Supplementary Material

A situated agent-based model to reveal irrigators' options behind their actions under institutional arrangements in Southern France

A. Key information from field surveys

a.1) Irrigation practices

At the beginning of the irrigation campaign, crops have already been planted, with no rotations until the end of the campaign in early October. Irrigation options mainly depend of the network hydraulic. The network is watered every first week of May. The flow entering the network is maintain between 90 and 150 $l\ s^{-1}$ at the network intake to prevent overflow on the road or in the village. Due to the functioning of the floodgate at each farm plot, flooding flow is fixed and estimated at 30 $l\ s^{-1}$ by the technician. This flow value also complies with the maximum withdrawal rate determined by prefectural order for the 2017 irrigation campaign. Thus, irrigators have a flood option if the canal branch supplying the plot is flowing enough to trigger gravity-fed irrigation at the floodgate of his plots. Volume adjustment of the irrigation is managed by farmers in terms of duration. If the canal branch supplying a plot is not flowing enough, small adjustments of the network flow consist in small flow increase without reaching the overflow rate. Asking for more water in the canal is thus a second option for the irrigators. In addition, irrigator’s availability to operate irrigation depends on current operation duration and the maximum time they accept to work in a day, which is about 12 hours during highly intensive periods (e.g. harvest periods). They usually flood plot one by one.

a.2) Irrigation decision-making

Operational decision-making is quite homogeneous from one irrigator to another according to the President of the collective institution and the other interviewees. It consists to irrigate crops after a number of days without sufficient precipitation inputs to contain as much as possible a maximum of successive non-irrigated days. Farmers don’t start flood operations when raining and farmers usually do not comply with water restrictions in order to maintain the network flowing and ensure irrigation, which is tolerated by the water police for these specific gravity systems.

a.3) Institutional arrangements for the operational sharing of water

Water sharing between the Aspres-Sur-Buëch irrigators through a daily slot calendar has been gradually abandoned during the last 15 years according to the irrigator union President. He explained that given the limited number of farmer members in the irrigator union, there is no longer any real interest in keeping a slot-based system that is temporally very restrictive. All the interviewees were familiar with the daily slot coordination when it was still in place, even it had undergone some changes that the technician, and to a lesser extent the President, mentioned (linked to the regrouping of the plots for example). We have captured the latest version in place, the one known to all the interviewees the branches of the canal are watered according to 4 time slots (A, B, C and D). For each slot, water flows in only some branches of the gravity-fed network and the different daily slots follow one after the other in a 10-day period. Currently irrigators don’t coordinate the irrigation network to trigger irrigation: the water flows simultaneously and continuously in all the branches of the canal during the whole irrigation campaign.

B. Complementary model description (ODD protocol)

b.1) Overview

Entities

Spatial entities – The spatial entities have 4 hierarchical levels. The spatial places, or pixels, represent the smallest landscape unit and thus the elementary spatial level (Figure S1). Farm plots are made of one or several pixels and have an area attribute. The farms, at which level irrigation decisions are made by the farmer agents, are represented as a set of farm plots. Finally, the water network area is made up of one or several farm plots that are served by the collective water network.

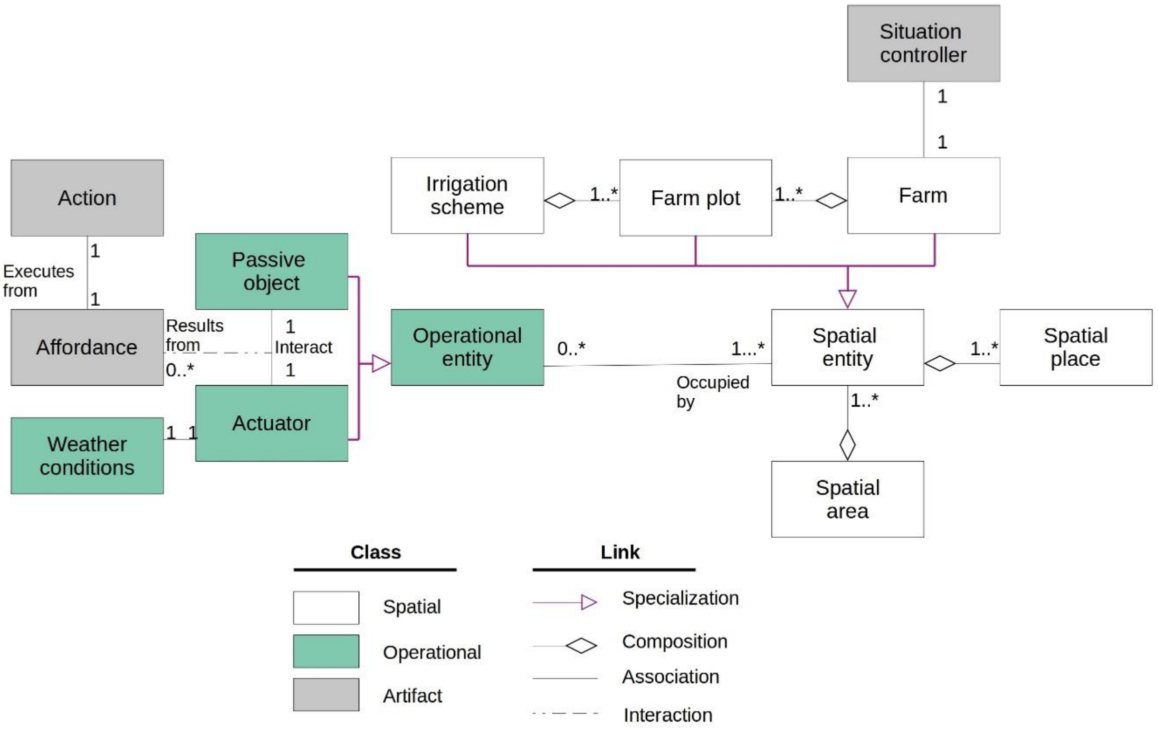


Figure S1: UML class diagram for the generic structure of the WatASit model. Each box with solid outlines represents a type of entity: a Class. White classes are spatial entities, green classes are operational entities, and grey classes are artifact entities. Links starting with diamonds represent compositions (e.g. a farm is composed of farm plots), purple links with arrows mean that one type of entity is a specialization of another (e.g. a farm and a farm plot are two particular spatial entities), dotted link are interaction between classes, and other links represent all other relationships (called associations).

Operational entities- Spatial entities are occupied by operational entities that physically represent the farmers and the elements situated in their spatial environment (see Table S1). Operational entities must be specified according to the case study. Each farm plot is occupied by a crop, and by a floodgate if served by the network. Operational entities are organized according to the idea inspired by the IODA (Interaction-Oriented Design of Agent simulations) approach (Kubera et al., 2011), and proposed by Afoutni et al (2014). The IODA approach distinguishes entities that perform actions, from entities that undergo actions. In such approach, any behavior is seen as an interaction between entities that may be active (source of an interaction) or passive (target of an interaction):

- *Actuators* are entities that are a source of interaction with a *passive object* as they can carry out actions, and therefore participate in the generation of affordances;
- *Passive objects* are entities that are the target of an interaction with an *actuator*, which is necessary to carry out an action.

Artifact entities- WatASit considers artifacts for explicitly representing abstract things of the real world such as action possibilities (i.e. the affordances) and actions. The options to irrigate thus result from the interactions between an *actuator* (i.e. a farmer) and a *passive object* (e.g. an irrigation equipment). In a given farm, they can interact according to conditions that define the situation of interaction. If conditions are fulfilled, an affordance artifact materializing an option to irrigate is generated. Among the agents' options, the chosen one becomes an action. As we need a neutral and abstract level to detect and reify these artifacts within each farm entities, we designed dedicated entities, called situation controllers. Inspired from Afoutni et al. (2014) place-agents, each farm is associated with a situation controller which is provided with artifact detection and reification mechanisms.

Table S1 presents all models entities, attributes and associated data sources.

Table S1: Model entities type, name, attributes, typical values and data source for the case study represented in WatASit. Values at t=0 are shown in brackets when relevant. PO and ACT denotes passive object and actuator, respectively. * NR stands for Not Relevant.

Type of entity	Name of entity	Main attribute(s)	Attribute typical value (value at *t* = 0)	Data source
Spatial	Spatial entity (pixel)	*resolution*	75 m	NR*
	Farm plot	*area*	[0.17 – 2.33] ha	RPG 2017
		myCrop	A crop entity	RPG 2017
		myFloodgate	A floodgate entity	HYDRA
	Farm	*myFarmer*	A farmer entity	NR*
	Irrigator union	*myFarmers*	A set of farmers	NR*
		myNetworkIntake	A network intake entity	HYDRA
		myNetworkJunctions	A set of network junction entities	HYDRA
		myNetworkBranches	A set of network branch entities	HYDRA
		myNetworkRejects	A set of network reject entities	HYDRA
Operational	Farmer$^{ACT/PO}$	*myFarm*	A farm entity	NR*
		capacitiyAsActuator	[Flood; AskMoreWater; DoSomethingElse]	Field data
		myActionToUndergoAsPassiveObject	DoSomethingElse	Field data
		myCurrentAction	An Action entity (none)	NR*
		K (irrigationStrategy)	12 days	Field data
		N (irrigationStrategy)	30 days	Field data
		P (irrigationStrategy)	120 mm	Field data
		state	[active; inactive] (inactive)	NR*
		myMeteo	Precipitation (0 mm)	SAFRAN
	Network intake^{PO}	*Qref*	0.09 $m^3 s^{-1}$	Field data
		Qmax	0.15 $m^3 s^{-1}$	Field data
		Qrung	0.01 $m^3 s^{-1}$	Field data
		state	opened	Field data
	Network junction^{PO}	*Q*	Computed (0 $m^3 s^{-1}$)	NR*
		divCoeff	0.5	Field data
		state	[opened; closed] (depending on DailySlots model configuration)	NR*
	Network branch^{PO}	*Q*	Computed (0 $m^3 s^{-1}$)	NR*
		seepageRate	0.0067 $m^3 s^{-1} km^{-1}$	Literature*
		state	[flowing; notFlowing] (notFlowing)	NR*
		Q	Computed (0 $m^3 s^{-1}$)	NR*

	Network reject^{PO}	*state*	[flowing; notFlowing] (notFlowing)	NR*
	Farm plot floodgate^{PO}	*state*	[opened; closed] (closed)	Field data
		Q	Computed (0 $m^3 s^{-1}$)	Field data
		Qflood	0.03 $m^3 s^{-1}$	Field data
		actionToUndergoAsPassiveObject	[plotBeFlooded; moreWaterAsked]	Field data
	Crop^{PO}	*type*	[Fodder ; Meadow ; Spring cereal ; Winter cereal ; Grain corn ; Estives ; Orchads ; Wasteland and others]	Adapted from RPG 2017
		myFarmPlot	A farm plot entity	RPG 2017
		daysFromLastIrrigation	A number of days (0 day)	NR*
		targetIrrigationDose	43.2 mm	Field data
		state	[NotBeingIrrigated; BeingIrrigated; Abandoned] (NotBeingIrrigated)	Field data
Artifact	Affordance	*type*	[Flood; AskMoreWater; DoSomethingElse]	Field data
		myActuator	An actuator entity (none)	NR*
		myPassiveObject	A passive object entity (none)	NR*
		place	A Spatial entity (none)	NR*
	Action	*type*	[Flood; AskMoreWater; DoSomethingElse]	Field data
		myAffordance	An affordance entity (none)	NR*
		targetDuration (D)	4 hour ha^{-1} for Flood action 1 hour otherwise	Field data
		realDuration	Computed	NR*
		timeWindow	*12h*	*Field data*
		state	[started; inProgress; stopped; ended] (none)	NR*
	Situation controller	*myFarm*	A farm entity	NR*
		myActuator	An actuator entity (none)	NR*
		passiveObjectsList	A list of passive object entities (none)	RPG 2017 + HYDRA
		currentAffordances	A list of affordance entities (none)	NR*
		currentAction	A list of action entities (none)	NR*

Process overview and scheduling

Figure S2 presents the activity diagram of the WatASit model.

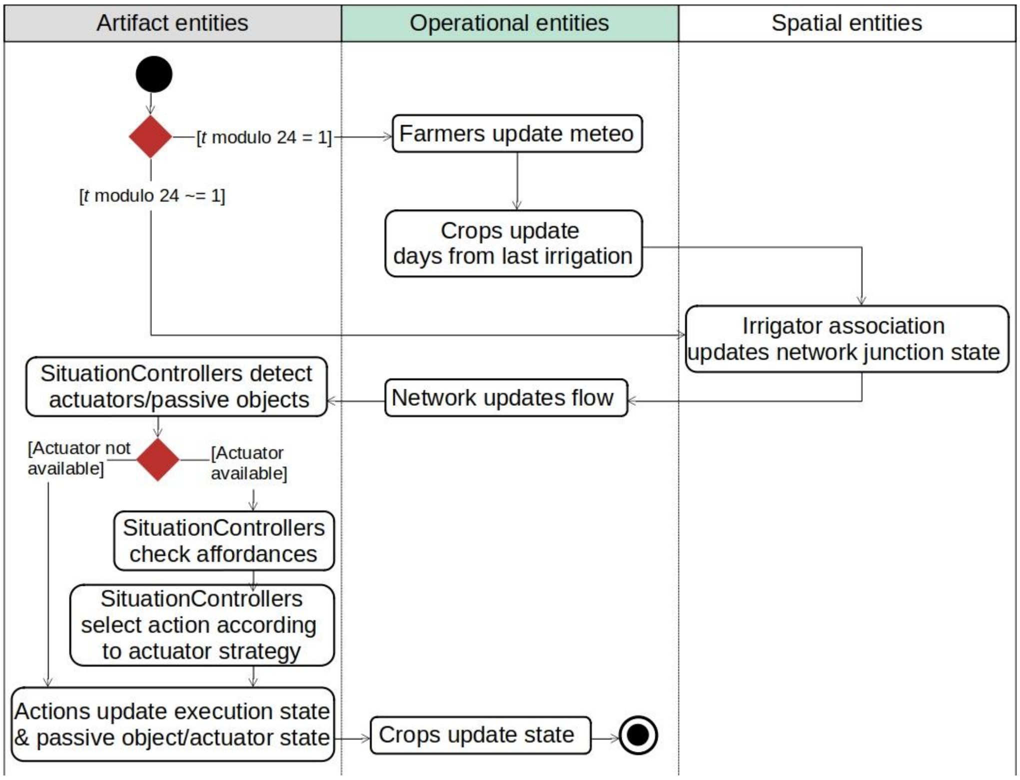


Figure S1: Activity diagram of the WatASit model

b.2) Design concepts

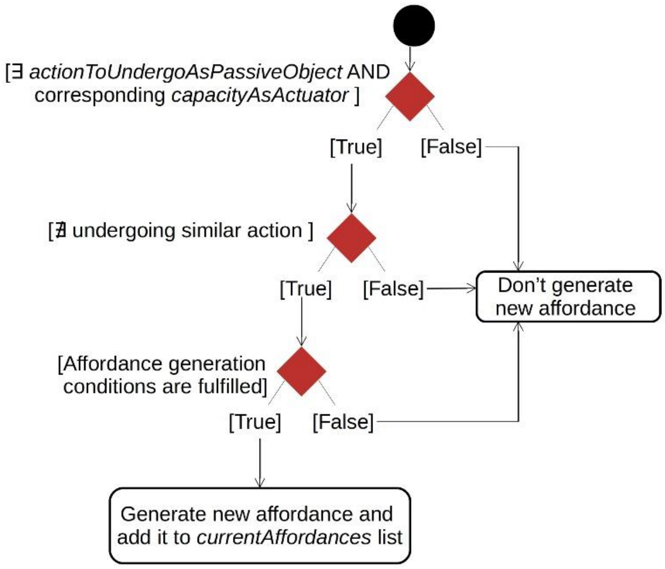
Fitness, learning, prediction and sensing

Agent behaviors follow a set of decision rules representing their operational irrigation strategy. This strategy determines the option to be chosen at each hourly time step among all the options of the agent. Agents do not predict the consequences of their behavior and do not change their strategy as a consequence of their behavior. However, agents' options are supposed to be perceived by them, and change according to the context of the moment, forcing agents to modify their behavior.

b.3) Details

Affordance generation sub-model

Figure S3 presents the activity diagram of the affordance generation sub-model. It works on the basis of matching rules (implemented in the form of a dictionary associating a value to each unique key). A test also verifies that the affordance is not already in action, and if it is, that its generation conditions are met.



***SituationController*' rules of correspondence**

capacityAsActuator		actionToUndergoAsPassiveObject
Legal flood	⟷	Plot be flooded
Illegal flood	⟷	Plot be flooded
Ask more water	⟷	More waterasked
Do something else	⟷	Do something else

Figure S2: Activity diagram of the affordance generation sub-model.

Action execution sub-model

To execute an action over time, the action execution sub-model modifies the state attribute of an action that reflects their execution state at each hourly time step: ”started”, ”in progress”, ”stopped ” or ”ended ”. This state is updated by the combination of two diagnostics detailed in the state-transition diagram presented in Figure S4:

- The remaining duration of the action is positive or not, and
- The execution conditions are fulfilled or not.

The direction of the arrows indicates the possible change between two states. While the generation conditions control the triggering of the action, the execution conditions can stop an action already started. The remaining duration is computed from a target duration which must be provided for each action considered in the model. A time step is subtracted from the target duration of the action if it is not stopped or ended. At each time step, this new duration called the remaining duration is calculated. As a result, the state of the action (i.e. ”started ”,”in progress”, ”stopped ” or ”ended ”) is determined at each hourly time step by these two diagnostics.

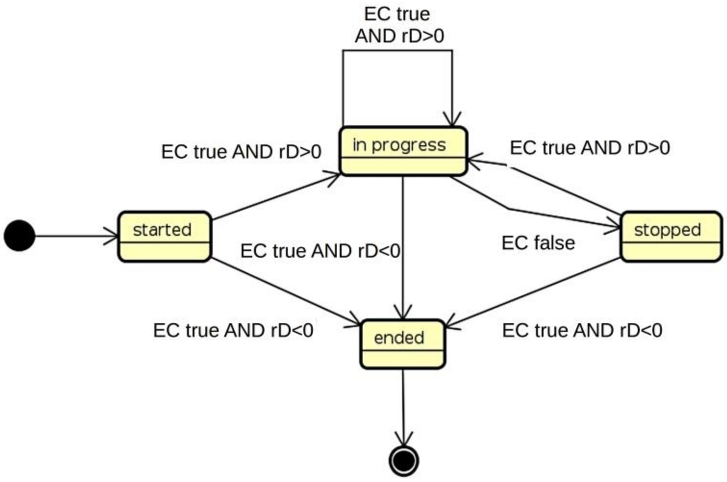


Figure S4: State-transition diagram of the action, eC stands for execution conditions, and rD for remain duration.

Representation of the flow in the water network

The sub-model representing the flow in the water network is specific to the functioning of gravity-fed irrigation and floodgates. A simplified view of the network hydraulic functioning is presented in Figure S5.

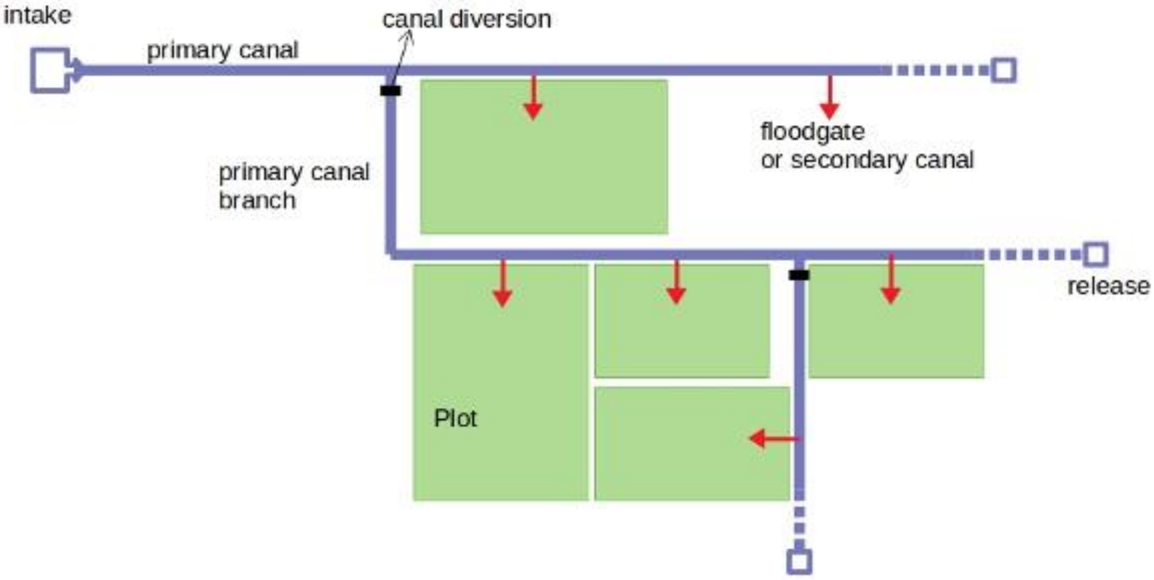


Figure S5: Simplified representation of the hydraulic network.

Making flood irrigation possible at a floodgate requires to reach and maintain a fixed network branch flow rate serving the floodgate. In addition, a seepage rate is taken into account for each network branch. The objective of this sub-model is not to simulate finely the hydraulic flow but to represent the link between the farmer's organization and the water flow rate serving the spatially distributed farm plots. It begins at a water intake, whose flow rate (*Qintake*) is set at the beginning of the irrigation campaign at the reference flow rate (*Qref*, Eq. 1).

$$Qintake\ (t = 0) = Qref \quad \text{(Eq. 1)}$$

Qintake supplies the main canal, which is divided into two branches at each diversion. The flow in each downstream branch (*Qdownstream*, in $m^3\ s^{-1}$) is obtained according to the diversion flow rate (*Qdiv*, in $m^3\ s^{-1}$) multiplied by a division coefficient (*divCoeff*) at each diversion (Eq. 2).

$$Qdownstream = Qdiv \times divCoeff \quad \text{(Eq. 2)}$$

Qdiv is calculated as the flow of the branch upstream (*Qupstream*, in $m^3 s^{-1}$) of the diversion minus seepage along the branch (*bS*, in $m^3 s^{-1}$) (Eq. 3):

$$Qdiversion = Qupstream - bS \text{ (Eq. 3)}$$

Seepage (*S*, in $m^3 s^{-1} km^{-1}$), i.e. water losses per unit length, is estimated by being measured on another gravity-fed network of the upstream part of the river basin with similar soil conditions (Charton, 2001). Then *bS* is calculated for each canal branch according to its length *bL* (in km), following Eq. 4:

$$bS = bL \times S \text{ (Eq. 4)}$$

To make flood irrigation possible at a floodgate, it is necessary, due to the size and the functioning of these floodgates, to reach and maintain a fixed branch flow rate (*Qflood*) serving the floodgate. This is consistent with the values found in the literature on similarly functioning gravity-fed irrigation networks, notably Hong (2014) mentions a floodgate flow of 0.35 $m^3 s^{-1}$ for the Crau case study (France). It means that a farm plot flood is not possible if the floodgate is not served by a branch of the canal that has a lower flow. While irrigation is triggered by the opening of a floodgate, *Qflood* is subtracted from the flow of the canal branch (Eq. 5). If simultaneous irrigation operations are started at the same time step, the maximum number of simultaneous irrigation is determined by the branch flow, which should allow the supply of all floodgates with *Qflood*.

$$Q = Q - \Sigma Qflood \text{ (Eq. 5)}$$

The flow that floods a farm plot is therefore fixed, following the functioning of the floodgates. But the duration is adjusted depending on the size of the farm plot to reach the target duration. Empirical target irrigation time per hectare was collected from the farmer interviews. Moreover, *Qintake* could vary by raising the floodgate by one rung compared to the graduations indicated on the measuring scale at its level. This results in an increase in Qintake by adding Qrung, unless it reaches the overflow rate (*Qmax*) (Eq. 6):

$$Qintake = \min(Qmax, Qintake + Qrung) \text{ (Eq. 6)}$$

C. Sensitivity analysis

Simulations runs of the sensitivity analysis are summarized in Table S2. A graphic of the simulation results is presented in Figure S6.

Table S2: Simulation runs of the one at a time sensitivity analysis to key forcing and parameters of the WatASit model, in the NoSlots and DailySlots model configurations.

Forcing or parameter name	Simulation value range	Model configuration
Precipitation (year)	[2005-2017]	NoSlots
		DailySlots
Daily time window (hours)	[6-24]	NoSlots
		DailySlots
Network intake flow (m^3s^{-1})	[0.05-0.35]	NoSlots
		DailySlots
DailySlots period (days)	[8-12]	DailySlots

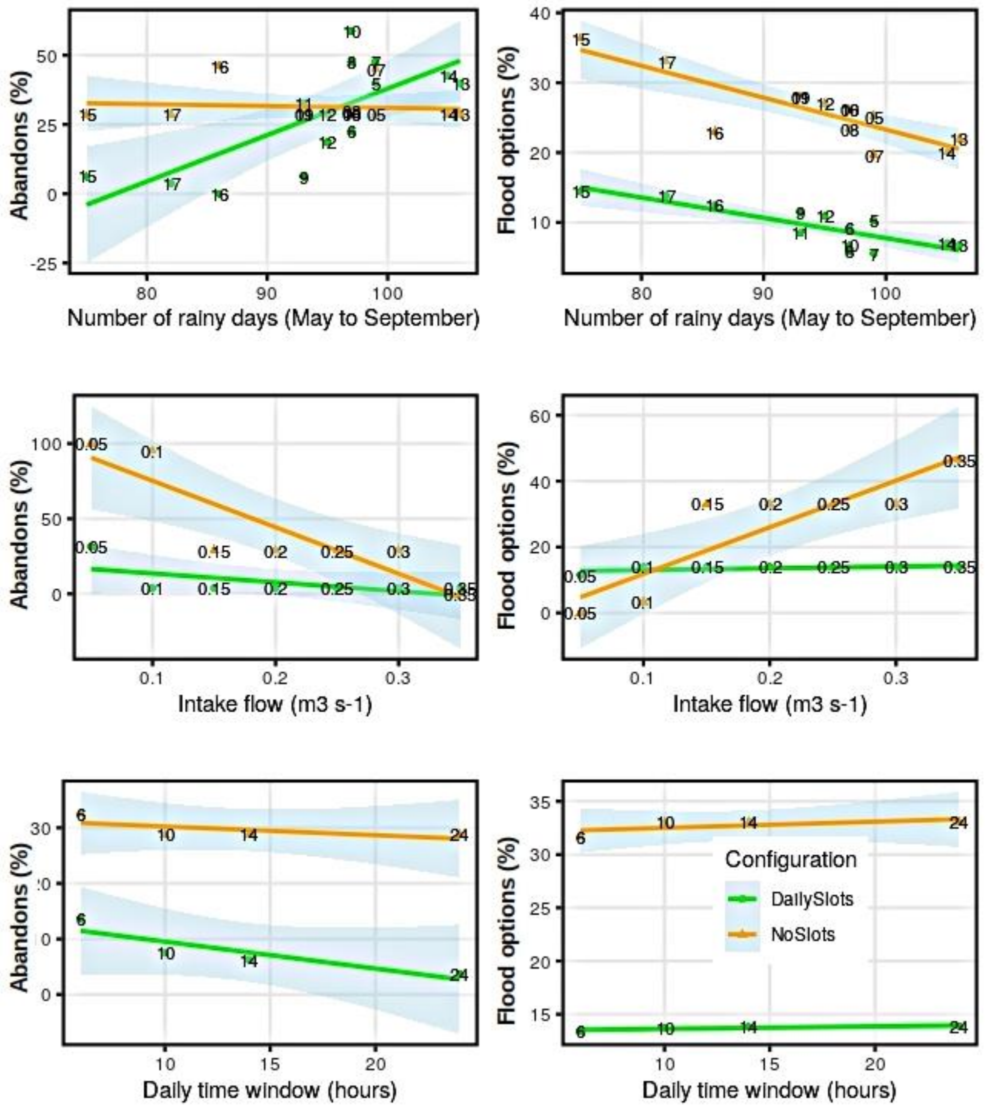


Figure S6: Scatter plots with the percentages of plots with an irrigation abandon (left-side) and with a Flood option (right-side) for the y-axis, and the forcing or parameter values in x-axis. Each point represent a simulation, for the DailySlots (green line) and NoSlots (orange line) model configurations.

References

Afoutni, Z., Courdier, R. & Guerrin, F. (2014). *A Multiagent System to Model Human Action Based on the Concept of Affordance*. Proceedings of the 4th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH 2014), Aug 2014, Vienne, Austria, pp. 664-651,hal-01466931.

Charton, P. (2001). *Etude d'utilisation des eaux sur deux périmètres d'irrigation gravitaire des Hautes-Alpes*. Rapport de la Chambre d'Agriculture des Hautes-Alpes.

Hong, S. (2014). *Optimisation des tours d'eau sur un réseau de canaux d'irrigation*. Manuscrit de thèse. Montpellier SupAgro. Soutenue le 11 juillet 2014. Directeurs: Gilles Bellaud and Pierre-Olivier Malaterre.

Kubera, Y., Mathieu, P., & Picault, S. (2011*). Ioda: An interaction-oriented approach for multi-agent based simulations.* Journal of Autonomous Agents and Multi-Agent Systems. 23(3):303–343.