Key processes and human activities of low-water management represented in the MAELIA multi-agent platform.

Processes	Nature of the model	Spatial/temporal resolutions
Ecological processes		
Climate change impacts on precipitations, ground-level air temperature and evapotranspiration	Scenarios for fine-scale climate projections on France for the 21st Century (Pagé and Terray, 2010)	Grid with resolution of 8 km × 8 km/h
Hydrology (surface and groundwater)	Land and routing phases of the semi distributed agro-hydrological model SWAT[a]	Reference watershed[b]/day
Crop growth	AqYield[c]: empirical generic crop model developed by INRA Toulouse	Field/day
Other plant growth	Simplified representation of SWAT formalisms	HRU[d]/day
Socio-economic processes		
Land cover evolution	Statistic and probabilistic model based on the analyze of Corine Land Cover data[e]	HRU/year
Demography	Statistic model	District/year
Domestic consumption	Econometric model	Withdrawal and reject points/day
Industrial consumption	Statistic model	Withdrawal and reject points/day
Human activities		
Crop allocation (cropping plan)	Multi-criteria decision based on Dempster-Shafer belief theory included in a Belief-Desire-Intention architecture[f]	Farm/year
Crop management (seeding, irrigation, harvesting)	Nested decision rules (If THEN ELSE)	Field and withdrawal points/day
Dam management	Nested decision rules (If THEN ELSE)	Dam and supplied river section/day
Water use restriction	Nested decision rules (If THEN ELSE)	Restriction zone/day

[a] Soil and Water Assessment Tool. (http://swat.tamu.edu/software/swat-model/).
[b] Finest watershed used by French administration to manage water.
[c] See Murgue et al. (2014).
[d] Hydrologic Response Units (HRUs) with homogenous soil, slop and land cover.
[e] Corine Land Cover France, 2012. Available on: http://www.statistiques.developpement-durable.gouv.fr.
[f] See Taillandier et al. (2012).

Table 3
Key indicators estimated with the MAELIA multi-agent platform. Indicators can be aggregated at all over levels of the calculation resolution presented in the table.

Key indicators	Spatial & temporal resolutions
Ecologic indicators	
River flow	Hydrological nodes/day
Water deficit	Hydrological nodes/year
Crop yield	Field-Farm/year
Crop diversity	Farm/year
Economic indicators	
Gross margin	Field-Farm/year
Income	Farm/year
Cropping plan	Farm/year
Social-governance indicators	
Water volume released	Hydrological nodes/year
Number of restrictions	Restriction zone/year
Levels (intensity) of restrictions	Restriction zone/year

4. Multi-level governance issues critical for modelling

As shown in Section 2 the multi-level governance and participatory management of low-water also involve different collective-choice arenas where actors negotiate to establish new rules to structure their actions (Ostrom, 1999; Allain, 2012). These social negotiations correspond to a particular class of processes whose formalization and taking into account by the integrated models remain a great challenge.

4.1. Decision-making in collective-choice arenas

Actors are involved in the negotiated elaboration of norms and procedural rules at least in three distinct phases: (1) the objectification of the state of the resources; (2) the definition of the nature of the problems and involved issues; (3) the identification and definition of possible measures (often considered as "solutions") to be implemented in order to change the state or the foreseen evolution of the socio-hydrosystem toward a more acceptable future. The negotiation ingredients may include the conflict development among stakeholders, breaches of discussions, the game of political influences, issue linking (involving issues other than those related to water), electoral considerations, preservation of the social peace, etc. Indeed, such practices are often observed in the social or political field. In such contexts, *integrated models* of water management are neither able to predict the outcomes of negotiations nor the precise nature or content of resulting decisions (if any).

This limitation is not tied to a specific model, to its design framework or methodology, to the completeness and fineness (granularity) of its representations, to its structure, performance or associated uncertainties. It is rather the fundamental impossibility to anticipate events resulting from the exercise of a group of people's free will. The nature of the interpersonal relationships, the multiplicity and interdependence of personal or group stakes, the effects of representations of self and of others, the confrontation of the information level of each player and their respective understanding of each situation, the effects of context (social, economic, environmental, etc.), the alteration of actors' positions as the debates evolves, shifting alliances, political tactics, and many other factors (in a different context though with similar dynamics see Cohen et al., 1972; Miner, 2006), intervene more or less in the conduct of discussion and decision making in a sometimes subtle way that is difficult to observe and even more, to analyze and model (Kørnøv and Thissen, 2010).

4.2. Negotiating the abstraction volumes for irrigation

Let us illustrate this complexity with a salient negotiation process recently occurring in the Adour-Garonne basin. In some watersheds the initial estimates of Abstraction Volumes (see Section 2.3) implied significant restrictions relatively to the volumes currently allocated to and withdrawn for agriculture before the proposed reform (Fig. 2). This definition of abstraction volumes

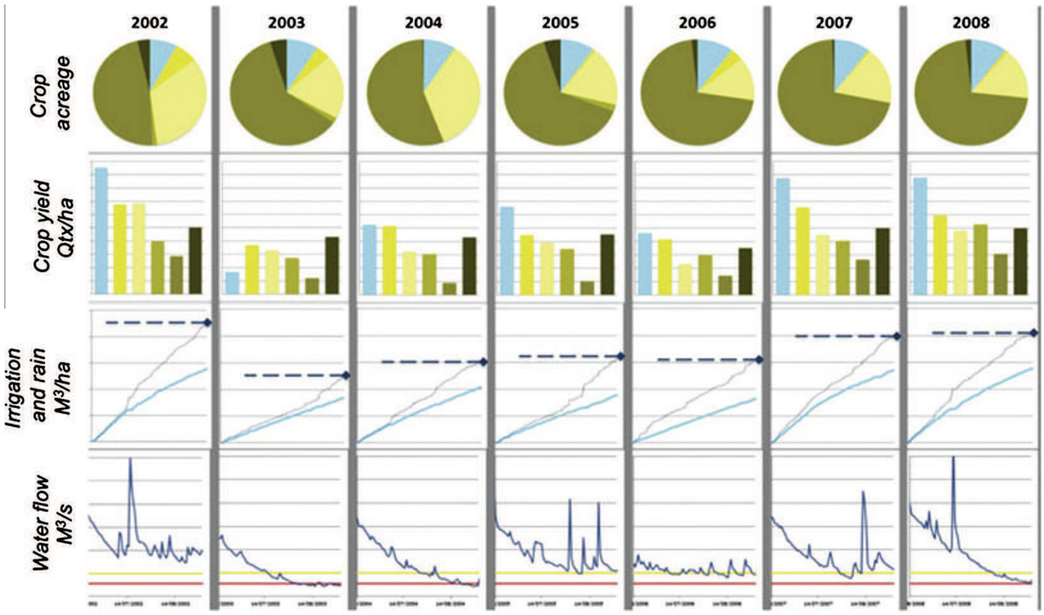

Fig. 1. From top to bottom, crop acreage at the river basin level, crop yields for the main irrigated (blue: corn) and rain-fed crops (yellow to green: wheat, sunflower, pea, rapseed, etc.), average cumulated water irrigation and rain in irrigated crop fields, water flow at the outlet of the river basin during the low-water period (yellow and red lines represent compulsory objective low-water flow and crisis flow) as simulated by the MAELIA platform over the period 2002–2008. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

was very badly received by the farming community that in particular has opposed economic needs related to irrigation and has criticized the merely ecological nature of the reform. Negotiations were launched in 2010 in the Adour-Garonne basin between representatives of the farming community and State services. They led to significant adaptations relative to initial Abstraction Volumes available for agriculture in many watersheds. The comparison of Fig. 2a and b shows that the changes of maps that ensued, significantly reduces the number of areas classified as "imbalanced", that is to say, areas where abstraction volumes are below the volumes collected the driest hydrological year out of five years.

However, these new developments of the reform of Abstraction Volumes were still not satisfactory to the agricultural profession which intensified its lobbying in Ministries to promote regulatory adaptations. This strategy has been effective since it led the government to specific arbitration in the Adour-Garonne basin, meeting the demands of the agricultural profession, on the basis of two main changes: (i) increasing the progressiveness of the reform implementation by postponing a return to a quantitative equilibrium of flows in 2021 (vs. 2015 as initially planned) and (ii) in unbalanced watersheds, implementing derogations to the LEMA (2006) by the allocation of an Abstraction Volume corresponding to the maximum annual water volume withdrawn in the past years. This last derogation has a strong significance as it leads to keeping the unbalance between water resources and demands unchanged precisely in watersheds under stress.

Today it is not even possible to know in what direction discussions and negotiations with and within the Single Organizations for Collective Management will guide the allocation of water volumes between irrigators. Until now, candidate institutions[7] applying for a *Single Organization* have not clearly described the method they intend to use to distribute water withdrawal authorizations between irrigators. Without actual experience, and without any modelling tool to assist them, these institutions have little information helpful to design sustainable water allocation plans.[8] Projects of dam construction, their approval and implementation, are also becoming an issue in the definition of abstraction volumes. Moreover the awarding of temporary authorizations remains flexible in interpretation and the allocation procedure leaves room for discussion and lobbying. The evolution of this state of affairs seems to escape any possibility of capture by models (with rational agents or any other technology), regardless of their sophistication.

5. Dealing with participatory multi-level governance issues through scenario exercises

One possibility for overcoming the critical issues raised by multi-level governance while keeping most advantages of integrated modelling is to use a different but complementary approach – that of participatory scenario exercises. In this section we consider the potential offered by scenarios for handling outcomes of negotiation in integrated assessment modelling. Scenarios can be seen as "*plausible stories about how the future might unfold, constructed using qualitative and/or quantitative models and information on current and past conditions*" (Biggs et al., 2007, p. 1). All in all, a scenario exercise (Alcamo and Henrichs, 2008) includes the development of different circumstances, the evaluation (possibly through the use of models) of their consequences by means of indicators and the comparison of the various outcomes (Therond et al., 2009; Leenhardt et al., 2012).

5.1. Specification of scenarios and system trajectories

Classically, once the indicators associated to the research question investigated by the model are defined, a scenario exercises relying on model simulations proceed by the following steps:

[7] Which in the vast majority of cases are Chambers of Agriculture or groups of them, or mixed associations between Public Territorial Basin Institution and Chambers (few cases).

[8] State services could propose that Single Organizations establish in consultation with field stakeholders some grids defining the needs depending on crop/soil of each basic unit, grids that would be used to ensure consistency of farmers' demands (which should declare the surfaces in culture) and as a basis for determining individual or group permissions.

- Choice of the main issues that scenarios will tackle like climate change, demographic changes, land use and land cover changes, implementation of norms or policy measures, etc. and definition of indicators to assess (Kepner et al., 2004; Millennium Ecosystem Assessment, 2005; Volk et al., 2009).
- Clear definition of each scenario and specification of all data allowing the execution of corresponding numerical simulations (initial and boundary conditions of state variables; values of process and procedure parameters; space–time series capturing the influence of external processes on the considered system).
- For each scenario, implementation of the simulation of the modelled socio-hydrosystem and assessment of the associated social, economic and environmental indicators (proxies).
- Identification and analysis of effects associated with each scenario and comparative analysis of paths and indicators induced by the different scenarios.

Scenarios that aim at producing *ex ante* descriptions of the possible evolution of water resources and socio-hydrosystems are likely to consider many criteria and issues (March et al., 2012). Most generally they take account of possible differences in the intensity and spatiotemporal distributions of resources, human activities (e.g. changes in agricultural systems) and other processes (e.g. droughts and floods, global warming, etc.), or disturbances observed on key processes themselves. However another class of scenarios is likely to take into account, at least crudely, the changes resulting from processes of collective negotiations.

5.2. Differentiated model accounting for collective decision making

To establish scenarios accounting for effects of negotiations on measures to be undertaken at various levels of governance, we distinguish three cases of increasing difficulty from the perspective of modelling:

- Cases where negotiations conclude with decisions translated into fixed rules, procedures, technical norms or parameter values: useful and unambiguous data and information are available *before performing simulations*. The outcomes of these decisions are explicitly introduced into the model. This is for example the case for the regulatory flows defined in the *Master Scheme for Water Planning and Management* (SDAGE) (cf. Section 2.1). The values of these flow rates are used as parameter values in the simulation model. Their crossing induces the actions of (virtual) agents provided by the norms and depending on the hydrological state of rivers simulated by the platform.
- Cases where decision outcomes have to be computed by simulation, because they are not known in advance: they must be calculated autonomously through the execution of a computer code. The model is equipped with modules representing the decision-making procedures and uses the information simulated for this purpose. This case includes for example the decision to issue water use restriction including the choice of the severity of the measure and its modalities of implementation (geographical area, durations, etc.; Mayor et al., 2012). The model can only represent the decision-making process according to the rules previously fixed and not their effective implementation resulting from social negotiation (sometimes beyond the limits of legality).
- Cases where complex decisions bear on more general rules that frame concrete rules in application within the system (e.g. issuing new rules of water management such as the multiannual inter-departmental State decree or the SDAGE, generating new responsibilities or regulatory thresholds, creating new organizations and endowing them with dedicated missions): the strategies of actors and outcomes of the discussions are not predictable. The only possibility for the modeler (according to various methodologies) is to make assumptions about the likely decision options that could emerge from the negotiation process and translate them in as many scenarios and associated simulations necessary to represent the range of options.

5.3. About the decisions of collective choice arenas

This last case is highly related to the nature of the water legislation applicable. In transposition of the European Water Framework Directive (EU WFD, 2000) new provisions have been enacted in order to decentralize the decision-making process and to give voice to all the stakeholders.[9] It is precisely this participative nature that is susceptible to make the modelling process intractable: although decisions are framed by the existing regulation, they are made taking into account elements that are *per se* unstable in the long-term and hardly predictable (i.e. negotiations and bargaining, problematic preferences, social acceptability and related impacts, power relationships, intervention of lobbyists, stakeholders' strategies and interests, etc.). The changing character of such elements has strong consequences for the modelling process: the elements to take into account change on a case basis and identical premises might lead to different outcomes. Furthermore, not all the decision processes that take place among the stakeholders or in the agents themselves at different times correspond to the same logic or kind of reasoning (i.e. purely rational, own-utility maximizing, consensus-seeking, etc.). As expressed succinctly by Eisenhardt and Zbaracki (1992, p. 23) "*in political model, people are individually rational, but not collectively so*".

The question has shifted from the construction of predictive models of multi-actor negotiations to the construction of useful scenarios: if there is presently no satisfactory model (i.e. reliable, observable, explanatory, predictive) capable of reproducing the process of collective decision-making about complex issues (see e.g. Eisenhardt and Zbaracki, 1992; Shepherd and Maynard Rudd, 2014), it is still possible to generate assumptions about the results of collective negotiations and produce scenarios on this basis. In summary, the kind of modelling we advocate and endorse (Alcamo, 2001; Liu et al., 2008; Mahmoud et al., 2009) represents the main alternatives negotiated within the collective-choice arenas in as many scenarios as needed, to produce the required simulations for a comparative analysis of possible induced changes in the socio-hydrosystem.

6. Discussion

The characteristics of the environment are often cited as causes of the difficulties in managing resources and are associated with increased risks that modern societies face. However, the devices used to objectify the state of the resource and to take measures to manage crises are social constructs,[10] which urges us to distance ourselves from the concept of a pre-existing environment with intrinsic characteristics. Pressure of farmers' representatives on State services is particularly strong in several French departments. This cultural trait sometimes results in negotiations relative to the flexibility of interpretation and application of the law in exchange for social peace at local or regional levels (Thoyer et al., 2004; Debril and Therond, 2012). Thus, socio-technical infrastructures that determine qualification of water-related risks and legal or political interventions, appear as the results of a complicated story (Fernandez and

[9] At the basin level, for example, the Basin Committee is a kind of "water parliament" composed of local authorities (40%), representatives of all users and stakeholders (40%) and the State services (20%).

[10] The same holds for the definitions of the *state* of a resource and of the *crisis* situations.

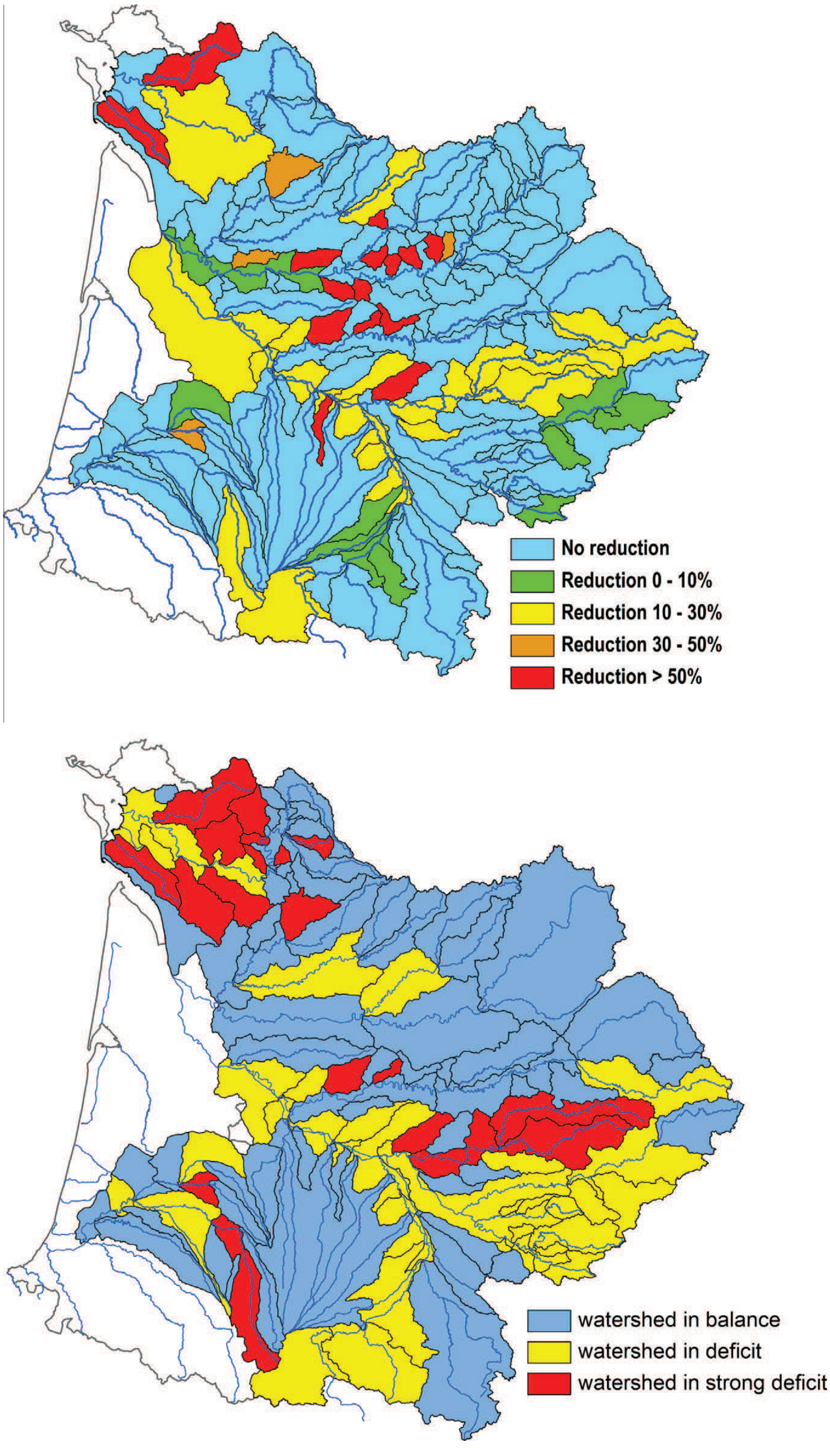

Fig. 2. (up) Difference between initial abstraction volumes and volumes withdrawn for irrigation in the driest hydrological year over five years; (down) difference between final abstraction volumes (after the full negotiation process – see text) and volumes collected in the driest hydrological year over five years. *Source*: Regional Directorate of Environment, Planning and Housing of Midi-Pyrénées Region.

Trottier, 2012) partly built upon hard times of negotiation between actors with distinct interests (Le Bourhis, 2009; Barbier et al., 2010).

The decisions produced within collective-choice arenas are especially exhibiting the following characteristics: (a) determinants involved in a given decision might change from time to time; (b) the same determinants can lead to different decisions; (c) the decision-making process does not follow every time the same path (procedure, argumentation, etc.) or the same logic. If negotiation dynamics linked to these characteristics are out of range of the models, an investigation in these arenas and interviews with key actors allows an analysis to be performed of the terms of the decisions made and of their degree of unpredictability. In some cases or situations, which are not known in advance, an evaluation of the acceptability of different decision alternatives according to actors or groups of stakeholders can be anticipated with some reliability. For example, it appeared from surveys and interviews with key actors that, for drought decrees, the outcomes of decision-making processes are quite predictable in many departments even if they are the subject of frequent discussions. This empirical knowledge is then usefully used to develop simplified models of the corresponding decision-making process or to develop different scenarios.

Apart from these cases, another use of scenarios is possible. This entails producing scenarios proposed by some of the negotiating groups involved in the management of water. The actors involved in an arena of collective choice define the context of the problem addressed, the terms of the negotiation, and may come to an agreement about the alternatives of possible decisions, either the most likely ones or the most interesting to explore. The associated scenarios, elaborated as detailed descriptions of procedures or management rules that may be finally chosen, are implemented to perform the simulations and comparative analysis of the induced effects. This process can fruitfully use formal approaches to scenario-building (Mahmoud et al., 2009). In this exercise, the integrated model retains all its usefulness and appropriateness of use. In particular it explicitly associates each actor that governance convenes in any collective-choice arena with the cognitive and material resources they use or control and by mediation of which he/she interacts with a defined set of other actors. This organization is the objective basis from which each actor develops his/her negotiation strategy, and more generally his or her behavior. Moreover, the model does not only provide descriptive elements, as it can also identify the actors (or resources) that are the most central in these decision-making process, those who are likely to play a role of intermediary between communities otherwise separated, the possible combinations of actors and resources running as a kind of sub-systems, through the analysis of the model structure (e.g. Carlsson and Sandström, 2008; Mazzega et al., 2012). This approach implies that water actors and scientific teams closely collaborate (Lemos and Morehouse, 2005; van Delden et al., 2011). In a certain way it confirms the implication of researchers themselves and of their technical tools in the management of water (Fundingsland Tetlow and Hanusch, 2012; Coombes and Barry, 2014). This change can be seen as a local governance reform which would facilitate treatment of the wicked problems (Head and Alford, 2013) of water management.

Integrated simulation models are becoming essential tools for producing *ex ante* knowledge about the evolution of socio-hydrosystems as a function of the implemented policies, differences in norm compliance, rapid changes or trend of environmental variables. The performance of these simulation models are progressing, allowing ever more realistic and precise inferences. The temptation might be also to use these tools to impose pre-designed decisions, favorable to a decision-maker in particular, justified on the basis of a few selected simulation results and of the scientific legitimacy of the simulation tool. Conferring such normative status to a simulation platform may lead to the confiscation of water stakeholders' rights to exercise their democratic rights and their ability to build collective compromises. The use of models for the simulation of low-water management scenarios makes sense and shows its usefulness when it is exerted by decision-makers or decision-making authorities/organisations legitimized to make collective decisions within the current normative framework (this framework can itself evolve). Integrated modelling of management of water resources can produce decision-support tools, but no decision tools.

7. Conclusion

Including actors' rationality (even under different variants and modalities) in the modelling of low-water management, progressively leads to the adoption of a sociological position which emphasizes the idea that actors' strategies can be quite distant from pure compliance with rules or norms. Furthermore, the instability of the socio-hydrosystem is not so much on the side of the autonomous actors but rather on the side of ambiguous or paradoxical changing rules that frame the management of water. Instabilities can also emerge from controversies surrounding the resource qualification and the relative versatility of normative texts, their interpretation or the concrete conditions of their implementation.

We assume that the use and utility of agent-based modelling will observe a growth in the years to come, in order to establish and evaluate various policy options for water management or norms of water management. However, following-up on different scholars, we experienced that the outcomes of the decisions made in most collective-choice arenas cannot be anticipated - even by models endowing autonomous virtual agents with any kind of rationality. The strategy then consists in constructing alternative policy scenarios with stakeholders involved in these collective-choice arenas according to their respective anticipations, and producing and analyzing simulations of the socio-hydrosystem evolution based on all the knowledge and data introduced in the integrated model.

On the one hand, these arguments draw major contours of the usefulness of integrated models for water management, but they also present limitations to a reliable application. On the other hand, these limitations of application provide a basis for drawing the contours of ethical rules for the use of socio-ecological models that we believe needs to be clearly established and shared. Indeed, we argue that the modelling approach does not replace, in any manner, the participatory debate and political negotiation that operate in a democracy, provided that they are guaranteed or strengthened by the institutional and legal frames of environmental governance at all levels of organization.[11] By presenting this position that we have illustrated with specific points relative to the collective decision-making in the management of low-water, we do not want to feed controversy, but simply feed the debate that questions the responsibility of research with regard to the use of its results in the design and conduct of environmental policy.

Acknowledgments

We thank the anonymous reviewers for their rich comments that prompted us to clarify our position, as well as for the indication of several references, opening up new perspectives. This research is developed in the frame of the MAELIA Project "*Multi-Agents for EnvironmentaL norm Impact Assessment*" (http://maelia1a.wordpress.com/) funded by the Thematic Network for Advanced Research "Sciences & Technologies for Aeronautics and Space" (RTRA STAE Foundation http://www.fondationstae.net/) in Toulouse, France. Dr H. March (in 2010-2011) and Dr R. Lardy (in 2013-2014) have benefited from postdoctoral grants funded by the RTRA STAE Foundation. The authors would like to thank all governmental organizations, private companies and others who supported our work by providing data and expertise necessary to feed the MAELIA model.

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[11] The issue of global environmental governance emerges acutely today – UNEP (2009); see also Hirji and Davis (2009) for a different point of view.

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