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Impact Assessment Modeling of Low-Water Management Policy

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Abstract. *We briefly present the main steps involved in designing and developing a platform for the numerical simulation of environmental and social impacts of the implementation of new environmental norms related to low-water management in France (MAELIA Project: multi-agents for environmental norms impact assessment). Some results are highlighted concerning in particular the structure of the underlying low-water management model and the process and agents' activity modeling.*

Resumo. *Apresentamos brevemente as principais etapas envolvidas na concepção e no desenvolvimento de uma plataforma para a simulação numérica dos impactos ambientais e sociais da implementação de novas normas ambientais relacionadas com a gestão de baixo nível de água em*

França (MAELIA Projeto: multi-agentes para avaliação de impacto das normas ambientais). Alguns resultados são destacados respeito sobretudo a estrutura do modelo de gestão de baixo nível de água e ao modelagem de processos e da atividade do agentes.

1. Low-Water Management in France

As an introduction we give a raw description of the water resource and demand on the Adour-Garonne basin and recast their management in the context of low-water management policy in France.

1.1 Water volumes and Flows in the Adour-Garonne Basin

The potential flow of water in the Adour-Garonne Basin (South-West of France) is $\sim 90.00 \text{ km}^3/\text{year}$. The average annual withdrawals are $\sim 2.50 \text{ km}^3/\text{year}$ equally divided between drinking water, industrial water and agricultural irrigation. However, water availability and uses have a very high variability in space - the rate of precipitation in the basin varies from 600 mm/year to 2000 mm/year, and in time - with the peak demand for irrigation during the period of low-water (summer and early autumn), precisely at the time of the year when the resource is scarce. At this time irrigation accounts for 70% to 80% of the withdrawals, mainly carried out on surface waters (either natural or artificial). About 0.36 km^3 of water supplies are available to support low-water and the preservation of aquatic ecosystems (half stored in dams dedicated to hydropower), plus 0.29 km^3 of water accumulated in approximately 15,000 small dams mainly managed by farmers for irrigation (AGWA, 2013).

1.2 Resource Scarcity during Low-Water Periods

For several years, a chronic deficit of ~ 250 million m^3 of water per year stands at the basin scale, leading to recurrent conflicts of competing uses (and users). The *objective flow* (considered as the minimum flow to be maintained throughout the year for a good functioning of aquatic ecosystems) is regularly taken each year. The *alarm flow* and *crisis flow* below which aquatic life is in danger, are also increasingly crossed every year. Most of the time, in response to the crossings of these flows (whose values are defined in the water regulation frame at several observation points in rivers of the Adour-Garonne basin), the competent State authority (Prefect of the basin) decides to publish decrees of restriction of water uses whose severity is proportionate to the seriousness of the crisis and extension is related to the concerned hydrographic areas, in accordance with the two principles of spatial continuity of levels of restrictions and upstream and downstream solidarity (Gazzaniga et al., 2011). These restrictions, unpredictable at the scale of a few days or weeks, induce economic insecurity for irrigating farmers by limiting their ability to properly plan and manage their productive activities and by reducing their income.

1.3 Towards a Management by Water Volume for Irrigation

The Law on water and aquatic environments (LEMA¹) provides for a transition from crisis management to structural management by setting the definition of *abstraction volumes for irrigated agriculture*, in the form of water volume quotas defined on

¹ Law n° 2006-1772 of 30 December 2006 on water and aquatic environments. Available (in French) on the public service for Law broadcasting [11/05/2013] <http://www.legifrance.gouv.fr/>

hydrological sub-basins or (connected) areas, and whose water allocation between each irrigating farmer of the area will be conducted by a *single collective management organization* (being created following a call for applications published in 2012). These abstraction volumes are defined by considering the driest year on a 5-year time window. They are the volumes remaining after the removal of those volumes required primarily for drinking water, the industrial uses and maintaining ecosystems from the “hydrological” annual volume of water (*natural* water cycle, broadly speaking) in the considered area. In recent years, the agricultural profession is engaged in a claim of requiring an alternative management relying on continuously observed flows, arguing that statistically 4 years over 5, some water which could be used to increase agricultural production and productivity will merely flow in water courses.

The *ex ante* simulation of social, economic and environmental impacts associated to the low-water management by abstraction volumes (statutory) compared the impacts associated to the management by observed flow rates (claimed by farmers irrigators) is the primary objective of developing and exploiting the MAELIA simulation platform.

2. Structure of the Low-Water Management Representation

Modeling is widely used to assess water resources (see e.g. Nayak, 2012, and references within), but also to promote their participatory management (e.g. Pahl-Wostl and Borowski, 2007) between a diversity of actors with different objectives and perceptions of the state and dynamics of water resources in different time frames and deadlines. The project presented here is in the line of integrated assessment approaches - covering a broad spectrum of methods (e.g. Cai et al, 2006; Döll and Hauschild, 2002, George et al, 2011) - that rely on modeling to help in the design or conduct of public policies for sustainable management of water resources. However, we focus here on the representation of the behavior of the main users of water during low-flow periods, namely farmers and resource managers, and on the framework for the conduct of their actions.

The main steps accomplished so far to build the simulation platform are now briefly described. They range from knowledge representation and sharing issues to properly modeling and coding, data gathering and harmonization, coding and human-machine interface conception and developing, and simulation.

2.1 Interdisciplinary Terminology

There are methods to build common ontologies or terminologies using methodologies for extracting knowledge from text corpora which are samples of the actual use of the terms in the disciplines involved (Condamines and Dehaut, 2011; Mazzega et al., 2011). In the MAELIA Project, a common reference terminology with over 250 terms was thus produced (Fèvre-Pernet, 2011) which offers to the actors the project a consensual basis of terms for working together and produce new knowledge.

2.2 A Participative Interdisciplinary Approach

The ARDI method (Etienne et al., 2008) allows the participants to collectively build a conceptual model of the functioning of the territory given a studied issue with respect to natural resource management. The construction of the common representation is done by means of four workshops during which Actors, Resources, Dynamics and Interactions

(ARDI) are identified and clarified. Applying the method researchers have to answer to the following questions: Who are the main stakeholders involved directly or indirectly in the management of water resources of the territory during low-water periods? What are the principal resources of these stakeholders? What are the main processes that drive strong changes in water managements and resources states? The last phase of the ARDI method consists in synthesizing answers to the three preceding questions by formalizing the interaction between stakeholders and resources. This core step of the exercise leads to a conceptual model representing all interactions related to low-water management issues. These participatory method allow to involve researchers from a diversity of disciplines in the interdisciplinary modelling process, to start the integration of their disciplinary knowledge and to support an on-going learning and negotiation process known as “social leaning” (Thérond et al., 2010).

2.3 Abstraction Hierarchies

A general framework for the organization and interrelation of different levels of abstractions used in the process of the simulation platform design and development has been established (Figure 1). In addition to the social ecological system of reference (e.g. Ostrom, 2009), this framework includes the meta-model, the conceptual models of the system considered (low-water management) derived in accordance with the requirements of the meta-model, the concrete model (management of low-water in the Adour-Garonne basin) and the implemented or simulation model (instantiation of the concrete model).

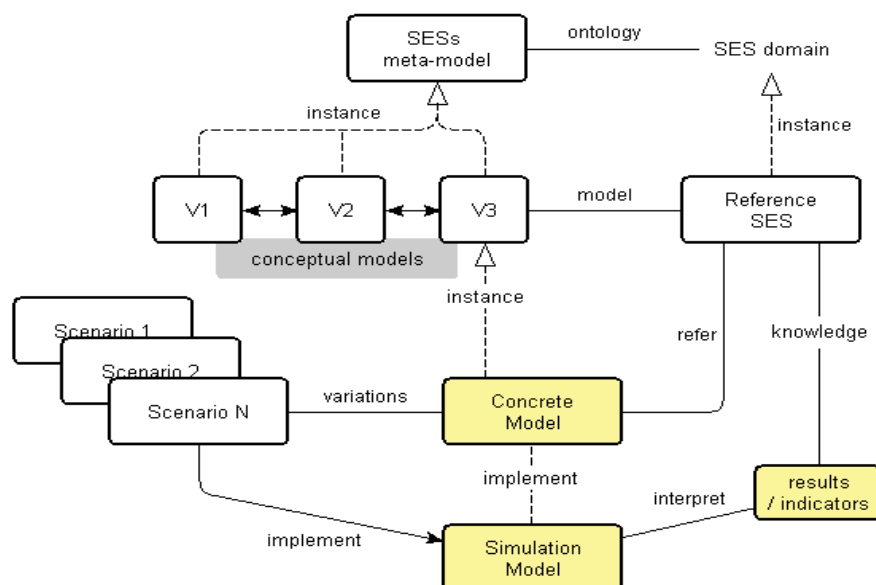


Figure 1. Organizational frame for abstraction hierarchies. Several conceptual models can be associated with the social-ecological system of reference. One of them is used to derive the concrete model which computer-implementation (with specific data) is the simulation model driven by scenarios. The comparison of scenario simulations is based on the production and analysis of a set of indicators.

2.4 A meta-model of Social-Ecological Systems

We have produced a meta-model that provides guidelines and prescriptions for deriving consistent conceptual models of social-ecological systems (Sibertin-Blanc et al., 2011).

The meta-model involves entities of three kinds – (rational) actors, material resources and cognitive resources- that are the constitutive elements of a system. An entity is characterized by properties whose values define the state of the entity, and operations, which process the properties. Entities are associated through relationships that can be processes (either social, economic or environmental) or activities achieved by an actor in the aim of fulfilling a goal. Those processes or activities external to the representation of the modeled social-ecological system are impacting the state of the entities via spatial or time series of variables involved in the system dynamics.

2.5 Actor-Resource Diagrams

The Actor-Resource diagram (hereafter ARD) stands as the structure of a conceptual model, representing the actors of the simulation, the resources at stake and the way entities of both types relate with each other, resulting into a coherent whole. The ARD takes form of a UML class diagram, where actors and resources are depicted within boxes containing their respective “attributes” and “methods”. Relationships are symbolized by the edges between the entities, along with their role and cardinality constraints.

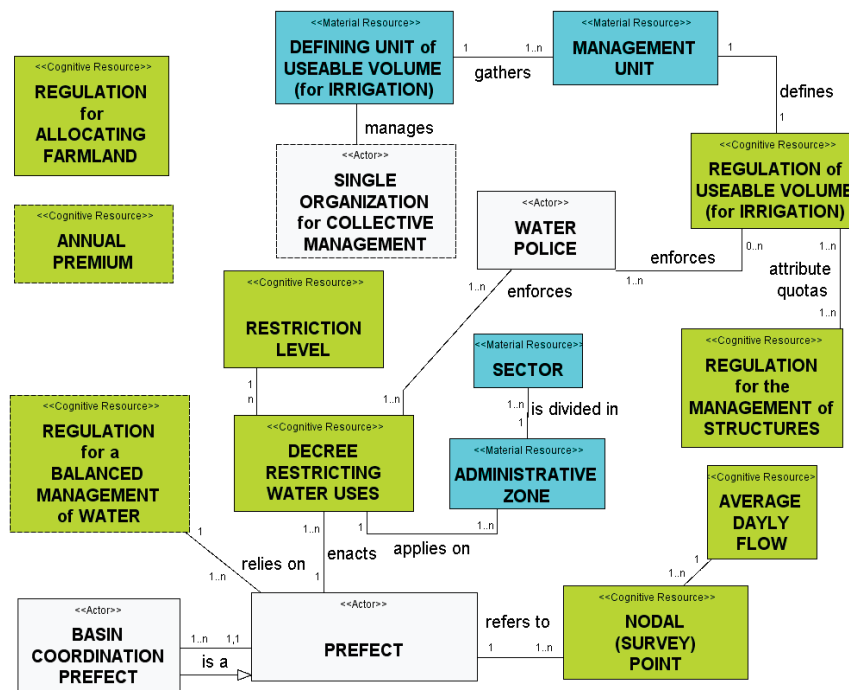


Figure 2. Normative sub-system of the French low-water management system (diagram derived in accordance with the requirements of the meta-model).

Entities are distributed in three types: “actors” (white boxes), “material resources” (blue boxes) and “cognitive resources” (green boxes).

For the sake of clarity the ARD of low-water management is decomposed (with some arbitrariness) in four interdependent subsystems²: the hydrological subsystem; the

² The four actor-resource diagrams can be found on the project website [11/05/2013]: <http://maelia1a.wordpress.com/>

agronomic subsystem; the subsystems of the other water uses (drinking water and water for industry); the normative subsystem (Figure 2).

3. Dynamics of the Low-Water Management Model

The representation of processes and activities making the states of the models entities evolve relies on a variety of tools: model equations (e.g. hydrology, plant growth, demography, etc.), cellular automata (e.g. land cover changes), procedural rules (e.g. decision making about decrees of water use restrictions), or rational decision making.

3.1 Decision-making

Only key virtual actors of the low-water management are endowed with a capacity of rational decision making: the farmers in their planning and managing of sowing, irrigation and harvesting; to a less extent Prefect and managers of dams or other kind of water equipment. The developed model of rationality is relying on a multi-criteria decision-making method based on the *belief theory* (Shafer 1976) and *evidence theory* (Dempster, 1967). This model as allowed to reproduce ~76% of observed decisions concerning crop rotation options taken by irrigating farmers over a 5 years period (Taillandier et al., 2012a).

Procedural decision-making is mainly encoded on the basis of an activity diagram that represents the triggering of predefined actions considering the state of environmental variables (attributes of some material and cognitive resources). Such approach is used in particular to represent and articulate the various steps that goes from the beginning of the low-water period (as detected from river survey), then passing to the convening of the drought cell, etc., till the possible enactment of a decree of water use restriction of a given severity over a well-defined territory.

3.2 Activity Modeling

Without entering into details, the *main* actors' activities modeled and coded in the platform are: crop management and crop rotation; sowing, irrigating and harvesting; preparing and enacting decrees of water use restrictions; withdrawing and distributing raw or treated water; releasing water from reservoirs (dams, hill reservoirs, etc.); controlling water uses and sanctioning water misuses; consuming / rejecting water (drinking and industrial waters). The market-like (e.g. agricultural inputs, agricultural products, tariffs of water consumption, etc.) and policy-like (e.g. agricultural premium) dynamics are accounted for in the form of time series ("external activities") not modified by the time evolution of the states of the platform entities.

3.3 Process Modeling

The *main* processes modeled in the simulation platform are: water / soil / plant interactions and plant growth (mainly crops); large-scale low-resolution hydrological processes and flows (using a SWAT-derived algorithm; Thérond et al., 2013); land cover and land use (LCLU) changes in the Adour-Garonne basin (e.g. Nguyen et al., 2012); evolution of the demography at the municipality level (disaggregating the demographic scenarios of the INSEE - 2011 model); diffusion of technological innovation on farmers' social networks.

The past and future (scenarios) spatiotemporal evolution of the precipitations, ground-level air temperature and evapotranspiration are treated as external processes, relying in particular on the time series provided by CERFACS (Pagé and Terray, 2010).

We have also developed a multi-scale integration scheme allowing the transfer of information between low resolution hydrological processes (hydrographic zones), medium resolution demographic and water use processes (municipalities), and processes represented at the metric resolution over the agricultural parcels (Figure 3).

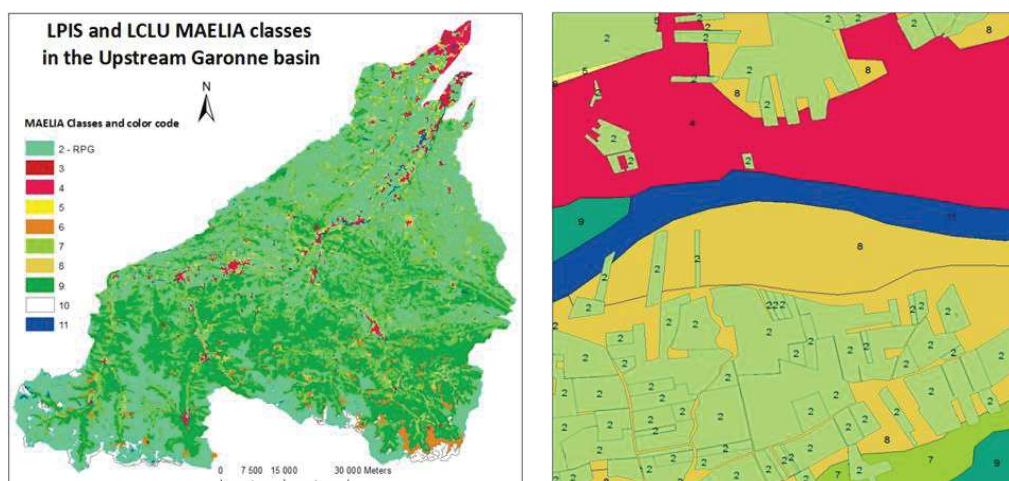


Figure 3. Multi-scale interlocking of territorial entities. Left: low and medium resolution: hydrology + land cover-land use; Right: high resolution: positioning of water resources, water uses and agricultural parcels (land use class #2; spatial positioning from LPIS, 2010; this example on a small area).

This multi-scale scheme limits the spatial resolution of hydrologic dynamics (and associated computation time) which fine detail is not required for the simulation of scenarios of water management on the horizon of several decades, while representing at the metric level the positioning and dynamics of both water resources on territories, farms, their irrigated parcels and crops.

4. Data Gathering, Harmonization and Integration

The data collected from many providers (State or private agencies, public web sites, interviewed key-actors, etc.) have to be gathered and integrated into a coherent simulation model. They are of different types like quantitative empirical observations, numerical model output, maps or texts, etc. Heterogeneous data space or time resolution, or “definition” often require to link data sets through simple but explicit (and thus revisable) rules (e.g. allocating the volume of withdrawn water aggregated at the municipality level to the most likely “reservoir” – water course, lake, dam, groundwater, etc.). The main information layers included in the GIS-module of the platform concern the localization of water resources and withdrawn volumes, populations and LCLU maps, precipitation data, farms and their irrigated parcels, etc. It includes in particular the localization (and values) of the sections of water courses and surface waters (IGN, 2013), near-surface groundwater, under-water surfaces (large watercourses, masonry basins, floodplains, etc.; IGN, 2013), reported withdrawn water volumes and points of agricultural levies (AGWA, 2013), nodal points where the river flows are surveyed and compared to the regulatory flows (AGWA, 2013), likely extension of decrees of water use restrictions, Corine Land Cover maps of the LULC in 2000 and 2006 (CLCF, 2013),

French land parcel information system (LPIS, 2010), administrative and hydrological limits (municipalities, departments, hydrographic zones, water basins, etc.). Regulatory maps of the authorized abstraction water volumes for irrigation (quota) and corresponding delimitation of the sub-basin under the authority of the single organism for collective management is expected soon. On Figure 4, a hydrographic area is covered with patches of different land classes (urban, suburban, forest, arable land, pasture, etc.) each with different water flow characteristics.

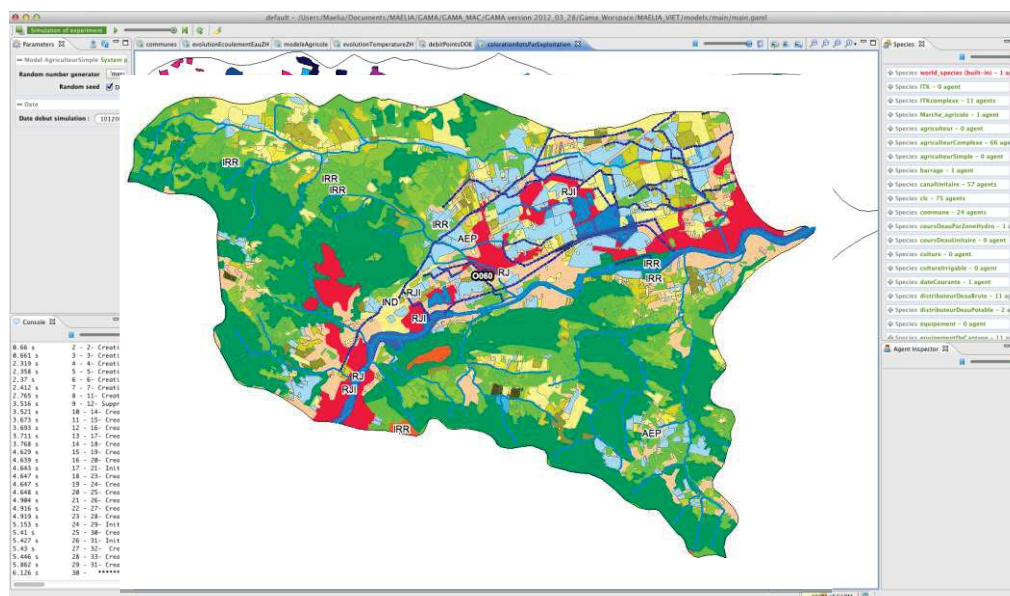


Figure 4. GIS layer in the Gama-based environment of the simulation platform here showing the distribution of land use classes over a hydrographic zone, and the list (right column) of the entities involved in its state evolution.

Different types of crops are planted on the parcels, each crop defining specific needs in terms of irrigation water, which is withdrawn from specific points on the water reserves of the area. The whole simulation platform is developed on a Gama-environment (Taillandier et al., 2012b).

5. Low-Water Management Scenarios

From a series of interviews of key-actors of the low-water management in the Adour-Garonne basin, the most important driving forces affecting the future of the Garonne river and which indicators may help to monitor such impacts have been identified and compared to the existing literature on water scenarios (March et al., 2012). We propose initially to produce four main model trajectories (set of values taken by all state variables or attributes of entities of the platform throughout the simulated time period) - thus four scenarios (S11 to S22) - whose impacts can be assessed and compared (Table 1).

Evaluation of social and environmental impacts of various scenarios is done by comparing the corresponding trajectories. The qualitative assessment of impacts relies on indicators that summarize the essential information produced by the simulation, and relevant to the predefined uses (indicators for water managers, for farmers, possibly for researchers, etc.). Some of the main relevant indicators estimated by the platform are: water flow at nodal points of objective flow; surplus / deficit of water (*wrt* objective flow, see Sec. 1.2); frequency of water crisis frequency; yield of irrigated corps;

agricultural production; sustainability of farms; changes in patterns of crop rotation; total and irrigated surfaces of farms; number of farms; cost of implementation / operation of alternative management policy (in €); acceptability (norm compliance, satisfaction level of various actors) of the implemented regulations or management devices.

Table 1. The four main scenarios to be simulated.

| | | Water Management by | |
|--------------------------|--|---------------------|---------------------|
| | | Water Flows | Abstraction Volumes |
| Climate Change Scenarios | Business as usual | S11 | S12 |
| | Reduction of precipitations in low-water periods | S21 | S22 |

Presently several process dynamics and activities have been “encapsulated” in sub-systems of the platform (large scale hydrological dynamics forced by climate scenario on precipitations; LUCL dynamics including urbanization and fallow development with the loss of some farms; plant growth and soil interactions for various kinds of crops; implementation of farmers’ crop management and activity development on their respective parcels; etc.). However the production of the full model trajectories is not yet performed. Note that a full description of the platform conception, design and implementation is developed and maintained.

7. Discussion

A simple approach to account for norms is sufficient to simulate satisfactorily basin-scale low-water management in France: in fact these norms mainly define the framework of procedural decisions (Sec. 3.1), or the volume of water available at a given time and place for a given community (see Figure 2). Agents’ rationality applies primarily for decision making about actions (irrigation, water release, crop rotation, etc.) constrained by the state of resources (crop growth, rainfall, weather forecast, agricultural calendar, etc.). Another part of the “system control” is external to its evolution, such as the level of annual premium to agriculture or the rules of agricultural land allocation, and play like a kind of top-down constraints. Thus the representation of truly “*normative*” rational agents is not necessary given our objectives.

The simulation of the dynamics of the state variables (attributes of entities) produces the information required to estimate and represent the spatial (maps) or temporal (time series and curves) evolution of useful indicators for decision-making regarding management options desirable considering their likely impacts. These indicators are first developed with managers and policy-makers to ensure their relevance and usefulness.

Thus the project quickly presented here has several advantages which integration in a simulation platform is probably an innovation: the design of a methodology for sharing knowledge from various disciplines involved in the analysis of the management of water resources; the design and operation of a rigorous framework for integrating this knowledge that leads from the formalization of the knowledge on the reference social-ecological system to the implementation of a model for the simulation of scenarios; the inter-operability of various simulation tools (equations, cellular automata, multi-agent models of rationality, GIS). All together they allow the multi-spatial / temporal scales

and multi-level transfer of information between entities linked dynamically. They produce simulated scenarios that fit closer to the territorial dynamics of the real system and indicators that make sense to the resource-manager or decision-maker.

6. Conclusion

We would like to conclude with a few general comments: a) the integration of knowledge and its formalization in simulation tools useful for managers is possible; b) the modeling process supports the clarification and explicit representation of knowledge; c) it identifies the relevant data and put constraints on their definition, acquisition and storage given an integrative purpose; d) finally though the analysis of *ex ante* simulation scenarios induces an additional constraint on the political scene or in decision-making forums, it is becoming an essential tool for resource and environmental management which must be associated with a culture of temperance.

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