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Abstract. The regulation of water use and water management has evolved considerably in recent years. The evolution of water regulatory systems includes the design of new management policies, which could benefit from *ex-ante* comparative impact assessments with regard to those of current or past practices. To this aim, the MAELIA project develops an integrated modelling and simulation platform for the assessment of alternative water management policies, especially during low-water crisis in the Adour-Garonne basin (South-West region of France). The development of such an integrated assessment and modelling platform requires the consideration and integration of many entities and processes involved in the system under consideration – water resources and flows, agricultural structures and activities, state and evolution of land cover and land use, etc. This article focuses on the formal representation of two alternative options regarding the choice of water withdrawal policy, which are likely to have considerable impacts on the whole socio-hydro-system s: management by rate of flow (currently applied); and management by volume quotas (alternative to be assessed). Furthermore, the article presents a conceptual framework for the integrated modelling of such social-ecological systems together with graphical notations for models' representation.

Keywords. Quantitative Water Management, Regulatory Impact Assessment, Policy-making, Socio-Ecological Systems, scenario, agent-based modelling, simulation.

1- Introduction

Water is a critical resource for a number of social and human activities and for the sustainability of ecosystems. Hence, societies pay great attention to the preservation and usage of this public good, with complex systems of norms, infrastructures, administrative bodies and devices aimed at organizing and regulating the water-related activities (Noël, 2009). At the time being, water regulatory systems come into question (Wallace and Wouters eds., 2006), since they become more and more complex (Bourcier et al., 2012) and suffer

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many adaptations to face: (a) changes in the nature of the demands and needs regarding water, due to the general evolution of human activities; (b) more ambitious objectives for the water-dependent services, e.g. the availability and quality of drinking water or the control of floods, and for the sustainability of aquatic ecosystems; and (c) issues raised by the climate change. In future decades, water scarcity will continue to be a major constraint for human activities, more particularly for agriculture (March et al., 2012).

In France, the implementation of the European *Water Framework Directive* (WFD 2000/60/EC) led government to reconsider the management of the agricultural use of water resources during low-water periods. The main objective of the Directive is the protection of aquatic ecosystem by ensuring that regulatory water flow rates will only exceptionally be crossed (Debril and Therond, 2012). The evolution of water regulatory systems includes the design of new management policies, which could benefit from *ex-ante* comparative impact assessments with regard to those of current or past practices.

To this end, the potential of model-based methods is well established for the analysis of management and policy issues, and approaches consisting in the simulation of various scenarios are increasingly applied in integrated assessment and modelling enterprise (see e.g. Sterk et al. 2009, McIntosh et al. 2007, Jakeman et al. 2006, Oxley et al. 2004). The MAELIA project develops an integrated assessment and modelling platform for the simulation of various options concerning the quantitative management of water resources during low-water periods, in the Adour-Garonne basin (covering the whole South-West region of France), which suffers a serious structural deficit in water resources.

Therefore, the aim of the MAELIA project is to jointly assess the environmental, economic and social impacts of alternative management policies (Gaudou et al., 2013). In particular, it focuses on the consequences of various regulations concerning agricultural water withdrawals corresponding to the current management, the new regulation whose implementation is in progress, and the management strategy proposed by farmers. To this end, the simulation model represents the interactions between hydrological processes (water flow, interactions with land cover, etc.), agricultural processes (growing of crop, cropping plan decision and crop management including irrigation) and water management processes (the focus of this paper) for each one of the low water management scenarios subject to assessment. We must note that , due to the nature of the question under consideration, the spatial resolution of the model is quite fine: the elementary sub-watershed for hydrology, the field and farm for agriculture.

The structure of the article is the following: after an outline of the regulatory French framework concerning the quantitative management of water resources (section 2) and a presentation of four scenarios to be considered (section 3), we present our proposal to model the social processes that enact the management scenarios and their relationships with the main hydrological and agricultural processes (section 4); finally, some discussion topics and conclusions are presented in section 5.

2- The French Framework for the Water Resource Management

The current water regulatory system is a hierarchical construct that extends from the European level, which defines long term general principles and objectives, to the elementary watershed level, where concrete operations take place. In the present section we outline the legislative basis and the main tools usable for the prevention and management of low-water periods, a key domain in water policy matters (see Gazzaniga et al. 2007 for full details).

2.1 Legislative bases and fundamental principles[2]

1. **European level:** The European Water Framework Directive (WFD 2000/60/EC; 23rd of October 2000) defines a strategic framework for water policy for the 27 Member States of the European Union. It sets out common objectives, timetables and working methods regarding mainly the availability of good quality water, the preservation of aquatic ecosystems.
2. **National level:** Although some bases of the French water policy go back to the 16th century, the current organization relies fundamentally on the Law of 16 December 1964, which organizes water management at the level of river basins. It has been supplemented according to updates in the objectives and changes in the situation, notably by: **(a)** the Law of 29 June 1984 ('Law on Fishing'); **(b)** the Law of 3 January 1992; **(c)** the Law of 21 April 2004 and the Law on Water and Aquatic Ecosystems of 30 December 2006 (LEMA, Law 2006-1772) both transposing the European Water Framework Directive into French law; **(d)** the Grenelle I and Grenelle II Laws, with the Environmental Code.
3. **Basin-river level:** The Basin Committee is the 'water parliament', which is composed of local authorities (40%), representatives of all users and stakeholders (40%) and the State services (20%). It defines the objectives to be reached, the overall orientations of water management and the means to bring into use in the basin. It adopts and monitors the SDAGE (*Water Management Master Plan,* "*Schema Directeur d'Aménagement et de Gestion des Eaux*"; see SDAGE 2009 for the Adour-Garonne basin) whose application is entrusted to various agencies and local authorities in charge of specific missions and duties. The Water Agency in charge of implementation of the SDAGE is funded by a tax paid by all the users of water resources.
4. **Watershed level:** This is the 'operational' level of integrated water management. In the Adour-Garonne basin, most issues regarding water uses and the preservation of aquatic ecosystems are related to water scarcity. Thus, many actions concern the prevention and the management of water scarcity, and they are guided by sub-basin scale "low-water management plans" (hereafter PGE for "*Plan de Gestion des Etiages*"[3]). A PGE aims at enabling a long-term satisfying coexistence of all the water uses (drinking water, industry, energy, agriculture, fishing, tourism and sport) together with the sustainable functioning of aquatic ecosystems. Many measures concern agriculture, which alone consumes 80% and withdraws 50% of the water in low-water periods, while the expansion of drought periods leads to an increasing demand for irrigation. After policies favouring irrigation (in the 1990s) and focused on increasing the offer (in the 2000s, by means of building dams and reservoirs and favouring water pumping in rivers and aquifers), from now on priority is given to the moderation of water demands in order to avoid resorting to new resources[4]. This means a stronger regulation, that aims in particular to a better use of the existing water resources, a rationalizing irrigation and reducing water leaks and wastage.

2.2 Main tools for low-water policing

The main management tools r for the control of the amount of water available for irrigation are the following:

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[2] Legal texts can be found on the EurLex http://eur-lex.europa.eu/en/index.htm and LegiFrance (part of the French legislation being translated in English) www.legifrance.gouv.fr/ web sites.

[3] Documents related to low-water management plans of the Adour-Garonne sub-basins are available on http://www.internet.eau-adour-garonne.fr/page.asp?page=1195

[4] In line with social protests against the building of big equipments that disturb the natural functioning of ecosystems.

a. **Authorization and declaration of water withdrawals:** The annual maximum volume, which can be abstracted from a withdrawal station by a drinking water provider, industrialist or farmer, is granted by a prefectural authorization. Each water withdrawal device must be equipped with a counter that measures the abstracted quantity, which has to be declared at the basin's Water Agency if it is over 5000 m^3 per year.

b. **Monitoring points and regulatory flow rates:** During the low-water period, the flow rate of streams and rivers are measured at so-called *monitoring points*. Water flow measurements allow computing the Average Daily Flow (QMJ, *Débit Moyen Journalier*). For each point, the following reference thresholds are defined, from higher to lower:

   - DOE (*Débit Objectif d'Etiage, Objective Low-Water Flow*): minimum water flow that does not endanger the functioning of aquatic ecosystems;
   - QA (*Débit d'alerte*, *Alert Flow*): alarm threshold, defined as 80% of DOE;
   - QAR (*Débit d'alerte renforcé*, *Reinforced Alert Flow*): reinforced alarm threshold, defined by the formula QAR = QCR + 1/3 (DOE − QCR);
   - QCR (*Débit de crise*, *Crisis Flow*): crisis threshold under which there is a risk for drinking water provisioning.

   The monitoring points' measurements serve to assess the current state and the *trend* over the last 3 and 7 days of water resources. They provide decision-makers with information to engage appropriate restriction measures in response to the current situation. Such responses usually consist on the application of a set of measures of increasing severity, giving priority to domestic and industrial water uses. In addition, some monitoring points are strategic and their DOE and QCR thresholds are regulatory flow rates fixed in the SDAGE.

c. **Reserved flow:** All water dams and lake reservoirs have a *reserved flow;* that is, the minimal flow rate that the infrastructure must constantly release to feed a river, under the responsibility of the operator.

d. **Water release:** Both the Water Agency and the local authorities contract with operators of water reservoirs (or any infrastructure destined to water storage) in order to buy a specified volume of water that shall be preserved for possible low-water crises. When the flow rate approaches the DOE threshold at some monitoring point(s) and if there is an upstream reservoir, the local authorities prompt its operator to release water, at a specified flow rate, over a given period of time. In some watersheds they also have to fully compensate agricultural withdrawals, whatever the measured water flow. The contracted water volumes are framed by the PGE. These water releases are dependent upon many constraints: maximum flow due to dam and river characteristics; allowed period of release (e.g. due to touristic activity); transfer time between the dam and the targeted monitoring points, emptying curve of the reservoir that indicates, according to the current stock of water, the probability (e.g. 2/3) to have enough water to release until the end of the low water period. Furthermore, due to the transfer time of water between dams and associated monitoring points, water releases have to be anticipated. However, since information on irrigated areas for the current year and farmer irrigation strategies along the time is usually lacking, authorities are obliged to estimate agricultural water needs on a daily basis. To this end, they use local references on irrigated crop areas and needs, which enable them to daily estimate the water flow needed to respect the compulsory flow at the monitoring points.

e. **Drought Decree:** During low-water periods, and depending on rivers' water flow rates, State services hold a *Drought Cell* gathering local authorities, dam managers, representatives of water users and local associations for environment protection, possibly several times a week. Within the framework stated by the PGE and SDAGE principles, Drought Cell members debate and negotiate about the appropriateness to limit water withdrawals. Then, in accordance with the upstream-downstream solidarity principle (that is, considering the dependence of the downstream watersheds towards the upstream ones) and the progressivity of the restrictions, the Prefect might decide to issue a Drought Decree that states withdrawal limitations or prohibitions in some places and for some duration (no less than one week). There exists a Generic Drought Decree (a template) that defines the pattern of any particular decree (cf. Arrêté cadre interdépartemental fixant un plan d'action en cas de sécheresse pour le bassin de la Garonne, 2004).There are three levels of restriction, which are more or less determined by the hydrological state and trends at the monitoring points with regard to their thresholds, and have globally the following effect concerning irrigation:

- QA < QMJ < DOE: alarm threshold, withdrawal is forbidden 1 or 2 days a week,
- QAR < QMJ < QA: first crisis, withdrawal is forbidden 3 or 4 days a week,
- QMJ < QCR: increased crisis, withdrawal is forbidden 7 days a week.

f. **Compliance control and sanctioning**: The afore-mentioned tools set a regulation regarding availability of water resources and their uses. Regarding irrigation, water police is ensured by the *ONEMA (Office National de l'Eau et des Milieux Aquatiques*, National Office for Water and Aquatic Ecosystems) and decentralized State services which control compliance with regulations. A detected infringement is verbalized in an official report which is then transmitted to the relevant administrative authority and, if needed, to the corresponding court of justice. Notwithstanding the possible sanctions (penalty or public disapprobation) entailed by infringements, farmers may prefer not to comply with regulatory norms, if they are felt too inappropriate or somehow endangering the farm.

3- Low-Water Management Options: from constant Volume-Quota *to daily* Flow-Rate management

So far, individual farmers or farmer associations apply every year, during spring, for water withdrawal volumes to State services in charge of the application of water regulation. After verifying that farmer demands are in compliance with general current regulation (e.g. the low-water management plan), State services notify farmers with the water volume (or flow) they are authorized to withdraw during the next low-water period. In fact, since State services have not the information that would enable them to accurately estimate the consistency between farmers' requests, farmers' needs and the available water resources in each watershed, they grant every year water withdrawal authorizations that correspond to farmer's requests. Water withdrawal authorizations are not a constraint for farmers since the current practice is to request an amount of water that is most often over their real needs (i.e. over the farmer's maximum water withdrawals of the past years). In such context, although quantitative water management is officially based on water volume and withdrawal authorizations; *de facto* it is based on observed flow rate, water releases intended to maintain water flow rates over the regulatory thresholds and drought decrees. In other words, local State services must regularly manage "water crises" and the non-respect of regulatory flow rates, especially in the Adour-Garonne basin which suffers an average annual deficit between demands and resources of 250 million m^3.

Noting the large number of river basins that present chronic deficits, the Law of 2006 on Water and Aquatic Ecosystems instituted a new way to regulate agricultural water withdrawals. One of the objectives of this law is to prevent water crises, that threaten the functioning of aquatic ecosystems, and to resort to water drought decrees no more than one year out of five on average. Its implementation, still in progress, led regional State services to determine for each elementary watershed the water volume that remains available for agriculture the driest hydrological year over a 5-year period (moving window), once the priority needs are satisfied[5]. This volume is to be distributed among the farmers of each Water Management Area (a coherent assembly of elementary watersheds) by an Organization of Collective Management – a local and participative organism to be instituted for this mission. Indeed, another objective of the law is to decentralize the distribution of withdrawal authorizations at the watershed level and to unload the State services from this conflict prone task. In many watersheds, the water volume estimated by State services is (largely) under the water volume currently withdrawn by farmers during normal or even dry climatic years. This reduction of available water volumes for irrigation has given rise to vehement protests of farmers and their representatives. They argue that four years out of five such a water management leads to restrict agricultural water withdrawals greater than necessary in order to ensure a safe water flow in rivers. Farmers claim that the only way to manage water in river basins in order both to ensure viability of current farming systems and to preserve aquatic ecosystems is to manage the resource according to the effective daily water flow.

Given this water management issue, the MAELIA platform will be used to perform an integrated impact assessment of four water management options:

(a) ***Management by rate of flow:*** the scheme currently applied and solicited by farmers, where the only way to manage low-waters relies on water releases and drought decrees that constitute, for a given period, adequate water use restrictions in order to maintain water-flows over the regulatory rate thresholds;

(b) ***Management by pluri-annual volume quota:*** the management option that the Water Law of 2006 is instituting, where farmers of each Water Management Area are assigned a predetermined volume that they may use at their discretion during the entire low-water period;

(c) ***Management by annual volume quota:*** a refined alternative of the previous option, the volume for the next low-water period is determined during spring according to the state of water resources and weather forecast at that time, instead of being defined once for all by means of hydrological statistics;

(d) ***Management by weekly or monthly volume quota:*** volumes are periodically defined and published according to the current water resource state and weather forecast, and thus farmers are assigned a determined volume each week or month. This last option is the most dynamic and accurate management option by volume quota. However, it presents some organizational difficulties due to the fact that the available quota must be calculated every time step, depending on the current and expected water flow rates and weather forecasts. An accurate calculation of the volume of water available (once subtracted the minimum volume for other essential uses and needs of aquatic ecosystems) implies using precise forecast hydrological models relying on constant updates on weather forecast and a careful monitoring of water flow rates at strategic monitoring points. Though being organizationally more demanding, this policy would ensure the optimal agricultural use of water resources, while respecting the spirit and objectives of the French Water Law in particular regarding the sustainability of aquatic ecosystems: a management based on volume quota ensuring a balance between water needs and resources. In fact, a management based on authorized volumes is merely an artefact to ensure a water flow that satisfies the needs of users and aquatic ecosystems, since a management by volumes defined for short periods results in a management by flow.

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[5] This volume is determined by the value of the DOE regulatory threshold, whose setting is the object of controversial debates, since it is nothing but a social definition of the good state of aquatic ecosystems .

These four management options integrate water releases during the low-water period both to compensate for agricultural withdrawals and to maintain water flow over the regulatory rates. They also integrate water drought decrees, similarly to the present rate of flow management option. The weekly volume quota option may avoid resorting to drought decrees and the monthly volumes quota option should have a limited use of this institutional instrument. One worthy finding of the MAELIA platform would be to determine the longest forecast period that does not oblige local authorities to resort to drought decrees to manage low-water periods. As for farmers' decisions concerning irrigation, the options (a), (b), (c) and (d) require specific rationalities which are increasingly demanding. Hence, in the following sections, we present MAELIA's modelling framework to evaluate those alternatives.

4- A Modelling Framework for a Normative Multi-Agent System

Integrated Assessment[6] is the natural approach to cope with questions about socio-ecological systems (SES). Based on modelling and simulation, the Integrated Assessment and Modelling of a SES requires a conceptual framework which serves to organize the knowledge brought by a wide range of scientific disciplines into a coherent description of the SES and allows an operational statement of the question under study (Toth and Hizsnvik 1998). The MAELIA project relies on a meta-model (Sibertin-Blanc et al. 2011) that identifies the types of the constitutive elements of SESs that have to be considered together with their relationships. According to this view, the model of a SES consists in a set of entities (its structure) weaved with a set of processes (its dynamic).

4.1 Structure of the system: *actor-resource diagrams*

The *structure* of a system is composed of *entities* and *relationships* between them. Entities are characterized by attributes, whose values constitute the state of every entity instance, and they are endowed with operations (or methods in the object-oriented terminology) that process attribute values. The meta-model we have developed distinguishes three categories of entities:

- ***Actors*** are human agents that perform some activities, be they an individual, a population of similar individuals or a collective (e.g. institution, association, etc.);
- ***Material resources*** are physical objects, spatially and temporally distributed (e.g. a water body, a field plot, a dam), involved or taking part to the system functioning;
- ***Cognitive resources*** are information, believes, expectations, aims or procedural knowledge that actors use or consider in the activities they undertake, in the formation of goals, in designing strategies or in their operational decision-making processes.

The structure of a SES is graphically represented by Actor-Resource Diagrams that follow the notations of UML class diagrams. The actor-resource diagram of Figure 1 shows the types of the main entities involved in the management of low-waters. The entities' attributes and operations, as well as the association cardinalities, are not mentioned to keep the diagram easily readable.

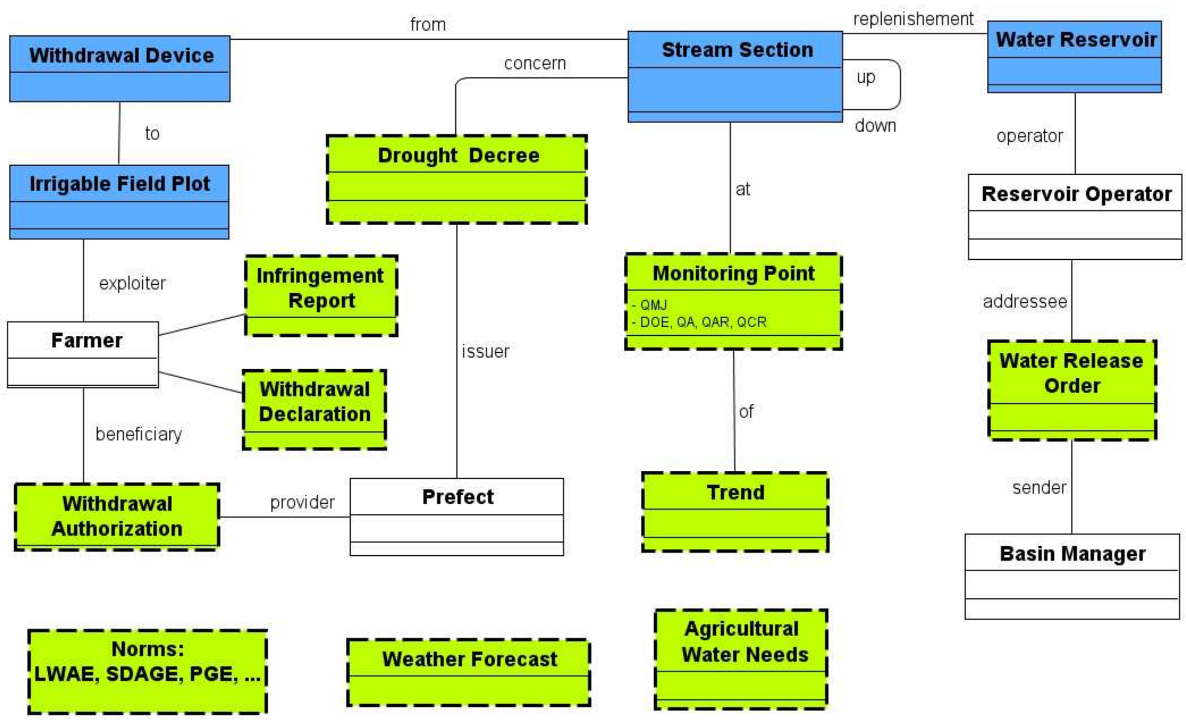
The model includes the types of actors "Prefect", "Farmer", "Reservoir Operator" and "Basin Manager". Prefect represents the individual that occupies this administrative position in the considered basin and it also includes State Services that are under his authority. There are as many instances of the type Farmer as the number of farms in the basin area, and the same holds for the Reservoir Operator type with regard to the water reservoirs in the basin. In each

[6] Rotmans and Asselt (1996) define Integrated Assessment as "an interdisciplinary and participatory process to combine, interpret and communicate knowledge from diverse disciplines".

basin, there are about ten (or even more) organizations having various legal statuses that take part in the management of water, only a few of them being mentioned in section 2 of this paper. There is no conflict between these organizations and they work in the same line; therefore, the model solely includes a single instance representing the Basin Manager actor; an agent who gathers local authorities and performs all the management tasks that are not attributed to another actor.

The types of material resources shown in Figure 1 are “Water Reservoir”, “Stream Section”, “Withdrawal Device” and “Irrigable Field Plot”. Only those water dams and lakes that are used as reserved flows or for releases (cf. 2.2.3c and 2.2.d) are instantiated as “Water Reservoirs” in the model. Stream Section instances are portions of river or stream, and more generally water bodies, that are concerned by Drought Decrees or have a Monitoring Point (please note that the model does not cope with the measurement devices of Monitoring Points). The up/down relationship between Stream Sections allows us to describe the flow of water in the hydrologic network and the up and down-stream solidarity principle of Drought Decrees.

The main cognitive resources used by actors for water management are « Drought Decree », « Infringement Report », « Monitoring Point », “Withdrawal Declaration”, “Withdrawal Authorization”, hydrological “Trend” and “Water Release Order”; they have been introduced in section 2.2. For the management options (b), (c) and (d) described in section 3, the actor-resource diagram of Figure 1 must be completed by material and cognitive resources related to the Water Management Areas. In addition, cognitive resources such as taxes paid by Farmers (and other water users) to the Water Agency or emptying curves[7] used by Reservoir Operators are omitted because, as explained in the next section, they are not involved in our model of the processes. However, the MAELIA platform includes a careful model of cognitive resources, since they are essential for the understanding of the influence of the management options on the actors’ behaviours and ultimately on the ecological, economic and social state of the system.



[7] A table that indicates, given the day and the remaining amount of water, the probability to be able to satisfy the needs of release until the end of the low water period.

Figure 1. Core of the Actor-Resource Diagram for the management of low-water.

4.2 Dynamics of the system: interaction and process diagrams

The dynamic character of SESs is modelled through the processes that generate the phenomena under study. Processes handle entities, and thus make the state and possibly the structure of the system evolve (e.g. disappearance of fields due to urbanisation). Three types of processes are distinguished:

- An ***Activity*** is a process executed by an actor intending to achieve some goals (e.g. irrigate a field plot; issue a drought decree; etc.).
- An ***Ecological process*** corresponds to the realization of interactions according to biophysical laws that determine the evolution of material resources (e.g. run-off of water; growing of crop; etc.).
- A ***Socio-economic process*** generates phenomena resulting from human beings' economic or social activities (e.g. change in land cover and use; the evolution of a market). Unlike activities, the model does not detail the embodiment ("who and how") of socio-economic processes.

Interactions between processes take place through their common uses and effects on the entities of the system structure: at each time-step of a simulation run, the current state determines the processes which are enabled and the processing they have to do, while the executions of these processing determine the system state at the next time-step. The structure of a SES may be viewed as the interface, or the glue, between its processes. Due to this conceptual representation of the way processes interact, each process can be described independently once all the members of the integrated modelling process agree on a common description of the SES structure.

The MAELIA platform includes a number of ecological processes related to hydrological dynamics (using the SWAT "*Soil and Water Assessment Tool*" model (Oeurng et al. 2011) and crop growth. It also includes socio-economic processes dealing with demography, land cover, domestic and industrial water uses (Gaudou et al., 2013). Here, we focus on the treatment of activities related to low-water management performed by the Prefect, Basin Manager and Reservoir Operator actors. The activities performed by Farmer actors (cropping plan decision and crop management) are presented in (Taillandier et al. 2012).
MAELIA simulations will be run over a twenty to thirty-year period, during which the fundamental principles presented in section 2.1 might be subject to some changes. However, the MAELIA platform does not consider the processes of law and policy adaptation and emergence that make these principles evolve or that motivate the implementation of new tools for low-waters' management (cf. 2.2). It only includes elements of the regulatory system that are involved in the concrete exercise of water management during every low-water period. Hence, the model does not deal with highly unpredictable activities or socio-economic processes such as the following:

- setting the level of water use taxes;
- setting the volume of contracted water;
- setting reserved flow;
- locating monitoring points and fixing their thresholds; or
- delineating the Water Distribution Areas, and so on.

Similarly, the model includes no process concerning the Drought Cell functioning (cf. 2.2.5). *Firstly,* it appears very difficult to model the yielding and the content of its meetings.

Secondly, this cell seems to mainly serve as an arena where stakeholders exchange information and State services present and argue the Drought Decree(s) that they foresee implementing during the week to come. It also allows preventing conflicts by the building of a shared representation of the hydrological and agricultural situation. The review of its functioning reveals that the Drought Cell plays a very important role for the quality of the social relationships among human actors in the system, but it has a limited impact on the statement of Drought Decrees. As a consequence, it does not influence the effective implementation of water management policies and, since our model does not comprehend agent's emotional state, it reveals to be irrelevant for the objectives of our simulation platform.
Following the same logic, MAELIA does not model a number of activities that influence the dynamics of low-water management but whose results can be automatically enforced in the state of the impacted entities. This concerns processes that: (1) become trivial in the simulation numeric world, such as the measurement of QMJs at monitoring points, the computation of trends or the diffusion of Drought Decrees; (2) are just the formal application of a compulsory norm but are actually ineffective in the SES, such as applying for withdrawal authorization and declaring the withdrawn volume of water in the mentioned scenario (a); (3) are somehow automatic and raise no significant doubt about the result of their performance such as the purchase of contracted volumes, the respect of reserved flows, the execution of Release orders by Reservoir operators, or the payment of taxes. Concretely, MAELIA includes a detailed model of the promulgation of Drought Decrees, the water release from reservoirs and the control of the farmers' compliance with withdrawal restrictions. Such a simplification focuses the model on the question that it is intended to highlight, limiting a complexity whose excess makes intractable the understanding of simulation results.

The essential of interactions between processes and entities are graphically represented by means of *Interaction Diagrams* as in Figure 2. An Interaction diagram displays processes and the entities they impact, the actors performing the activities and the main cognitive resources they consider. It reads as follows: a dashed-arrow corresponds to an ecological or socio-economic process and it connects the main resources impacted by its occurrences; an arrow corresponds to an human activity, whose source is the actor responsible for its performance and its target is the main impacted resource (an activity may also control an ecological process, as the "irrigate" and "release" activities that control the natural flow of water); finally, a grey line between an actor and a cognitive resource means that the latter is essential for the actor's activities.

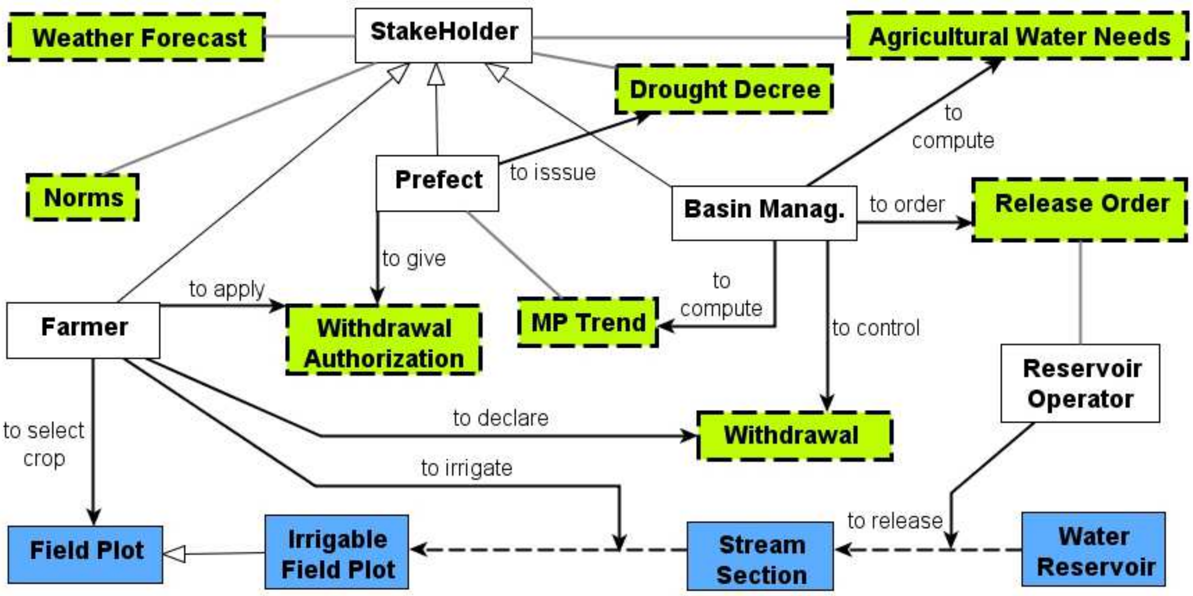


Figure 2. Interaction Diagram of the main activities related to the management of low-water, option (a)

Farmer, Prefect and Basin Manager are Stakeholders (an abstract actor type) that carefully consider the cognitive resources of types “Norms”, “Weather Forecast”, “Agricultural Water Needs” and “Drought Decree”. In addition, the Prefect considers the Trend of Monitoring Points (MP trend) and Dam Operators consider the Release Orders. Figure 2 shows the activities for the management option (a). In option (b), any Withdrawal Authorization is no longer given by the Prefect, but by the new actor in charge of the distribution of water quota among the Farmers within each Area. Options (c) and (d) include in addition the Basin Manager’s strategic activity that determines the available volume of water in each Area for the considered period (year, month or week).

A *Process Diagram* describes the dynamics of a process at the required level of detail. The dynamics of a process is described by systems of equations, automata, algorithms or systems of (event-condition-action) rules, according to the most appropriate way for the researchers in charge of its representation. Given phenomena under interest each process has its own relevant *temporal (and spatial) resolution* that determines how it must be dealt with by the simulation engine. Figure 3 presents a UML activity diagram describing the dynamics of the water releases management and the Drought Decree resorting. Other examples of such diagrams are available on the MAELIA web site (cf. MAELIA project 2012).

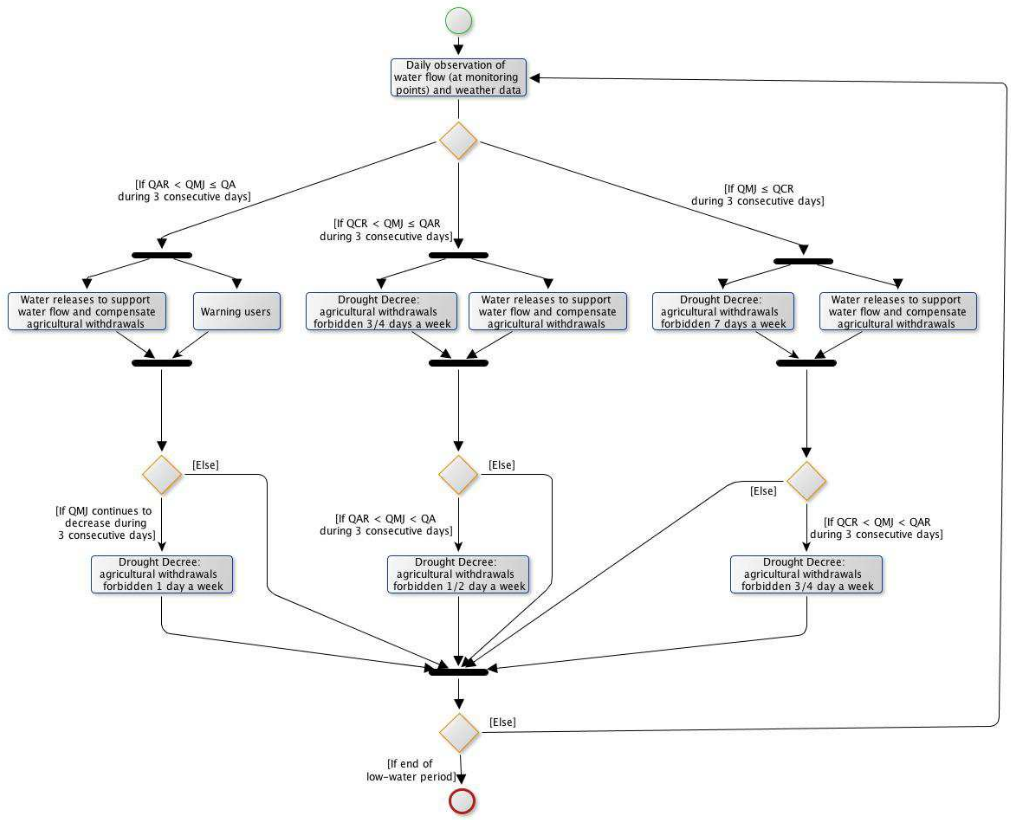


Figure 3. Sketch of an activity diagram describing the decision-making processes regarding water releases management and publication of Drought Decree, in watersheds where the water flow at the targeted monitoring point can be supported through releasing water from dams.

5 Discussion and Conclusion

The understanding of norms in complex systems is one of the most active fields of research in multi-agent systems (e.g. Leite et al., 2011; Jiang et al., 2012). This is challenged, however, by the difficulty of comprehending the recursive inter and intra-agent dynamic interactions. The specific strength of multi-agent systems as a modelling approach is that they allow representing social and institutional relations among agents, resources and norms and thus enable us to capture more accurately socio-normative (including socio-legal) phenomena characteristically involved in norm compliance issues.

This article presents elements of the methodology and results of formalizing the French regulatory framework for managing low-waters and low-water crises implemented in the multi-agent based model of the MAELIA platform. Variants of the regulation (e.g. management by the water volumes *versus* management by flow rates) are quite easily formalized and implemented in the platform by relying on a robust meta-model of socio-ecological systems, that eases the integrated modelling. The direct and indirect effects of these variants of the regulation are recorded through indicator values computed by the MAELIA platform. These indicators represent the final state, the variation or the variability of social, economic and ecological state variables of given individual entity or class of entities on a period of several decades. Among others, MAELIA will be able to produce all the data regarding the previous low-water management campaign that are reported to the members of the Drought Cell at the start of each low-water period.

These simulation results, together with necessary precautions for their use given the limitations inherent in any modelling approach, are of interest for various water stakeholders, in particular: the Water Agency, which coordinates the preparation of SDAGE and low-water management plans; the State services which are responsible of planning of low-water management and of water crisis management; the dam managers that plan releases of water; the Organizations of Collective Management – being under creation – that will develop local regulations of abstraction volumes for irrigation at the level of Water Management Area. They are also of interest for professionals from various sectors - of course in the first instance farmers. Indeed, the farmers' lack of visibility on the water resource availability due to restrictions by prefectural decrees entails a reduction in agricultural productivity and therefore a weakening of farms sustainability.

In the longer term, the platform will be enhanced by the inclusion of processes that explore other policy options and actors' adaptation strategies such as a change of water pricing (e.g. progressive pricing), the construction of new upstream water reservoirs, the implementation of different rules of allocation between agricultural users (e.g. collective vs. individual allocations), etc. The platform will also exploit the successive updates of the best scenarios of climate change.

We can observe that the regulation and norms framing the quantitative water management (including low-water management) are rapidly evolving in France. The increasing involvement of stakeholders in a participatory management, the conduct of multi-level negotiations and the political games, all determine the standards used in the actual management of resources. However, in the MAELIA project we limit our modeling effort to take into account the results of such collective decision-making processes. We do not intend to reproduce the dynamics of the negotiations, let alone try to predict their most "technical" outcomes (see Mazzega et al. 2012, for a detailed argumentation for this position).

Indeed, field surveys as well as the updating of documents produced by State agencies show clearly that the water management regulation and norms effectively implemented at various levels of governance "encapsulate" the trade-offs between water stakeholders. Moreover, the purpose of the MAELIA model is not to mimic the behaviour of the SES of reference. It is to build a numeric world whose structural and behavioural properties may be credibly interpreted in terms of phenomena occurring in the SES, enabling to compare the respective effects of different management policies.

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