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Coupling agent-based and agro-hydrological modeling to represent human actions within an agro-hydrosystem. Application to collective irrigation in the Buëch catchment (France).

Bastien Richard

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THESE DE DOCTORAT

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par

Bastien RICHARD

Coupling agent-based and agro-hydrological modeling to represent human actions within an agro-hydrosystem. Application to collective irrigation in the Buëch catchment (France).

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”Toute réponse aux besoins d’eau est forcément locale. Corollairement, aucune solution technique n’est valable partout. S’il y a de mauvais barrages, il en est d’excellents. Si dessaler la mer menace ici les écosystèmes, plus loin l’opération sera sans risques et rendra d’irremplaçables services. Tout dépendra toujours de la géographie. Un progrès planétaire ne peut résulter que de l’addition de progrès locaux.”

Erik Orsenna, *l’Avenir de l’eau* (p.455).

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Contents

Acknowledgements	iii
Contents	iv
List of Figures	xiii
List of Tables	xv
Abbreviations	xvii
1 Introduction	1
1.1 Context	1
1.1.1 From hydrology to "socio-hydrology" : the need for methods to dynamically account for the mutual influences between human activities and water resources	1
1.1.2 Importance in documenting short-term interactions within an agro-hydrosystem	4
1.1.3 Difficulties related to the local nature and spatial distribution of irrigation interactions within an agro-hydrosystem	6
1.1.4 The coupling between agent-based models and biophysical models could help to overcome these difficulties	7
1.2 Thesis project	8
I Situating research questions in the literature and in the field	13
2 Representations of human action in agricultural agent-based models - A review	17
2.1 Working definitions	18
2.1.1 What is meant by the representation of an action?	18
2.1.2 What is meant by a multi-agent system / an agent-based model ?	18
2.1.3 What is meant by an agent ?	19
2.1.4 What is meant by the environment ?	20
2.1.5 What is meant by an interaction ?	20
2.1.6 Time representation	20
2.1.7 Space representation	21
2.2 Representations of human action in agricultural agent-based models - A review	21

2.2.1	Introduction	21
2.2.2	Materials and methods	24
2.2.2.1	Definitions	24
	Approaches for the representation of human action	24
	Economic	24
	Empirical	24
	Planned	25
	Situated	26
	Other approaches	27
	Action	27
	Action influence factors	27
	Levels of action	27
2.2.2.2	Paper selection and assessment	28
2.2.3	Results and discussion	29
2.2.3.1	General characteristics	29
2.2.3.2	Human action representations in agricultural ABMs	32
	Use of approaches	32
	Action representation characteristics	34
2.2.3.3	Limitations and outlook	35
2.2.4	Conclusions	37
3	Case study	39
3.1	Introduction	40
3.2	General characteristics of the Buëch River basin	42
3.2.1	Hydro-climatic regime	42
3.2.2	Water uses and crop distribution	43
3.2.3	Data availability	45
3.3	Material from field surveys	46
3.4	The operational challenges of irrigation management on the Buëch River basin	50
3.5	Functioning of the collective irrigation networks	56
3.6	Focus on a particular case: the Aspres-Sur-Buëch gravity-fed network	64
	Network functioning	65
	Farming system	68
	Work load capacity	68
	Weather conditions	68
	Water restrictions	68
	Operational decision-making	68
	Irrigator availability	68
3.7	Conclusion	70
II	Representing collective irrigation at the operational level	73
4	The WatASit model	77
4.1	Introduction	78
4.2	Modeling problematic, scope and concepts	79
4.2.1	Terminology	79

4.2.2	Modeling problematic for the Aspres-Sur-Buëch case study	80
4.2.3	Chosen approach	81
4.2.4	Modeling scope	81
4.2.5	Modeling objectives	82
4.2.6	Objectives of the model in view of coupling it with biophysical models	82
4.2.7	Key concepts	83
4.2.7.1	Originality of the situated approach	83
4.2.7.2	The concept of Affordance and its mobilization in our work	84
4.3	Code and data availability	86
4.4	Description of the WatASit model (ODD protocol)	87
4.4.1	Overview	87
4.4.1.1	Purpose	87
4.4.1.2	State variables and scales	87
	Spatial entities	88
	Operational entities	88
	Artifact entities	88
4.4.1.3	Process overview and scheduling	89
4.4.2	Design concepts	90
4.4.2.1	Basic principles, emergence and adaptations	90
4.4.2.2	Fitness, learning, prediction and sensing	91
4.4.2.3	Interactions and collectives	91
4.4.2.4	Stochasticity	91
4.4.2.5	Observation	92
4.4.3	Details	92
4.4.3.1	Initialization	92
4.4.3.2	Input	92
4.4.3.3	Sub-models	93
	Affordance generation sub-model	93
	Action execution sub-model	93
	Representation of the flow in the water network	94
4.5	Conclusion	96
4.6	Appendix	97
4.6.1	Appendix 1	97

5 Using the Affordance concept to help interpret agent trajectories in ABMs 99

	Abstract	100
	Keywords	101
	Résumé en français	101
	Mots clefs	101
5.1	Introduction	102
5.2	Material and Methods	104
5.2.1	Affordances as option-set of an actor	104
5.2.2	Model overview	106
5.2.3	Case study	107
5.2.4	Model specification and parameterization	108

5.2.5	Model configurations that we compared	110
5.2.6	Model outputs and verification	113
5.3	Results	114
5.3.1	Tracing back at the collective level	114
5.3.1.1	Abandons of irrigation	115
5.3.1.2	Irrigation trajectories and option-sets	115
5.3.2	Tracing back at the individual level	116
5.3.2.1	Case of the most impacted farmer	117
5.3.2.2	Case of the farmer impacted in the DailySlots model configuration	118
5.3.3	Sensibility of model outputs to key forcing and parameters	120
5.4	Discussion	124
5.4.1	Potentials of the Affordance concept to help interpret ABM outputs	124
5.4.2	Limitations and outlook	126
5.5	Conclusions	128
5.6	Acknowledgments	128
III	Coupling with agro-hydrological models	131
6	COPAT: coupling plant and agent trajectories	135
	Abstract	136
	Keywords	137
	Résumé en français	137
	Mots clefs	137
6.1	Introduction	138
6.2	Description of the COPAT framework	140
6.2.1	Crop dynamics at the plot level: Optirrig-D	141
6.2.2	Irrigation at the network level: WatASit (ODD protocol)	144
6.2.2.1	Overview	144
	Purpose	144
	State variables and scales	145
	Spatial entities	146
	Operational entities	146
	Artifact entities	146
	Process overview and scheduling	146
6.2.2.2	Design concepts	147
	Basic principles, emergence and adaptations	147
	Fitness, learning, prediction and sensing	148
	Interactions and collectives	148
	Stochasticity	148
	Observation	148
6.2.2.3	Details	148
	Initialization	148
	Input	149
	Sub-models	149
6.2.3	COPAT overview and scheduling	149

6.2.4	Case study: the Aspres-Sur-Buëch gravity-fed network	151
6.2.5	Inputs	153
6.2.6	Parameterization	153
6.2.7	Scenario and model evaluations	154
6.3	Result	157
6.3.1	Irrigation dates and model verification	158
6.3.1.1	When irrigation is not coordinated	158
6.3.1.2	When irrigation is coordinated	158
6.3.2	Spatial distribution of cereal stress severity	160
6.3.3	Average stress dynamics of cereals	162
6.4	Discussions	162
6.4.1	Added value of the COPAT framework	165
6.4.2	Limitations and outlook	166
6.4.3	Conclusion	168
6.4.4	Acknowledgment	168
6.4.5	Appendices	169
7	COWAT: coupling water resources and agent trajectories	171
7.1	Introduction	172
7.2	Material	175
7.2.1	Models	175
7.2.1.1	J2000	175
7.2.1.2	WatASit	178
7.2.2	Application site and available data	180
7.3	Concept of the coupling	182
7.3.1	Coupling objectives	182
7.3.2	Coupling stages and requirements	182
7.3.3	Coupling variables	185
7.4	Models' spatial modifications	186
7.4.1	Overview of J2000 and WatASit spatial editing	186
7.4.2	HRU delineation in J2000	186
7.4.2.1	HRU delineation method 1: size reduction	186
7.4.2.2	HRU delineation method 2: concept of HRU-plot	188
7.4.3	Specification of a new spatial entity in WatASit	190
7.5	Model's temporal modifications and coupling scheduling	191
7.5.1	From J2000 to J2000-D	191
7.5.2	Scheduling of the coupling	192
7.6	Conclusions and discussion	193
8	Discussion	197
8.1	Introduction	197
8.2	A modular approach at the crossroad of irrigation scales and disciplines	198
8.2.1	Using complementary tools for addressing short-term interactions between irrigation and agro-hydrological processes within entangled spatial scales	198
8.2.2	Documenting anthropogenic and natural causal links by (partially) facilitating the interpretation of ABM outputs	202

8.2.3	Key limitations	204
8.3	Coupling or not coupling, that is the question	206
8.3.1	What are the coupling requirements to tackle interactions at fine spatio-temporal scales ?	206
8.3.2	What are the needs of coupling in terms of parameterization ?	209
8.3.3	What are the generic potentials of the COPAT and COWAT cou- pling methodologies ?	210
8.4	Back to the case study	211
8.4.1	Contribution in relation to the case study	211
8.4.2	The use of a real application case also leads us to think about hydrology in a different way	213
8.5	Back to interdisciplinarity in “socio-hydrology”	214
8.5.1	”Socio-hydrology” emanates above all from hydrologists, with a vision centered on modeling, and with sociological aspects that remain limited	214
8.5.2	The Affordance concept connects hydrology to the interdisciplinary debate of socio-ecological feedback mediated by the environmental cognition	216
8.6	Perspectives	218
8.6.1	Endowing our farmer agents with better decision-making abilities in WatASit	218
8.6.2	Quantitative validation of the COPAT framework	220
8.6.3	Scaling-up the COWAT method at the basin-scale	222
9	Conclusion	225
A	Complementary description of the case study	231
A.1	The context of water management in the Durance River basin in France	231
A.1.1	Hydrological studies in the Durance River basin: future quantita- tive water sharing in question	231
A.1.2	A multitude of governance scales	233
A.1.3	Environmental preoccupations through the prism of technical de- bates and operational problems	234
A.2	Description of the irrigated systems of the Buëch River basin from the agrarian diagnosis point of view	235
B	Interview guides	243
B.1	Interview guide with irrigators (original French version)	243
B.1.1	L’exploitation aujourd’hui (10 min)	243
B.1.2	Les productions végétales et animales (30 min)	244
B.1.3	La gestion de la campagne d’irrigation (30 min)	244
B.2	Interview guide with institutional actors (original French version)	245
B.2.1	Caractéristiques de l’usage ”besoin en eau des milieux”	245
B.2.2	Perception des autres usages de l’eau	246
B.2.3	Expérience des sécheresses	246
B.2.4	Mesures d’adaptation	246
B.2.5	Déterminants potentiels	247

C Paper	249
Résumé	250
Mots clefs	250
Abstract (english)	250
Keywords	251
C.1 Introduction	251
C.2 Matériel et méthodes	254
C.2.1 Le cas d'étude	254
C.2.2 Les données	255
C.2.2.1 L'occupation du sol	255
C.2.2.2 Les infrastructures d'irrigation	256
C.2.2.3 Les conditions météorologiques	256
C.2.2.4 Les restrictions en eau	256
C.2.3 Le modèle à base d'agents WatASit	256
C.2.3.1 Cadre théorique	256
C.2.3.2 La structure du modèle WatASit	257
C.2.3.3 Le séquençage du modèle WatASit-Aspres	260
C.2.3.4 La représentation du réseau d'irrigation gravitaire	261
C.2.3.5 L'implémentation du modèle et la paramétrisation de l'état initial	262
C.2.3.6 Les scénarios et les sorties de simulations	263
C.2.4 Résultats de simulations	263
C.2.4.1 Impact du mode de partage sur la localisation des irri- gations et abandons	263
C.2.4.2 Impact sur le nombre de possibilités d'actions et d'actions	264
C.2.4.3 Les capacités d'irrigation des agriculteurs rendues plus inégales par l'abandon des tours d'eau	267
C.2.5 Discussion	269
C.2.6 Conclusions	272
C.2.7 Acknowledgements	273
D List of publications	275
E Résumé long en français	279
Bibliography	285

List of Figures

1.1	Traditional and new paradigms	2
1.2	Thesis stages overview	11
2.1	Source types	32
2.2	General characteristics	33
2.3	Action approaches	34
2.4	Approaches over times	35
2.5	Action characteristics	36
3.1	Location of the Buëch River Basin	43
3.2	Comparative view of the Petit Buëch	44
3.3	Hydrogramm	44
3.4	View of downstream Buëch	45
3.5	Water uses	46
3.6	Crop types	47
3.7	Crop surface areas	48
3.8	Field workshop	52
3.9	Temporal context of quantitative water management of the Buëch River basin	57
3.10	Photos of main crop types	57
3.11	Irrigator unions of the Buëch	59
3.12	Operational calendar	60
3.13	Photos of agricultural operations	60
3.14	Overview of a gravity-fed network	62
3.15	Flood irrigation	64
3.16	Map of the Aspres-Sur-Buëch irrigator union	65
3.17	Plots of each farmer	66
3.18	Aspres-Sur-Buëch	67
3.19	The floodgate	67
4.1	WatASit class diagram	89
4.2	Activity diagram	90
4.3	Affordance generation sub-model.	93
4.4	State-transition diagram	94
4.5	Representation of the irrigation network	95
5.1	Schematic example of planned and situated approaches.	106
5.2	Sequence diagram of the WatASit model.	108
5.3	Case study	109

5.4	The operational strategy	112
5.5	Abandoned plots	115
5.6	IR	117
5.7	Radar plot	119
5.8	Farmer 4	119
5.9	Farmer 2	120
5.10	Scatter plots	123
6.1	Simplified view of the Optirrig model	145
6.2	Sequence diagram of the WatASit model	147
6.3	Scheme of the coupling simulation framework.	151
6.4	Presentation of the Aspres-Sur-Buëch study area	152
6.5	Irrigation strategy	155
6.6	Irrigation dates	159
6.7	Dates of irrigation possibilities and missed irrigation	160
6.8	Cereal number for each water stress severity level.	161
6.9	Localization of maximum stress severity	163
6.10	LAI, WSI and irrigation number evolutions	164
7.1	J2000 components and contexts	177
7.2	Schematic of the J2000 model	178
7.3	Situation map of the Grand Buëch catchment	181
7.4	Schematic view of the four coupling stages	184
7.5	Key steps of J2000 and WatASit spatial editing.	187
7.6	Boxplots of the 8 HRU delineation cases.	189
7.7	The HRU-plot concept	190
8.1	Overview of irrigation scales and the various tools used in the thesis work.	200
8.2	Formalism and spatial discretization of several hydrological models.	211
A.1	The Durance River Basin	232
A.2	Water management perimeters	234
A.3	Farming systems evolution	241
C.1	Les niveaux structurel et opérationnel de l'irrigation	253
C.2	Présentation de la zone d'étude	255
C.3	Diagramme de classe UML du modèle WatASit	259
C.4	Simulations des actions	264
C.5	Nombre d'affordances et d'actions	266
C.6	Analyse en composantes principales	270

List of Tables

2.1	Overview of literature selection stages and resulting number of articles in review based on a topic search (TS) using the <i>Web of Science</i>	29
2.2	List of reviewed studies (N=78) and their source type. *C denotes full conference paper. **A indicates an article.	30
2.3	Overview of the 13 review criteria used for the detailed evaluation. * denotes multiple matches possible.	31
3.1	Data types and sources used for the characterization of collective irrigated systems of the Buëch River basin.	46
3.2	Stakeholder type and number of interviewees for the semi-directive interviews. Field observation, meeting and workshop realized during the field surveys.	51
3.3	Main similarities and differences between the functioning of pressure, mixed and gravity-fed networks	63
4.1	Model entity type, name, attribute and typical value of the WatASit model. ACT indicates an actuator and PO a passive object. RPG refers to year 2017.	98
5.1	The network specific constraints in the WatASit model.	110
5.2	The affordances considered in the modeling approach and the associated actuator/passive object pairings. For each affordance, the generation conditions are presented.	111
5.3	Execution conditions, target duration and effect of the actions.	111
5.4	Daily slot network coordination of the <i>DailySlots</i> model configuration. The seven canal branches of the canal are denoted <i>b1</i> to <i>b7</i> (see Figure 5.5). Every 10 days, the period starts again at 0. Canal branches <i>b1</i> and <i>5</i> are watered during the first three days of each 10-days period, then <i>b1</i> , <i>b2</i> , <i>b3</i> and <i>b6</i> are watering during the next three days, etc, until the end of the 10-days period, which starts again.	113
5.5	Model output level, name and description. * Irrigable means the plot that can be supplied with water by the collective network. ** A crop is abandoned for irrigation if it has not been irrigated during <i>N</i> days consecutively.	114
5.6	Mean irrigation option ratio time-serie (<i>IOR</i>), ask more water option ratio time-serie (<i>AMWOR</i>) and abandon ratio at the en of the irrigation campaign (<i>AR</i>) for the <i>NoSlots</i> and <i>DailySlots</i> model configurations for all, upstream and downstream plots, respectively. * indicates the value is the average over the whole simulation period.	116

5.7	<i>IOR</i> , <i>AMWOR</i> and <i>AR</i> of the downstream plots for the <i>NoSlots</i> and <i>DailySlots</i> model configurations. NA is reported when farmers don't have any downstream plots. * indicates the value is the average over the whole simulation period.	118
5.8	<i>AR</i> and mean <i>IOR</i> range resulting from the one at a time sensitivity analysis to key forcing and parameters of the WatASit model, in the <i>NoSlots</i> and <i>DailySlots</i> model configurations.	121
6.1	Main characteristics of Optirrig and WatASit models.	142
6.2	Specification of the network specific constraints.* indicates that when this constraint is the only one which is not fulfilled, a "missed" irrigation is recorded.	155
6.3	Collective strategies of network coordination considered in the study, and extra irrigation constraints. The seven canal branches of the canal are denoted <i>b1</i> to <i>b7</i> . For example, in the Network_DailySlots scenario, water network coordination is done in 10-day periods. Thus, canal branches <i>b1</i> and <i>b5</i> are flowing during the first three days of each 10-days period, then <i>b1</i> , <i>b2</i> , <i>b3</i> and <i>b6</i> are flowing during the third following days, etc	157
6.4	Value ranges of the 4 <i>WSI</i> classes.	161
6.5	Characteristics of the 16 cereal plots	169
7.1	Name, type and unit of the coupling variables with respect to each model definitions. Arrows show the direction of the transfer of information for each variable.	185
7.2	SIG layers for the overlay operation to delineate HRUs.	188
7.3	Experience plan for HRU delineation according to <i>subbasin_min_area</i> and <i>HRU_min_area</i> parameters of overlaying processes.	188
A.1	Structural and low-flow water management objectives, instruments, variables and regulatory frameworks (compilation by the author).	236
C.1	Les affordances du modèle WatASit-Aspres et les couples opérateur/objet passif associés. Pour chaque affordance, les conditions d'interaction pour leur génération sont présentées. <i>Q</i> , <i>Qmin</i> et <i>Qmax</i> renvoient aux débit, débit minimum et débit maximum dans le canal d'irrigation. <i>Qéchelon</i> correspond à l'augmentation de débit en entrée du réseau consécutivement au relevage de la vanne d'un échelon de mesure	261
C.2	Conditions d'exécution, durée potentielle et effet des actions. <i>Q</i> , <i>Qmin</i> et <i>Qmax</i> renvoient aux débit, débit minimum et débit maximum dans le canal d'irrigation. <i>Qéchelon</i> correspond à l'augmentation de débit en entrée du réseau consécutivement au relevage de la vanne d'un échelon de mesure	261
C.3	Somme, moyenne et écart-type de la différence des abandons d'irrigation entre le scénario de référence (SR) et le scénario alternatif (SA). OBS renvoie aux observés lorsqu'ils sont disponibles. ND signifie non disponible	268
C.4	Différence (SR - SA) entre le scénario de référence (SR) et le scénario alternatif (SA) de la somme, la moyenne et l'écart-type des affordances et des actions. OBS renvoie aux observés lorsqu'ils sont disponibles. ND signifie non disponible	268

Abbreviations

ABM	Agent-Based Modeling or Models
API	Application Program Interface
ASA	"Associations Syndicales Autorisées" or irrigator union
DMB	"Débit Minimum Biologique" or Biological Minimum Flow
DOE	"Débit d'Objectif D'Étiage" or Low-Water Target Flow
DR	"Débit Réservé" or Instream Flow
EDF	"Electricité De France"
EPTB	"Etablissement Public Territorial de Bassin"
JAMS	Just Another Modeling Platform
LAI	Leaf Area Index
LEMA	The 2006 "Loi sur l'Eau et les Milieux Aquatiques"
OUGC	"Organisme Unique de Gestion Collective de l'irrigation"
PACA	"Provence-Alpes-Côte-d'Azur-Région"
PGRE	"Plan de Gestion des Ressources en Eau"
QMNA5	The minimum monthly flow with a 1/5 probability of not being exceeded
SAGE	"Schéma d'Aménagement et de Gestion de l'Eau" or Water Development and Management Plan
SCP	"Société du Canal de Provence"
SDAGE	"Schéma Directeur d'Aménagement et de Gestion de l'Eau" or Water Development and Management Master Plan
SEM	"Société des Eaux de Marseille"
SMADESEP	"Syndicat Mixte d'Aménagement du Lac DE SERRES-PONÇON"
SMAVD	"Syndicat Mixte d'Aménagement de la Vallée de la Durance"
SMIGIBA	"Syndicat Mixte de Gestion Intercommunale du Buëch et de ses Affluents"
WFD	Water Framework Directive

WSI	Water Stress Index
ZRE	”Zone de Répartition des Eaux”

Chapter 1

Introduction

1.1 Context

1.1.1 From hydrology to "socio-hydrology" : the need for methods to dynamically account for the mutual influences between human activities and water resources

Taking into account the mutual influences between human activities and natural resources is fundamental for addressing current societal debates. Human societies face difficult choices about water use development and management recognizing the need to preserve common good, such as water, that is essential to human viability and well-being ([Castelletti et al., 2012](#)). Sustainability of water uses has been therefore highly promoted in recent years with significant efforts made to embed it into natural resources management and preservation ([Koutsoyiannis et al., 2009](#)), and with integrated water resources management (IWRM) widely adopted by decision-makers ([Savenije and van der Zaag, 2008](#)). As water is increasingly used for many purposes - the basic human needs, the production of energy, the ecosystem needs -, current challenges for water management differ according to the variety of local contexts, where water resources and their uses evolve jointly but at different time regimes. Despite the advances in IWRM, local crisis for the sharing of water affects many regions worldwide ([Srinivasan, 2015](#)). Among the various water uses, irrigation is often described as an important cause of water withdrawals ([Foley et al., 2011](#), [Godfray et al., 2010](#)).

In this context, the hydrology research community is questioning the relevance of its models, which are better suited for simulating and predicting hydrological processes in catchments with little human activity (Montanari et al., 2013). Paradoxically, the literature is rich in studies concerning the impact of climate change on the water cycle (e.g. van Dijk et al., 2013, Vörösmarty et al., 2010), where the complexity of modeled processes concerns hydrology, especially with the appearance of distributed models (Vogel et al., 2015). But human activities, such as irrigation, are represented in a more or less aggregated way and assuming a fixed structure over time (Sivapalan et al., 2012).

Within the scientific decade *"Panta Rhei - Everything flows"* promoting the study of changes in environmental and social systems (Montanari et al., 2013), Sivapalan et al. (2012) have advocated "socio-hydrology" as *"the fundamental science underpinning the practice of IWRM"*, with human activities included as *"part and parcel of water cycle dynamics"* (Sivapalan et al., 2012, : p. 1271). The key novel element is the reject of stationary models with a fixed representation of human activities over time (Figure 1.1), in favor of studying *"the co-evolution and self-organization of people in the landscape, also with respect to water availability"* (Sivapalan et al., 2012, : p. 1271). In 2015, a series of publications (Gober and Wheeler, 2015, Loucks, 2015, Sivapalan, 2015, Troy et al., 2015) in the journal *Water Resources Research* continued the reflections on a first approach proposed by Di Baldassare et al. (2013).

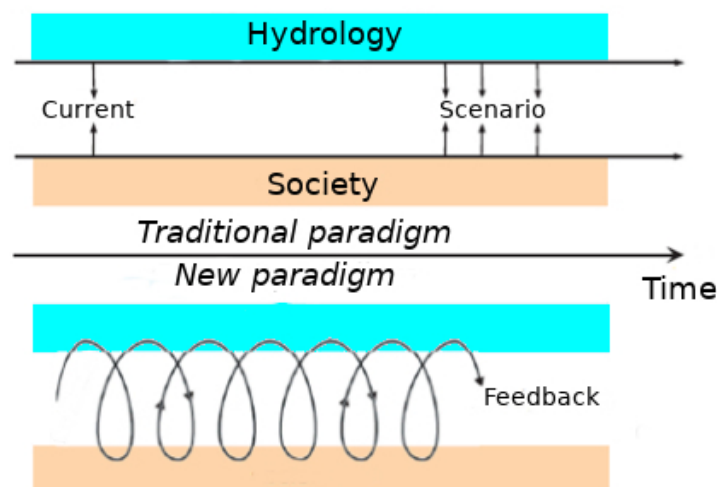


FIGURE 1.1: Stationary and non-stationary representation of the mutual influences between hydrology and society over time (adapted from Di Baldassare et al., 2015).

Vogel et al. (2015) recall some historical facts that help to grasp the emergence of "socio-hydrology". First of all, the interdisciplinary journal *Water Resources Research* was founded in 1964, with the editorial line of "original research in the natural and social sciences of water". Then, Falkenmark (1977) was surely the first to introduce a scientific approach to understanding the mechanisms of mutual interactions between water and human systems in his article "Water and mankind - a complex system of mutual interaction", and to propose "hydrosociology" as a field of hydrological sciences (Falkenmark, 1979). These considerations were then reflected in the IWRM concept that emerged in the 1990s (Kadi, 2014). In addition, the special issue "Creating partnerships between hydrology and social science: A priority for progress" of the *Journal of Hydrology* claimed for more collaborations with social sciences: "If hydrology is to continue to have a beneficial impact on the water resource and the community it needs to seek to place itself in partnership with social scientists" (Reddy and Syme, 2014).

In parallel, a community of researchers grouped under the name "Coupled Human and Nature Systems" (CHANS) has specifically investigated the endogenous modeling of non-linear interactions and feedback between these "human" and "natural" dynamics (Liu et al., 2007). CHANS have emerged in the 2000s as a branch of complex systems that are characterized by non-linear dynamics, feedback loops, time delays, heterogeneity and unexpected behaviors (Liu et al., 2007). CHANS are largely similar to socio-ecological systems as defined by (Ostrom, 2007) and have many human and non-human processes operating at multiple levels that are hierarchically nested (Ostrom, 2009).

The CHANS and "socio-hydrology" research streams are currently converging to address coupled human-water systems. As pointed out by such research streams, there is a need to better document the mutual influences between human actions and water resources (Liu et al., 2007, Sivapalan et al., 2012), including variables and fine spatio-temporal scales of dynamic interactions over time (Ceola et al., 2016).

1.1.2 Importance in documenting short-term interactions within an agro-hydrosystem

In the vein of "socio-hydrology", efforts have been mainly used for the representation of long term co-evolution between human actions and water resources (Pande and Sivapalan, 2017). However, some authors argue that the dynamic interactions between humans and water have not been adequately addressed in the short term to study the balance between water supply and demand, both spatially and temporally (Kallis, 2010, Sivapalan and Blöschl, 2015).

Considering irrigation within an agro-hydrosystem, the interactions with the biophysical components of the system depend on the multiple adaptation scales of the farming system. Indeed, the traditional description of multi-scale farming adaptations is divided into three categories (Dury et al., 2012, Janssen and van Ittersum, 2007) : 1) In the long term, strategic adaptations for the structural organization of the farm for the coming years, including cropping systems and agricultural techniques envisaged to ensure the best possible income in a given socio-economic context, and technological investments such as access to irrigation or its optimization (e.g. Koundouri et al., 2006) 2) In the medium term, tactical adaptations for the structural adjustment of cropping systems and their agricultural techniques based on more precise knowledge (e.g. natural resource availability, agricultural markets) at the beginning of a cropping campaign (e.g. Robert et al., 2016b), and 3) in the short term, the operational management for the optimization of daily or sub-daily practices by the farmer during the course of a cropping campaign (e.g. Daydé et al., 2014).

Considering short-term interactions between irrigation operations and natural resources is important, as operational management of irrigation is one of the adaptation scales that can significantly influence agricultural outputs, with potential economic and environmental impacts (Martin-Clouaire, 2017). Indeed, when the irrigation campaign begins, farmers can have limited possibilities in space and time to operate irrigation in situations that are difficult to foresee in advance (Daydé et al., 2014, Reynaud, 2008) or present a lack of alternative such as insufficient water availability. Meanwhile, it is important to have a dynamic representation at the operational level since there is a

growing demand for knowledge of operational practices (Daydé et al., 2014), which also participate in the uncertainty of knowledge, a major challenge for water management in many places (Thompson et al., 2017). This is particularly the case for irrigated systems in an uncertain hydro-climatic context.

For example, in France, small irrigator unions are particularly solicited to modernize and optimize the operational functioning of their irrigation scheme for complying with new regulations such as irrigation quotas or restrictions. In the Buëch catchment, in particular, collective irrigation is still based on numerous gravity-fed networks whose operational functioning often derived from old irrigation or drainage systems that do not allow fine control of water withdrawals. Understanding the operational constraints of these systems is of interest to local actors of water management in order to understand 1) the local impact of such constraints on agriculture and local hydrology to precisely identify the places where their interactions lead to insufficient water flow for the preservation of ecosystems and for designing measures reconciling agricultural production and ecosystem water needs, and 2) to best assess the inter-dependencies at the scale of the hydrological basin between the natural flows and its modifications by the irrigation operations distributed in the basin, and also the inter-dependencies between the irrigated perimeters between themselves. As part of the actions carried out by the “Zone Atelier Bassin du Rhône”¹, a modeling process embodied in the RADHY research project (“*Représentation intégrée des Adaptations individuelles et des Dynamiques Hydrologiques sur le bassin du Buëch*” in French) on the Buëch catchment started in January 2019. It aims to study the functioning of water uses of the Buëch catchment at the local level, and in particular gravity-fed irrigation systems during low-flow periods as they are involved in modernization programs dealing with their operational functioning and difficulties to finely pilot water withdrawals. The steering committee of this project, which includes the representatives of the main stakeholders involved in the water management of the basin, wished the development of a modeling tool for these gravity-fed networks representing such operational functioning, as well as an overview of the irrigated systems in which such gravity-fed systems evolve.

¹See <https://www.graie.org/zabr/>

1.1.3 Difficulties related to the local nature and spatial distribution of irrigation interactions within an agro-hydrosystem

Mutual influences of irrigation operations and water resources rely in particular on multiple and diffused local interactions with biophysical processes, such as plant dynamics, soil infiltration and runoff, among others. Representing dynamically such interactions in a way that is not spatially centralized is still an open question (Vogel et al., 2015).

Indeed, hydrological feedbacks do not operate at the same spatial scale as human activities (Ehret et al., 2014). This is particularly the case for irrigation which results from a network of individuals operating at farm plots, farm or larger scales such as irrigation schemes while hydrology is meaningful at basin, sub-basin or catchment scale. Hydrology describes well the evolution of water resources at the watershed scale but often does not go down to a sufficiently fine spatial scale to be able to describe the impact of a hydrological situation on an irrigation system and to take into account the hydraulic and management constraints within this system. Hydrological processes do not therefore necessary match with the scales operating for the local irrigation operations. For example, gravity-fed systems of the Buëch catchment are involving very local interactions between irrigator and water resource, for instance at the network intake into the river or at the level of the plot supplied with water by the canal. As cross-scale interactions with hydrology also imply various time regimes from sub-daily to pluri-annual time steps, there is a variety of heterogeneous spatio-temporal scales to be considered (Sivapalan and Blöschl, 2015).

In recent years, the hydrological community has developed numerous distributed models to better integrate the spatial heterogeneity of the biophysical components. Such models allow taking into consideration local biophysical specificities such as hydro-geology, land use, soil nature or climatic forcing. However, when a distributed model is used by stakeholders to help managing water resources, the human dimension is often represented as a global or aggregated parameter, missing out its spatio-temporal complexity (Vogel et al., 2015).

1.1.4 The coupling between agent-based models and biophysical models could help to overcome these difficulties

Agent-based modeling (ABM) is one of the several approaches to tackle CHANS. Three general reviews by [An \(2012\)](#), [Filatova et al. \(2013\)](#) and [Letcher et al. \(2013\)](#) give an overview of the profusion of articles in which ABMs are applied to CHANS. As noted by many researchers, ABM is well suited to study dynamic human-environment interactions ([Matthews et al., 2007](#), [Parker et al., 2002](#)). Indeed, ABM allows to best match to real-world systems through an empirically-based framework that capture key biophysical and institutional aspects rather than drastically simplifying system representations ([Tsfatsion, 2016](#)). Agents can represent a large panel of entities ranging from passive physical objects to sophisticated human decision-makers, and ABM helps to design systems in which inter-dependencies between agents and their environment are critical to encompass system dynamics ([Parker et al., 2003](#)). ABM has also a good ability to model individual behavior, decisions and subsequent actions, incorporating heterogeneity and feedback ([Gimblett, 2002](#)).

As a consequence, researchers are increasingly using ABM to study coupled interactions among human behaviors and natural processes and notably to model human behaviors in CHANS ([An, 2012](#)). Among the numerous approaches for representing human actions, some approaches investigate the implementation phase of an action rather than only considering decision-making mechanisms. Human actions are then determined by a set of operational possibilities, continuously changing over time, and forcing the actor to adapt to it. Such approaches could be of interest to tackle interactions due to irrigation management at the operational level within an agro-hydrosystem.

The coupling of agent-based models describing decentralized human behaviors with biophysical models for the natural components of the system is an approach clearly identified in the literature ([Vogel et al., 2015](#)) and still in infancy. In particular, the representation of distributed hydrological processes taking into account the spatial heterogeneity and agent evolutions has been recently explored to capture local human-nature interactions (e.g. [Gaudou et al., 2014](#), [Robert et al., 2016b](#), [van Oel et al., 2010](#)). The emergence of these distributed hydrological models represents therefore an important

step forward in terms of coupling possibilities with ABMs to address the local nature and spatial distribution of irrigation interactions within an agro-hydrosystem.

1.2 Thesis project

In this context, the general questions explored in the thesis are the following:

- (1) How can we represent the actions of irrigators in space and time to take into account in a dynamic way their short-term interactions with the agrohydrological components of the system ?
- (2) What could this representation bring to a specific case study ?

First, we use the term "case study catchment" to design the Buëch River basin, whose coupling between local irrigation operations and basin-wide hydrology is the focus of Chapter 7. The term "case study" refers to the Aspres-Sur-Buëch irrigator union which is the local irrigation area studied in Chapter 5 and Chapter 6.

Our research strategy is divided into 3 parts (Figure 1.2). A first part of the thesis situates the research questions in the literature and in the field: 1) literature review and 2) description of the stakes of irrigation management in the Buëch case study catchment in which is located the Aspres-Sur-Büech case study chosen as representative of the gravity-fed irrigation networks of the basin for the modeling of short-term interactions dealing with irrigation. In Chapter 2, a review of the forms of representation of human action in agent-based models dealing with agricultural systems is carried out. We observe that situated approaches represent actions at the operational level that could facilitate the representation in the short term of irrigation interactions with the biophysical environment.

In the Chapter 3, we describe the challenges of irrigation management in the Buëch catchment, which has been subject to an imbalance between water needs and available resources for the last fifteen years mainly due to collective irrigation withdrawals, and in

which understanding the operational constraints and the functioning of such collective irrigation perimeters is of interest to local actors of water management in order to assess the potential impacts on agriculture and water resources. We present our material from the fieldwork we have carried out in order to: 1) characterizing the variety of irrigated systems at the scale of the case study catchment and identifying the irrigation problematic, in particular how the irrigated systems are challenged by the operational management of irrigation involving short term interactions between irrigators and their environment (i.e. the crop, the water resources), and which irrigation networks from the variety of systems are challenged, 2) describing the functioning of such networks with particular attention given to the elements involved in the short-term interactions of irrigation and 3) presenting the Aspres-Sur-Buëch local case study as representative of the gravity-fed networks in terms of operational problematic such as the abandon of the traditional coordination of the water network through daily slot coordination, which is the object of the WatASit model developed in Chapter 4, as it could potentially impact farmer possibilities of irrigation (Chapter 5), and could interfere with plant dynamics (Chapter 6) and with natural hydrology (Chapter 7).

Modeling irrigation operations depending on the coordination of a collective water network, and comparing simulations when the network is coordinated or not, requires to simulate the local interactions taking place in the short term between the farmers, the irrigated crops and the flow within the water network. In the second part of the thesis, we first propose an agent-based model (WatASit) developed specifically to represent the short term interactions due to the irrigation operations taking place when water supply and sharing for irrigation depends on a collective water network (Chapter 4). In particular, this model makes explicit the possibilities of action available for each agent over the irrigation campaign. We then apply in Chapter 5 the WatASit model to the Aspres-Sur-Buëch case study: a typical gravity-fed network of Aspres-Sur-Buëch which has abandoned the historical sharing of water by daily slots (Richard et al., 2020a). We also explore how changes in the trajectory of agents in a model such as WatASit can be linked to changes in their possibilities of action, and how the representation of these possibilities helps in the interpretation of simulation outputs by providing an intermediate level of visualization and analysis (Richard et al., 2020c, under review).

In the second part of the thesis, crops and water dynamics are not simulated with

process-based models. The third part of the thesis proposes to address the coupling of the WatASit model with two biophysical models, a crop model (Optirrig) and a distributed hydrological model (J2000). The objective of Chapter 6 is first to show the feasibility of coupling an agent-based model at the network level (WatASit), with a crop model at the plot level (Optirrig), in order to better assess the impact on crop dynamics (i.e. crop growth and water stress) of the specific network constraints in situation of tension for the sharing of water (Richard et al., 2020b, submitted). To capture the potential feedback effects of such constraints on plant dynamics during a collective irrigation campaign, we proposed the COPAT (COupling Plant and Agent Trajectories) approach that allows comparing different scenarios of network coordination. As the hydrological constraint at the network intake were still not dynamically represented, we then propose in Chapter 7 COWAT (COupling Water and Agent Trajectories) as a coupling methodology with the distributed hydrological model J2000 to account for the low flow constraint over the irrigation campaign that result from hydrology at the basin scale, but also to modify local hydrology in accordance with irrigation operations (Richard et al., 2021, in preparation).

Finally, we discuss the contribution, limitations and consequences of our work to take into account in a dynamic way the local interactions due to irrigation operations with the agrohydrological components of the system (Chapter 8).

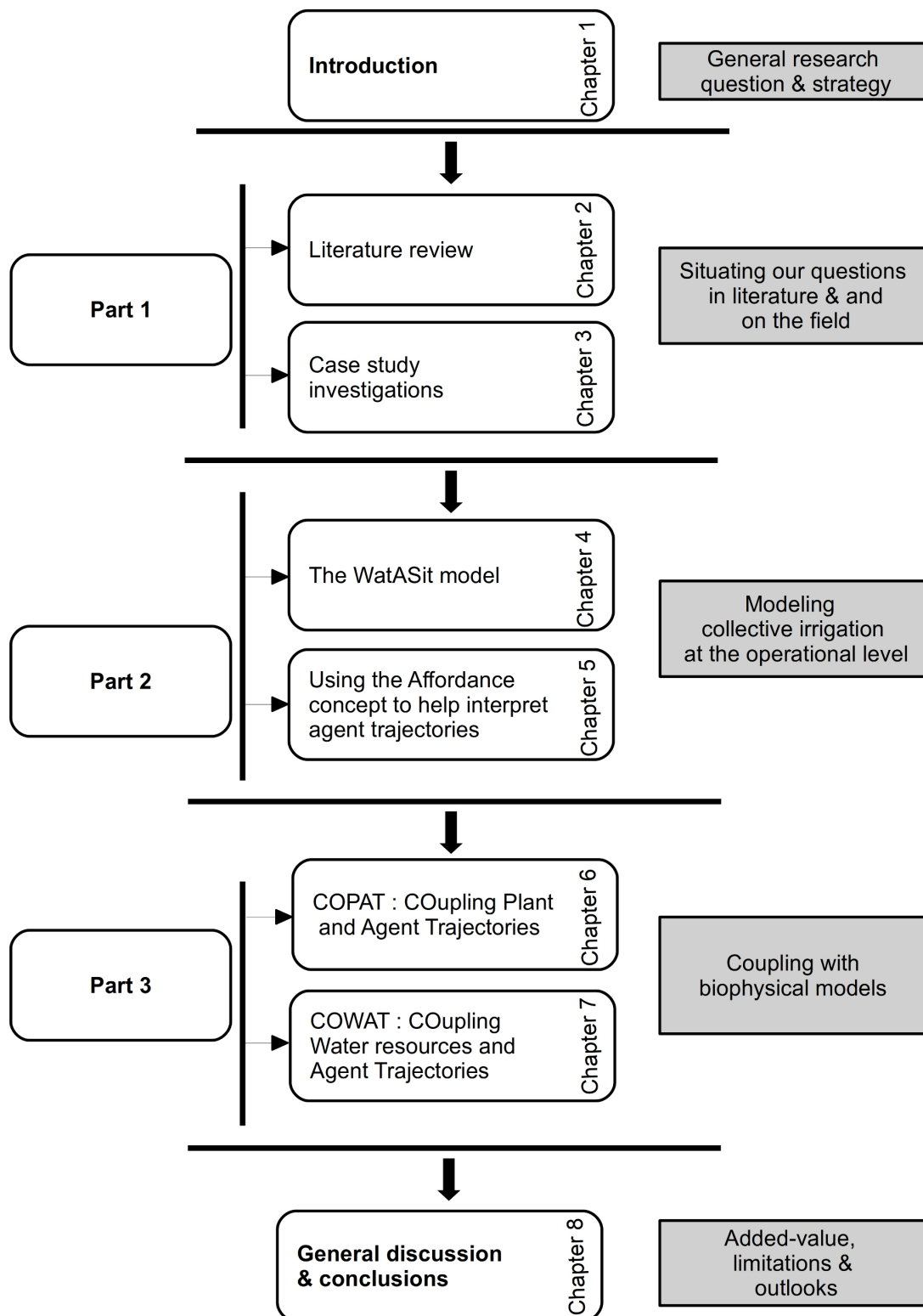


FIGURE 1.2: Overview of the main thesis stages.

Part I

Situating research questions in the literature and in the field

Abstract of Part 1

This first part of the thesis situates the research questions in the literature and on the field: literature review and description of the stakes of water management in the case study, the Buëch catchment in the Durance region.

As there is a diversity of ways to represent human action in ABMs dealing with agricultural systems, this part starts by exploring this diversity by reviewing 78 studies. First, general characteristics of the studies were assessed regarding their purpose, subject, case study and scale basis. Then, action characteristics such as levels of action, main influence factors and empirical basis were surveyed.

Results of the review show that most representations of human action in agricultural ABMs represent human action as decision-making, disregarding the implementation phase. Consequently, actions at the operational level are under-represented. However, representing human action at the operational level in ABMs dealing with agriculture could be of interest as operational management can potentially influence agricultural output, with significant economic and environmental impacts.

After reviewing the literature dealing with human representation in agricultural agent-based models, this part then investigates irrigation management within the Buëch River basin that we chose as our case study catchment because it is a basin on which the host research laboratories have already worked on, and also because it is a catchment where collective irrigation is still based on numerous gravity-fed networks whose operational functioning often derives from old irrigation or drainage systems that do not allow fine control of water withdrawals. After providing general characteristics of the catchment, we conducted field surveys in order to: 1) Identifying the irrigation problematic, in particular how the irrigated systems are challenged by the operational management of irrigation involving short term

interactions between irrigators and their environment (i.e. the crop, the water resources), and which irrigation networks are challenged, 2) describing the functioning of such networks with particular attention given to the elements involved in the short-term interactions of irrigation and 3) presenting the Aspres-Sur-Buëch local case study that we have chosen as representative of the gravity-fed networks in terms of operational problematic, with the abandon of the traditional coordination of the water network through daily slot coordination, and which is studied in the following part of the thesis.

Such abandon could impact irrigated crops, water resources and farmers' ability to irrigate. Modeling irrigation operations depending on the coordination of such a collective network, and comparing simulations when the network is coordinated or not, could be of interest to assess these potential impacts and requires to model interactions taking place in the short term between the farmers, the irrigated crops and the flow within the water network.

At the basin scale, identifying precisely the locations where the natural river flow is modified or could be insufficient for the preservation of ecosystems is also a key point for the design of future irrigation and water policies. The assessment of the influences of the network withdrawals located upstream of the basin on the water availability of the ones located downstream could also support the ongoing discussions, as it is a source of tensions between irrigators.

Chapter 2

Representations of human action in agricultural agent-based models - A review

Contribution to the thesis project: In this chapter, we first introduce the main concepts we use ABM and we then review human action representations in the literature about agricultural ABMs. A systematic survey of the characteristics (e.g. object, subject, level, nature of the approach) of human action representations by reviewing 78 studies is presented. The key result of the review is that most agricultural ABMs conceptualize human action as decision-making rather than on the implementation phase of acting. This literature review allows us to clarify the general question raised in the introduction, and to hypothesize that the mobilization of the Affordance concept in ABM could facilitate the representation of the short-term interactions between irrigation operations and the local biophysical state of the environment.

2.1 Working definitions

2.1.1 What is meant by the representation of an action?

By the representation of an action, we mean in this work the set and nature of the characteristics considered to conceive an action. Moreover, the term "subject" of an action refers to the actor of an action.

2.1.2 What is meant by a multi-agent system / an agent-based model ?

Distributed Artificial Intelligence (DAI) proposes to decompose a problem into a set of sub-problems, each having a specific solver. This approach contrasts with the classical artificial intelligence approach where the solution of a problem was assigned to a single program that was sometimes difficult to develop and maintain (Boissier et al., 2004). In the vein of DAI, multi-agent systems (MASs) are composed of a set of entities and have a broader scope than problem-solving alone. Ferber (1995) has proposed to define a MAS as :

- A set of objects which are located. These objects are passive or active (the agents). Passive objects can be perceived, created, destroyed and modified by the agents,
- A set of relations that unite the objects between them,
- A set of operations (actions) allowing agents to perceive, produce, consume, transform and manipulate objects,
- Operators responsible for representing the application of these operations and the world's reaction to this attempt at modification, which will be called the "*laws of the Universe*".

Boissier et al. (2004) define three main areas of application : 1) Modeling, observing, explaining or predicting the behavior of complex real systems, 2) Creating simulations in which agents play the role of human beings and 3) Solving problems in a distributed context. Our work mainly deals with the first area, in particular modeling, observing

and explaining.

In this work, we build a model of multi-agent system in the sense of the Modeling and Simulation (MS) approach (Michel et al., 2009). In the Agent community (especially French-speaking), such models are called Agent-Based Models (ABMs), and there are interesting formalization initiatives proposing rich and generic meta-models such as the one proposed by Treuil et al. (2008). Our work is based on the Agent meta-model of the CORMAS platform (Bommel et al., 2015) dedicated to the design of models of multi-agent systems. We stay in line with the CORMAS meta-model that considers that an agent-based model is simply a "model of MAS" and where an Agent is an entity that represents a social entity in real life. We will use the term ABM in this sense in the following. The "social" part and the "environment-human" interactions of the ABM developed in this work will however use a specific meta-model developed in Chapter 4. The description of environmental dynamics will be based on other formalism such as distributed hydrology (Chapter 7) for example.

2.1.3 What is meant by an agent ?

Several definitions of an agent exist, but they converge on the agent property of autonomy. Ferber (1995) considers an agent as "*an autonomous entity, real or abstract, which is capable of acting on itself and its environment, which, in a multi-agent universe, can communicate with other agents, and whose behavior is the consequence of its observations, knowledge and interactions with other agents*". Jennings and Wooldridge (1998) define an agent as "*a computer system, located in an environment, capable of acting autonomously and flexibly to achieve its objective*". In these definitions, the term "situated" means that the agent perceives its environment and is capable of modifying it, the term "autonomous" refers to an agent's ability to act without external control or intervention and to control its internal state and actions, and the term "flexible" refers to an agent's potentially reactive, proactive and social behavior. In summary, an agent perceives and acts autonomously. ABMs are distinguished by their ability to "*bring out collective behaviors that are the result of individual actions and interactions*" (Jean and Pesty, 1997).

2.1.4 What is meant by the environment ?

The agent's environment can refer to two ideas. The "simulated environment" (Helleboogh et al., 2007) is part of the model to represent the real environment in which the agents are located. The "simulation environment" is the software infrastructure in which the simulation runs. Without specification, we will use the term environment in ABMs in the sense of the simulated environment. According to Weyns et al. (2007), the simulated environment is used to structure agents physically, socially and to communicate between agents. It must be able to manage access to resources as well as to impose rules for the evolution of system entities. The environment may have its own internal processes.

2.1.5 What is meant by an interaction ?

Interactions are usually of two types: the interaction of an agent with its environment via its perception and its ability to act, and/or the interaction of an agent with other agents in the system that allows collective behavior. Ferber (1995) writes: "*for an agent, interacting with another agent constitutes the source of its power and the origin of its problems. It is indeed because they cooperate that agents can accomplish more than the sum of their actions, but it is also because of their multitude that they must coordinate their actions and resolve conflicts*".

2.1.6 Time representation

According to Fianyo et al. (1998), the notion of time in multi-agent simulation refers to three ideas: (i) the time in which the real phenomenon is observed (real time), (ii) the time that corresponds to the representation of real time by the simulator (virtual time) and (iii) the time that the simulator uses to construct the results of the simulation (execution time). The execution time must respect the course of virtual time, meaning a causality rule which means that an event having been caused by another event must be executed after the latter. In a simulation with constant time steps, time increment is done by a constant duration and the agents are activated at each time step in a fixed or random order. The execution of the actions of the agents immediately influences the variables of the environment. Michel (2004) shows that according to the order of

activation of an agent, its perception and knowledge to determine its action may differ. In an event-based simulation, agents are activated following a triggering event (Payet et al., 2006). Questions concerning the sequential and simultaneous activation of agents are not only related to the constant time step approach, but more broadly to the design of the action which, once triggered, directly modifies the environment (Michel, 2004).

2.1.7 Space representation

In ABMs space can be represented discretely or continuously (Ferber, 1995). A discrete representation is either in the form of a graph or as a grid of cells linked together by neighborhood links (4 or 8 adjacent cells). The perception of an agent is thus limited to a number of assembled cells. A continuous representation considers space as a single block where the entities of the system have real-valued spatial coordinates. In this case, each agent to know its neighbors must know the distance separating it from the other agents and recalculate it at each of its movements.

2.2 Representations of human action in agricultural agent-based models - A review

2.2.1 Introduction

General reviews by An (2012), Filatova et al. (2013) and Letcher et al. (2013) show that agent-based models (ABMs) have been widely used within the last few years to study systems involving complex interactions between human actions and their biophysical and/or social environment. This is because they offer possibilities for incorporating disparate entities and for studying their local interactions (Bousquet and Le Page, 2004, Filatova et al., 2009, 2013, Matthews et al., 2007, Parker et al., 2002, 2003). They are well suited to take into consideration key micro-level constraints rather than drastically aggregating system representations (Tsfatsion, 2006), especially agriculture-environment interactions (e.g. Valbuena et al., 2010).

ABMs usually consider various layers of landscape and agent processes which are combined into a spatial, cell-based framework (Parker et al., 2003). The dynamic of each

landscape entity is processed by specific biophysical modules. ABMs help designing systems structures that consider a one-to-one correspondence of real-world entities and model entities (Parker et al., 2003). Agents can represent a large panel of entities ranging from passive physical objects to sophisticated human decision-makers. Indeed, decision-making has been widely explored in ABMs to represent autonomous, interacting and communicating agents that are able to modify other agents or their social and/or biophysical environment (An, 2012). Many reviews specifically focus on decision-making in ABM, such as An (2012), Groeneveld et al. (2017), Huber et al. (2018). Individual decisions have been notably represented in a lot of ABMs for incorporating substantial heterogeneity in cumulative or collective behaviors (e.g. Gimblett, 2002). Such heterogeneity is crucial for ABMs dealing with agriculture, as reviewed by (Nolan et al., 2009) and (Kaye-Blake et al., 2010), in which farmers are locally interacting with their biophysical environment (e.g. modifying plant growth or resource allocation). Several other reviews about ABMs do not explicitly focus on decision-making but devotes to it a substantial or prominent part of the description of agents' behaviors (e.g. Filatova et al., 2013, Kremmydas et al., 2018) which reflects the importance of decision mechanisms in the current literature.

In many approaches, decision-making processes are important and can be very elaborate (An, 2012). One of the most prominent economic approach of human decision-making is Expected Utility Theory (EUT). EUT considers that the decision-maker chooses the option that promises the highest expected utility (e.g. Machina, 2008). Such rational representation of decision-makers has been challenged by the concept of bounded rationality (e.g. Gotts et al., 2003), assuming for instance that the decision maker has aspiration and stop it search for better options as soon as an option meets its aspiration. There is also a rich body of psychological approaches of which a prominent one is the Theory of Planned Action (TPA), also called the Theory of Planned Behavior, developed by Ajzen (1985, 1991). TPA considers that decision-makers perceive the ease or difficulty of performing the behavior reflecting past experiences as well as anticipated obstacles (e.g. Schwartz and Ernst, 2009). In TPA, any action is determined by a state to be achieved and a plan to achieve it (Miller, 1960a). Agents are mainly cognitive agents that choose the best plan from a pool of preexisting plans (Martin-Clouaire and Rellier, 2009), and which can be rescheduled if the situation changes. Decision-making

processes are important in agricultural ABMs and can be very elaborate (Robert et al., 2016a), especially compared to other levels of representation of an action. In particular, Guerrin (2009) proposes to be vigilant about the confusion that could result between the choice of action and its implementation.

Indeed, there are other approaches to represent human action, which are more interested in the implementation phase of the action. In particular, the Theory of Situated Action (TSA; Dreyfus, 1972, Suchman, 1987) appeared in response to a fundamental question: how can the plan, which is an abstract representation of reality conceived *a priori*, be linked to the concrete conditions of the implementation of an action? By proposing to represent human actions based on their local conditions of interaction with the environment, actions are also determined by a set of operational possibilities in constant evolution (Suchman, 1987).

The diversity of representations of human actions in agricultural ABMs may be confusing to make a choice about the appropriate representation for a specific level of action. Is it necessary to represent the decision phase, the implementation phase, or both? How are long-term actions represented in the literature? What about short-term actions at the operational level? If the literature is rich in attempts to structure decision-making in agricultural ABMs, this is not the case when distinguishing the choice of action from its implementation. To inform this debate, and to reflect the current practices in agricultural ABMs, we conducted a quantitative review of 78 studies. We used a standard questionnaire for investigating the way human actions are represented in these studies, in particular:

- What are the general characteristics of the studies in which agricultural ABMs include human actions, regarding their purpose, object, subject, case study and scale basis?
- What are the dominant approaches? How human action is represented in these studies, by decision-making, implementation or both? What is the level of the action (e.g. structural in the long-term, operational in the short-term) and what are its main influence factors? Is action representation based on empirical basis?

2.2.2 Materials and methods

In this section, we provide working concepts and definitions before presenting the paper selection process and assessment.

2.2.2.1 Definitions

Approaches for the representation of human action Different approaches are mobilized in agent-based models dealing with agriculture to represent human actions, with heterogeneous levels of decision and action implementation mechanisms. We describe below the main approaches and the place they give to these mechanisms.

Economic In the economic approaches, which are commonly used in agriculture, the action is represented as a decision-making process by optimizing an utility or objective function under constraints (Hazell and Norton, 1986). The actor is considered to know all the available alternatives in order to choose the best one (Hazell and Norton, 1986). The actor is thus rational with well-defined preferences and choosing the option that meets its preference best. EUT is the most prominent economic approach in agriculture (Groeneveld et al., 2017). In contrast, behavioral economic theories (BET) have considered the actor with bounded rationally: actor’s decision is based on limited information due to access, cognitive or time restrictions. The Game Theory (GT) also refers to the utility paradigm, as the approach formalizes action as the finding of the best choice when facing a well-defined decision situation through games (Fudenberg and Tirole, 2001). The underlying assumption is that individuals are rational and optimize their payoffs, or utility, when faced with strategic decisions.

Empirical Empirical approaches are usually representing human action as driven by effective on-site strategies from both quantitative and qualitative data (An, 2012). Such data come from direct observations, experience-based studies or other ”real-world” studies (Albino et al., 2006). For example, participatory approaches consider real people directly telling the modeler what they would do under certain conditions (Simon and Etienne, 2010). Role-playing games (RPG) and Companion Modeling (CM) share this paradigm. Empirical data or observations can also be derived as behavioral rules (also

called heuristic) using a large panel of methods such as decision tree or statistical or probabilistic or stochastic analysis (An, 2012).

Planned In the planning approaches, attention is mainly given to the development of a plan, the action being mainly caused and controlled by it which is the means to achieve the actor's goal. Prioritizing the plan according to different levels, strategic, tactical up to the operational level, breaks down the action and its sequencing to obtain a plan composed of a set of sub-plans. The plan and the sub-plans make it possible both to steer, via feedback loops, and to execute actions (Miller, 1960a). If the current configuration of the system corresponds to that of the goal, the action is completed. If the effect of the action on the system does not correspond to the desired state, the agent reschedules its sequence of actions. As a plan can be adaptive, actors are both reactive and anticipatory, and can be rational or bounded rational. The action is thus caused by a decision-making process as an iterative interpretation of a flexible plan (Martin-Clouaire and Rellier, 2009) representing both the temporal constraints of the actor and the characteristics of the environment (e.g. rainfall, water availability). Flexibility is allowed by the possibility of using different operations according to the constraints expressed. This representation is very widespread in agronomy (e.g. Aubry et al., 1998, Bergez et al., 2016, Martin-Clouaire and Rellier, 2009, Robert et al., 2016b). At the operational level, the decision is generally limited to the observation of the characteristics of the environment and the application of decision rules among a set of operations. Also, the plan construction process is not detailed and the flexibility of the plan depends on the ability to foresee all possible situations that the actor might encounter during the operational phase. A rich body of psychological approaches dealing with plans has emerged from behaviorists such as the Theory of Activity (TA; Leont'ev, 1978, Vygotsky, 1930), the TPA (Ajzen, 1991) or the Theory of Reasoned Actions (Fishbein and Ajzen, 1977). In such approach, decision-makers act under subjective norms (i.e. social influence) explicitly considered as "*perceived social pressure to perform or not perform the behavior*" (Ajzen, 1991, p.188). The TA shares with TPA the cognitive process of generating a plan. However, in TA, the plan is seen as one of the controllers of action at the operational level, in the sense that operations are first conditioned by environmental conditions and then by what was foreseen in the plan.

There are also hierarchical planning approaches (HPA) coming from artificial intelligence (Bitran and Hax, 1977), which allow the progressive construction of the plan to be modeled. Longer-term decisions impose constraints on shorter-term decisions that may also feedback to longer-term decisions (e.g. Akplogan, 2013). For a given operation, the refinement of the plan is therefore a three-step process. The mechanism associated with the construction of the plan remains an optimization procedure. In contrast, non-linear planning (NLP) is based on the least-commitment planning method (Etzioni and Weld, 1994), which aims to construct plans that are partially ordered by determining sequential constraints only when this is indispensable for plan execution. Finally, some approaches propose to better take into account the farmers' desires, seen as their objective, as well as their beliefs, which represent their knowledge, and finally their intentions, which constitute the general plan followed by the farmer. This is the belief-desires-intentions (BDI) approach proposed by Bratman (1987). The farmer is reactive by continually updating his beliefs with the arrival of new information. The decision is limited to a choice among a collection of plans built upstream, and the construction of the plan is not taken into account in the decision-making process.

Situated In the TSA popularized by Dreyfus (1972) and Suchman (1987), the main idea is to study how actors use the circumstances around them to carry out an action in an intelligent way in direct link with the surrounding world, i.e. at the operational level. There is a direct connection between the perceived information and the action. It is a question of looking at the relationship between the action, the resources and the constraints offered by the physical and social contingencies that the actor encounters. A plan can be necessary for specifying the general framework, i.e. the main characteristics of the actions (e.g. nature, operating conditions). However, the details of the actions (e.g. possibility, duration) remain unknown until the moment when the actor interacts with the environment (i.e. is in a situation). A situation is defined as “*a limited portion of the world over some location and time*” (McCarthy and Hayes, 1969). The goal is no longer the objective to be reached, but the explanation of the actions that have been carried out: the actor did this because he wanted to do it but could not in this situation. When the situation is no longer favorable for the execution of the action in progress, this action ends. In the next situation, a new action can be undertaken among the available options. The actor has a bounded rationality as his trajectory depends not only on

changes in the state of the objects surrounding the actor, but also on actor's ability to perceive them and what he is able to do with them (Lave, 1988).

Other approaches Other approaches exist that focus, for example, on how farmers perceive their environment via mental maps (e.g. Winsen et al., 2013), which represent the vision of one or more farmers. For instance, the Fuzzy Cognitive Maps (FCM), derived from cognitive maps, are graphs that contain a set of concept and directional edges (each edge representing the influence of a concept on another), and address complex human or animal behaviors (Tolman, 1948). Moreover, the integrated agent approach of Feola and Binder (2010) defines the farmer's intentions based on his feelings and the supposed consequences of the targeted action. We should also mention the Theory of Adaptive Expectations (TAE, Cagan, 1956), which is more frequently used in economy, when individuals revise their expectations in each period according to the degree of error in their previous expectations. Finally, control theory (Anderies et al., 2007) focuses on exploring alternative strategies for dealing with highly uncertain social and ecological dynamics.

Action In this review, we distinguish the phase of choice of the action (i.e. decision-making) from the implementation phase related to the physical environment of the operator. We consider that a decision does not always give rise to an action, and that an action may sometimes not be preceded by a decision.

Action influence factors We define five categories of factors that can influence agent behavior: 1) economic (e.g. grant, financial product as income, market) 2) social (influence from groups of actors, social networks), 3) biophysical (e.g. availability of natural resources, plant dynamics, or other dynamics related to the natural environment of the agents), 4) political (driven by the implementation by a public or private institution of a policy in a specific domain) and 5) other factors (all other factors not previously mentioned).

Levels of action We distinguish two levels for agent actions: structural and operational. The structural level of action refers, in this review, to monthly, annual or pluri-annual strategic choices relative to changes in the structure of the farming system

(Sebillote and Soler, 1990, ten Berge et al., 2000) such as material investments, for example to access water (Koundouri et al., 2006), choice of the cropping system and rotation for the coming season (Janssen and van Ittersum, 2007). Indeed, once the structural choices have been made, the farmer has to make operational choices (Aurbacher et al., 2013, Martin-Clouaire, 2017): farm management on the short term, with special emphasis on irrigation and fertilization decisions (Sebillote and Soler, 1990) allowing daily or sub-daily operational adjustments to the actual contingencies of the actor.

2.2.2.2 Paper selection and assessment

The publications analyzed for this review were selected on the Web of Science to obtain an in-depth and unbiased literature selection. We conducted a Topic Search (TS) with the search term “TS = ((farming OR agricultur* OR irrigat*) AND (human) AND ((agent-based) OR (agent based) OR (multi agent*) OR (multi-agent*)) AND model*)”. The Web of Science search was limited to document type “Article” (excluding book chapters) and “Conference Proceedings for publication years 2000-2019. We obtained 242 search results (see Table 2.1 for details of the selection process). Each publication was evaluated by title and abstract to exclude papers not related to an ABM approach dealing with agriculture. We also only kept full conference paper significantly different from the articles and excluded reviews (see Table 2.2 for the source type of each reviewed paper). We obtained 114 publications that were then evaluated in more detail following a standard questionnaire with 13 review criteria (Table 2.3). During this more detailed evaluation, we filtered 78 publications that fit the scope of our review, i.e. agent-based models which represent human actions within an agricultural system, and that provided a model description. Land use agent-based models were only considered if they deal with an agricultural issue integrating explicit human actors (e.g. farmer, household).

We used a review questionnaire that distinguish general criteria from action representation criteria (Table 2.3). The latter focus on approaches used for representing agent action. As these approaches do not necessarily concern the same phase of the action (i.e. choice, implementation), we consider that they are not necessarily opposed: one can have an EUT theory for the decision phase combined with a TSA theory for the implementation phase. Information was sometimes not stated in the text and not clearly

TABLE 2.1: Overview of literature selection stages and resulting number of articles in review based on a topic search (TS) using the *Web of Science*.

Source	Selection stage	Paper number
Web of Science	TS	274
	Publication years: 2000-2019	251
	Document type: Article and Conference proceeding	242
Literature database	First scan : Title and Abstract	114
	Detailed evaluation : 19 review criteria	78

understandable by reading the paper: we entered a ‘NA’ for the respective criterion.

Finally, we used the R Statistical Computing Environment ([RCoreTeam, 2018](#)) to transform all review criteria into binary (if two possible answers) or numeric (if more than two possible answer) variables.

2.2.3 Results and discussion

In this section, we first present the general characteristics of the reviewed studies (i.e. purpose, object and subject of human action, case study, scale and source). We then give an overview of human action representations (i.e. used approaches, influence factors, representation form, levels and empirical basis of actions), before discussing the results and the limitations of the review.

2.2.3.1 General characteristics

78 papers were reviewed accounting for 32 journals and 5 international conferences. One journal was dominant (N=14 papers, 18% of all reviewed papers): *Agricultural Systems* (Figure 2.1). Other prominent journals are *Environmental Modelling and Software* (N=7), *Ecological Modelling* (N=5), *Ecology and Society* (N=5) and *Journal of Artificial Societies and Social Simulation* (N=5). The main study purpose is ”system understanding” (N=38, 49%). This result has also been observed in other types of agent models, such as agent-based land use change models ([Groeneveld et al., 2017](#)). Prospective and decision support purposes are also well represented (Figure 2.2).

TABLE 2.2: List of reviewed studies (N=78) and their source type. *C denotes full conference paper. **A indicates an article.

Citation	Source type	Citation	Source type
Afoutni et al. (2011)	C*	Holtz and Pahl-Wostl (2012)	A
Afoutni et al. (2014)	C	Huber et al. (2013)	A
Allain et al. (2018)	A**	Joffre et al. (2015)	A
Amadou et al. (2018)	A	Kaufmann et al. (2009)	A
Angourakis et al. (2017)	A	Kaye-Blake et al. (2010)	A
Aurbacher et al. (2013)	A	Lan and Yao (2019)	A
Badmos et al. (2015)	A	Le et al. (2010)	A
Bai et al. (2015)	A	Lobianco and Esposti (2010)	A
Baillie et al. (2016)	A	Luo et al. (2018)	A
Bannwarth et al. (2016)	A	Malawska and Topping (2016)	A
Barnaud et al. (2008)	A	Manson et al. (2016)	A
Barreteau et al. (2004)	A	Marohn et al. (2013)	A
Becu et al. (2003)	A	Mathevet et al. (2003)	A
Belem and Saqalli (2017)	A	Matthews (2006)	A
Bell (2011)	A	Matthews et al. (2007)	A
Berger et al. (2017)	A	Mena et al. (2011)	A
Bert et al. (2011)	A	Miyasaka et al. (2017)	A
Bithell and Brasington (2009)	A	Morgan and Daigneault (2015)	A
Brady et al. (2012)	A	Murgue et al. (2016)	A
Cameroni et al. (2014)	A	Naivinit et al. (2010)	A
Carauta et al. (2018)	A	Nguyen et al. (2019)	A
Castella et al. (2005)	A	Olabisi et al. (2015)	A
Chang and Liu (2018)	A	Perello-Moragues et al. (2019)	A
Chen et al. (2019)	A	Pérez et al. (2003)	A
Courdier et al. (2002)	A	Quang et al. (2014)	A
Delmotte et al. (2015)	A	Saqalli et al. (2010)	A
der Straeten et al. (2010)	A	Saqalli et al. (2011)	A
Ding et al. (2015)	A	Schouten et al. (2013)	A
Dobbie et al. (2018)	A	Schreinemachers and Berger (2011)	A
Etienne et al. (2003a)	A	Tian et al. (2016)	A
Etienne et al. (2010)	A	Tsai et al. (2015)	A
Gaudou et al. (2014)	C	van Oel et al. (2010)	A
Grashof-Bokdam et al. (2017)	A	Wise and Crooks (2012)	A
Grillot et al. (2018a)	A	Xu et al. (2018)	A
Grillot et al. (2018b)	A	Yamashita and Hoshino (2018)	A
Grinblat et al. (2015)	A	Yuan et al. (2017)	A
Grovermann et al. (2017)	A	Yu et al. (2012)	C
Guerrin et al. (2016)	C	Zheng et al. (2013)	A
Guzy et al. (2008)	A		
Happe et al. (2006)	A		

TABLE 2.3: Overview of the 13 review criteria used for the detailed evaluation. * denotes multiple matches possible.

General characteristics	
<i>Study overview</i>	
1. Purpose of the study*	System understanding / Prospective / Policy design / Communication / Theory development / Hypothesis testing
2. Object of human action*	Agriculture / Urban / Water / Climate / Land use
3. Subject of human action*	Individual / Household / Group / Institution
4. Case study	Yes / No
5. Scale	Local / Regional / National or Global
6. Source	/ Year, source name
Human action representations	
<i>General</i>	
7. Influence factors for action*	Economic / Social / Biophysical / Political / Other
8. Level of action	Structural / Operational / Both
<i>Approach</i>	
9. Approach used*	EUT / BET / GT / Heuristic / CM / RPG / TA / TPA / BDI / TA / TRA / TSA / TAE / FCM / Other (name?)
<i>Action representation</i>	
10. Decision-making	Yes / No
11. Explicit action implementation	Yes / No
<i>Empirical basis</i>	
12. Action based on empirical data	Yes / No
13. Kind of data	Qualitative / Quantitative / Both

A large majority of the papers were grounded on a case study (N= 71, 91%). The number of papers based on a local case study (N=40) is higher than those based on a regional case study (N=30), and the spatial scale encompassing national and global case studies is poorly represented (N=3). In our review we kept track of three types of human action subject: 1) Individual, 2) Household - or farm - and 3) Group of individuals. Our results show that individual (N=43) and household (N=35) are most often used. Note that the total of reviewed papers using such subjects is larger than the total number of reviewed papers as both subject types can be used in the same paper (e.g. [Bai et al., 2015](#)). Four papers have both individual and household subjects, one paper has both household and group subjects, and one encompasses the three subjects. Not surprisingly, object of human action was agriculture management in a substantial number of papers (N=40, 51%). However, land use management is also very much present (N=25, 32%). This is because, as noticed by [Groeneveld et al. \(2017\)](#) in their review of human decision-making in agent-based land use models, lot of ABMs dealing with land use issue concern agricultural systems (e.g. [Amadou et al., 2018](#), [Angourakis et al., 2017](#), [Chen et al., 2019](#)).

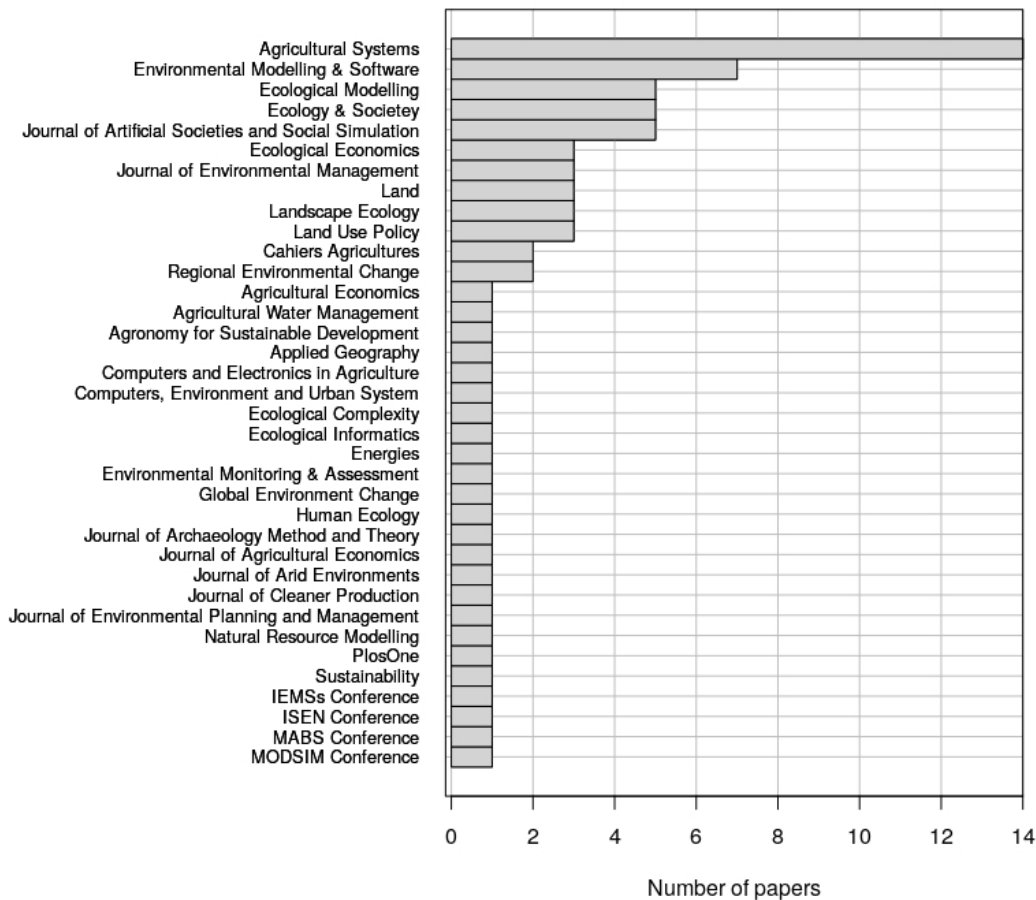


FIGURE 2.1: Distribution of the reviewed papers (N=78) across source types (i.e. journal or conference name).

2.2.3.2 Human action representations in agricultural ABMs

Use of approaches Most often, studies are based on empirical approaches (N=30, Figure 2.3), mainly heuristic (N=23), but also participatory such as RPG (N=7, e.g. Castella et al., 2005, Etienne et al., 2003b). These studies nevertheless bring together a rather disparate set of approaches. Some represent action using decision-making trees (e.g. Bai et al., 2015) or a set of decision rules (e.g. Grillot et al., 2018a), and others make assumption-based rules based on sociological fieldwork (e.g. Saqalli et al., 2010). When they are not empirical-based, very often the studies are grounded on economic approaches (N=23, e.g. Holtz and Pahl-Wostl, 2012). This has already been observed, for example concerning land use agent-based models (Groeneveld et al., 2017).

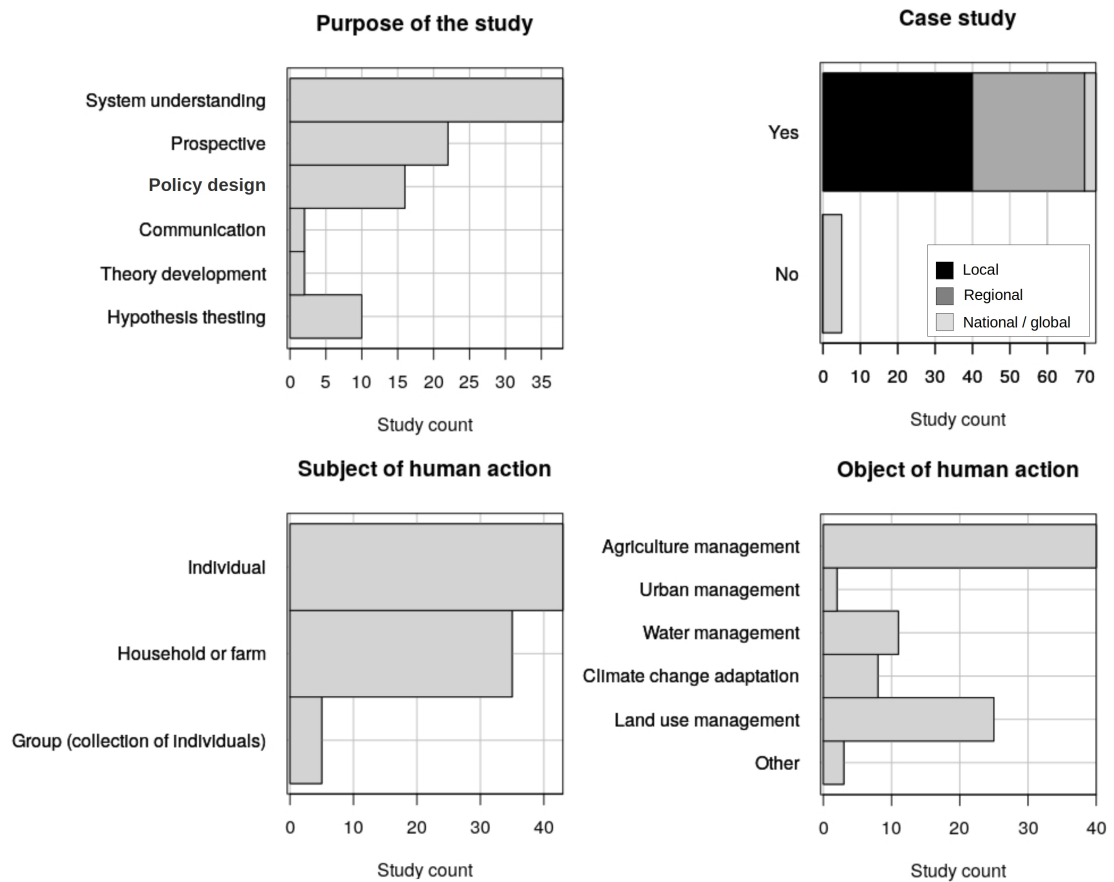


FIGURE 2.2: Overview of general characteristics of the reviewed studies. Numbers do not have to add up to the total number of reviewed papers ($N = 78$) because multiple entries (e.g. multiple purposes) are possible.

Action planning approaches are also well represented ($N=10$, Figure 2.3) as TPA is used in 7 studies (e.g. Kaufmann et al., 2009) and BDI in 2 studies (e.g. Allain et al., 2018). Situated approaches are much more confidential ($N=3$, e.g. Afoutni, 2015). The other studies ($N=9$) have approaches where the action is represented very differently from one study to another, with either calibration-based rules (e.g. Miyasaka et al., 2017), TAE (e.g. Grovermann et al., 2017) or FCM (e.g. Mehryar et al., 2019). Notice that one study mobilizes both the TSA and the TPA (Guerrin et al., 2016) as a plan is called in addition to specific concepts for situated action such as the concepts of affordance (Gibson, 1977) and stigmergy (Grassé, 1959). Information were not available or clear in 6 studies. Over time (Figure 2.4), we observe an average of 1.2 studies per year over the 2000-2009, and an average of 6.8 studies per year over the 2010-2019 period, with a greater number of studies where information is not available in our review.

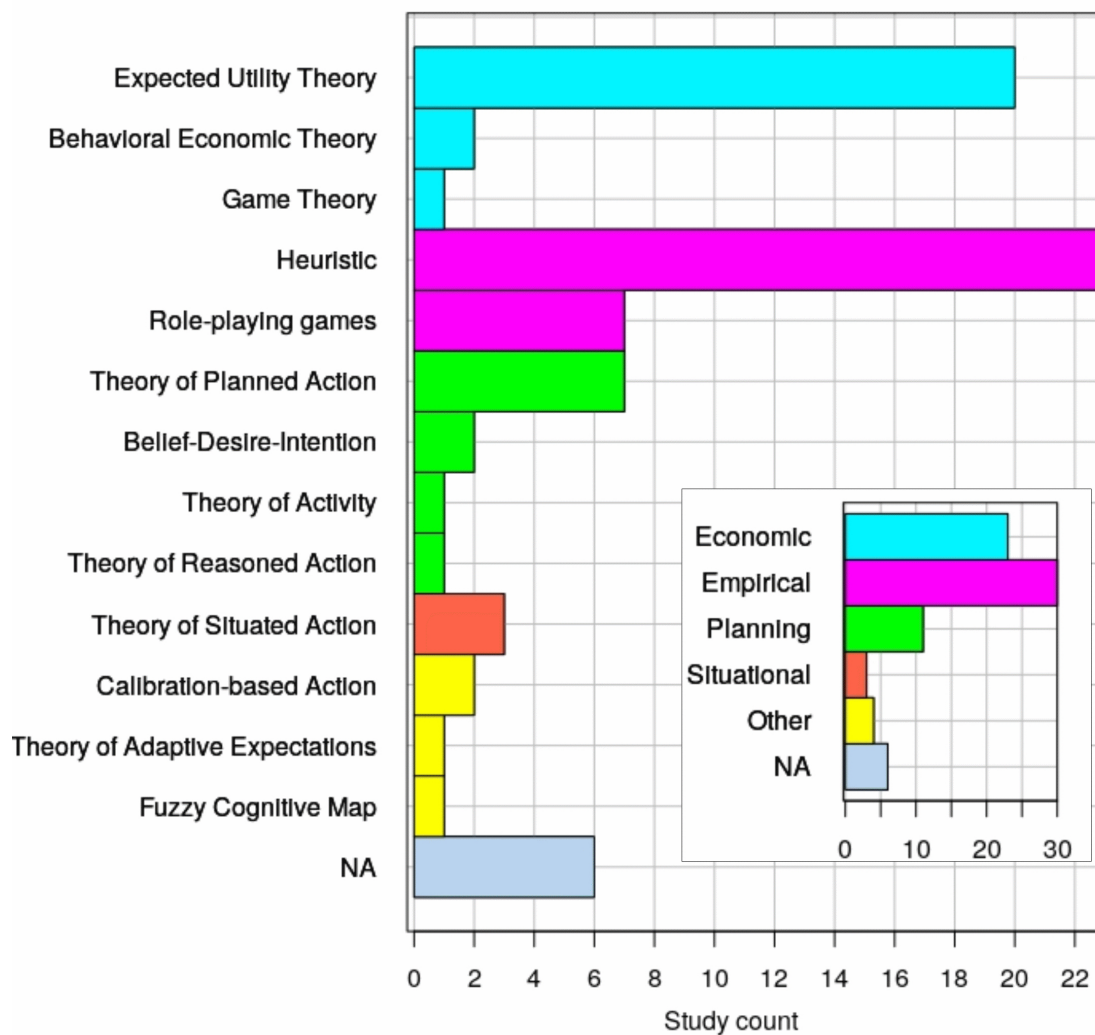


FIGURE 2.3: Used of action approaches in the reviewed studies. Numbers do not have to add up to the total number of reviewed papers ($N = 78$) because multiple entries (e.g. multiple purposes) are possible.

Action representation characteristics Looking at the influence factors of human action, biophysical factors ($N=60$, Figure 2.5) are following by economic factors ($N=48$) and social factors ($N=30$). The trajectories of agents are often influenced by agronomic processes such as plant growth, hydrological or climatic processes, resource availability and often by many of these processes (e.g. Bithell and Brasington, 2009, Gaudou et al., 2014, van Oel et al., 2010). Economic influence factors are most of the time the yield or income of the farmer.

An important characteristic we have investigated is the representation of the action as decision-making, action implementation or both stages. A striking result is that

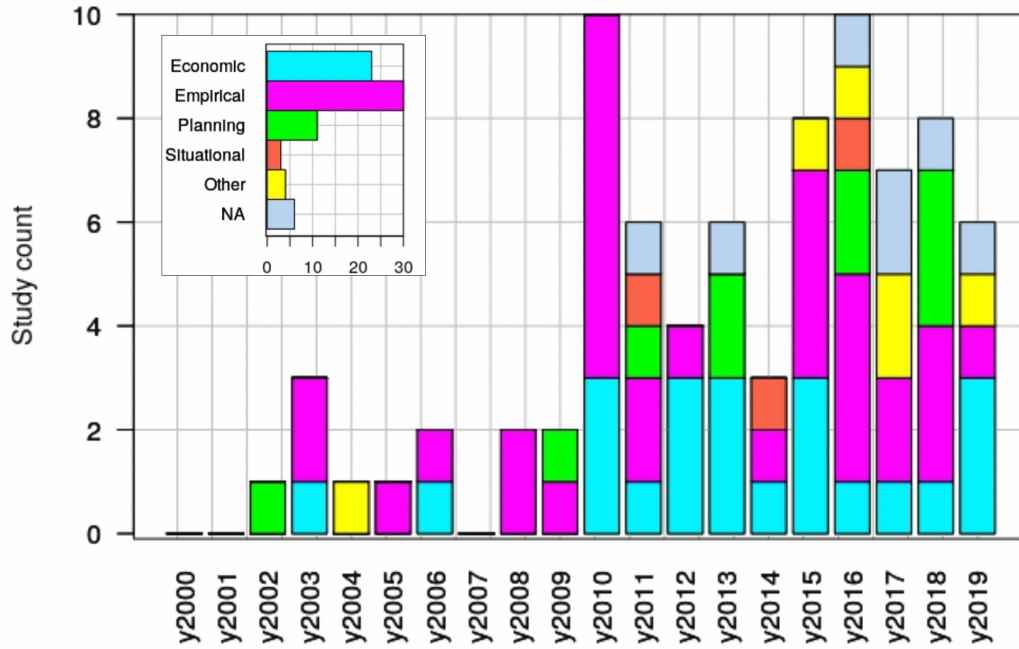


FIGURE 2.4: Use of action approaches over time over years (y) 2000 to 2019.

the implementation of the action was represented in only 9 studies (Figure 2.5), while decision-making in 69 studies. If this result is not surprising because ABMs have historically been used to represent decision-making mechanisms between actors (Huber et al., 2018), it nevertheless shows that the constraints linked to the progress of the action itself are little considered. Moreover, actions at the operational level, which some authors consider difficult to represent without processes of implementation of the action (e.g. Guerrin, 2009, Guerrin et al., 2016), concern only 17% of all studies. Actions at the operational level can also be represented with operational decision-making mechanisms, and in this case are often associated with specific methodologies, such as stock-flow diagrams derived from the system dynamic approach (e.g. Grillot et al., 2018b). However, most of the studies mainly focus on the structural level, in particular when action is conceptualized as decision-making disregarding implementation (Figure 2.5). In addition, a few studies represent action at both structural and operational levels (N=9).

2.2.3.3 Limitations and outlook

The first difficulty stems from the emergence of mixed approaches that mobilize several theoretical foundations as it is not always easy to well identify them all. For instance,

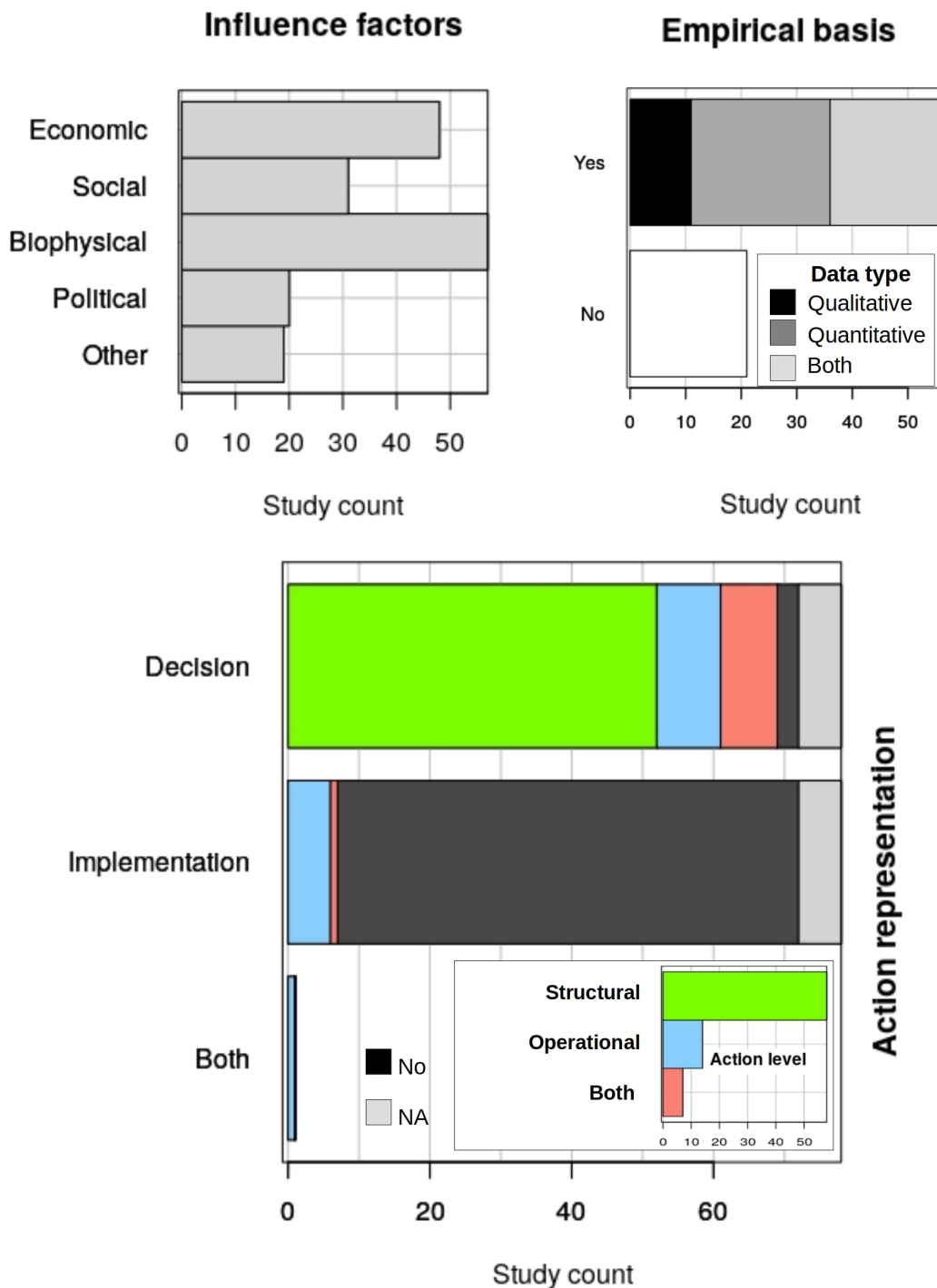


FIGURE 2.5: Influence factors, empirical basis, levels and representation of action in the reviewed studies. Numbers do not have to add up to the total number of reviewed papers (N = 78) because multiple entries (e.g. multiple purposes) are possible.

Olabisi et al. (2015) developed an empirical ABM equipped with micro economic mechanisms. A second difficulty is the choice of the levels of action considered in this study. Indeed, some authors define decision-making at three temporal scales: strategic, tactic

and operational (e.g. [Robert et al., 2016a](#)). As we were not focusing on decision-making, we have preferred to use the term "structural" in reference to the evolution of a farm planned in advance in opposition with the operational contingencies. But we are aware that the term "structural" do not distinguish long-term from medium-term aspects of farm management. One key limitation of the study is related to the fact that existing standardized protocols for describing ABMs are very well designed for the description of agent decision-making, and not specifically tackle the implementation phase of human action. This is notably the case for the ODD protocol ([Grimm et al., 2006](#)) or the MoHub (Modeling Human Behavior) framework presented in [Schlüter et al. \(2017\)](#). Discussions are probably welcome to see how this implementation phase of the action could be described in a formal and standardized way, and what features would be interesting to describe them. Describing the characteristics of the action implementation phase (e.g. duration, operator, object, continuous or intermittent time regime) and its consequences for the operator (e.g. reduction of the time available to act, the possibility to perform several actions simultaneously with other operators) and for the object of the action (e.g. state during and after the implementation of the action, the consequence for the availability of the object) seems to us to be a good starting point. Finally, consolidating and enlarging the representation of human actions in agent-based models dealing with agricultural systems may be achieved by using complementary approaches (e.g. the TSA), learning from other disciplines, notably fostering collaboration with social scientists and psychologists, and get closer to stakeholders in the field.

2.2.4 Conclusions

As human action can take different forms in the literature of agent-based models dealing with agricultural systems, we explored in this study their forms of representation to inform about current practices by reviewing 78 studies. First, general characteristics of the studies were assessed regarding their purpose, object, subject, case study and scale basis. Then, action characteristics such as levels of action, main influence factors and empirical basis were surveyed. Results of the review show that most representations of human action in agricultural ABMs represent human action as decision-making, disregarding the implementation phase of acting. Consequently, actions at the operational level are under-represented despite their importance for agricultural production. If actions at the operational level are represented by economic or planned approaches

with operational decision-making mechanisms, representing the implementation phase of the action in ABMs dealing with agriculture may be beneficial to simulate local operational alternatives on the short-term. Some authors have already proposed conceptual approaches, such as [Afoutni \(2015\)](#), which would require a proof of concept.

Chapter 3

Case study

Contribution to the thesis project: *After having reviewed the literature in the previous chapter, we describe in this chapter the challenges of irrigation management in the case study catchment, the Buëch catchment, in which understanding the operational constraints and functioning of irrigation is of interest to local actors of water management to assess the potential impacts on agriculture and water resources. We present our material from the fieldwork we have carried out in order to: 1) characterizing the variety of irrigated systems at the scale of the case study catchment and identifying the irrigation problematic, in particular how the irrigated systems are challenged by the operational management of irrigation involving short term interactions between irrigators and their environment (i.e. the crop, the water resources), and which irrigation networks from the variety of systems are challenged, 2) describing the functioning of such networks with a particular attention given to the elements involved in the short-term interactions of irrigation and 3) presenting the Aspres-Sur-Buëch local case study as representative of the gravity-fed networks in terms of operational problematic such as the abandon of the traditional coordination of the water network through daily slot coordination, which is the object of the WatASit model developed in Chapter 4, as it could potentially impact farmer possibilities of irrigation (Chapter 5), and could interfere with plant dynamics (Chapter 6) and with natural hydrology (Chapter 7).*

3.1 Introduction

Irrigation is at the confluence of the worlds of agriculture and water resources, and connects the agricultural systems to the multiple scales of water management. Locally, water management has been mainly ensured along with history through collective management institutions as part of traditional social schemes (Sanchis-Ibor and Molle, 2019) for ensuring sufficient quantitative water supply. Today, the irrigation sector is asked to adjust water demand as water resources are increasingly used for other uses, such as urban, industrial and environmental needs. There is in particular a raising awareness to develop freshwater resources in a way preserving biodiversity (Poff and Schmidt, 2016), and taking into account climate change and drought periods. Consequently, all around the world, water saving programs are spreading and the operations of collective networks inherited from the past are examined and questioned for their water losses in order to recover ecological values (Kneebone and Wilson, 2017, Schiemer et al., 1999, Shah et al., 2007). As the success of such programs is variable and required very high investment (Lamouroux et al., 2015), this has led to adopt water regulations for irrigation in major river basins where freshwater resources are being depleted (Poff et al., 1997, Vörösmarty et al., 2010), and to create basin-scale arrangement based on existing institutions (Thompson et al., 2017) such as irrigator unions.

In the European countries, common water regulations are shared under the Water Framework Directive (WFD) of the European Union (EU), which slowly moves to demand-side management. In France, collective irrigation networks are mainly managed by irrigator unions (called ASAs in French for “*Associations Syndicales Autorisées*”) and regional water management companies (Loubier et al., 2019). While regional companies were created after the Second World War, irrigator unions often derived from old irrigation or drainage systems dating sometimes from the Middle Ages, and have considerable autonomy in terms of operating rules (Loubier et al., 2019). A quarter of the 2000 irrigator unions are managing gravity networks, with tens of hectares and members, and wide variation in their ability to perform maintenance works and organize water sharing. Operating rules of collective irrigated systems such as irrigator unions are particularly challenged by the introduction of new water management instruments (Loubier et al., 2019). Since the *2006 Water Act*, a maximal total volume which may be abstracted by

irrigation is defined in each river basin where significant imbalance remains. Based on this total volume, a maximum withdrawal rate is determined for each collective network. In the Durance River basin, after several decades of equilibrium between supply and demand, water resources have been subject to tensions since the 1990s because of the rise in environmental concerns and tourism (Santoni, 2014, Sauquet, 2015). For example, the Buëch sub-basin has been subject to a quantitative water resources management plan aimed at reducing by 30 % total abstraction from irrigation to maintain a minimum natural flow. In this context, small irrigator unions are particularly solicited to modernize their functioning for complying with new regulations. Structural water policies are not the only ones to evolve, as following the 2003 European heat wave, drought management plans have been gradually implemented including frequent daily irrigation restrictions (Sauquet et al., 2019).

In our work, we chose the Buëch catchment as our case study catchment because it is a basin on which the host research laboratories have already worked for example in the framework of the R2D2 2050 project (Sauquet, 2015), and because in terms of spatial scale, it corresponds to the management scale of local managers such as the Buëch river syndicate (SMIGIBA). It is also a basin where collective irrigation is still based on numerous gravity-fed networks whose operational functioning often derives from old irrigation or drainage systems that do not allow fine control of water withdrawals and for which local actors need to study the existing possibilities of improvement and current constraints that relies on cumulative interactions at the short term in multiple locations and with multiple spatio-temporal scales.

In this chapter, we describe the challenges of operational management of irrigation in the case study catchment, in which understanding the operational constraints and functioning of irrigation is of interest to local actors of water management to assess the potential impacts on agriculture and water resources. We present our material from the fieldwork we have carried out in order to: 1) characterizing the variety of irrigated systems at the scale of the case study catchment and identifying the irrigation problematic, in particular how the irrigated systems are challenged by the operational management of irrigation involving short term interactions between irrigators and their environment (i.e. the crop, the water resources), and which irrigation networks from the variety of systems are challenged, 2) describing the functioning of such networks with particular

attention given to the elements involved in the short-term interactions of irrigation and 3) presenting the Aspres-Sur-Buëch local case study as representative of the gravity-fed networks in terms of operational problematic, such as the abandon of the traditional coordination of the water network through daily slot coordination.

3.2 General characteristics of the Buëch River basin

The Buëch River basin (Figure 3.1) is a subbasin of the Durance River basin. A description of the water management context in the Durance River basin is provided in Appendix A of the manuscript. The Buëch River basin has an area of 1,490 km² and extends mainly over the Hautes-Alpes county. Facing north/south, it extends between the Baronnies, the Dévoluy, the Ecrins and the Vercors mountain ranges. It is a territory of medium mountains and transition between the Alps and Provence. The altitude varies from 2,700 m at the summit of Pic de Bure to 400 m at the confluence with the Durance at Sisteron. The Buëch catchment area has 53 municipalities, about 20,000 inhabitants and is mainly rural and forested with an agricultural and tourist vocation. Its Y-shape is divided into three sections: the Buëch downstream from the clue at Serres, the Grand Buëch upstream in the West, and the Petit Buëch upstream in the East. The Grand Buëch has its source in the commune of Lus-La-Croix-Haute at an altitude of 2,000 meters, while the Petit Buëch has its source in the southern foothills of the Dévoluy Massif and the Pic de Bure. The Petit Buëch joins the Grand Buëch to the north of the town of Serres upstream of the clue. The Buëch is fed on both sides of its network by 19 tributaries. Collective irrigation is by far the most important use of water resources, in particular during the main low flow period between July and October.

3.2.1 Hydro-climatic regime

The hydrological regime of the Buëch (Figure 3.3) is a rainfall and snowfall type with two maxima: during spring (due to snow-melt and heavy rainfall) and during autumn (due to rainfall). The low flow period is very marked in August (Figure 3.2) and can extend until October due to the Alpine and Mediterranean climatic influences (Gautier, 1992). The high peaks of the Dévoluy strongly influence the hydrological regime of the

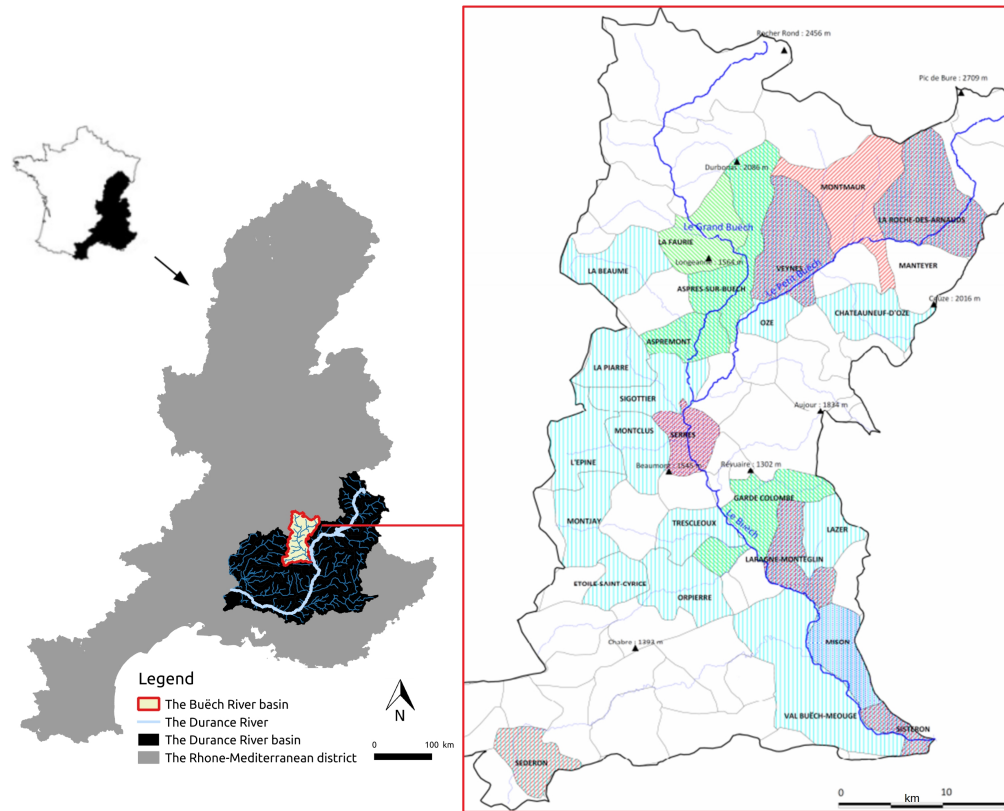


FIGURE 3.1: Location of the Buëch River Basin (source : *BD Carthage* and *SMIGIBA*, 2017).

upstream part of the river basin. More than 19 % of the watershed is above 1500 m above sea level, this upper part receives snowfall from January to February. Overall, the Buëch is a torrential river of 120 km long experiencing sudden and sometimes violent flooding in spring and autumn. The morphology of the riverbed is therefore braided (Figure 3.4) and evolves with different dynamics over time. Exceptional floods are capable of disrupting the minor bed. A specificity of this part of the Durance region is the "adou", which are appendages of the river flowing at the margin of the major bed in the riparian zone (Gautier, 1992). They are fed by resurgences of the alluvial groundwater and play an essential role in maintaining the low flow rate in the summer period.

3.2.2 Water uses and crop distribution

For the past fifteen years, the Buëch River basin has been subject to recurrent tensions on water resources between users, due to large water withdrawals and several droughts. As



The Petit Buëch, April 2019

The Petit Buëch at the same location, August 2019

FIGURE 3.2: Comparative view of the Petit Buëch in April and August 2019, at the same location (credit : C. Distinguin).

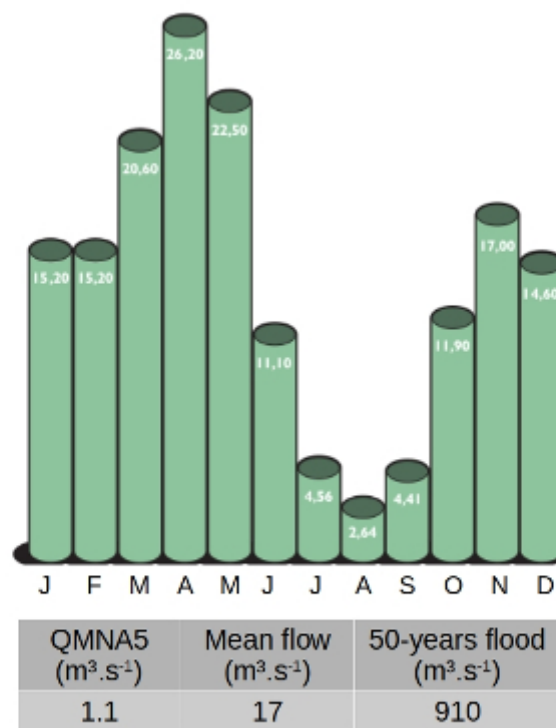


FIGURE 3.3: Average monthly natural flow of Buëch (m³.s⁻¹) calculated at Serres ("Les Chambons") over 41 years (1969 to 2009) (source: Banque Hydro). In the table below, QMNA5 is the minimum monthly flow with a 1/5 probability of not being exceeded in a given year.

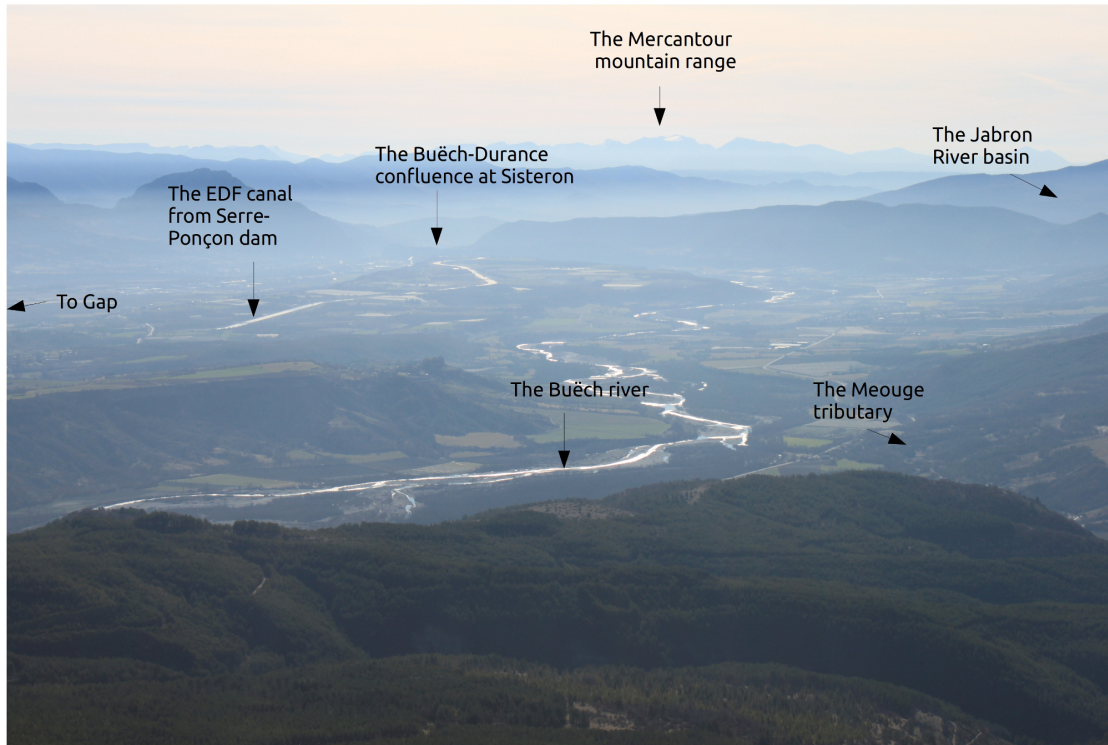


FIGURE 3.4: View of the Buëch river in the downstream part of the river basin. The river joins the Durance River at the level of the town of Sisteron. On the left, the *EDF* canal that goes from the Serre-Ponçon dam is visible (crédit : B. Richard).

during the low flow period hydro-power is turned off (Figure 3.5, top), irrigation became predominant in terms of water abstraction from May to September with 24 million cubic meters (Figure 3.5, bottom). Figure 3.6 maps the several crops cultivated within the Buëch River basin in which meadows (13.8 %), fodders (also called forages sometimes) (7.3 %), cereals (7.2 %) and orchards (2 %) dominate excepting estives and grazed woods (66 %). Figure 3.7 compares crop area in upstream and downstream parts of the Buëch River basin for the year 2017. Note that the separation is the confluence of the two upstream river branches (see Figure 3.6). Fodders (+676.11 ha), orchards (+901.82 ha) and industrial crops (+543.68) are much more established in the downstream part of the basin. Permanent meadows (+542.4 ha) and estives or grazed woods (+4356.8) are strongly established in the upstream part.

3.2.3 Data availability

The modeling work presented in the following chapters requires data that are mainly the types of crops on each farm plot of the Buëch catchment, the location and geometry of the

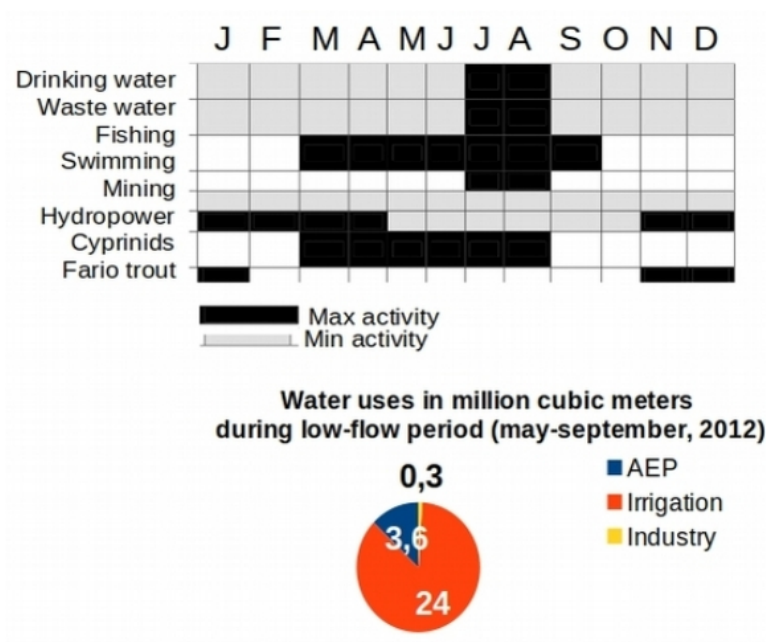


FIGURE 3.5: Maximum and minimum activities of water uses (top) and percentages of main uses during May-September low-flow period (source: *EVP*, 2012). AEP denotes drinking and sanitation waters

TABLE 3.1: Data types and sources used for the characterization of collective irrigated systems of the Buëch River basin.

Data type	Data source
Climatic (total precipitation, reference evapotranspiration, temperature, global radiation)	French <i>SAFRAN</i> reanalysis
Water restrictions (date and levels)	<i>PROPLUVIA</i> database
River shapefiles, length, width and tributaries	<i>BD Carthage</i>
Plot shapefiles, areas and crop types	" <i>Registre Parcellaire Graphique</i> " (RPG)
Irrigation infrastructures	<i>BD HYDRA v2</i> (2015)
Soil characteristics	<i>PACA Regional Soil Reference System</i>
Land cover	<i>SENTINEL 2</i>
<i>DEM</i> 25m	<i>IGN</i>
Geology	<i>BRGM</i> 1:25000

farm plots, shape files of hydraulic infrastructures and climatic forcings (precipitation, temperature, evapotranspiration, net radiation). Data type and source available through databases are summarized in Table 3.1.

3.3 Material from field surveys

To complement information available from databases, we conducted field surveys for:

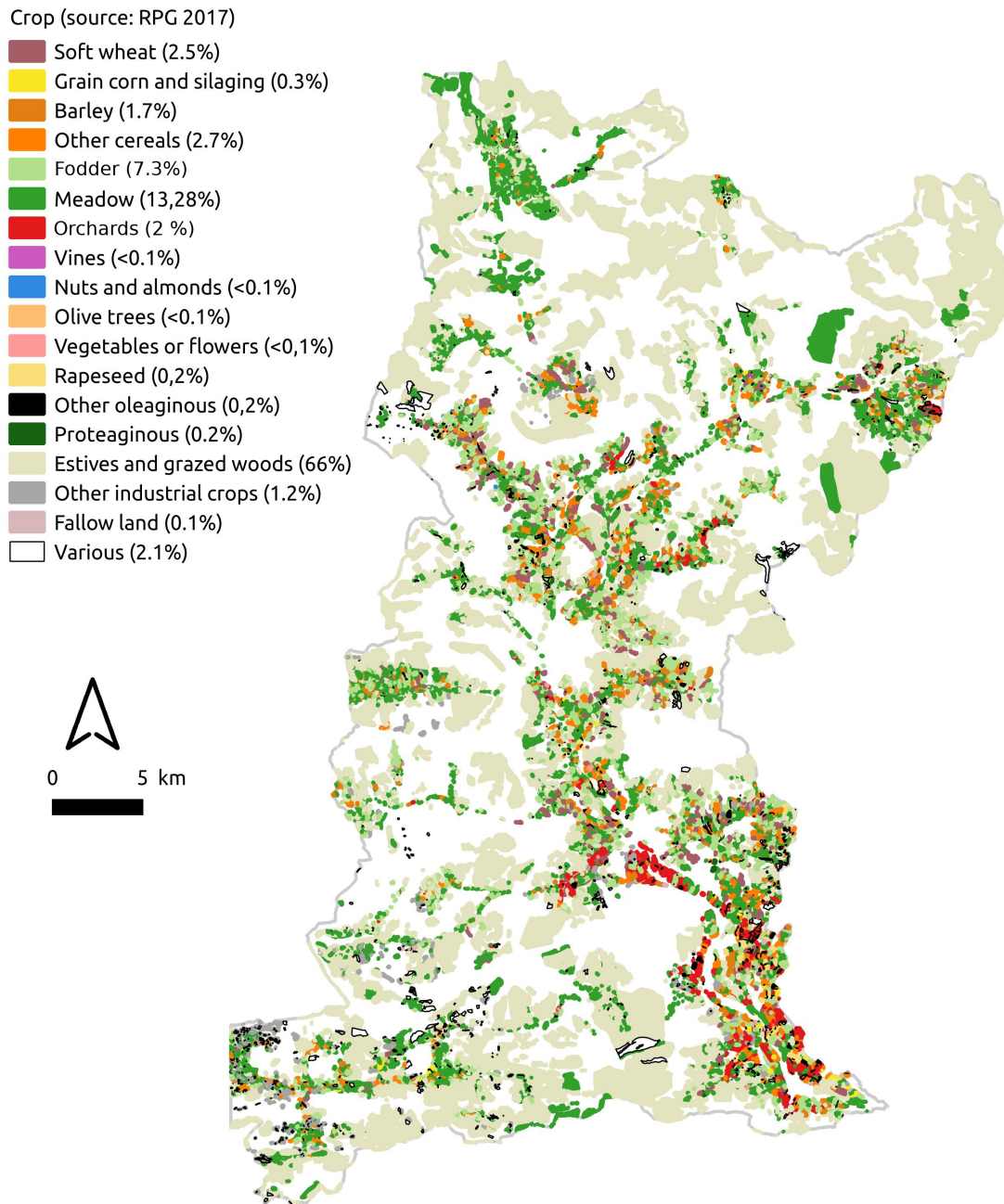


FIGURE 3.6: Crop type within the Buëch River basin (source: *RPG*, 2017). "Other industrial crops" are mostly aromatic plants. "Various" are truffle fields, oak and chestnut groves.

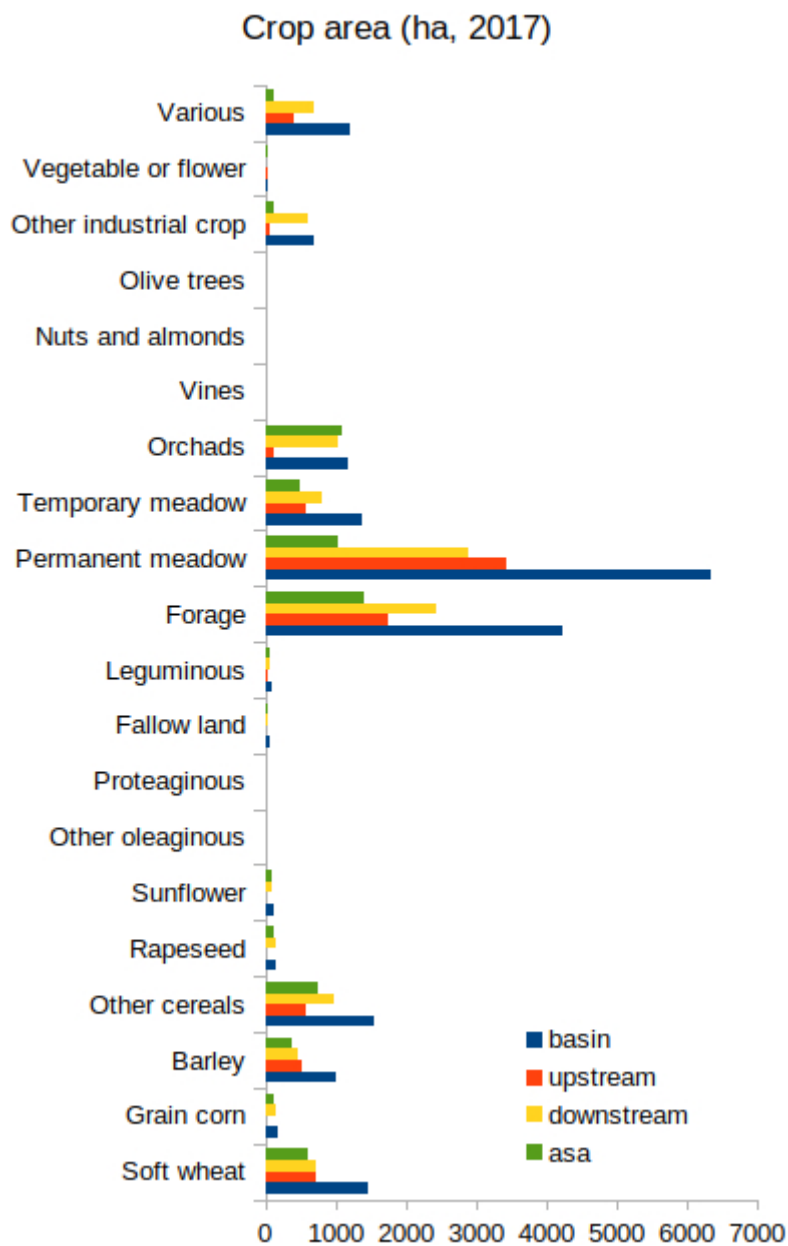


FIGURE 3.7: Crop area (ha) in the whole Buëch River basin, its upstream and downstream parts, and of the irrigator unions ("asa") for the year 2017 (source: *RPG* 2017). The separation between upstream and downstream parts is the confluence of the two upstream river branches. "Other industrialcrops" are mostly aromatic plants. "Various" are truffle fields, oak and chestnut groves.

- Application 1: Characterizing the variety of irrigated systems at the scale of the case study catchment, which is important in the perspective of the coupling with an hydrological model at the basin scale (Chapter 7) and for the scaling-up perspective of the WatASit model design at the network level in (Chapter 4), to identify precisely the irrigated systems of the Buëch catchment which are problematic, and for which extent operational management is linked to current water management stakes such as identifying precisely where interactions due to irrigation are challenging ecosystems and what are the inter-dependencies with natural hydrology and between irrigated networks themselves that rely on cumulative and multiple interactions on the short-term,
- Application 2: Better understanding the functioning of collective networks, especially gravity-fed ones, which are at the heart of the problematic in terms of poorly understood impacts on agriculture and also water withdrawals, and identifying the elements interacting in space and time when operating irrigation that would structure the design of the WatASit model,
- Application 3: Focusing on a particular case: the Aspres-Sur-Buëch gravity-fed network, in which the abandon of the traditional coordination of the water network through daily slot coordination is a good example of operational recent changes modifying short-term interactions of irrigation.

First, we summarized the variety of irrigated systems at the scale of the case study catchment using the agrarian diagnosis method. Several semi-directed interviews (the guides of interview are available in Appendix B of the manuscript) were conducted with the various stakeholders (Table 3.2), including County State Services; individual irrigator and farmers/Presidents of numerous irrigator unions within the whole Buëch River basin. We reconstructed the chronology of water management programs in the Buëch River basin since the identification of a structural deficit.

Second, we restrained the semi-directive interviews and field observations (Table 3.2) more specifically on the functioning of the collective networks (i.e. pressure network with sprinklers, gravity-fed or mixed networks) at the scale of the whole basin, but with particular attention given to the gravity networks located upstream of the basin, which

are the most concerned by the measures of the water management programs. Numerous interviews were conducted to collect the schedules of agricultural and irrigation practices and to investigate key constraints and current difficulties to ensure irrigation. We also questioned their production objectives and their irrigation strategy, with a special emphasis on operational management.

Third, we focused on a particular gravity-fed network, the Aspres-sur-Buëch case study, as this irrigator union is quite representative of the irrigator unions managing a gravity-fed network in terms of irrigated area, crop types, location and operational difficulties. We have regularly visited this study area for two years (Table 3.2): we punctually observed the irrigator operations during the 2018 and 2019 irrigation campaigns to record their difficulties and adjustments according to their current contingencies (e.g. crop water needs, water availability, precipitation). We led semi-directive interviews with the President of the irrigator union, its technician in charge of piloting the network, and with three irrigators. We collected information (i.e. number of plots that have been irrigated or not, number of irrigation by plot) with them to reconstruct the 2017 irrigation campaign which was particularly subject to low-flow and water restrictions, and which is the year of simulation in the following chapters. We questioned its past and current functioning. We have also regularly taken news by phone regarding current and future irrigation operations, in particular with the President and the technician.

3.4 The operational challenges of irrigation management on the Buëch River basin

The modeling work developed in the following chapters was made in interaction with some of these stakeholders, from informal contacts and shared fieldwork to project workshops in the framework of the RADHY Büech project. This project seeks to represent in an integrated way, social and hydrological dynamics based on the study of local adaptation strategies (individual and collective) of irrigation. A steering committee has been set up, including the County State Services, the French Office for Biodiversity, The Buëch river syndicate and the County Chamber for Agriculture. The steering committee

TABLE 3.2: Stakeholder type and number of interviewees for the semi-directive interviews. Field observation, meeting and workshop realized during the field surveys.

Stakeholder type	Number of interviewees	Application.s
<i>Irrigators</i>		
Irrigator members of a collective gravity-fed network	14	1-2-3
Irrigator members of a collective pressure network	12	1
Irrigator members of a collective mixed network	4	1
Individual irrigator	3	1
President of a collective gravity-fed network	8	1-2-3
President members of a collective pressure network	6	1
President of a collective mixed network	3	1
Technician of a collective gravity-fed network	2	2-3
Technician of a collective mixed network	1	2
<i>Other stakeholders</i>		
Büech River Syndicate "SMIGIBA"	1	1
Durance River Basin Syndicate "SMAVD-EPTB"	3	1
French Office for Biodiversity – Büech sector	3	1
County State Services of Hautes-Alpes	3	1-2
Regional State Services of Provence-Alpes-Côte-d'Azur	1	1
County Chamber for Agriculture of Hautes-Alpes	2	1-2
County Council of Hautes-Alpes	1	1-2
County farmer syndicate "FDSEA"	3	1
County farmer syndicate "JA"	1	1
County farmer syndicate "Confédération Paysanne"	1	1
Water Agency	1	1-2
Dam manager "EDF"	1	1
Field observation, interview, meeting and workshop	Date	
Meeting with the SMAVD-EPTB	2018, March 5	1
Field observation and interviews : study area	2018, March 30	3
1st meeting with Durance researchers or experts	2018, April 27	1
Field observation and interviews: study area	2018, May 3-4	3
Field observation and interviews: study area	2018, May 30-31	3
Field observation and interviews: study area	2018, June 18	3
Field observations in similar Durance subbasins	2018, July 12-14	1
Field observation and interviews: study area	2018, August 6	3
"PGRE" meeting at the Hautes-Alpes prefecture	2018, September 13	1-2
2nd meeting with Durance researchers or experts	2018, October 16	1
Meeting with the County State Services, field observation	2019, January 16	2
RADHY project steering committee	2019, April 3-4	1
Interviews : study area and Büech basin	2019, April 8-19	2-3
Field observations in Cévennes gravity-fed networks	2019, May 20-22	1
Interviews: study area and Büech basin	2019, July 1-19	2-3
RADHY project steering committee	2019, Sept. 26-28	1



FIGURE 3.8: Workshop in presence of the County State Services, the County Chamber for Agriculture, the Buëch River Syndicate, the French Office for Biodiversity and the dam manager *EDF*. The exercise requires to localized the main tensions for water resource management due to irrigation withdrawals (credit : B. Richard).

requested a study giving an overview of the irrigated systems of the Buëch River basin, the variety of farming systems involved and their irrigation uses and distribution at the basin scale.

For this reason, an agrarian diagnosis was carried out during the internship made by Claire Distinguin from March to August 2019 (see Appendix A of the manuscript, Section A.2). Concretely, an important bibliographical review of the history of agriculture and irrigation in the Buëch River basin was carried out, supplemented by numerous interviews on the farm trajectories over the last century. Several landscape readings in different points of the basin then made it possible to characterize the land use according to the natural vegetation, the nature of the soils and reliefs, the climate, the main types of crops and especially their irrigation. More generally, an investigation of the viability of the irrigator unions was proposed. The main limitation concerns the lack of economic analyses that could not be integrated into the diagnosis, as well as the difficult quantification of the representativeness of the information collected in the absence of cluster analysis. The steering committee met at the beginning of the project to discuss the tensions concerning irrigation management in the basin (Figure 3.8) and also at the

end of the internship to present the results of the agrarian diagnosis.

The agrarian diagnosis has provided an overview of the irrigated systems in the Buëch River basin due to the major changes that have led to the current state of irrigated agriculture which represents 362 farms covering a total of 32418 ha, with 89 ha per farm in average (statistics for the year 2017). Perennial crops are about 10.6 ha per farm compared to 11.8 ha per farm for the Hautes-Alpes county. 26 % of these farms have orchards which are mainly located in the downstream part of the catchment where water access is secured by the Saint-Sauveur dam. 68 % have livestock, of which 49 % are sheep or goat farms and 19 % are cattle farms. The average size of a cattle herd is 16 units compared to 77 in the entire Hautes-Alpes county. It identified the gravity-fed irrigated systems as the most challenged by the irrigation issues and ongoing water management programs.

During the agrarian diagnosis, semi-directive interviews with the stakeholders also helped to understand the irrigation problematic at the basin scale. According to the County State Services, the *1992 Water Act* has strongly reinforced the notion of preservation of aquatic environments. It led to the implementation of two new tools: the *Water Development and Management Master Plan (SDAGE)* and the *Water Development and Management Plan (SAGE)*. These development plans aim to better understand and protect the functioning of river aquatic environments (Salles, 2006). Revised every 6 years, they set the fundamental orientations for a balance management of water resources and integrate the obligations defined by the *WFD* as well as the orientations of the environmental conference. The *1992 Water Law* also gives local authorities the means to intervene in water management. According to the *Buëch River syndicate* (called *SMIGIBA*), in 2001, the *National Commission for River and Bay Contracts* signed the file to draw up the *Rivière du Buëch* contract based on six major objectives: 1) Preserving water quality, 2) Preserving the environment through heritage management, 3) Guaranteeing protection against flooding, 4) Ensuring the balanced sharing of water resources, 5) Coordinating the contract and 6) Disseminating information and developing communication. A few years later, *SMIGIBA*'s missions expanded to include the maintenance of the banks of the rivers of the watershed, the management of aquatic environments, and the water resources. In 2008, the first contract for the Buëch River and its tributaries was signed for a period of 7 years and then renewed.

According to the County State Services, the *2006 LEMA* water law then promulgated "the implementation of a program to reduce the imbalance between water needs and resources and the collective management of irrigation withdrawals through the creation of the single bodies provided for in Article L. 211-3 of the environment code and the implementing decree 2007 - 1381 of September 24, 2007". In other words, it is developing the establishment of a unique organization (called *OUGC*) for collectively managing irrigation. According to the Water Agency, the classification of the basin as *ZRE* in 2015 is the official recognition of an imbalance between the water resource and the existing withdrawals on the territory. This status strengthens the regulatory arsenal for monitoring water withdrawals and increases water taxes.

According to the County State Services, chronic water low-flow situations within the Buëch River basin are not compatible with the objective of ensuring sustainable management of water resources that meets all uses and the needs of the natural environment. Over the last decade, several initiatives have been put in place to recover quantitative water balance (Figure 3.9). In 2012, a diagnosis showed that the Buëch River basin had a 30 % deficit of water resources with respect to total water demand. It has also proposed Low-Water Target Flow at reference points distributed throughout the catchment to maintain a minimum water level for the aquatic environment.

According to the County Chamber of Agriculture, the *OUGC* was created in 2013, putting the water rights of irrigator unions on hold. The Chamber of Agriculture was designated as the *OUGC* to manage requests for withdrawals for agricultural irrigation as a unique body. The Buëch *OUGC* is in charge of the distribution of water withdrawal quotas for irrigation. Every year from 2015, the irrigator unions and individual irrigators define their water needs. At the same time, the County Chamber of Agriculture and *SMIGIBA* were co-piloting the development of a water resource management plan (called *PGRE*), which identified the need of decreasing by 30% the global irrigation withdrawals of the Buëch River basin. Between 2015 and 2017, the first multi-annual authorization for all Buëch irrigators was adopted with a target of a 30 % reduction in irrigation withdrawals. It has been renewed for the period 2018-2020.

Irrigation on the Buëch River basin is mainly due to collective perimeters, equipped either for gravity-fed irrigation or for pressure irrigation, or both, and managed by 38 irrigator unions. According to the 2017 prefecture authorization for irrigation withdrawals, gravity-fed irrigation accounted for 7.3 % of irrigable areas and for 44.7 % of the authorized volumes withdrawn, with meadows as the main crops (43.6 %, Figure 3.10 A), followed by cereals (29.7 %, Figure 3.10 C) and fodders (22.2 %, Figure 3.10 B). In 2017, the authorized volume of water collected for one hectare of the irrigable area was about 9 times higher for gravity-fed irrigation than for pressure irrigation. If a precipitation deficit persists in autumn, later low flow levels can be observed as was the case in 2017. During these periods of tension, the gradual implementation of water use restrictions via drought decrees was necessary. Between 2003 and 2017, irrigation was restricted for at least 10 years out of 15 to an "alert" level, the first level being legally binding, i.e. two days of restriction per week. In 2018, the consultation under the *PGRE* was relaunched after several years of stagnation. Finally, the *PGRE* was approved by all the stakeholders in December 2019, focusing on local and evolving projects carried out mainly by collective irrigator unions, in particular, gravity-fed networks located in the upstream part of the basin, such as:

- Modernization of gravity-fed networks to finely pilot water withdrawals, to better regulate water flows and to reduce network seepage, which require in-depth understanding of their functioning, current constraints and possibilities of optimization,
- Conversion of gravity-fed networks to pressure networks,
- Creation of small reservoirs or substitution pumping,
- Increase of water transfer capacities from the Durance *EDF* canal for the irrigator union located downstream of the basin.

During the meeting with the Prefect of the Hautes-Alpes County and the President of the irrigator unions of the basin, a large part of the discussions focused on the operational functioning of the gravity-fed networks which are located in the upstream part of the basin. The viability of these gravity-fed networks is not assured and depends on the in-depth understanding of the local interactions that take place between the irrigators and the water resource when operating irrigation in the short term within a collective network. There is a need for identifying the potential practices that are not optimal for

the piloting of water withdrawals or for ensuring equality between irrigators in terms of their ability to irrigate, and also the possibilities of improvement if they exist. In this context, the modeling of the short-term interactions between current irrigators' practices and the water resources by comparison with alternative practices (the objective of Chapter 4) is a stake for local managers. The potential consequences on the farmers' ability to irrigate (Chapter 5) and on plant dynamics (Chapter 6) is also very important for the ongoing discussions.

Moreover, the perspective of modeling several irrigation networks to assess their spatio-temporal inter-dependencies would also be a contribution to support their discussions. The consequences of the cumulative effects of the irrigation operations at the basin scale have appeared poorly understood. In addition to the operational difficulties internal at the irrigator unions, there is also a strong demand to assess how irrigation operations made by the upstream networks impact the downstream one in terms of water access during the low-flow period. Identifying precisely the locations where the natural river flow is modified or could be insufficient for the preservation is also of interest for assessing the objectivity of some arguments such as that backflows to the river/environment compensate the water withdrawals made by the irrigation networks. However, other stakeholders point out very localized places where the ecological continuity could be endangered. Modeling the local interactions in the short-term in relation to the hydrology at the basin scale is the objective of Chapter 7, of which a perspective is the scaling-up of the irrigation networks at the basin scale to account for cumulative interactions due to the distributed irrigation operations.

In the next section, we restrain the semi-directive interviews and field observations (Table 3.2) more specifically on the functioning of the collective networks (i.e. pressure network with sprinklers, gravity-fed or mixed networks), but with particular attention given to the gravity networks with operational management issues.

3.5 Functioning of the collective irrigation networks

The irrigator unions (i.e. ASAs) are groups of landowners sharing the execution and maintenance tasks and cost for both public and private use (Loubier and Garin, 2013).

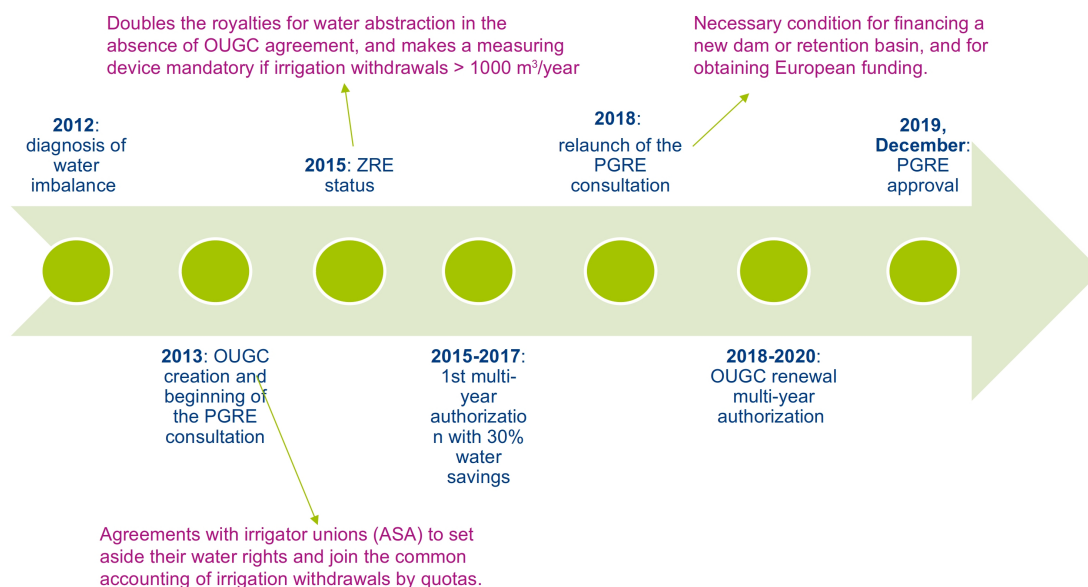


FIGURE 3.9: Temporal context of quantitative water management of the Buëch River basin. *PGRE* is the water resources management plan, *ZRE* is a legal status for river basin with significant deficit between water supply and demand. *OUGC* is the institutional body for the collective management of irrigation.

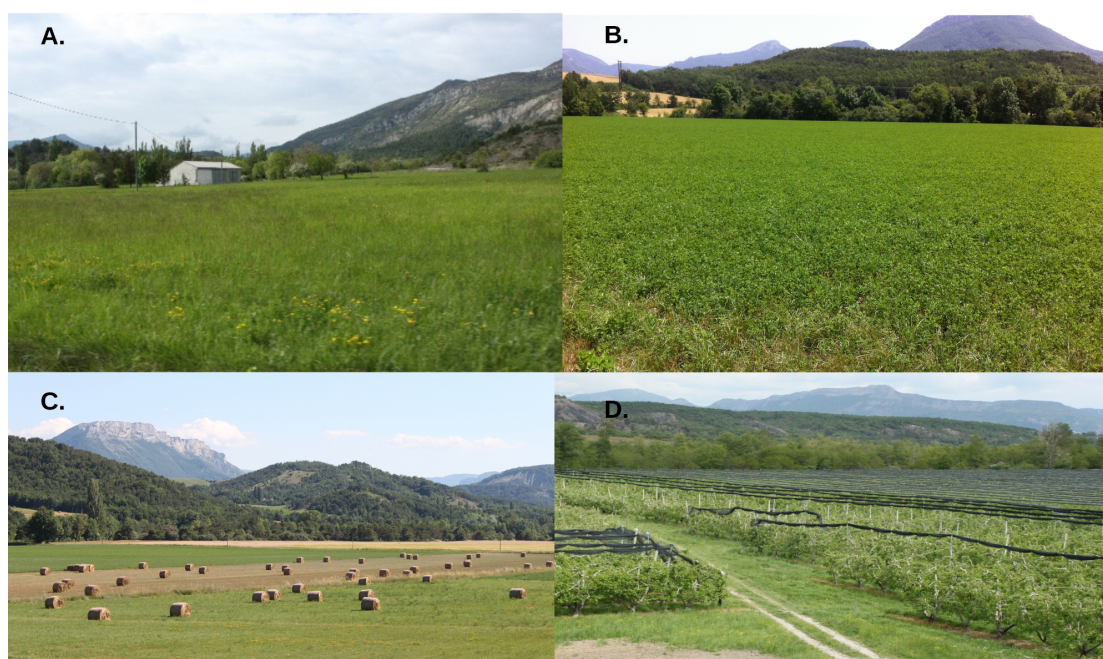


FIGURE 3.10: Main crop types of the Buëch River basin. A, B, C, D show a permanent meadow, alfalfa, straw bales after the wheat harvest, and an apple orchard, respectively (credit : B. Richard).

An irrigator union has an assembly of landowners which elects a President and draws up the statutes of the irrigator union, and also proposes its perimeter and has total autonomy of the decision on operating rules. The prefect should authorize the irrigator union with a status of a public establishment, with accountancy to the public tax collectors of the County. Legally, irrigator unions were constituted on the basis of the law of 21 June 1865 and the amended decree of 18 December 1927. The ordinance 2004-632 of 1 July 2004 and its implementing decree 2006-504 of 3 May 2006 brought these texts up to date. According to [Loubier and Garin \(2013\)](#), it reflects the desire from the State to use the irrigator unions for land-use planning policy by controlling their future with evolutions such as eligibility for public funding and separation of roles between the president and the tax collector in order to facilitate budgetary control.

Figure 3.11 maps the collective irrigation networks distributed within the Buëch River basin. Gravity-fed networks are mainly located in the upstream part, while pressure networks are predominant in the downstream part. Note that the red box situates the case study used in the following chapter, which is described further in the next section. In this section, we describe some functioning aspects of the collective irrigation networks, but emphasizing on the gravity-fed networks.

Figure 3.12 shows, in a general way, the calendar of the main crop operations in the Buëch River basin common to the irrigators from all irrigation networks. Irrigation is mainly carried out through collective campaigns that run from about the beginning of May to the end of September. The irrigation period is concomitant with the cereal harvesting period and the haying period. Meadow and fodder crops can be mowed three to four times, depending on the climatic and irrigation inputs. Usually, the last growth is left for grazing at the beginning of the autumn. The haying requires several operations (Figure 3.13) such as mowing the meadows, wallowing and swathing hay to make bales of hay with a press trailer. Typically, the farmer has an island of fodder, cereals and permanent or cultivated meadow plots served by an irrigation system. In this island, the meadows are mowed a first time between the end of May (1st cycle), with a second cut 30 to 45 days later (2nd cycle), then possibly a third cut between the end of July and the end of August (3rd cycle), and the last growth in September is grazed until autumn (4th cycle).

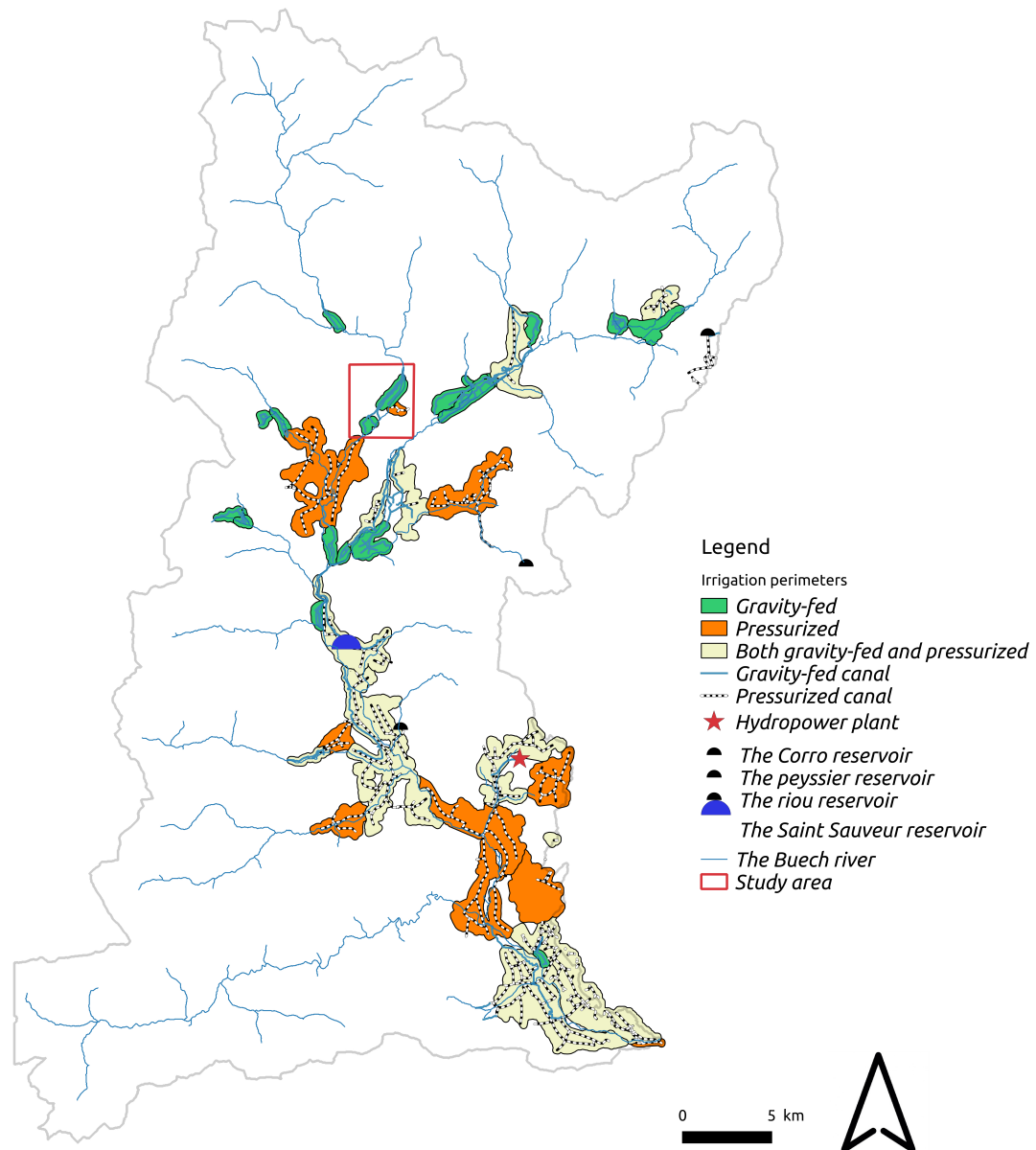


FIGURE 3.11: The irrigator union within the Buëch River basin (source : BD HYDRA 2015).

For gravity-fed networks, irrigation requires the watering of the gravity-fed canal by the irrigator union. In most of the gravity-fed networks we observed, the river is directly diverted using a "merlon", which is a pebble dike. An entry channel is then used to conduct the diverted water to the intake of the primary canal. This system makes it possible to adapt the entry channel to the water intake when the minor riverbed moves within the major riverbed, which is common after a flood. The water intake is not always equipped with a water level regulation system such as a floodgate. The water

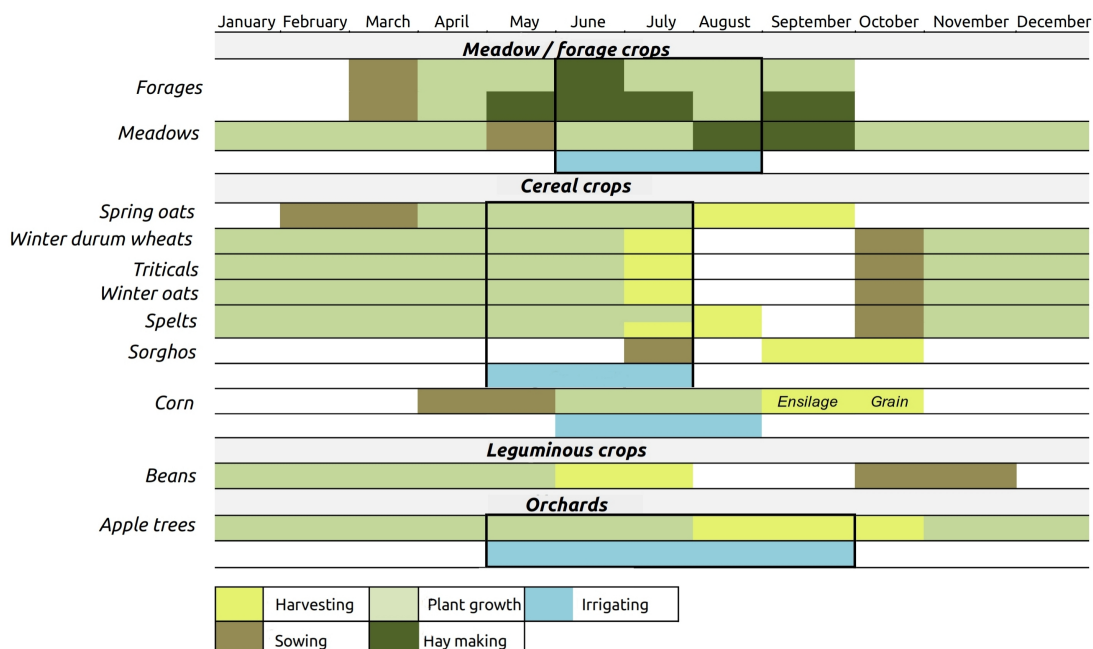


FIGURE 3.12: Operational calendar for the main crop of the Büech River basin determined from the semi-directive interviews.

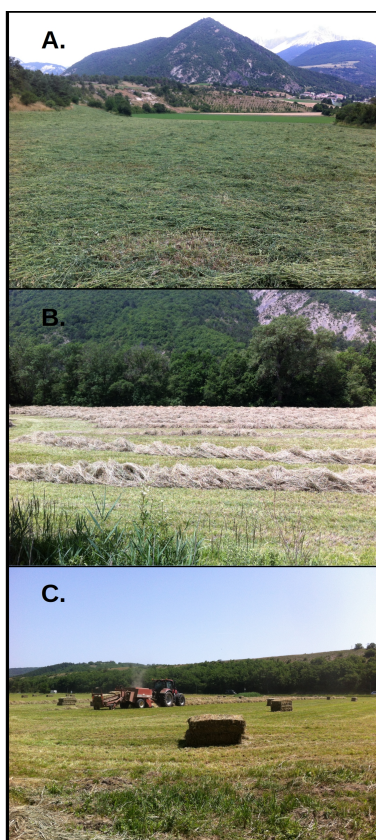


FIGURE 3.13: A shows a mowed meadow which is the tedding. B is the swathing to make bales of hay with a press trailer (C) (credit: B. Richard).

then flows through the network to the junctions with the secondary and then tertiary branches of the canal, and finally to the floodgate serving the farm plot. Figure 3.14 gives a schematic view. Once the floodgate is open, flooding can take several hours, depending on the size of the plot and the advance of the water front.

Usually, a schedule of charges includes a period of preparatory work in all irrigator unions. For the gravity-fed network, the villagers are sometimes mobilized (the historical “*corvée*” in French). Today, a service provider is often called to clean the canals and creating the entrance channel. The “*merlon*” allows the water to be diverted at river level is rebuilt each time the minor riverbed changes location. The specifications also provide for the period of watering which is often the first week of May. The canal will then flow during the whole irrigation campaign. The rare interruptions are related to the heavy rainfall and flood events to prevent turbid water from flowing into the canal. The farmer is therefore dependent on other farmers in a gravity-fed network. The water intake is calibrated empirically: the network must not overflow, especially on roads, which could lead to liability in the event of an accident. But the inflow must be large enough to allow the water to flow as far as possible into the branches of the network, especially downstream. This is why the water intake is generally fixed, its control is not very dynamic during the irrigation campaign, and generally only small adjustments are made.

Historically, the different branches of the canal are watering in an order that allows time to be shared between the different sectors of the network: this is the daily slot calendar system. The first round of water is generally started at the beginning of May and lasts 7 to 10 days on average, depending on the irrigator union. When it is his turn, i.e. when one of his plots is supplied with water, the farmer observes the weather and the turbidity of the water (generally at the beginning of the day) and opens the floodgate of his plot if he decides to irrigate it. He then observes the water front flowing gently, and may be led to modify the flow of water in the plot by adjusting the canal, the floodgate or even the plot topography. The maintenance of the floodgate allows to calibrate the irrigation flow in the plot. The flood duration corresponds to an empirically defined irrigation dose. In case of rain or turbid water, the farmer usually stops the flood operation and will finish it later. The water round takes place every 10 to 15 days from the beginning of May, and there are about 8 to 10 water daily slots per meadow, and about 6 for

the cereals. The restrictions do not really affect this type of gravity-fed irrigation by water daily slots, but they restrain the use of sprinklers from other water sources. In any case, the flow of water in the network is tolerated by the Water Police during the period of restriction, because it would not be technically possible to stop and restart irrigation as quickly as restrictions due to the time required for watering the canal system.

Main functioning similarities and differences between pressure, mixed and gravity-fed networks are summarized in Table 3.3.

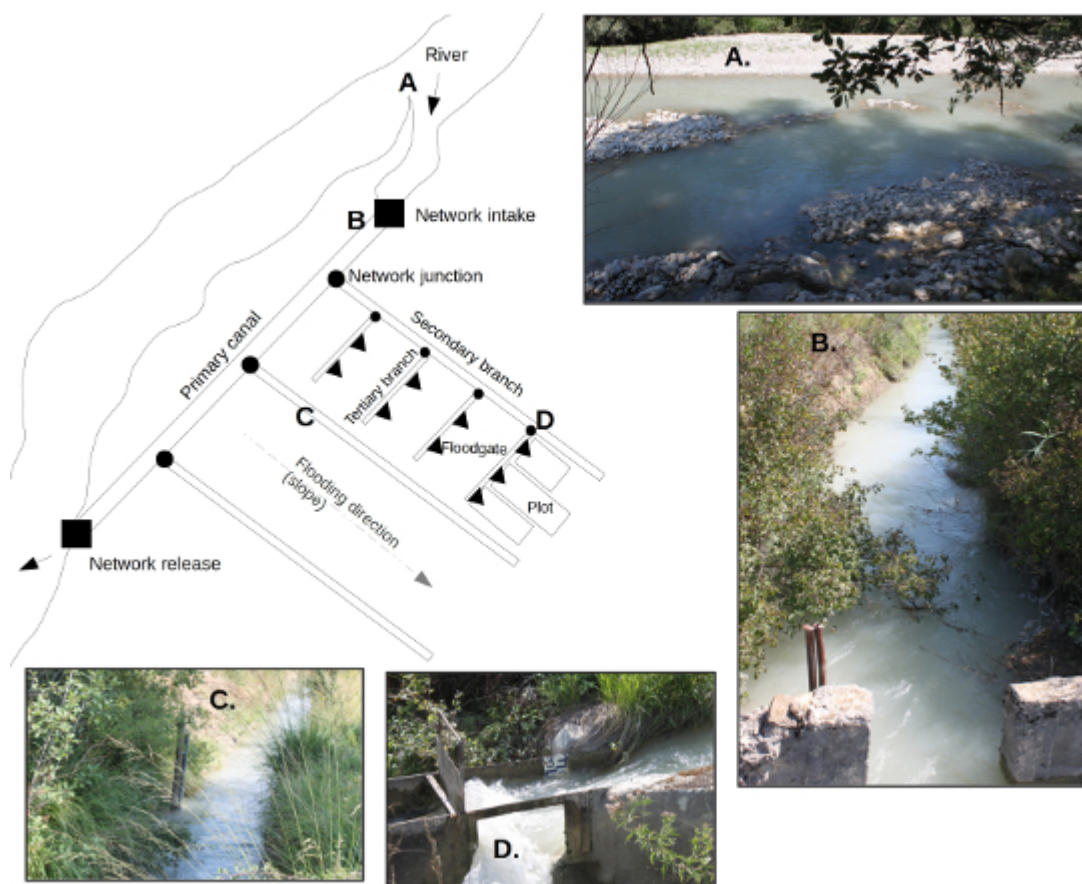


FIGURE 3.14: Overview of an irrigation network fed by gravity. A. shows the river diversion with a "merlon" which is an accumulation of pebbles. B. is a primary canal and C. a secondary branch instrumented by a probe measuring the water level. D. shows a network junction (credit : B. Richard).

TABLE 3.3: Main similarities and differences between the functioning of pressure, mixed and gravity-fed networks

Network type	Characteristic
	<i>Management spatial scales</i>
Pressure	Irrigation scheme, farm and farm plot
Mixed	Idem
Gravity-fed	Idem
	<i>Network intake type</i>
Pressure	Pump
Mixed	Floodgate at the river,
Mixed	pump in the canal
Gravity-fed	Floodgate
	<i>Intake regulation</i>
Pressure	Dynamic
Mixed	Not very dynamic
Gravity-fed	Not very dynamic
	<i>Irrigation equipment</i>
Pressure	Sprinkler, dripper
Mixed	Sprinkler, dripper
Gravity-fed	Floodgate at the plot
	<i>Irrigation triggering</i>
Pressure	Reactive
Mixed	Reactive
Gravity-fed	Not very reactive
	<i>Plot irrigation flow</i>
Pressure	Dynamic
Mixed	Dynamic
Gravity-fed	Fixed
	<i>Simultaneous irrigation per farmer</i>
Pressure	Usual
Mixed	Usual
Gravity-fed	Unusual
	<i>Operational piloting</i>
Pressure	Fine piloting based on elaborate measurements (weather (rainfall, wind), soil type and moisture, crop growth and stress)
Mixed	Idem as for pressure network
Gravity-fed	Empirical habits based on rainfall, plant growth
	<i>Key structural constraints</i>
Pressure	Cropping system, network maintenance, water access
Mixed	Idem
Gravity-fed	Idem
	<i>Key operational constraints</i>
Pressure	Pump robustness, silty water when raining, energy, quota
Mixed	Wind and restriction for sprinklers
Mixed	Idem as for pressure network plus
Gravity-fed	downstream insufficient flow risk, overflow risk, Downstream insufficient flow risk, overflow risk, time-slot calendar, silty water when raining, quota

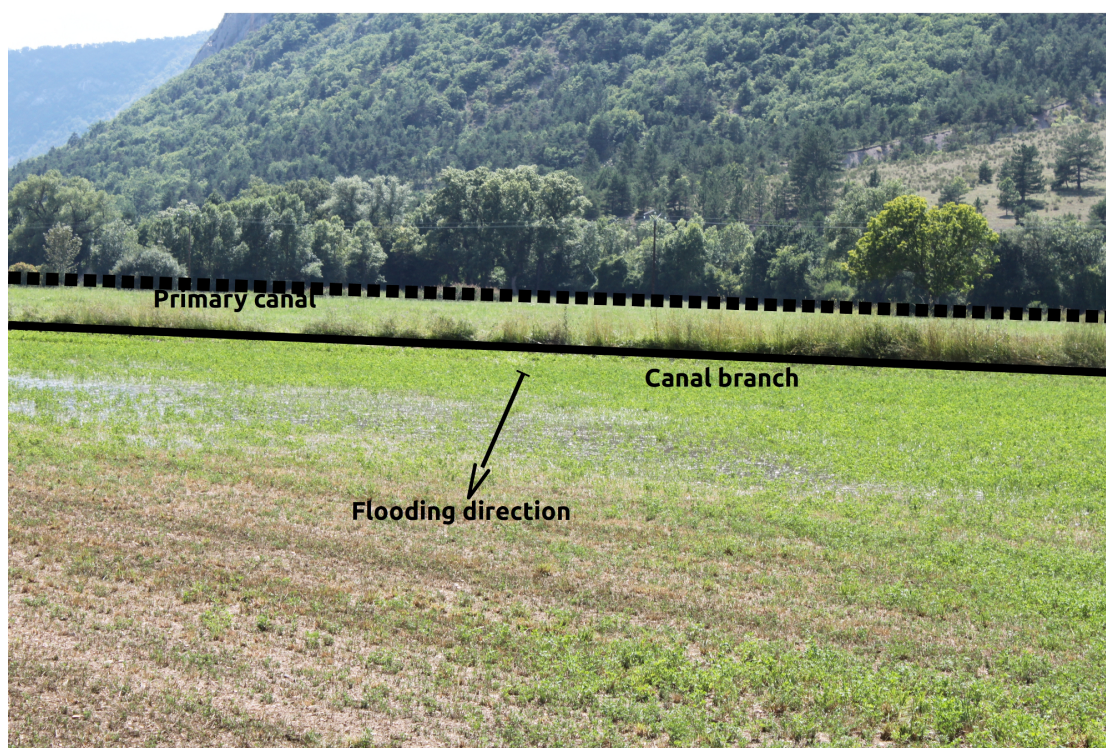


FIGURE 3.15: View of an alfalfa plot during a gravity-fed flooding operation at the first mowing (credit : B. Richard).

3.6 Focus on a particular case: the Aspres-Sur-Buëch gravity-fed network

We have chosen the Aspres-Sur-Buëch gravity-fed network as a case study because it is fairly representative of the gravity-fed networks in terms of location (in the upstream part of the basin), irrigable surface area (with 75 ha whereas the average is 50 ha), and crop rotation (with 38.9 % meadows, 29.5 % fodders and 23.7 % cereals). It is also representative in terms of change in operational management, with the abandon of the traditional coordination of the network by daily slots, that could impact farmers' possibilities of irrigation, crop production and local water resources. In addition, this change involves modifications in the short-term interactions between the irrigators and the crops to be irrigated through the water flow in the canal that match our research question.

Figure 3.16 maps the crop types and the network infrastructure of the case study. Note

that the plots located at the right-side of the river are not supplied any more by the water network of the Aspres-Sur-Buëch irrigator union (but are still included in the land tenure). The study area (Figure 3.18) includes 205 plots, 74 of which are irrigated within the collective gravity perimeter by 10 irrigators. Farm plots of each irrigator that are included in the irrigation scheme are presented in Figure 3.17. Farmers 2, 7 and 10 are included in the irrigation scheme are presented in Figure 3.17. Farmers 2, 7 and 10 are the three surveyed, and farmer 9 is the President of the irrigator union. Key information collected concerning the functioning of this irrigator union is described below.

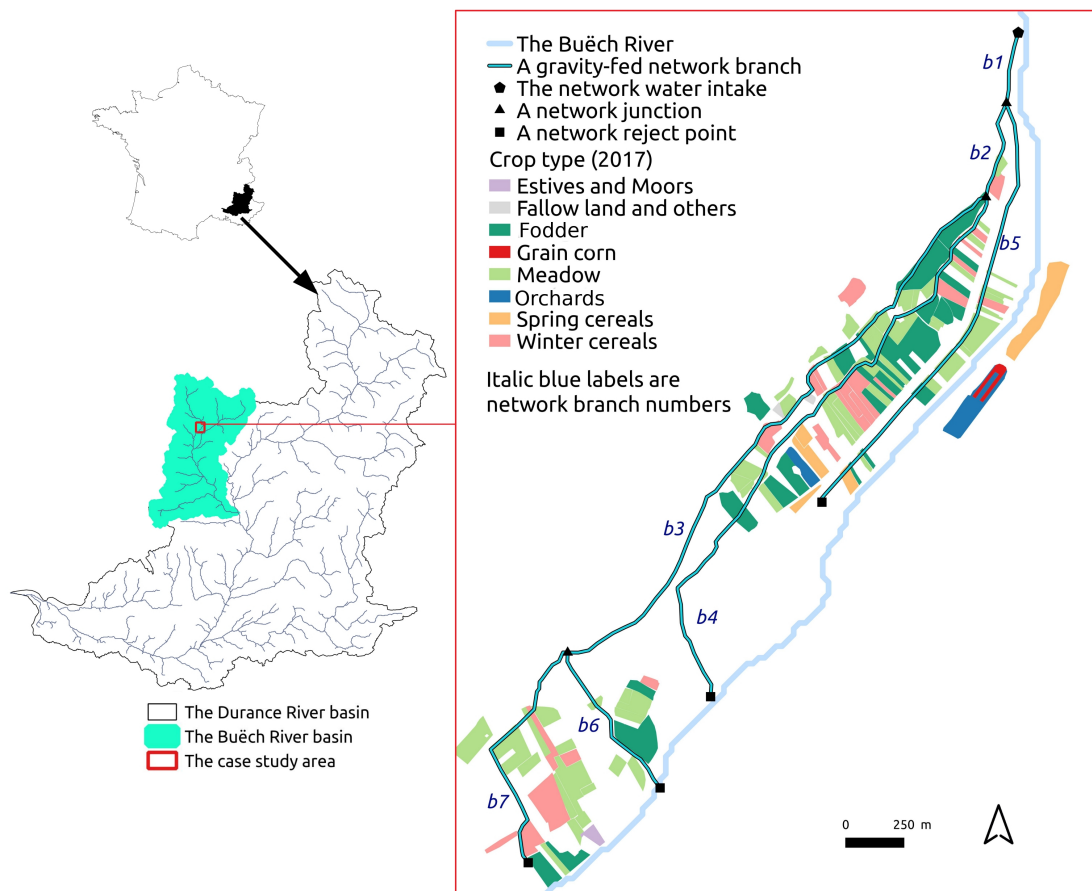


FIGURE 3.16: Perimeter, network and crop types within the Aspres-Sur-Buëch irrigator union.

Network functioning The network is watered every first week of May according to its own specifications. The organization of water sharing between the members of the irrigator union through a calendar has been abandoned for a few years due to the limited number of professional farmers. Farmers can irrigate without any coordination. The current level of maintenance does not make possible to irrigate all the plots served

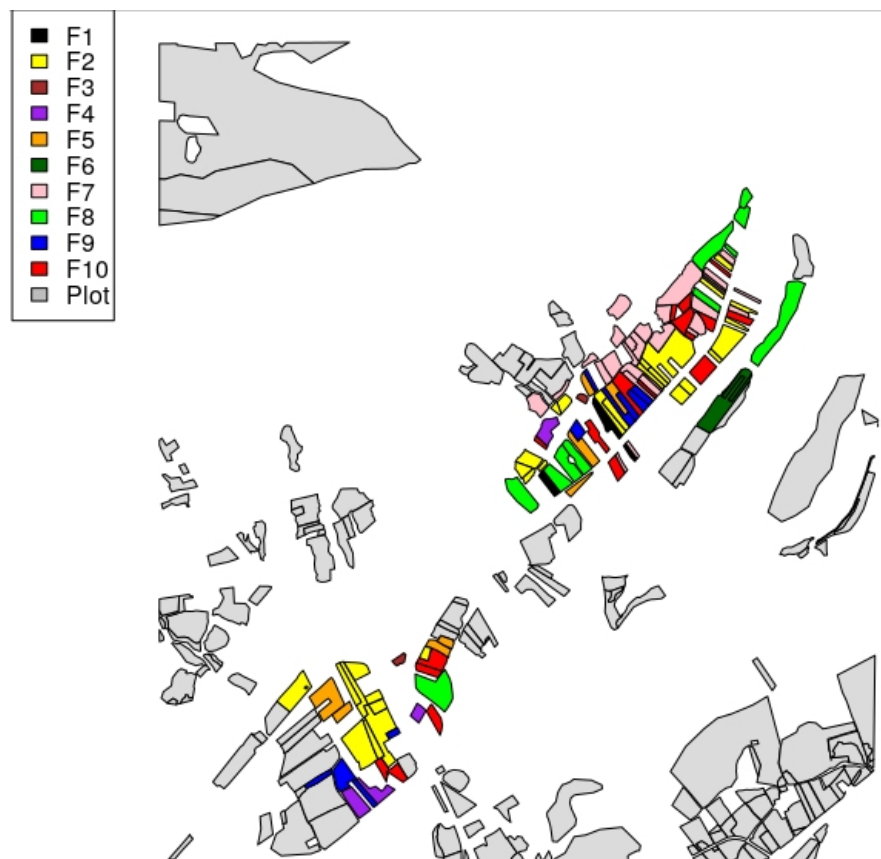


FIGURE 3.17: Location of the farm plots of each farmer within the Aspres-Sur-Buëch irrigator union. Each color is a farmer, F1 to F10 stands for farmer 1 to farmer 10.

by irrigation network, due to a lack of sediment cleaning in the canals. In particular downstream plots are not correctly served by the network. Due to this maintenance level, in case of an increase of the intake flow there are risks of overflow on the road or in the village. Overflow rate is estimated by the technician at 150 ls^{-1} at the network intake. Due to the functioning of the flood gate, incoming flow rate to the plot is fixed and estimated at 30 ls^{-1} by the technician. Volume adjustment of the irrigation is managed by farmers in terms of duration. As a result, the collective network requires to keep a fairly constant flow at the intake, measured at 90 ls^{-1} at the beginning of the 2017 irrigation campaign, with low variations over time instead of setting aside small adjustments that consist in small flow increase without reaching the overflow rate, to take into account farmer inquiries. This flow also complies with the maximum withdrawal rate determined by prefectural order for the network.

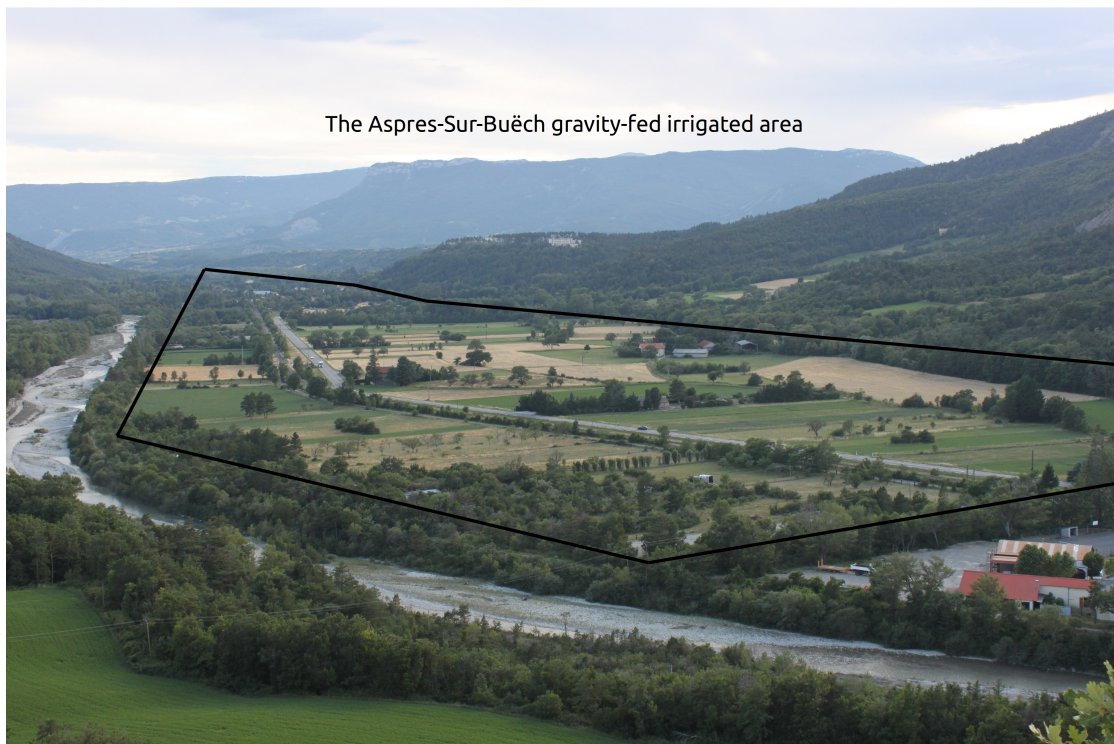


FIGURE 3.18: View of the Aspres-Sur-Buëch gravity-fed irrigated area (credit : B. Richard).



FIGURE 3.19: The floodgate of the water intake of the Aspres-Sur-Buëch gravity-fed network (credit : B. Richard).

Farming system At the beginning of the irrigation campaign crops have already been planted, with no rotations until the end of the campaign in early October.

Work load capacity Farmers have quite similar capacities in terms of equipment access and human work load, they ensure only one operation at a time, they do not hire temporary work load, and each operation requires full availability.

Weather conditions Farmers don't start or stop flood operations when raining.

Water restrictions 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.

Operational decision-making Operational irrigation strategy is quite homogeneous from one irrigator to another. 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.

Irrigator availability Farmer's availability depends on operation duration, which could vary notably with precipitation, and also on the maximum time they accept to work in a day, which is about 10-12 hours a day during intensive periods (e.g. harvest periods). They usually flood plot one by one to

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 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 binding. All the interviewees were familiar with the daily slot coordination, but when it was still in place, it had already undergone some changes that the technician, and to a lesser extent the President, mentioned (linked to the regrouping of the plots for example). I have captured the latest version in place, the one known to all the interviewees. It seems that

the abandon of the coordination is linked to a more general evolution, some elements of which have also been described on other gravity networks (Loubier and Garin, 2013):

- Decrease over time in the number of farmers, and therefore in the number of workers to maintain the canals. The less the canals are maintained, the fewer plots they serve, or the smaller the flow of water they can carry, because of overflow or because water no longer circulates in certain secondary canals. There is therefore less interest in coordinating the network under these conditions, and some farmers have gradually lost interest, with few members who coming to the meetings,
- The network coordination through daily slots required a technician to do a minimum of maneuvers at the network junctions and floodgates, but the technician is over 70 years old and has no successor,
- Daily slots are not very flexible, and some farmers prefer to be able to irrigate the plots well supplied with water when they want to, leaving out others that are not well-supplied anyway and that they consider unprofitable.

The current level of maintenance encounters difficulties to irrigate all the plots served by the gravity-fed network, due to insufficient water supply in the downstream part. In case of an increase of the intake flow there are risks of overflow on the road or in the village or exceeding maximum regulatory withdrawal rate. But in case of reduction of the intake flow it becomes difficult to serve the plots with sufficient flow to flood them (an example of flooding can be seen in Figure 3.15). Due to the functioning of the flood gate, incoming flow to a plot is fixed and volume adjustment of the irrigation is managed by farmers in terms of duration. As a result, the network requires to keep a fairly constant flow at the intake (Figure 3.19) with low variations during the irrigation campaign. The viability of this gravity-fed network first depends on their members and their interest to ensure cooperation tasks and costs. The members of the irrigator union, who were originally all farmers, have for the most part been replaced by private individuals who are not professional farmers and who have few interests in cooperation. Thus, of the 100 landowners of the Aspres-sur-Buëch irrigator union, only 10 were farmers in 2017. The other landowners are villagers or holiday homes. A few of them irrigate small gardens, but this use is very limited today as the village is located in the downstream part of the network, where the flow is usually very low, and also as the maintenance of

the secondary canals that were supplying the gardens is not made anymore. The village can be seen in the Figure ???. As these are not agricultural plots reported to the State Services, they are not represented in the RPG database.

During the semi-directive interviews and the meeting organized by the State Services on 15 September 2018, most of the Presidents of the irrigator unions managing a gravity-fed network mentioned these operating difficulties, and in particular the cooperating aspects due to a tendency to seek flexibility and autonomy on the part of the irrigators. They rejected the project of building a large reservoir in the upstream part of the river basin, explaining that they could not cover their maintenance costs. They then turned to a multitude of local projects aimed at reducing the operational constraints of gravity-fed irrigation, and optimizing it, while controlling operating costs at their level. Today, the viability of these gravity-fed networks is not assured, it depends on a handful of volunteer irrigators for the technical and administrative tasks, which are time-consuming. Many irrigator unions have already abandoned the ancestral cooperation for sharing water and maintenance tasks, considered too much constraining in view of the financial benefits, and their irrigators are ready to switch to individual irrigation under pressure. Modernization projects aim at a simpler and more efficient regulation of water flow in the network, from the intake to its various branches, and more efficient water use, to maintain an interest in cooperation between irrigators.

3.7 Conclusion

Irrigation management within the Buëch River basin faces operational mutations to comply with new environmental considerations and associated management norms. Collective irrigation is by far the most important use of water resources within the Buëch River basin during the low flow period. Due to quantitative imbalance, a water resources management plan has been adopted in which a number of measures are discussed to reduce the water abstraction from collective irrigation. The agrarian diagnosis we have carried out has identified the gravity-fed irrigated systems as the most challenged by the operational issues. Indeed, modernization of gravity-fed networks to finely pilot water withdrawals, to better regulate water flows and to reduce network seepage is planned

under the scope of the ongoing water management programs. During the semi-directive interviews we made with the local stakeholders and from the meeting attended, a large part of the ongoing discussions required an in-depth understanding of the operational constraints and possible alternatives of their functioning. There was a need of identifying the potential practices that are not optimal for the piloting of water withdrawals or for ensuring equality between irrigators in terms of their ability to irrigate. In this context, the modeling of the short-term interactions between current irrigators' practices and the water resources by comparison with alternative practices is a stake for local managers, as the potential feedback on the plant dynamics. At the basin scale, identifying precisely the locations where the natural river flow is modified or could be insufficient for the preservation of ecosystems is also a key point for the design of future irrigation and water policies. Moreover, the perspective of modeling several irrigation networks to assess their spatio-temporal inter-dependencies on cumulative impact would also be a contribution to support their assessment of the influences of the network withdrawals located upstream of the basin on the water availability of the ones located downstream, as it is a source of tensions between irrigators.

Part II

Representing collective irrigation at the operational level

Abstract of Part 2

The first part of the thesis was devoted to the literature review and the material from the field. In this second part, we build on the field surveys concerning the operational challenges of irrigation management on the Buëch catchment and of the specificities of the Aspres-Sur-Buëch case study.

The main specificity concerns the short-term interactions that take place more between the farmers and their environment rather than between the farmers themselves. Taking into account this observation and the literature review, we propose in the following chapter to use an agent-based modeling approach based on the Situated Action Theory.

Originality relies on the representation of a situation of action as the relationship between the action and resources or constraints offered by the physical and social circumstances encountered by the actor. This representation is of interest for modeling interactions depending on the local state of the environment, meaning the local water availability in the network, but doesn't specify how the link between an actor and the environment can be established concretely. We use the concept of Affordance to clarify this link and to design the WatASit agent-based model.

This model aims to simulate the irrigation operations of irrigators sharing a common water network during a collective irrigation campaign by explicitly representing the interaction possibilities left by their operational constraints. We demonstrate the feasibility of this approach to represent the Aspres-Sur-Büech case study. We present an implementation of the model and its use to compare scenarios of coordination.

In the following chapter, we use this realization to explore in more detail how agent trajectories can be linked to their simulated interaction possibilities according to our use of the affordance concept, and whether this link can help to interpret the output of

the WatASit model, as output interpretation remains a challenge for many agent-based models.

Agent possibilities of action provided an intermediate level of information for interpreting agent trajectories in different model configurations (i.e. parameterization). At the collective level, the absence of irrigation options relates to a lack of water in the downstream branches of the network that causes irrigation abandons in the model configuration in which the network is not coordinated.

At the individual level, the options of the farmer agents inform on the different nature of their irrigation abandons in each of the two model configurations, and for each farmer situation. The model configuration in which the network is not coordinated leads to an overload situation due to the collective behavior of the farmers: overload is maximal if all the farmers irrigate at the same time. However, the model configuration in which the network is coordinated leads to a different situation. Irrigation is no longer dictated primarily by the behavior of other farmers, but by the number of plots of a farmer to be flooded during the same irrigation time slot.

As part of sensitivity analysis, agent option-sets help interpret the threshold effects of model forcing or parameters. Irrigation options are more sensitive to the number of rainy days when the network is coordinated, making this model configuration more interesting to reduce the irrigation abandons up to a certain number of rainy days. Visualizing the possibilities of the agents is also useful to take a step back on what the model does and how agents are represented in it. In WatASit, agents are not surprisingly limited in terms of anticipation. This is because the affordance concept is mobilized to clarify the agents' possibilities of actions but not as a substitute for agent decision-making.

Chapter 4

The WatASit model

Contribution to the thesis project: *In this second part of the thesis, we focus on the modeling of collective irrigation at the operational level. In this chapter, we first present the modeling objectives, scope and concepts chosen according to the literature review and case study specificities from the first part. We then describe the WatASit model based on the Affordance concept and specifically developed to represent irrigation operations during an irrigation campaign. The description of the model follows the ODD standardized protocol and is under review in Socio-Environmental Systems Modelling as an appendix of the paper presented in Chapter 5. The key objective of the model is to explicitly represents the agent-environment interactions in the short-term, especially the irrigation possibilities left by the operational constraints (e.g. water availability in the network, meteorology) of the irrigators sharing water through a collective irrigation network. An article has been published in La Houille Blanche as a proof of concept ([Richard et al., 2020a](#)) and is available in Appendix C of this manuscript to avoid conceptual redundancies with Chapter 5.*

4.1 Introduction

In Chapter 2, we saw that most of the reviewed studies about human action in agricultural agent-based model focus on the decision making processes leading to the action and on the effect of the action, without explicitly considering the actual carrying out of the action itself (who does it, when, where, for how long). From our point of view, this is due both to the time horizon and the thematic of these studies, which are mainly interested in strategic or tactical choices dealing with landscape structuring (e.g. [Guzy et al., 2008](#)), technology adoption (e.g. [Allain et al., 2018](#), [Bithell and Brasington, 2009](#)) or resilience to external shock (e.g. [Chen et al., 2019](#)) which do not require to account for operational aspects of agriculture. Moreover, such operational aspects have been historically addressed by process-based models, statistical models based on historical observations or economic optimization models ([Jones et al., 2016](#)).

However, representing human action at the operational level in ABMs dealing with agriculture could be of interest as operational management can potentially influence agricultural outputs ([Martin-Clouaire, 2017](#)), with significant economic and environmental impacts. Indeed, when the irrigation campaign begins, strategical and tactical choices concerning the structure of the farm have already been made, such as the cropping system for the current season ([Janssen and van Ittersum, 2007](#)). The number of plots to be irrigated and the type of irrigation technology used constrain the possibilities in space and time to operate irrigation. In addition, some situation are difficult to foresee in advance ([Reynaud, 2008](#)), for example when water resource is insufficient for ensuring all irrigation needs such as during low-flow or water shortage periods. During such periods, irrigation relies on operational management based on local observations to irrigate some crops in priority. As every operation may affect the sets of current and future alternatives ([Daydé et al., 2014](#)), it is also important to have a dynamic representation of the operational practices since their consequences actively participate to the uncertainty of knowledge, which is a major management challenge in agriculture ([Lipshitz and Strauss, 1997](#)).

In Chapter 3, we have identified some evolutions in the operational management of the gravity-fed networks of the Buëch catchment, such as the abandon of the coordination of irrigation using daily slots, that could impact irrigated crops, water resources and farmers' ability to irrigate. Modeling irrigation operations depending on the coordination

of such a collective network, and comparing simulations when the network is coordinated or not, could be of interest to assess these potential impacts. It requires to model interactions taking place at the short term between the farmers, the irrigated crops and the flow within the water network.

This chapter first presents the modeling problematic, scope and concepts of the WatASit model developed for such purpose. Then, the model is described using the ODD protocol which is classically used to formalize the description of ABMs. A proof of concept is then proposed in the following chapter and in [Richard et al. \(2020a\)](#) (Appendix C) by applying the model to the Aspres-Sur-Buëch case study, a typical gravity-fed network that had abandoned network coordination by daily slots.

4.2 Modeling problematic, scope and concepts

4.2.1 Terminology

The traditional description of multi-scale farming adaptations is divided into three categories (Janssen and Ittersum, 2007; Dury et al., 2012; Robert et al., 2016): 1) in the long term, strategic adaptations for the organization of the farm as a whole for the coming years, including the cropping system and techniques envisaged to ensure the best possible income in a given socio-eco-hydro-climate context and technological investments such as access to irrigation or its optimization, 2) in the medium term, tactical adaptations for the adjustment of cropping systems and their technical itineraries based on new knowledge (hydro-climatic, agricultural markets, etc.) more precise on the current season, and 3) in the short term, the operational adaptations for the adjustment of daily practices at each plot level by the farmer during a campaign. After having adopted this terminology initially, we encountered some difficulties:

- During field surveys, some farmers used the term "irrigation strategy" to refer to daily operational adjustments of irrigation, based on local observations of plants and soils for example,
- It is more common to speak of strategic and tactical adaptation in the sense of a decision, while an operational adaptation concerns rather the concrete implementation in the short term,

- Strategic and tactical decisions often concern the structure of the farm: land tenure, crop rotation and the adoption of technology adapted to this rotation. It is not really useful in the context of our work to distinguish precisely these levels, but it is useful to identify the structural elements that constrain the operational level.

For these reasons, we propose to regroup all the adaptations of the strategic and tactical levels in a single structural level. This classification is not perfect, and the term structural does not have the same meaning as when speaking of structural measures in the prevention of natural risks, for example. In the restricted framework of our work, using the structural/operational classification and terminology is interesting to emphasize the dichotomy between the possibilities of adjustments at the time of acting, and the constraints already fixed at that time that limit these possibilities. As used in the literature review in Chapter 2, we also keep it in the following.

Moreover, to avoid misunderstandings concerning the use of the term "irrigation strategy", we will use the term "operational irrigation strategy" to describe decision rules concerning the operational management of irrigation in the following.

4.2.2 Modeling problematic for the Aspres-Sur-Buëch case study

In Chapter 3 we have learned the specificities of the short-term interactions dealing with the irrigation operations of the Aspres-Sur-Buëch case study. Such operations are mainly due to the farmers irrigating their crops during the irrigation campaign that usually takes place from May to September. Interactions are direct between each farmer and the floodgates located on their farm plots. Such interactions mostly depend on the local state of the environment, meaning the local water availability in the network at the floodgate to be able to trigger the flooding of the plot. They also depend on the rainy conditions and on the operative availability of the farmer, with generally one farmer per farm. Interactions between farmers themselves are mainly indirect through the water flow in the canal which is modified by each farmer's operation of irrigation and thus influences the downstream farmers. The minimum duration of an operation is one hour on the case study which is also a sufficient duration for a change in the flow

upstream of the network to be transmitted downstream of it and affect the possibilities of irrigation. In addition, social interactions between farmers appear more and more limited during the irrigation campaign. Our problematic is to be able to model such direct and indirect interactions mediated mainly by the water flow in the network before and after the abandon of the network coordination by water daily slots, and during an irrigation campaign subject to low-flow such as during the year 2017.

4.2.3 Chosen approach

Chapter 2 has highlighted the existence of a situated approach in ABMs in which changes in the environment interfere with the action during its implementation phase. In particular, [Afoutni \(2015\)](#) has proposed a conceptual approach using artifact entities called "affordances" that make explicit the possible interactions between a farmer agent and the objects he perceives in his environment and with whom he interacts. She designed and implemented this conceptual model with a virtual case study which needs a proof of concept. The virtual case study was composed of two farms and focused on the flows affecting their agricultural stocks (e.g. fertilizers and manure) due to the agricultural operations of the farmer agents. Such an approach is a good candidate for modeling direct and indirect interactions mediated by water that take place in our case study but requires in-depth adaptation and new developments that are detailed below.

4.2.4 Modeling scope

The design of the WatASit model need to be:

- Specific to the representation of interactions due to the irrigation operations made by farmers sharing a water network and that taking place during the several months of an irrigation campaign (usually from May to September) notably subject to low-flows. The potential irrigation operations due to non-farmer members of the irrigator union are not represented as they are limited in the Aspres-Sur-Buëch case study and data for localizing and describing it are not available,
- As generic as possible concerning the structure of the model so as it can be instantiated both for pressure, gravity-fed or mixed water networks, except for the

sub-model flow that should be adapted to the gravity-fed network, and with a first test on the gravity-fed network of the Aspres-Sur-Buëch case study.

4.2.5 Modeling objectives

The model aims to simulate, at each hourly time step, the action possibilities of a farmer agent dealing with irrigation during the course of an irrigation campaign. Action possibilities should result from the constraints the farmer encounters due to the local water availability at the floodgate he interacts with on each farm plot. Action possibilities should also depend on his availability to operate irrigation in a given structural context, in particular the cropping system that conditions the number of plots to be irrigated with potential simultaneous ones. The model aims to emphasize on the influence of irrigation operations on each other within the water network and from a time step to another rather than on the operational decision mechanisms. The flow entering into the water network should be representative of the minimum threshold observed during field surveys, adjusted at the beginning of the irrigation campaign in relation to the maintenance status of the network branches, and that can only be slightly increased up to a maximum threshold value that corresponds to the overflow as long as there is sufficient water in the river.

4.2.6 Objectives of the model in view of coupling it with biophysical models

Simulating crop dynamics such as plant growth on each plot, and water flow in the river at the network level, are not the objectives of the WatASit model but of the coupling with a crop model (Chapter 6) and with a distributed hydrological model at the basin scale (Chapter 7 and perspectives at Section 8.6). In fact, such coupling has two objectives:

- Assessing the feedback effects of the irrigation operations made by the farmer agents on the crop dynamics and on the local natural runoff (on each plot) and natural river flow processes,
- Updating the local state of the environment interfering with the irrigation operations, as crop dynamics (maturity, water stress) conditioning the interactions with

the farmer agents, or the river flow potentially constraining the flow entering into the water network, notably during low-flow periods such as the year 2017.

In the perspective of the coupling with a crop model, the structure of the WatASit model should integrate a spatial entity representing the plots, with crop type and crop area characteristics that will be necessary to set up the crop model parameters. It also requires to represent the spatial position of the plots in relation to each other within the irrigation scheme as it could influence the coupling for the spatial iterations of the crop model.

4.2.7 Key concepts

4.2.7.1 Originality of the situated approach

The Theory of Planned Action ([Miller, 1960b](#)) considers that action is determined by a state to be achieved and a plan to achieve it. The actor has an objective, he plans the actions to do in order to reach his objective. If the plan is not adapted anymore to his objective, he could reschedule the actions he plans to take. The Theory of Activity ([Vygotsky, 1930](#)) postulates that action is a complex hierarchical structure and that its determinants vary according to the "level" considered. For example, the "activity" level is determined by an objective, the "action" level by a plan and the "operation" level essentially by environmental conditions. Both approaches start with a goal to be achieved and planning mechanisms before considering the operating conditions.

The originality of the Theory of Situated Action ([Dreyfus, 1972](#), [Suchman, 1987](#)) is to reverse the logic: what are the possibilities of the actor at the moment of acting? The key difference relies on the explicit consideration of the operational alternatives to choose the one to be operated. In other words, when the actor acts, he would only seize the opportunities for action offered to him by the situation he is in. The unit of analysis of the situated action is the relationship between the action, resources and constraints offered by the physical and social circumstances encountered by the actor: an action cannot be understood outside its real situation ([Suchman, 1987](#)). Another originality of this theory is that the objective of acting can emerge as a result of an action and

not only *a priori*. The action is completed when the execution of the action modifies the situation in which the actor is or when the situation is no longer favorable to the execution of the current action. Then the action ends and another action may possibly emerge if the situation becomes favorable again (Suchman, 1987).

The basic idea is to implement a feedback loop between the possibilities of action offered by the environment and action. The notion of situation refers to the state of the environment, at a given time and in a given location, from the perception of the actor. The way of modeling the action is original because elements such as the actor capacities for action are added to the objects constituting the environment, which is considered as the set of resources for the action and not as its controller and it is thus not a simple "stimulus/response" scheme (Suchman, 1987). In addition, the notions of planning and memory are not rejected but are based on the set of action possibilities. In short, the actor is forced to adapt and respond to his possibilities. This is particularly interesting to model interactions between the farmers and the multiple plots that could be, or not, be irrigated in the short-term according the local water availability. Moreover, the key point of the situated approach in relation to other approaches representing action in ABM is the fact that an agent is always situated in an explicitly spatial and temporal action context. This point could be useful for coupling purposes by facilitating the identification of the common spatial and temporal scales of communication between the models.

4.2.7.2 The concept of Affordance and its mobilization in our work

The situated approach needs to link the actor and his environment, according to Gibson (1986), the concept of affordance seeks to establish this link. In the literature different variants of this concept have been described (Chemero, 2003, Stoeffregen, 2003a, Turvey, 1992). Turvey defined affordances as intrinsic properties of the environment which, combined with the actor capacities, gives rise to action. According to Stoeffregen affordances have two levels: the first allows an affordance to emerge and the second allows an action to be carried out according to the actor's intention. From the Chemero point of view, an affordance does not exist apart from its relationship with an actor and a

particular situation.

Thus, according to both Chemero and Stoffregen, affordances emerge neither only from the environment nor only from the agent but from their interaction, and that is the definition of affordance adopted in this work. The three definitions mention the following key properties for an affordance:

- The environment influences the determination of the actions of an actor (an affordance is action-oriented),
- Perceiving an object means perceiving what it is possible to do with it in terms of actions (an affordance is significant),
- The actor does not systematically need to have a mental representation of his environment to understand it and act accordingly (an affordance is directly perceived).

There is therefore no actor/actor interaction but only between actor and environment since each actor acts only in response to the objects he perceives in his local environment. Based on the formalization of Chemero (2003), Papasimeon (2009) proposed a model of agent-environment interaction based notably on affordances in the context of military operations. In his work, an affordance takes the form of annotation and its detection responds to conditions in the form of properties that the agent and the object must have for the affordance to manifest itself. Sequeira et al. (2007) used affordances to allow agents to identify all the possible interactions with objects they can have in the environment on the basis of their past interactions. The use of affordances in ABMs can also be found in Cornwell et al. (2003) and Raubal (2001).

More recently, Afoutni (2015) proposes in her approach distinguishing entities that perform actions (called "actuators") from entities that undergo actions (called "passive object") and we used the same distinction in the following (see Section 4.4.1.2). Afoutni (2015) also separates a micro level in which the actuators and passive objects of the environment interact, from a macro level in which the possibilities of action (represented by the affordances) can be detected by an entity dedicated to each spatial place (called

”place-agent”). In fact, Afoutni (2015) considers that the knowledge to detect an affordance is specific to each spatial place. For example, the possibility of a ”sowing” action only exists if the farmer agent is located on a farm plot where this knowledge is useful. If this is the case, an affordance can be detected based on condition rules and can manifest itself in the form of a dynamic annotation (called ”artifact”). In concrete terms, the farmer agent is explicitly represented and his perception depends on his spatial location.

In our approach, the perception is not limited to the location of the farmer agent but to its management perimeter: the farm. Detection of the irrigation possibilities is done on each farm spatial entity by a unique entity that managed the situations of interaction (called situation controller, see Section 4.4.1.2) on each plot of the farm. Each farmer agent moves from one plot to another at each hourly time step according to the location of the action he operates, and systematically perceives all possibilities of action he has with the passive objects located on his farm.

4.3 Code and data availability

Hardware required: 64-bit PC with Linux or Windows, 5 – 10 GB of free disk space (depending on application). We recommend using a high-speed processor and at least 8 GB of RAM.

Software required: CORMAS (from Version 2017, Smalltalk language, <http://cormas.cirad.fr>) for loading the model, R Software (version 3.0.1 or higher) for constructing input files and for initializing/running simulations. R is also recommended for analyzing simulation results.

Availability and cost: The model is downloadable for Linux or Windows at the following link: <https://www.comses.net/codebases/0d8dcaf1-8772-4e57-9f03-1f6c062bbe60/releases/1.2.0/>. It is provided directly with the CORMAS platform and the case study data set so that it can be directly executed using the R script associated called ”*Rcoupler*”, by following the instructions provided.

4.4 Description of the WatASit model (ODD protocol)

4.4.1 Overview

4.4.1.1 Purpose

The WatASit ABM is designed to simulate the irrigation operations of irrigators sharing a common water network during a collective irrigation campaign. It explicitly represents the irrigation possibilities left by the operational constraints of the irrigators. The constraints taken into account in WatASit are of the following nature:

- Existence, or not, of daily slot coordination of the network or other coordination conditions,
- Precipitation of the day,
- Maximum irrigation operations at a time per irrigator (number of irrigator per farm to be defined),
- Availability, or not, of the irrigator during the operation duration and daily time window for triggering irrigation operations,
- Minimum network flow to trigger a flood irrigation.

In WatASit, an irrigation possibility is generated on the plots where these constraints make irrigation possible at a given hourly time step.

4.4.1.2 State variables and scales

All entities of the model, their characteristics, typical values and data sources are available in Appendix 1 of this chapter. WatASit covers the spatial area of an irrigator union during the several months of an irrigation campaign. The model is based on the distinction between the elements that are involved in operations (called operational entities, see Table 4.1), such as the irrigators, the crops or the irrigation infrastructure, and the areas over which operational entities can operate (called spatial entities). A third kind of entities (called artifact entities) explicitly represents the abstract possibilities of irrigation. Thus, the model has three types of 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 4.1). The 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 irrigator agents mobilizing their irrigation strategy, 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.

Operational entities Spatial entities are occupied by operational entities that physically represent the irrigators and passive objects (i.e. crops, floodgates, branches of the network). They 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 to make explicit some abstract things of the real world such as action possibilities (i.e. the affordances) and actions. Possibilities of irrigation thus result from the interactions between an actuator (i.e. a farmer agent) and a passive object (i.e. a piece of irrigation equipment represented in the model). In a given farm, they can interact according to conditions that define the situation of interaction. If conditions are fulfilled, an irrigation possibility is generated. Among the possibilities, the chosen one becomes an irrigation 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 by Afoutni et al. (2014) "place-agents", each farm is associated with a situation controller.

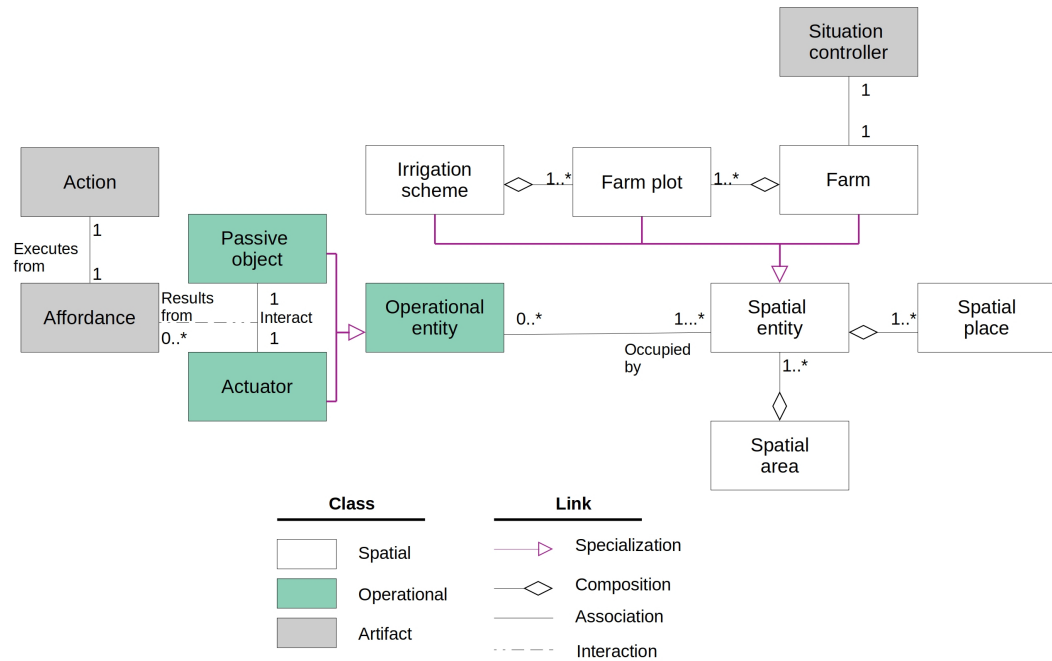


FIGURE 4.1: UML class diagram for the generic structure of the WatASit model. Each box with solid outlines represents a type of entity: a Class. White classes are spatial entities, green classes are operational entities, and grey classes are artifact entities. Links starting with diamonds represent compositions (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).

4.4.1.3 Process overview and scheduling

The model is based on a double time step. Each day, there is first initialization of the current precipitation and restriction conditions, and also of the number of days since the crops have not been irrigated (Figure 4.2). Then, every hour, the flow is updated in the network according to network junction state (i.e. "opened" or "closed") and ended actions. Irrigation options are then generated on each farm according to the states of actuators and passive objects. Depending on the actuator's operational strategy, an option can be chosen to make an irrigation action or ask for more water in the canal.

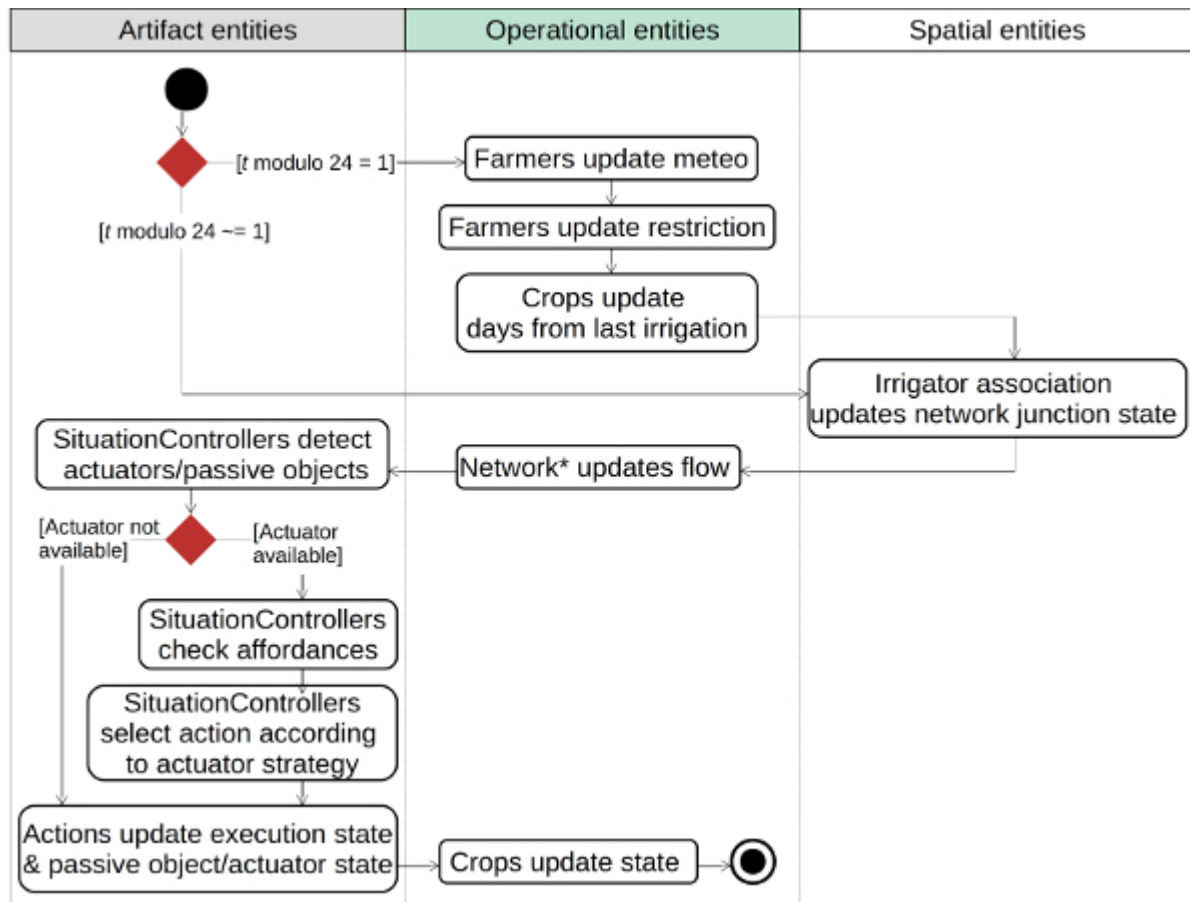


FIGURE 4.2: Activity diagram of the WatASit model.* indicates that both network intake, junction, reject and branches entities do the method.

4.4.2 Design concepts

4.4.2.1 Basic principles, emergence and adaptations

WatASit is based on the theory of Situated Action (Dreyfus, 1972, Suchman, 1987) which represents the phase of implementation of actions according to the operational constraints of the actors. In the model, the behavior of the irrigator agents is determined by their possibilities of irrigation, which are re-evaluated at each hourly time step. The agents choose, or not, depending on their operational strategy, to select one of the possibilities to perform it. As water is not always sufficiently available to irrigate a plot, irrigator agents have 4 possibilities:

- Irrigate a plot with crop needing water and having an irrigation possibility,

- Irrigate a plot with crop needing water and having an irrigation possibility during a restriction period,
- Ask for more water in the network by increasing its flow if overflow rate is not yet reached,
- Do something else during this time step.

4.4.2.2 Fitness, learning, prediction and sensing

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

4.4.2.3 Interactions and collectives

WatASit allows direct interactions between the actuators (i.e. the irrigator agents) and the passive objects of their spatial environment (e.g. the floodgates to deliver water to their plot from the collective network). By triggering or not irrigation operations, irrigator agents thus also interact indirectly with each other by reducing the amount of water available for the irrigators located downstream of the network.

4.4.2.4 Stochasticity

Stochasticity can be included for climate forcing, but the initialization of the cropping systems for each irrigator is usually made from a geo-referenced dataset of the irrigation campaign year and the model is usually deterministic.

4.4.2.5 Observation

Simulation outputs are collected from the model by recording attributes of model entities with CORMAS probes or directly in the R Software through the *RCormas*¹ method, which was already available, but which is mobilized in the *Rcoupler* API that has been developed in this work to pilot to configure and pilot simulations of the WatASit model.

4.4.3 Details

4.4.3.1 Initialization

Spatial entities are usually initialized from shapefile (e.g. the "Registre Parcellaire Graphique"² RPG database) using a pre-processing that consists of rasterizing the farm plot shapefiles. Farm plots belonging to each farm are identified, and crop type are associated to each farm plot. The collective water network is initialized using shapefiles (e.g. the HYDRA database³). At the initialization, farm plots served by the network are listed for each canal branch.

4.4.3.2 Input

Daily precipitations usually come from the French near-surface SAFRAN reanalysis (Vidal et al., 2010). The water use restrictions adopted on the study area during the 2017 year come from the national PROPLUVIA database⁴, which provides the dates of entry into force and the associated level of restriction. Their consequences on irrigation are explained in the Hautes-Alpes Drought Master Plan⁵, which provides the limitation for irrigation: two days per week if the restriction level is "alert", and four days in case of "enhanced alert" level. Days on which such restrictions were adopted on the case study during the 2017 year were published in the Official Journal⁶ through the decrees issued by the Hautes-Alpes Prefecture.

¹Rcormas is available at <https://gitlab.irstea.fr/cormas-dev/r-cormas>

²A version 2.0 distributed since 2015 is directly accessible online at <http://professionnels.ign.fr/rpg>

³Accessible online at http://hydra.dynmap.com/index_.php?grFrame=1.

⁴Accessible online at <http://propluvia.developpement-durable.gouv.fr>

⁵Accessible online at <http://www.hautes-alpes.gouv.fr/le-plan-cadre-secheresse-a1895.html>

⁶Accessible online at <https://www.journal-officiel.gouv.fr/>

4.4.3.3 Sub-models

Affordance generation sub-model Figure 4.3 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.

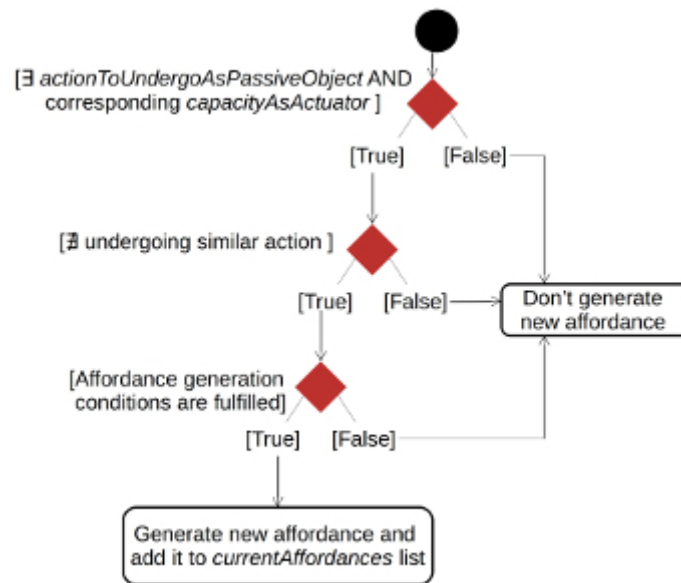


FIGURE 4.3: Activity diagram of the affordance generation sub-model.

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 4.4 :

- 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.

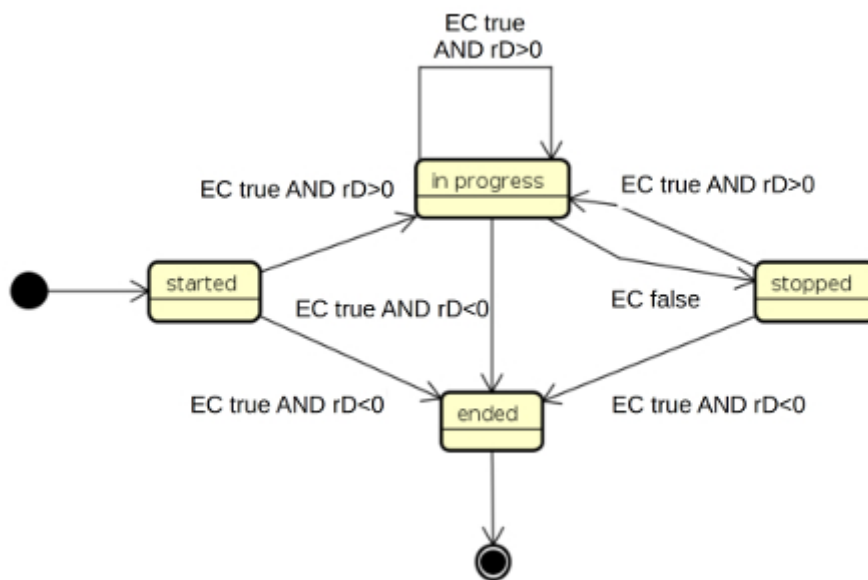


FIGURE 4.4: State-transition diagram of the action, eC stands for execution conditions, and rD for remain duration.

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. 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. A simplified view of the network functioning is presented in Figure 4.5. It begins at a water intake, whose flow rate (Q_{intake}) is set at the beginning of the irrigation campaign at the reference flow rate (Q_{ref} , Eq. 4.1).

$$Q_{intake}(t = 0) = Q_{ref} \quad (4.1)$$

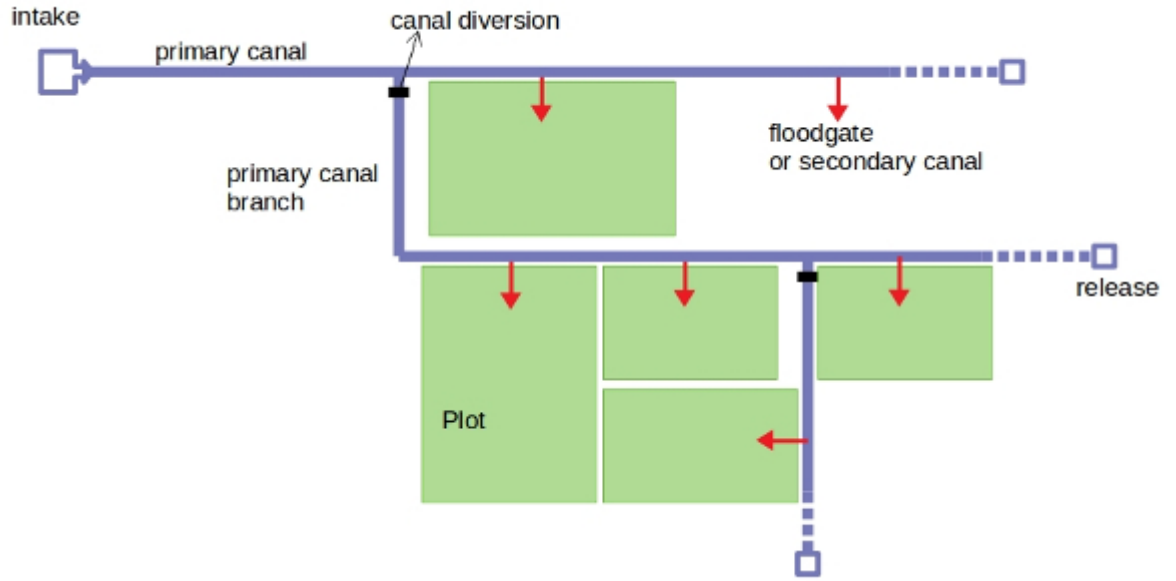


FIGURE 4.5: Simplified representation of the irrigation network.

Q_{intake} supplies the main canal, which is divided into two branches at each diversion. The flow in each downstream branch ($Q_{downstream}$, in $\text{m}^3 \text{s}^{-1}$) is obtained according to the diversion flow rate (Q_{div} , in $\text{m}^3 \text{s}^{-1}$) multiplied by a division coefficient ($divCoeff$) at each diversion (Eq. 4.2).

$$Q_{downstream} = Q_{div} \times divCoeff \quad (4.2)$$

Q_{div} is calculated as the flow of the branch upstream ($Q_{upstream}$, in $\text{m}^3 \text{s}^{-1}$) of the diversion minus seepage along the branch (bS , in $\text{m}^3 \text{s}^{-1}$) (Eq. 4.3):

$$Q_{diversion} = Q_{upstream} - bS \quad (4.3)$$

Seepage (S , in $\text{m}^3 \text{s}^{-1} \text{km}^{-1}$), 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. 4.4:

$$bS = bLxS \quad (4.4)$$

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 (Q_{flood}) 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 $0,35 \text{ m}^3 \text{ s}^{-1}$ 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, Q_{flood} is subtracted from the flow of the canal branch (Eq. 4.5). 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 Q_{flood} .

$$Q = Q - \sum_{irrigating\ floodgates} Q_{flood} \quad (4.5)$$

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, Q_{intake} 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 Q_{intake} by adding Q_{rung} , unless it reaches the overflow rate (Q_{max}) (Eq. 4.6):

$$Q_{intake} = \min(Q_{max}, Q_{intake} + Q_{rung}) \quad (4.6)$$

4.5 Conclusion

In this chapter, we have first drawn lessons from the first part of the thesis, notably from the field surveys concerning the specificities of our case study. The main specificity concerns the short-term interactions that take place more between the farmers and their

environment rather than between the farmers themselves. Taking into account this observation and the literature review proposed in Chapter 2, we proposed to use an agent-based modeling approach based on the Situated Action Theory, whose originality relies on the representation of a situation of action as the relationship between the action and resources or constraints offered by the physical and social circumstances encountered by the actor. This representation is of interest for modeling interactions depending on the local state of the environment, meaning the local water availability in the network, but doesn't specify how the link between an actor and the environment can be established concretely. Following a proposal made by (Afoutni, 2015), we used the concept of Affordance to clarify this link and to design the WatASit agent-based model. This model aims to simulate the irrigation operations of irrigators sharing a common water network during a collective irrigation campaign by explicitly representing the interaction possibilities left by their operational constraints. Richard et al. (2020a) demonstrate the feasibility of this approach to represent the Aspres-Sur-Büech network. This paper, available in Appendix C, presents an implementation of the model and its use to compare scenarios of coordination. The following chapter builds on this first realization and explores in more detail how agent trajectories can be linked to their simulated interaction possibilities according to our use of the Affordance concept, and whether this link can help to interpret the output of the WatASit model, as output interpretation remains a challenge for many agent-based models (Lee et al., 2015).

4.6 Appendix

4.6.1 Appendix 1

TABLE 4.1: Model entity type, name, attribute and typical value of the WatASit model.
 ACT indicates an actuator and PO a passive object. RPG refers to year 2017.

Entity type	Entity name	Entity attribute.s (Source)	Typical value
Spatial	Spatial entity (pixel)	resolution	75 m
	FarmPlot	area (RPG)	[0.17–2.33] ha
		myCrop (RPG)	a crop entity
		myFloodgate (HYDRA)	a Floogate entity
	Farm	myFarmer	a Farmer entity
	IrrigatorUnion	myFarmers	A set of farmer entities
		myNetwork (HYDRA)	a network id
Operational	Farmer (ACT/PO)	myFarm (RPG)	a farm entity
		myCapacities (Field data)	[openFloodgate;askWater doSomethingElse]
		myCurrentAction state	an action entity [active;inactive]
		myMeteo (SAFRAN)	a rainfall value (in mm)
		myRestriction (PROPLUVIA)	[vigilance;alert;alert+;crisis]
	NetworkIntake (PO)	Qref (Field data)	$0.09 \text{ m}^3 \text{ s}^{-1}$
		Qmax (Field data)	$0.15 \text{ m}^3 \text{ s}^{-1}$
		Qrung (Field data)	$0.01 \text{ m}^3 \text{ s}^{-1}$
		state	[opened;closed]
	NetworkJunction (PO)	Q	computed
		state	[opened;closed]
	NetworkBranch (PO)	Q	computed
		seepageRate (Charton, 2001)	$0.0067 \text{ m}^3 \text{ s}^{-1}$
		state	[flowing;notFlowing]
	NetworkReject (PO)	Q	computed
		state	[flowing;notFlowing]
	Floodgate (PO)	Q	computed
		state	[opened;closed]
		Qflood (Field data)	$0.03 \text{ m}^3 \text{ s}^{-1}$
	Crop (PO)	type (RPG)	a crop type;
		myFarmPlot (RPG)	a FarmPlot entity
		daysFromLastIrrigation	computed
		state (Field data)	[irrigated;abandoned;else]
Artifact	Affordance	type (Field data)	[legalFlood;illegalFlood; askMoreWater; doSomethingElse]
	Action	myActuator	an actuator entity
		myPassiveObject	a passive object entity
		type	same as affordance
		myAffordance	an affordance entity
		targetDuration (D) (Field data)	4 hour ha^{-1} (flood) 1 hour ha^{-1} (else)
		realDuration	
		timeWindow (Field data)	12 hours
		state	[started;ended; inProgress;Stopped]
	SituationController	myFarm	a farm entity
		myActuator	an actuator entity
		myPassiveObjects	a set of passive object entities
		currentAffordances	a set of affordance entities
		currentAction	an action entity

Chapter 5

Using the Affordance concept to help interpret agent trajectories in ABMs

***Contribution to the thesis project:** In this chapter, we further explore the use of the Affordance concept in ABM. In particular, we focus on the changes in agent possibilities of actions due to the parameterization of the model. The key point of this chapter is that agent possibilities of action provide an intermediate level of information for interpreting agent trajectories, allowing to take a step back on what the model does and how agents are represented. As part of sensitivity analysis, agent sets of possibilities also facilitate understanding the effect that changing simulation input or parameter values have on simulation outputs. We reproduce here the paper ([Richard et al., 2020c](#)) which is under review in *Socio-Environmental Systems Modelling*.*

Using the Affordance concept to help interpret agent trajectories in ABMs: application to collective irrigation coordination

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Abstract Output interpretation still remains highly complex for numerous agent-based models, in particular explaining the causal links with model configuration (i.e. parameter values) when agents evolve in a changing environment. This paper explores how changes in agent trajectories can be linked to changes in their possibilities of action due to the model configuration. We proposed mobilizing the concept of Affordance to make explicit the possible options of each agent at each daily time step. We applied the WatASit model based on this concept to a collective irrigation network of Southern France under two model configurations (i.e. network coordination or not). Agent sets of possible options provided an intermediate level of information for interpreting agent trajectories in each model configuration. Agent trajectories are primarily caused by insufficient water downstream of the network when it is not coordinated. However, agent trajectories are more dictated by their individual irrigation workload when the network is coordinated. As part of sensitivity analysis, agents' sets of options help interpret the threshold effects of model forcing or parameters. Irrigation options are more sensitive to the number of rainy days when the network is coordinated, making this model configuration more interesting to reduce the irrigation abandons up to a certain number of rainy days. Agent sets of options are also useful to take a step back on how agents are represented. In WatASit, agents are not surprisingly limited in terms of anticipation as the Affordance concept was mobilized to clarify agent possibilities of actions they directly perceive in their environment, and not as a substitute for agent decision-making.

Keywords output ; agent-based modeling ; affordance ; situated action ; collective irrigation.

Résumé en français L'interprétation des résultats reste très complexe pour de nombreux modèles à base d'agents, en particulier pour expliquer les liens de causalité avec la configuration du modèle (c'est-à-dire les valeurs des paramètres) lorsque les agents évoluent dans un environnement changeant. Cet article explore comment les changements de trajectoires des agents peuvent être liés aux changements de leurs possibilités d'action en fonction de la configuration du modèle. Nous proposons de mobiliser le concept d'Affordance pour rendre explicites les options possibles de chaque agent à chaque pas de temps quotidien. Nous avons appliqué le modèle WatASit basé sur ce concept à un réseau d'irrigation collectif du sud de la France selon deux configurations de modèle (coordination du réseau ou non). Les ensembles d'options possibles des agents ont fourni un niveau d'information intermédiaire pour l'interprétation des trajectoires des agents dans chaque configuration du modèle. Les trajectoires des agents sont principalement causées par l'insuffisance d'eau en aval du réseau lorsqu'il n'est pas coordonné. Cependant, les trajectoires des agents sont davantage dictées par leur charge de travail individuelle en matière d'irrigation lorsque le réseau est coordonné. Dans le cadre de l'analyse de sensibilité du modèle WatASit, les ensembles d'options des agents aident à interpréter les effets de seuil liés aux forçages et aux paramètres du modèle. Les options d'irrigation sont plus sensibles au nombre de jours de pluie lorsque le réseau est coordonné, ce qui rend cette configuration du modèle plus intéressante pour réduire les abandons d'irrigation jusqu'à un certain nombre de jours de pluie. Les ensembles d'options des agents sont également utiles pour prendre du recul sur la façon dont les agents sont représentés. Dans le modèle WatASit, les agents sont limités en termes d'anticipation, ce qui n'est pas étonnant car le concept d'Affordance a été mobilisé pour clarifier les possibilités d'actions qu'ils perçoivent directement dans leur environnement, et non comme un substitut à la prise de décision.

Mots clefs sorties de simulation ; modélisation à base d'agents ; affordance ; action située ; irrigation collective.

5.1 Introduction

Output interpretation still remains highly complex for a large number of agent-based models (ABMs) (Lee et al., 2015). In particular, cause-effect relationships can't always be easily interpreted when agent behavior adapts to a changing environment (Letcher et al., 2013).

Human behavior representations in ABM are based on a large panel of theories (An, 2012). Among the most prominent ones, Expected Utility Theory (EUT) assumes that the actor rationally chooses the option that promises the highest expected utility (e.g. Machina, 2008). The Theory of Planned Behavior (TPB) developed by Ajzen (1985, 1991) assumes that actors are decision-makers perceiving the ease or difficulty of performing the behavior reflecting past experiences as well as anticipated obstacles (e.g. Schwartz and Ernst, 2009). These theories conceptualize human behavior by focusing on decision-making.

Other theories propose a different paradigm for representing operational behaviors. Among these the Theory of Situated Action (TSA) proposed originally by Dreyfus (1972) and developed by Suchman (1987), focuses on the modalities of the implementation of action in a given situation (i.e. at a given place and time). The actor's behavior is determined by a set of possible actions (called option-set in the following) when it comes to acting, in addition to the decision-making processes (e.g. Guerrin, 2009). To clarify how the actor's option-set can be established in a given situation, Gibson (1977) has proposed the Affordance concept that focuses on the actors and objects occupying the environment, and allowing to "afford" different interactions that constitute possibilities of action. Such option-set is continuously changing according to the current situation, and is constrained by it, forcing the actor to adapt to his current situation. The use of affordances in ABM can be found in Cornwell et al. (2003) and Raubal (2001). Perhaps the most significant work to date is a conceptual model proposed by Afoutni (2015) for the representation of situated actions based notably on affordance, and deployed on a virtual school case. Richard et al. (2020a) have also proposed the WatASit ABM based

on the Affordance concept and designed to simulate the irrigation operations of irrigators sharing a common water network during a collective irrigation campaign.

Representing agent option-sets in evolving situation is of interest for addressing the complexity of tracing back cause-effect relationship in ABMs. The design and analysis of simulation experimental plan usually consist of estimating the effect of parameter values (called “model configuration” in the following) and external drivers (called “forcing” in the following). Their effect on outcome indicators summarizing the time series of agents or environmental state variables is assessed through sensibility analysis, spatio-temporal analysis, visualization or communication to non-expert stakeholders (Lee et al., 2015). Visualizing explicitly the option-set of each agent and its evolution over time could give access to an intermediate level that link agent trajectories (characterized by their state variables) with the model configuration.

Irrigation constraints are either structural (Sebillote and Soler, 1990), relative to the choices that have been made for the farming system in place (e.g. the cropping system and rotations, the access to water), or operational (e.g. Martin-Clouaire, 2017) notably in situations that are difficult to foresee in advance (Reynaud, 2008). Once the structural choices have been made, the farmer has to make operational choices: short-term adjustments of irrigation and fertilization inputs (Sebillote and Soler, 1990), and consideration of regulatory constraints such as water restrictions (e.g. Sauquet et al., 2019). In places where irrigation is managed collectively for the sharing of water, farmers can have limited possibilities in space and time to operate irrigation. In such systems, irrigation inputs depend on the functioning of the shared network (Malaterre, 2008, Plusquellec, 1988) and the associated operational constraints (e.g. upstream-downstream gradient of the water level, the maximum number of simultaneous irrigation operations). Such constraints are part of operational management of irrigation that can lead to inequalities between farmers in terms of irrigation capacity (Richard et al., 2020a) and significantly impacts agricultural outputs of the season (Martin-Clouaire, 2017). Collective irrigation is therefore of interest for exploring farmer agent option-sets evolving during the course of a simulated irrigation campaign.

The objective of this paper is to explore how changes in the trajectories of farmer agents can be linked to changes in the trajectories of their option-sets due to the model configuration. We mobilized the concept of Affordance to make explicit the operational option-set of each agent at each daily time step. We illustrated the approach by applying the WatASit model based on this concept to a typical gravity-fed network of Southern France under two model configurations (i.e. network coordination or not). First, we explored the model outputs (i.e. final trajectories and intermediate options of the farmer agents) at the collective and individual levels during the simulated irrigation campaign. Second, we analyzed the sensitivity of model outputs to key model forcing and parameters.

The next section explains the Affordance concept as the option-set of an actor. We then give an overview of the WatASit ABM and describe the application case. We also explain model specification and parameterization, the model configurations we compared and the model outputs and verification. Section 5.3 explores simulation outputs at the collective (Section 5.3.1) and individual (Section 5.3.2) levels, and their sensitivity to key forcing and parameters (Section 5.3.3). Potentials of the Affordance concept to help interpret agent trajectories in each model configuration, limitations and outlook are discussed in Section 5.4, before concluding.

5.2 Material and Methods

5.2.1 Affordances as option-set of an actor

In the vein of TSA, Gibson's ecological approach refers to affordance as any possibility of interaction offered to actors by their environment: "*the affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill*" (Gibson, 1977). For example, water has the affordance of "*stand on*" for a finite number of animals, as a large part of the insects afford with water by their capacities to stand on the water. For all other animals, water has the affordance of "*do not stand on it*".

Gibson argues that species live in an environment designed as a set of affordances complementary to them (Simone, 2011). Man is the clearest example of this since he produces new affordances to make his environment easier to live in. Variations in the concept have been proposed (Chemero, 2003, Stoeffregen, 2003b, Turvey, 1992), but they have in common that:

- An affordance is action-oriented: the environment influences the orientation and determination of actors' actions,
- An affordance is significant: the perception of an object is the perception of what it is possible to do with it in terms of action,
- An affordance is directly perceived: the actor does not need to have a symbolic representation of its environment to understand it and act accordingly.

Thus, actors use the possible actions (i.e. affordances) offered to them by the other elements (actors or objects) they perceived (Clancey, 2002, Gibson, 1986, Johnston and Brennan, 1996). So the action does not result only from a plan that needs to be rescheduled (Figure 5.1, top), but from a limited subset of possible actions occurring in a precise place at a given time (Figure 5.1, bottom). Actors can choose, or not, to select one possible action to execute, depending on their operational decision-making.

$$Structure \rightarrow affordance \rightarrow behavior$$

What happens when we change the structure of a system ? A change in structure propagates to a change in the affordances, which propagates to changes in behavior:

$$\Delta structure \rightarrow \Delta affordance \rightarrow \Delta behavior$$

In our modeling approach, we represent different structures of the system by different configurations of our model and we thus consider that affordances might be a meaningful intermediate level between the model simulation outputs and the model configuration, by making explicit the possibilities of action faced by each agent over time.

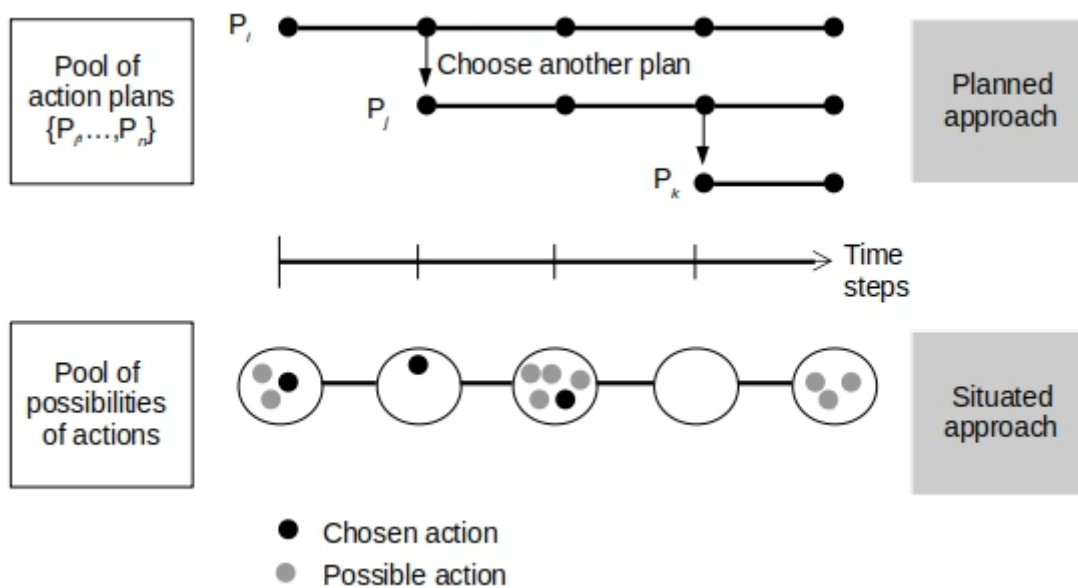


FIGURE 5.1: Schematic example of planned and situated approaches.

5.2.2 Model overview

In this section, we present the key points of the WatASit ABM following the ODD protocol (Grimm et al., 2006).

The model is designed to simulate the irrigation operations of farmer agents sharing a common water network during a collective irrigation campaign. The behavior of the farmer agents is determined by their possibilities of irrigation, which are re-evaluated at each hourly time step. The agents choose, or not, depending on their operational strategy, to select one of the possibilities to execute it as an action.

The model explicitly represents the irrigation possibilities left by the operational constraints of the farmers. The constraints taken into account in WatASit are presented and specified in Section 5.2.4 in Table 5.1. In WatASit, an irrigation possibility takes place on a plot where these constraints make irrigation possible at a given hourly time step. The network sub-model is specific to a gravity-fed network. Flood irrigation is possible if a minimum flow is maintained in the network branch serving the plot. As the water at the floodgate is not always sufficiently available to irrigate a plot, farmer agents have 4 possibilities: (1) irrigate plot with crop needing water and having an irrigation

possibility, (2) irrigate plot with crop needing water and having an irrigation possibility during a restriction period, (3) ask for more water in the canal by rising the flow at the canal water intake if maximum flow at intake is not yet reached, and (4) do something else- during this time step.

The structure of the model is based on the distinction between the elements that are involved in operations (called operational entities), such as the farmers or the irrigation equipment, and the areas over which operational entities can operate (called spatial entities) which are the farm plot, the farm and the irrigation network area. An actuator is an operational entity with the capacity to carry out actions with the passive objects located on the spatial entities under its control. In the model, the actuators are the farmers. A passive object is an operational entity that is actionable by an actuator to carry out an action. A third kind of entity (called artifact entities) explicitly represents agent possibilities of actions, agent actions and their mechanisms of control.

An overview of the model scheduling is given in Figure 5.2. Each day, there is first an initialization of the current precipitation and restriction conditions, and also of the number of days since the crops have not been irrigated. Then, every hour, the flow rate is updated in the network according to network junction state (i.e opened or closed) and ended actions. Irrigation options are then generated on each farm according to the states of actuators and passive objects. Depending on the actuator operational strategy, an option can be performed to make an irrigation action or ask for more water in the canal.

5.2.3 Case study

In France, water resource management plans are being drawn up for many river basins to restore a structural water balance, by notably saving water from irrigation withdrawals. Among the 2000 collective irrigated networks managed by an irrigator union, a quarter are gravity-fed networks (Schlüter et al., 2017). Most of them cover small irrigated areas with tens of hectares and members, with wide variation in their ability to perform maintenance works and to organize water sharing among their members. This is

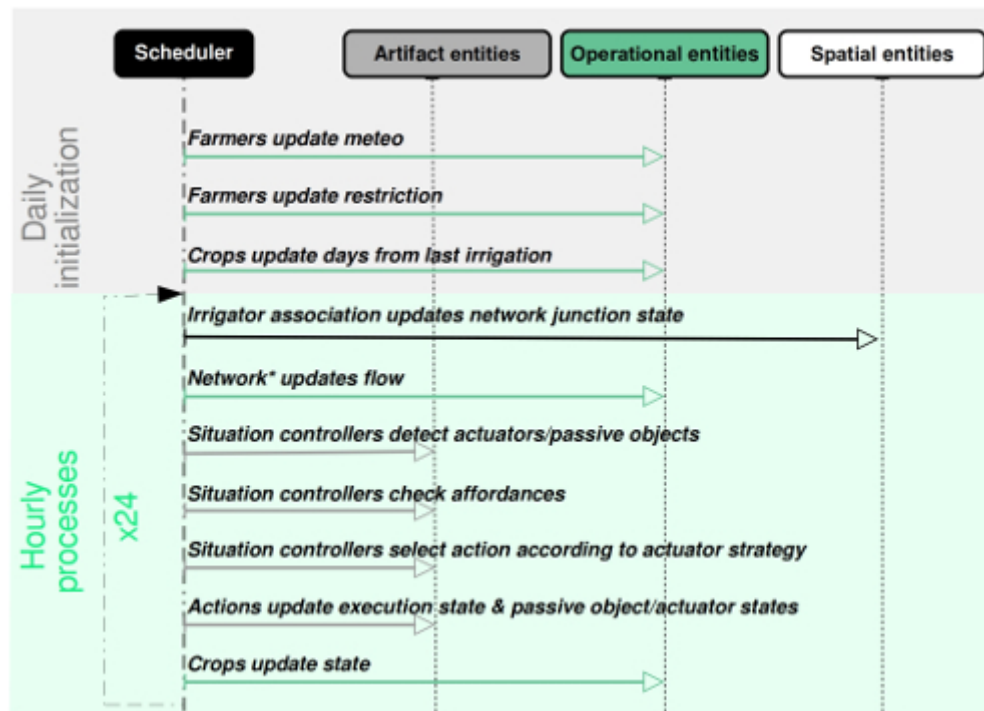


FIGURE 5.2: Sequence diagram of the WatASit model. Black, green and grey arrows indicate methods of the spatial, operational and artifact entities, respectively.* indicates that both network intake, junction, reject and branches do the method.

notably the case of the Buëch River basin in the Durance valley, where the operational functioning of small gravity-fed networks encounters difficulty for the sharing of water among irrigators during the irrigation campaign from May to September, in particular during the year 2017. The Aspres-Sur-Buëch collective network (Figure 5.3) is chosen as an application case because it is fairly representative of the Buëch’s gravity networks in terms of location (in the upstream part of the basin), irrigable surface area (with 75 ha in 2017 whereas the average is 50 ha), and crop types (with 38.9% meadows, 29.5% fodders, and 23.7% cereals whereas the average are 43.6, 29.7 and 22.2, respectively (in 2017 according to the RPG database). It includes 83 plots served by the gravity-fed network and belonging to 10 farmers.

5.2.4 Model specification and parameterization

The WatASit ABM has been already deployed on the Aspres-Sur-Buëch case study (Richard et al., 2020a) in which the model specification and the parameterization for the case study are detailed. In particular, model entities and specific network constraints

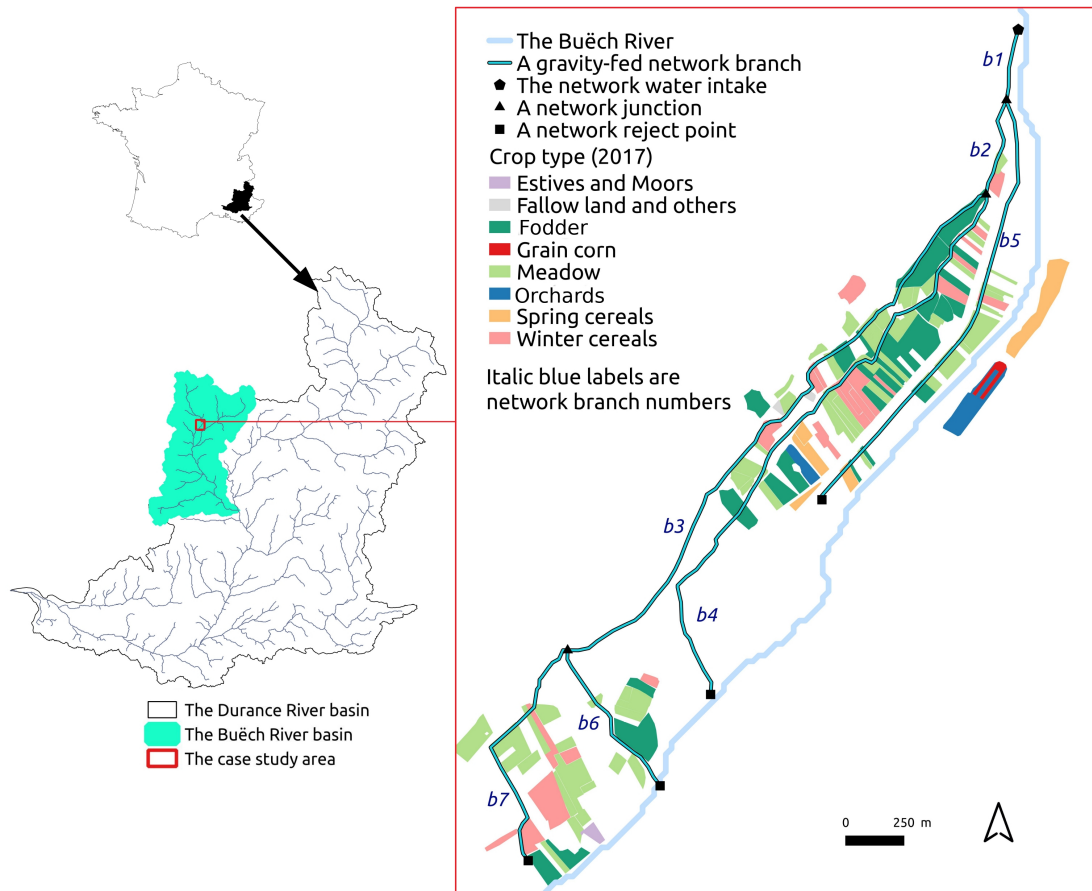


FIGURE 5.3: The study area (red box) is located in the Buëch River basin (in blue), a tributary of the Durance River basin. The colors represent the types of crops that are located on the plots served in water by the gravity-fed network (source: BD Cartage, RPG 2017 and BD Hydra consulted in March 2019).

(Table 5.1) have been specified according to field surveys in the form of observation of irrigation practices and semi-directive interviews to collect information about the 2017 irrigation campaign. The President of the Aspres-Sur-Buëch water network, its technician in charge of the technical management, and 3 irrigators were interviewed.

According to field surveys, operational entities such as crops and network intake, branches, junctions and rejects have been created as types of passive objects. Affordances are relative to the floodgate management mentioned by farmers. For each affordance, a couple of actuator/passive object and the generation conditions are detailed in Table 5.2. A *legalFlood* or *illegalFlood* affordance means that the canal branch supplying the plot is flowing enough to trigger gravity-fed irrigation during an unrestricted period or a restricted period, respectively. A *askMoreWater* affordance means that the canal branch

TABLE 5.1: The network specific constraints in the WatASit model.

Network constraint	Specification
Number of irrigator per farm	<i>One irrigator per farm</i>
Number of simultaneous irrigations per irrigator	<i>One irrigation at a time per irrigator</i>
Plot flood duration	<i>Fixed</i>
Target irrigation dose	<i>Fixed</i>
Required branch canal flow rate serving the plot floodgate	\geq <i>plot flood rate (Q_{flood})</i>
Functioning of the network while raining	<i>Irrigation is not triggered if there is precipitation</i>

supplying the plot is flowing, but not enough to trigger gravity-fed irrigation. The execution conditions and effects of the corresponding action are described in Table 5.3. The *illegalFlood* affordance is only informative of flood operations occurring during a restriction period, as such operations are tolerated on the case study but informally. Operational irrigation strategy consists to irrigate crops after a number of 12 days without irrigation or sufficient precipitation inputs to contain as much as possible a maximum of successive non-irrigated days (Figure 5.4).

Other parameters are specific irrigation operations and gravity-fed network characteristics mentioned by the irrigators. In particular, the reference flow rate at the network intake (Q_{ref}) was determined by the irrigators to both avoiding overflow (Q_{max}) and complying with the river abstraction rules during the 2017 low-flow period. In addition, an irrigation continues until reaching a target plot flood duration (D) for a plot area of 1 hectare. Crops that have not been irrigated over a long period of days (N) are considered as abandoned for irrigation and operations are not possible on them anymore. In addition, farmers start the campaign considering that their plots need to be irrigated (i.e. they have not been irrigated since K days).

5.2.5 Model configurations that we compared

Ferber (1995) has described three key components of interaction situations between agents: 1) the agents' objectives (concordant or contradictory, they are incompatible if the satisfaction of one leads to the dissatisfaction of the other), 2) the relation to the

TABLE 5.2: The affordances considered in the modeling approach and the associated actuator/passive object pairings. For each affordance, the generation conditions are presented.

Affordance	Actuator /passive object	Generation conditions
<i>legalFlood</i>	Irrigator / floodgate	Actuator availability No precipitation Actuator availability Restriction level < "alert" Passif object state ($Q \geq Q_{min}$)
<i>illegalFlood</i>	Irrigator / floodgate	Actuator availability No precipitation Actuator availability Restriction level \geq "alerte" Passif object state ($Q \geq Q_{min}$)
<i>askMoreWater</i>	Irrigator / floodgate	Actuator availability No precipitation Passif object state ($Q < Q_{min}$)
<i>doSomethingElse</i>	Irrigator / a passive object	Actuator availability

TABLE 5.3: Execution conditions, target duration and effect of the actions.

Action	Execution condition(s)	Target duration	Action effect
<i>legalFlood</i>	Passive object state ($Q \geq Q_{min}$)	4 hours/ha	$Q = Q - Q_{min}$
<i>illegalFlood</i> (restriction)	Passive object state ($Q \geq Q_{min}$)	4 hours/ha	$Q = Q - Q_{min}$
<i>askMoreWater</i>	None	1 hour	$Q = \min(Q_{max}, Q + Q_{runcg})$
<i>doSomethingElse</i>	None	1 hour	None

agents' resources (i.e. to all the environmental and material elements useful for carrying out an action, which may be sufficient or insufficient for all the agents) and 3) the skills of an agent to carry out a task (are they sufficient or do they require the help of other agents?). We simulated 2 model configurations in which farmer agents have compatible goals (i.e. applying their irrigation strategy), sufficient capacities and insufficient water resources. It is usually a case of overload situation (what Ferber called "*encombrement*" in French). In this kind of interaction situation, we consider that affordances traduce the impact of all agents in the options given to each agent.

According to field surveys, farmers have abandoned, over the past 15 years, the network coordination by daily slots, and can trigger irrigation without coordination during the 2017 irrigation campaign. Thus, only the temporal organization between farmers is

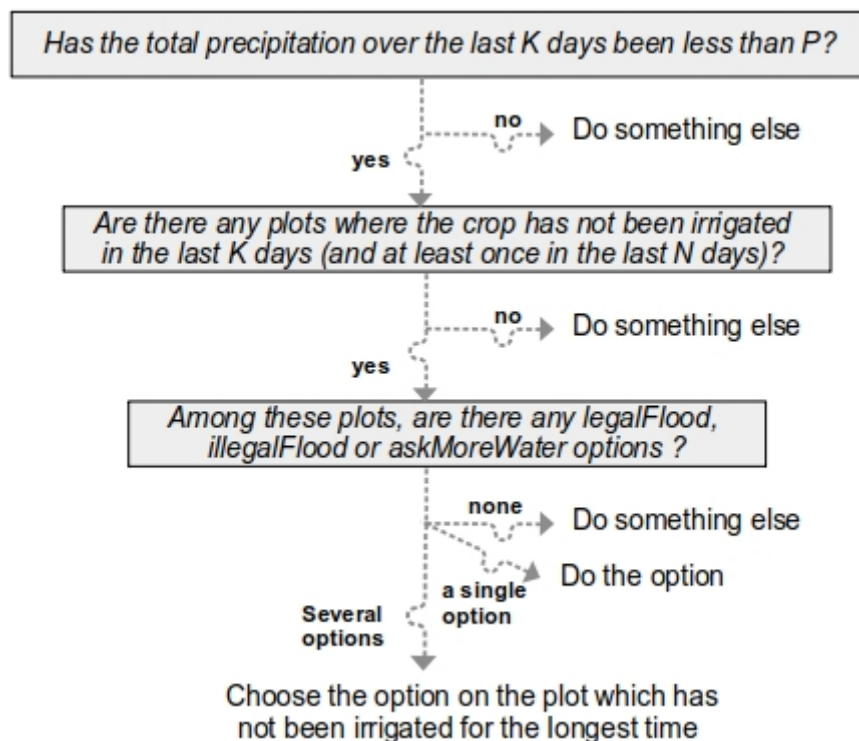


FIGURE 5.4: The operational strategy considered for the farmer agents. Typical values are $K=12$ days, $P=120$ mm and $N = 45$ days.

modified from one model configuration to another. We called “*DailySlots*” the configuration in which network flow is coordinated. *DailySlots* uses daily slots for each network branch, constraining temporally irrigation: the branches of the canal are watered according to 4 time slots (A, B, C and D, Table 5.4). These four time slots are due to the four water release points of the network (Figure 5.5). For each slot, water flows in only some branches of the gravity-fed network (e.g. branches 1 and 2 for slot A), and the different daily slots follow one after the other in a 10-day *DailySlots* (Table 5.4), which begins again with each new ten-day period. “*NoSlots*” is the configuration in which farmers don’t coordinate the irrigation network: the water flows simultaneously in all the branches of the canal during the irrigation campaign (Table 5.4). Farmers can trigger irrigation but the sharing of water is constrained by the network capacity that cannot distribute water everywhere at the same time. The simulation period covers the irrigation campaign from May 1st to September 30th of the year 2017.

TABLE 5.4: Daily slot network coordination of the *DailySlots* model configuration. The seven canal branches of the canal are denoted $b1$ to $b7$ (see Figure 5.5). Every 10 days, the period starts again at 0. Canal branches $b1$ and 5 are watered during the first three days of each 10-days period, then $b1$, $b2$, $b3$ and $b6$ are watering during the next three days, etc, until the end of the 10-days period, which starts again.

	Slot A	Slot B	Slot C	Slot D
Slot duration within the 10-days period	First three days	Next three days	Day 7	Last three days
Network branches which are watered during the slot	$b1+b5$	$b1+b2+b3+b6$	$b1+b2+b3+b7$	$b1+b2+b4$

5.2.6 Model outputs and verification

We consider two levels of model outputs that we represent in Table 5.5: agent trajectories (i.e. the final indicators) and agent option-sets (i.e. the intermediate indicators). Please note that an irrigation abandon only denotes the absence of irrigation operations on a plot during N consecutive days (see Figure 5.4). An abandon can be due to the difficulties to implement irrigation which are materialized by the absence of irrigation options (i.e. *legalFlood* or *illegalFlood* options), or the existence of *askMoreWater* options. An abandon can also occur if the irrigation strategy is fulfilled by precipitation forcing, as a rain-fed crop. In this case irrigation options exist. Also note that since farmers don't have the same number of irrigable plot, we consider for all trajectories the ratio of the number of options or plot characteristics divided by the total number of irrigable plots.

We verify some qualitative observations made during the field surveys to ensure that model outputs made sense. While we were unable to collect irrigation dates for all cereal plots, we observed that all plots located in the downstream area of the gravity-fed network were abandoned for irrigation during the 2017 campaign.

TABLE 5.5: Model output level, name and description. * Irrigable means the plot that can be supplied with water by the collective network. ** A crop is abandoned for irrigation if it has not been irrigated during N days consecutively.

Output level	Output name	Output description
Agent trajectories	Abandon ratio (AR)	Number of the farmer's irrigable* plots that were abandoned** for irrigation at the end of the simulated irrigation campaign divided by the total number of the farmer's irrigable plots.
	Irrigation ratio (IR)	Time series over the simulated irrigation campaign of the daily number of irrigated plots (i.e. with a <i>legalFlood</i> or <i>illegalFlood</i> action) of a farmer divided by the total number of his plots.
Agent option-set	Ask more water ratio ($AMWR$)	Time series over the simulated irrigation campaign of the daily number of plots with an <i>askMoreWaterOption</i> action of a farmer divided by the total number of his plots.
	Irrigation option ratio (IOR)	Time series over the simulated irrigation campaign of the daily number of plots with an irrigation possibility (i.e. with a <i>legalFlood</i> or <i>illegalFlood</i> affordance) of a farmer divided by the total number of his plots
	Ask more water option ratio ($AMWOR$)	Time series over the simulated irrigation campaign of the daily number of plots with an <i>askMoreWater</i> possibility of a farmer divided by the total number of his plots

5.3 Results

5.3.1 Tracing back at the collective level

In this section, we present the tracing back cause-effect relationships at the collective level (i.e. all farmers), by firstly observing the plots where irrigation was abandoned by the farmers (Section 5.3.1.1), and then looking for the changes in the irrigation trajectories and associated option-sets (Section 5.3.1.2) that can be linked to the abandons.

5.3.1.1 Abandons of irrigation

We distinguish farm plots located in the upstream part of the irrigation network (Figure 5.5 a, red contour line) from plots located downstream (blue contour line). In the *NoSlots* configuration, 23 irrigable plots were abandoned for irrigation during the simulated irrigation campaign, instead of 2 in the *DailySlots* configuration (Figure 5.5). All these abandoned plots are located in the downstream part of the irrigation network, making a strong dichotomy with the upstream part. This result is consistent with the observations made during field surveys: all downstream plots were abandoned for irrigation while farmers did not coordinate the irrigation network during the 2017 campaign.

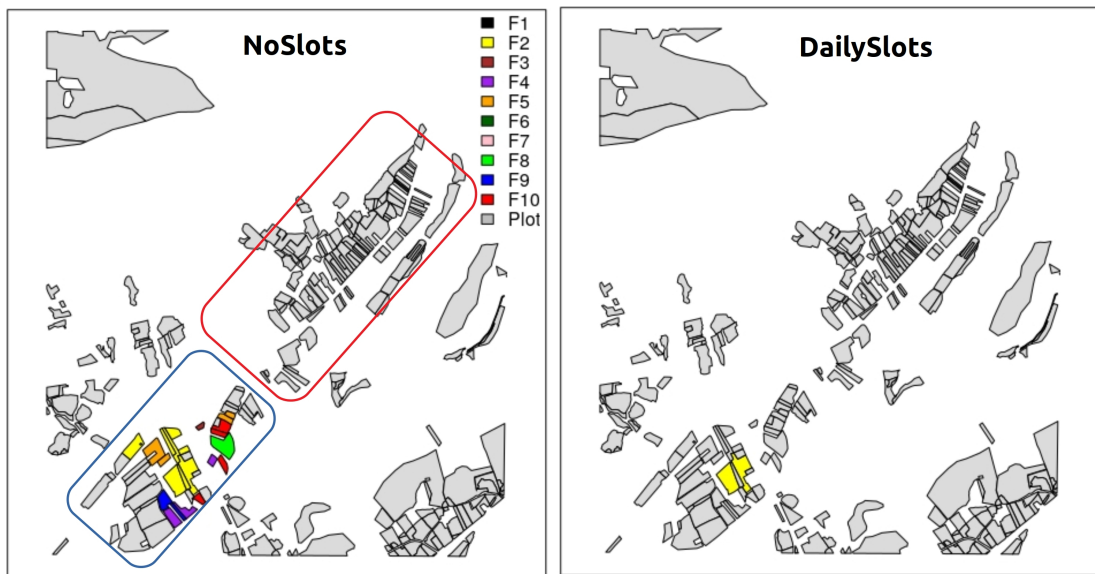


FIGURE 5.5: Abandoned plots for the *NoSlots* and *DailySlots* model configurations. F1 to F10 denotes Farmer 1 to Farmer 10. Red contour line delimits upstream plots, while blue one delimits downstream plots.

5.3.1.2 Irrigation trajectories and option-sets

Figure 5.6 shows, at the top, irrigation ratio (IR , see Table 5.5) of all irrigable plots over the simulated irrigation campaign. Not surprisingly, IR is better distributed over the simulated irrigation campaign when the network is coordinated (i.e. *DailySlots* configuration) than when it is not (i.e. *NoSlots* configuration). However, maximum IR is higher when the network is not coordinated with 49% instead of 39% when coordinated. At the bottom, Figure 5.6 distinguishes IR of upstream and downstream plots. For the

TABLE 5.6: Mean irrigation option ratio time-serie (*IOR*), ask more water option ratio time-serie (*AMWOR*) and abandon ratio at the en of the irrigation campaign (*AR*) for the *NoSlots* and *DailySlots* model configurations for all, upstream and downstream plots, respectively. * indicates the value is the average over the whole simulation period.

	IOR	AMWOR	AR
All plots			
<i>NoSlots</i>	33.06*	2.25*	29
<i>DailySlots</i>	13.89*	0.57*	2
Upstream plots			
<i>NoSlots</i>	46.40*	1.76*	0
<i>DailySlots</i>	15.69*	0.62*	0
Downstream plots			
<i>NoSlots</i>	0*	4.24*	100
<i>DailySlots</i>	10.39*	0.24*	9

upstream plots, *IR* globally follows the same dynamic as for all irrigable plots. This is not the case for the downstream plots, in which *IR* is null over the campaign when the network is not coordinated (*NoSlots*).

As abandons occurred before irrigation restriction came into effect, we focus on the following on *legalFlood* and *askMoreWater* farmers' options rather than on *illegalFlood* ones. In Table 5.7, we clearly observe that *IOR* is null for the downstream plots when the network is not coordinated (*NoSlots*), meaning that water was not flowing in the canal branches supplying these plots. *AMWOR* is also 18 times higher for the downstream plots when the network is not coordinated than when it is (*DailySlots*).

Collectively, irrigation abandons therefore all stem in the downstream part of the network where irrigation was not implemented. This is caused by the absence of irrigation options for these downstream plots due to an insufficiency of water at their floodgates when the network is not coordinated.

5.3.2 Tracing back at the individual level

In this section, we present the tracing back cause-effect relationships at the individual level. We first observe how a farmer is impacted by the change of model configuration in terms of irrigation abandons, and then we look for the changes in its irrigation trajectories and associated option-sets with visualization examples.

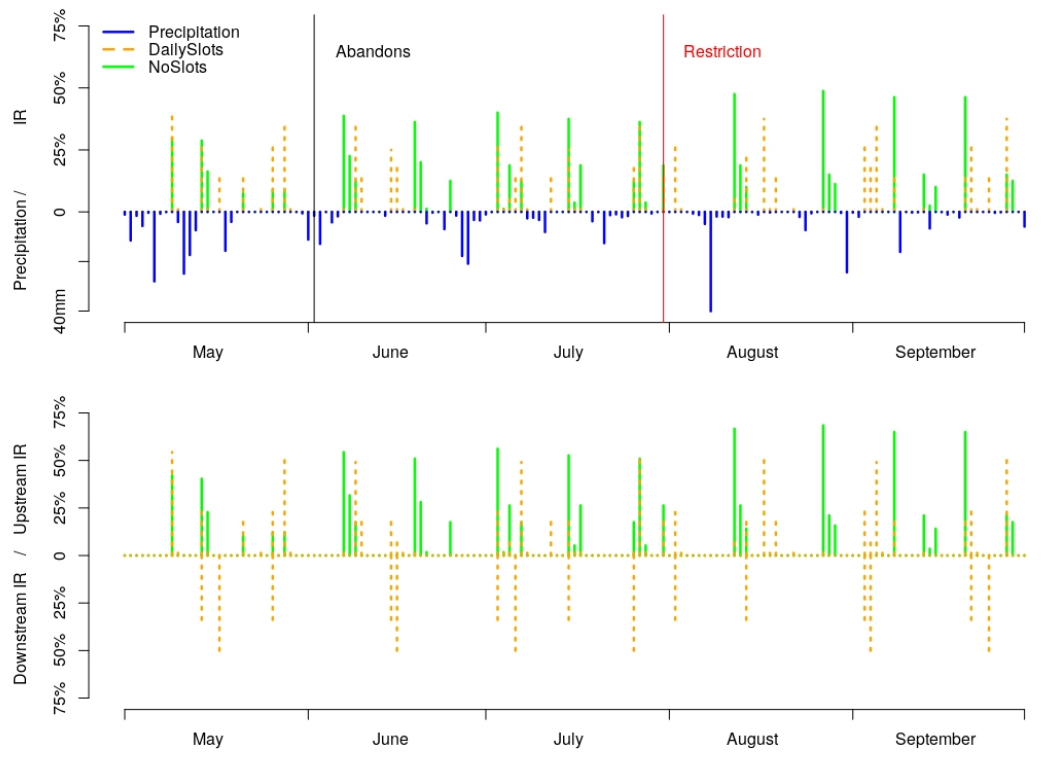


FIGURE 5.6: Top: IR (in percentage) and precipitation (in mm) time-series over the simulated irrigation campaign from May 1st to September 30th. Bottom: IR for the upstream plots (*upstream IR*) and downstream plots (*downstream IR*) over the irrigation campaign. The red bar denotes the beginning of the irrigation restriction period that restrict irrigation every Tuesday and Thursday.

5.3.2.1 Case of the most impacted farmer

Farmers are not equally impacted by the abandons of irrigation (Figure 5.7). Farmers 1, 6 and 7 are never impacted since they have no irrigable plots in the downstream part of the irrigation network. However, Farmer 4 has the more important change in AR , which is going from 0 when the network is coordinated (Figure 5.7, *DailySlots*) to 75% when it is not (*NoSlots*).

In Table 5.7, we focus on downstream plots of each farmer because they are the ones concerned by the irrigation abandons: farmer 4 has a null downstream mean IOR when the network is not coordinated (*NoSlots*). In Figure 5.8 (top), the irrigation options appear to be generated more frequently in the absence of network coordination. However, a look at the irrigation actions shows that irrigation only concern the plot 1 located upstream of the irrigation network (Figure 5.8, bottom). The change in model configuration therefore leads to a lack of water in 3 of its 4 irrigable plots when the network is

TABLE 5.7: *IOR*, *AMWOR* and *AR* of the downstream plots for the *NoSlots* and *DailySlots* model configurations. NA is reported when farmers don't have any downstream plots. * indicates the value is the average over the whole simulation period.

Farmer id	Model configuration	IOR	AMWOR	AR
1	<i>NoSlots</i>	NA	NA	NA
	<i>DailySlots</i>	NA	NA	NA
2	<i>NoSlots</i>	0*	0.98*	40
	<i>DailySlots</i>	3.10*	0.08*	15
3	<i>NoSlots</i>	0*	9.15*	50
	<i>DailySlots</i>	16.34*	0*	0
4	<i>NoSlots</i>	0*	3.05*	75
	<i>DailySlots</i>	8.50*	0*	0
5	<i>NoSlots</i>	0*	2.29*	57
	<i>DailySlots</i>	10.45*	1.31*	0
6	<i>NoSlots</i>	NA	NA	NA
	<i>DailySlots</i>	NA	NA	NA
7	<i>NoSlots</i>	NA	NA	NA
	<i>DailySlots</i>	NA	NA	NA
8	<i>NoSlots</i>	0*	7.84*	10
	<i>DailySlots</i>	16.34*	0*	0
9	<i>NoSlots</i>	0*	4.25*	33
	<i>DailySlots</i>	4.57*	0.33*	0
10	<i>NoSlots</i>	0*	2.12*	36
	<i>DailySlots</i>	13.40*	0*	0

not coordinated (*NoSlots*). Water circulates in the branches of the network serving the downstream plots, but insufficiently to trigger irrigation, as these plots are occupied by a *askMoreWater* option (Figure 5.8 bottom, *NoSlots*).

5.3.2.2 Case of the farmer impacted in the DailySlots model configuration

Farmer 2 is the only one with irrigation abandons when the network is coordinated. This farmer is thus impacted in both *NoSlots* and *DailySlots* model configurations.

We can see in Table 5.7 that farmer 2 has the lower downstream mean *IOR* among farmers when the network is coordinated (*DailySlots*). This configuration leads to a lack of water in 3 of its 20 irrigable plots. When water circulates in a network branch, the water level is always sufficient to trigger irrigation, otherwise we would observe an *askMoreWater* option (Figure 5.9 bottom). As irrigation options are driven by the temporal slots, the key difficulty to trigger irrigation concerns the plots with a single day slot

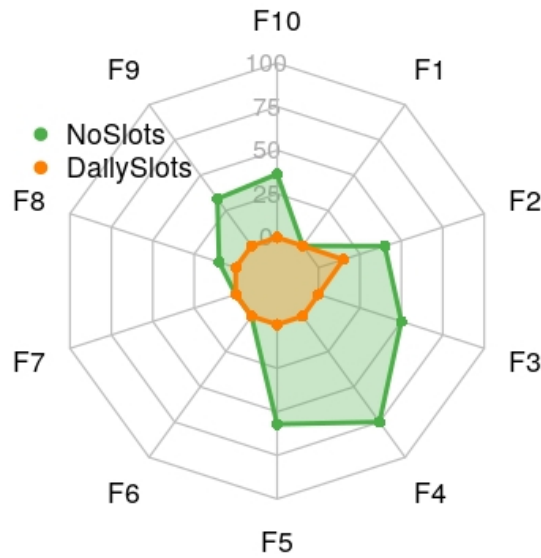


FIGURE 5.7: Radar chart of irrigation abandon ratio in the two model configurations *NoSlot* and *DailySlots*. F1 to F10 denotes Farmer 1 to Farmer 10.

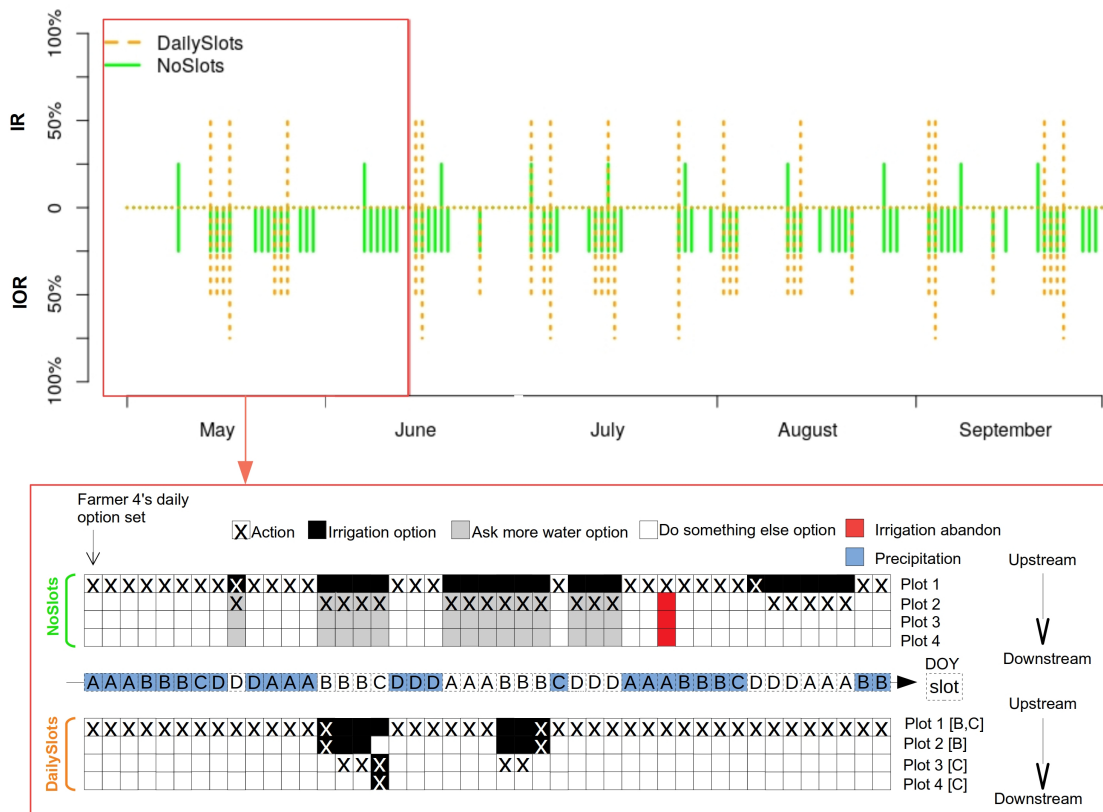


FIGURE 5.8: Top: *IR* (in percentage) and *IOR* (in percentage) time-series for farmer 4 over the simulated irrigation campaign from May 1st to September 30th. Bottom: visualization of farmer 4's daily option-set in both *NoSlot* and *DailySlots* model configurations, from May 1st to June 14th.

(slot C). These plots are clearly too numerous to be all irrigated during this time slot. Indeed, when farmer 2 gets several irrigation options during the same day, it irrigates as much as possible within the limit of its maximum daily working time, and according to the time required for each plot (which depends on its size).

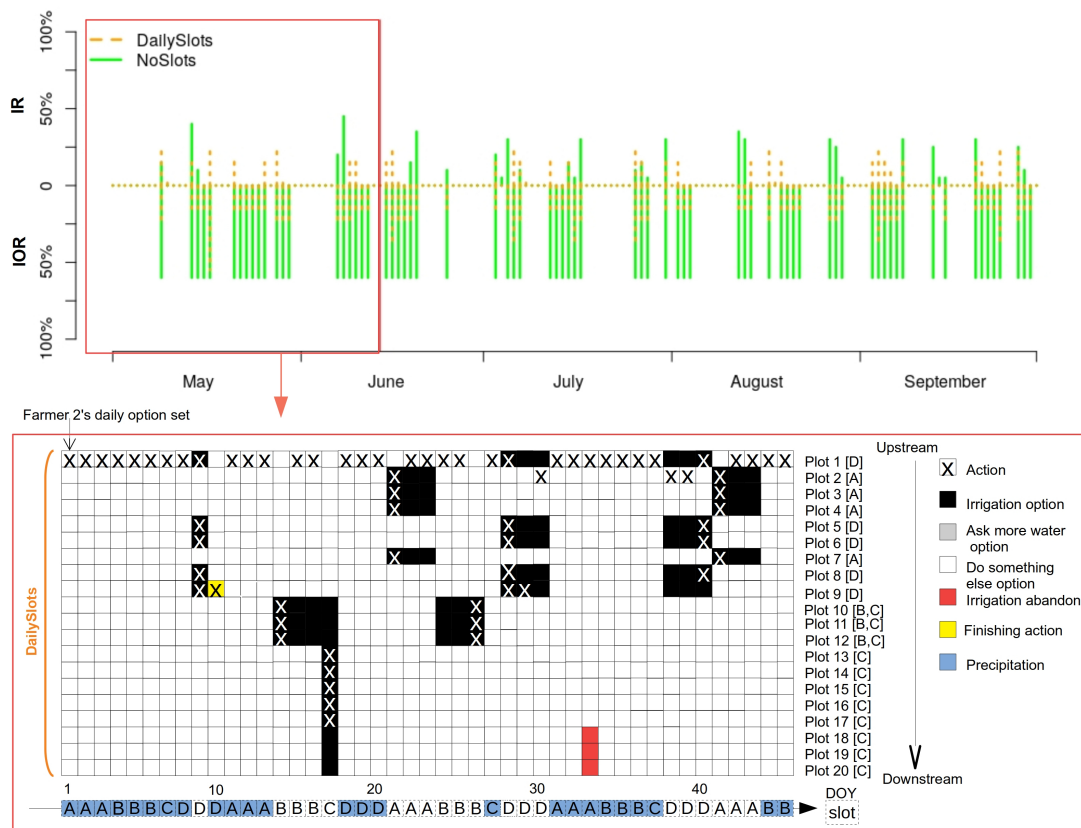


FIGURE 5.9: Top: IR (in percentage) and IOR (in percentage) time-series for farmer 2 over the simulated irrigation campaign from May 1st to September 30th. Bottom: visualization of farmer 2's daily option-set for the *DailySlots* model configuration, from May 1st to June 14th.

5.3.3 Sensibility of model outputs to key forcing and parameters

In this section, first, we assessed AR and IOR sensitivity to precipitation forcing. We made 12 simulations over the simulated irrigation campaign, by only changing the precipitation forcing from one simulation to another (years 2005 to 2017). We repeated these simulations for the two model configurations *NoSlots* and *DailySlots*. Second, we performed a one-at-a-time exploration to assess the influence of key model parameters (i.e. network intake flow, daily time window and daily slot period) by changing the

TABLE 5.8: *AR* and mean *IOR* range resulting from 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	Value range	Mean IOR range (%)	AR range (%)
Precipitation (year)			
<i>NoSlots</i>	[2005-2017]	[19.62-36.32]	[28.7-46.2]
<i>DailySlots</i>		[5.55-14.39]	[0-58.7]
Daily time window (hours)			
<i>NoSlots</i>	[6-24]	[31.67-33.06]	[28.7-32.5]
<i>DailySlots</i>		[13.42-13.89]	[3.7-13.7]
Network intake flow (m^3s^{-1})			
<i>NoSlots</i>	[0.05-0.35]	[0-46.4]	[0-100]
<i>DailySlots</i>		[11.4-13.89]	[3.7-31.2]
DailySlots period (days)			
<i>DailySlots</i>	[8-12]	[13.89-15.37]	[0-13.7]

values of each parameter one at a time and letting the others to their nominal value: number of rainy days is 82 (year 2017), initial intake flow is $0.09 \text{ m}^3\text{s}^{-1}$, and daily time window is 12 hours. We also repeated simulations for the two model configurations *NoSlots* and *DailySlots*. Only the *DailySlots* configuration could be considered for the daily slot period parameter, as the *NoSlots* configuration is not concerned. Table 5.8 sums up forcing or parameter value range and resulting mean *IOR* and *AR* range.

Figure 5.10 shows scatter plots with *AR* (left-side) and *IOR* (right-side) for the y-axis. At the top line, x-axis is the number of rainy days from May to September. Each point represents a simulation for years 2005 to 2017, and for the *DailySlots* (green line) and *NoSlots* (orange line) model configurations.

AR appears not sensitive to precipitation when the network is not coordinated (Figure 5.10 top, orange line). However, *IOR* decreases when the number of rainy days increases (Figure 5.10 bottom, orange line), as in the model raining prevents to generate irrigation options. This is because precipitation constrains the possibilities of irrigation on the upstream plots, but don't influence the downstream plots where irrigation is not possible anyway due to insufficient water in the network (see Section 5.3.1). Comparing the two model configurations, the configuration when the network is coordinated therefore appears to be more interesting with smaller *AR* than when not coordinated up to a

certain precipitation threshold, which is about 98 mm in our simulations (Figure 5.10, top).

However, when the network is coordinated, *AR* appears sensitive to precipitation and increases when *IOR* decreases. This is because precipitation constrains irrigation possibilities and reduces the need to irrigate (see Figure 5.4). Indeed, in this configuration, irrigation possibilities are not limited by insufficient water in the network, but by the time slots (see Section 5.3.2), which are even more reduced by the presence of precipitation. But, in the model, irrigation abandons is triggered based on a number of consecutive days without irrigation. While the fact that irrigators do not irrigate when it rains is not surprising, they would not abandon irrigation in the reality on plots that have not been irrigated for a long time. It is a bias of the *AR* final indicator for years of simulation with many rainy days. This is not the case of year 2017 used as reference in our study. Indeed, this is the second least-rainy year after 2015 over 2005-2017 in terms of the number of rainy days on the study area, with 82 rainy days from May to September against 94 days over the period 2005-2017. *AR* outputs are thus less biased than for the year 2017 than for years with many rainy days such as 2013 or 2014 for example (see Figure 5.10).

Moreover, *AR* is sensitive to the flow at the intake when the network is not coordinated (Figure 5.10 middle, left-side, orange line), with no irrigation abandons when flow exceeds $0.35 \text{ m}^3 \text{ s}^{-1}$. This is because the increase in network flow leads to an increase in *IOR* (Figure 5.10 middle, right-side, orange line), notably for the downstream plots. When the network is coordinated, *AR* is slightly sensitive to the intake flow (Figure 5.10 left-side, green line) as *IOR* is not strongly correlated with the network flow in this configuration (Figure 5.10 middle, right-side, green line). Comparing the two model configurations, the lower the flow at the water intake, the more interesting is the configuration in which the network is coordinated to reduce AR.

If we now have a look at the influence of the other parameters, the longer the duration of the time window (i.e. the duration the farmers can act each day) the smaller *AR*, in particular when the network is coordinated (Figure 5.10, green line). Longer daily

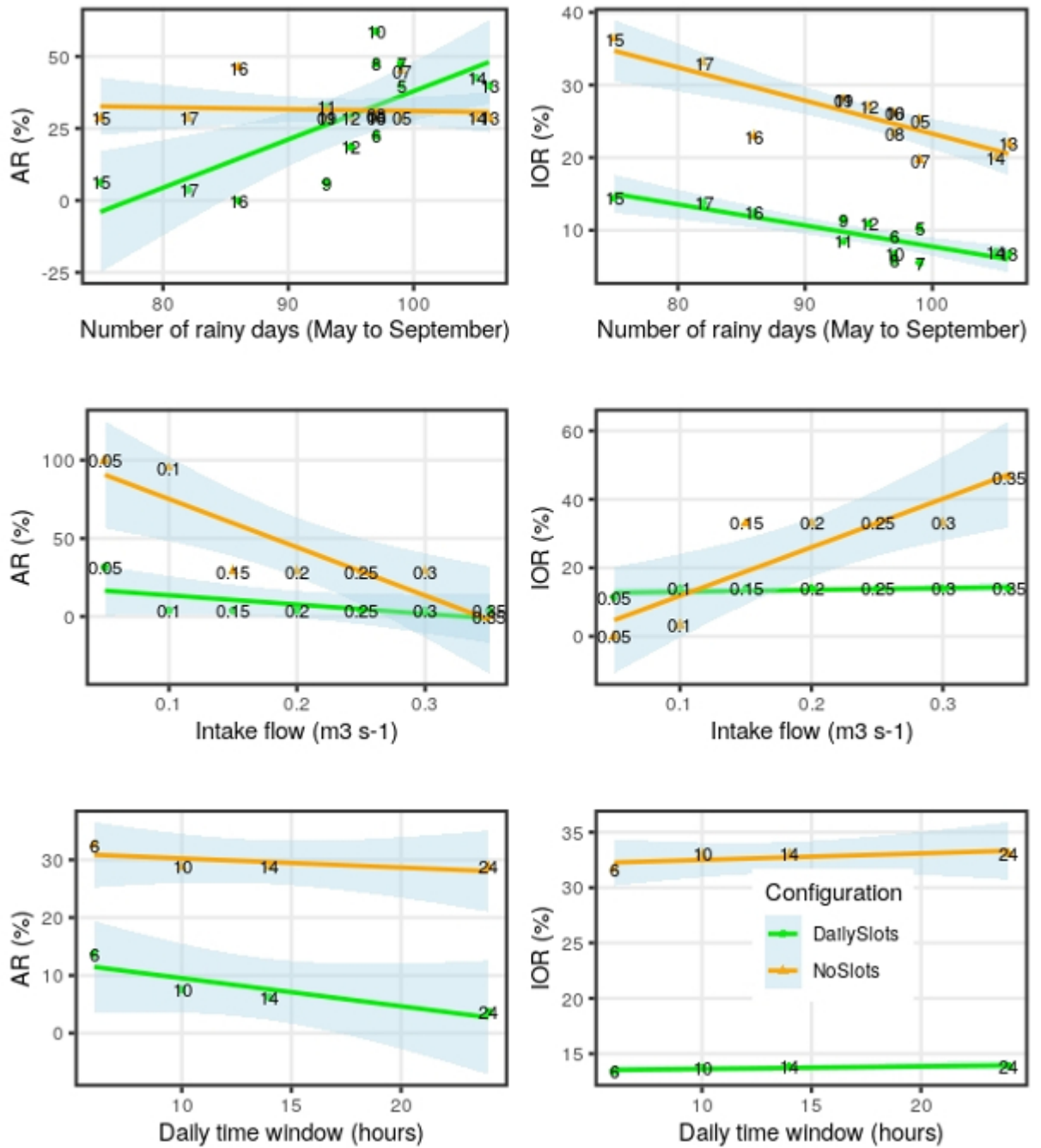


FIGURE 5.10: Scatter plots with *AR* (left-side) and *IOR* (right-side) for the y-axis, and the forcing or parameter values in x-axis. Each point represent a simulation, for the *DailySlots* (green line) and *NoSlots* (orange line) model configurations.

time window facilitates the exploitation of irrigation slots by farmer agents. Considering the *DailySlots* period parameter (Table 5.8), a period of 8 consecutive days has been assessed, organized as follow: the two first day for Slot A (i.e. network branches b1+b5 are watered, see Table 5.4), the next two days for Slot B, day 5 for Slot C, and the last 3 days for Slot C. This coordination allows more frequent irrigation of plots during slot C, which leads to no irrigation abandons at the end of the simulated irrigation campaign.

5.4 Discussion

5.4.1 Potentials of the Affordance concept to help interpret ABM outputs

Agent option-sets provided an intermediate level of information for interpreting agent trajectories and associated final indicators. In particular, it helps identify the link between agent trajectories and model configuration. At the collective level, for example, the absence of *legalFlood* options and the high ratio of *askMoreWater* options relate to an insufficiency of water in the downstream branches that causes a higher *AR* value in the *NoSlot* model configuration (see Section 5.3.1.1). At the individual level, the options of the farmer agents inform on the different nature of their abandons in each of the two model configurations, and for each farmer situation. The case of farmer 4 (see Section 5.3.2.1) illustrates the impossibility to trigger irrigation in the downstream plots. In the *NoSlot* model configuration, the farmer agent with the highest *AR* indicator is thus the one having the most downstream plots. But the case of farmer 2 (see Section 5.3.2.2) which has abandons in both model configurations, shows that, in the *DailySlots* model configuration, the *AR* indicator is not related to a lack of irrigation options in the downstream plots. In this model configuration, *AR* of farmer 2 is due to an overload of work in a very short period of time, as in particular 11 plots can only be irrigated during the same daily slot (Figure 5.9).

The location of the options also points out that the spatial constraint appear prominent in the *NoSlot* model configuration, for which irrigation possibilities are only located in

the upstream plots. Indeed, this configuration is very sensitive to the intake flow parameter (see Section 5.3.3) that controls the network water availability, in particular to the downstream plots. With low-flow entering in the network, this model configuration thus leads to a typical overload situation described by [Ferber \(1995\)](#). Farmer agents have compatible goals, sufficient capacities and insufficient water resources for supplying the whole spatial area. The overload then comes from the collective behavior of the farmers: it will be maximal if all the farmers irrigate at the same time.

The distribution over time of the options provides complementary elements of interpretation. Not surprisingly, the temporal constraint appears stronger than the spatial constraint when the network is coordinated, with irrigation options dictated by the irrigation time slots. Indeed the *DailySlots* model configuration is sensitive to the daily slot period parameter that controls the generation of affordance according to irrigation slots, and the daily time window parameter, allowing farmer agents to exploit more or less these irrigation slots (see Section 5.3.3). The *DailySlots* model configuration is also sensitive to the precipitation forcing when the network is not coordinated, as precipitation constrain the generation of irrigation option on the rainy days. This model configuration thus leads to a situation where the irrigation options are voluntarily reduced to limit the overload, with the water resource available intermittently. Irrigation is no longer dictated primarily by the behavior of other farmers, but by the needs of the farmer himself. Irrigation abandon will then concern farmers with a large number of plots to be flooded during the same irrigation time slot.

Agent option-sets can also be integrated into sensitivity analysis, which remains a major challenge in ABM output analysis ([Lee et al., 2015](#)). In contrast to visualizing options at the individual level, joint sensitivity analysis of final and intermediate indicators can be easily systematized to large populations of agents using time series directly representative of a type of option, such as *IOR*. It helps detect some threshold effects of the model: to a certain precipitation threshold, the *DailySlots* configuration appears to be more interesting to reduce the number of irrigation abandons than the *NoSlots* configuration which is not linked to *IOR* (see Section 5.3.3).

5.4.2 Limitations and outlook

Analyzing the sensibility of the option-set of the agents is also useful to help reveal biased indicators, as *AR* for the *DailySlots* configuration due to a decrease in irrigation possibilities in years with many rainy days. This is not the case of year 2017 used as the reference in our study (results of Sections 5.3.1 and 5.3.2 are based on this year), as we choose it to be representative of less frequent precipitation. *AR* outputs are thus less biased than for years with many rainy days such as 2013 or 2014 (see Figure 5.10). But rather than using this indicator, it would be better to directly simulate the consequences of the agent trajectories and irrigation operations into agronomic impacts for plants, which would allow better assessment of their biophysical consequences. A good candidate could be the *Water Stress Index* (*WSI*) which controls crop growth and results from both irrigation and precipitation (Jones, 1992).

Visualizing the option-set of the agents also helps to take a step back on what the model does and how agents are represented in it. For example, the case of farmer 4 reports that our agents appear limited in terms of anticipation by repeating the same actions several times in a row in the *NoSlot* configuration (see Section 5.3.2.1). The farmer first irrigated the well-supplied plot with water (Figure 5.8 bottom, *NoSlots*). He then asked for more water on one of the under-supplied plots, before deciding to abandon them to irrigate the well-supplied plot again. This is one of the consequences of the irrigation strategy considered in the model that makes farmer agent 4 focus on plot 2 with insufficient water supply in the *NoSlot* model configuration. Better anticipation on the part of farmer 4 could result in him trying to irrigate plot 1 instead of continuing to request more water on plot 2. The case of farmer 2 shows that margins of anticipation appear small in the *DailySlots* configuration (see Section 5.3.2.2). Indeed, during the second irrigation of plots 10, 11 and 12, the farmer agent 2 waits until the end of the three days on which he has a possibility to irrigate (Figure 5.9 bottom). This is because his irrigation strategy considers 12 days before a plot needs to be irrigated again. With a more flexible strategy, he could have irrigated one or two days before, but no more.

The lack of anticipation by the agents is not surprising as the Affordance concept, as mobilized in our model, is not a substitute for decision-making and cognitive capacities of

the agents. Indeed, the Affordance concept refers to the interdisciplinary debate of socio-ecological feedbacks mediated by the environmental cognition, that is, the perception, interpretation, evaluation of environmental change, and decision-making, as reviewed by [Meyfroidt \(2012\)](#). Our mobilization of the concept inherits from the Gibson's ecological approach in which actor's perception of his possible actions is direct, meaning the capture of information during the action to adapt to its environment ([Luyat and Regia-Corte, 2009](#)). We focused on some limited operations, and some of their modalities that we have observed in the field. Decision-making was not the object of the study, and was limited to a basic set of rules. Agent trajectories are thus mainly based on a perception-action loop, in line with [Afoutni \(2015\)](#) and [Guerrin et al. \(2016\)](#), without calling for complex decision algorithms. However, human agents actively re-evaluate their beliefs, values, and functioning ([Filatova et al., 2013](#)). An important follow-up of this work is therefore to extend the approach to a triple perception-cognition-action loop, using for instance elaborated *Belief-Desire-Intention (BDI)* algorithms, as done for operational decision-making by [Martin-Clouaire \(2017\)](#). It might take advantage of the direct perception of the environment allowing by the Affordance concept to nourish the beliefs of the agents.

The approach has been illustrated in a specific case study. The conceptual structure of the WatASit ABM is designed to be as generic as possible for the representation of collective irrigation networks, but required several modifications to be applied to another irrigation network. This would lead to initialize the new spatial entities (i.e. farm plots part of the collective network and of each farm), for example from GIS data that are now easily available. It could also require creating new types of operational entities such as other passive objects (e.g. other pieces of equipment) or actuators (e.g. multiple irrigators per farm), and new types of affordances and actions. For instance, inter-related operations between crop harvesting and irrigation can impact farmer capacity to operate irrigation ([Merot et al., 2008](#)). They could be considered by adding a *harvestCrop* affordance in the model. It means that detailed information is necessary to set up the affordance parameters, which could limit the spatial scale. In addition, a network hydraulic sub-model may have to be developed to represent the local functioning of the network.

5.5 Conclusions

In this paper, we explored how changes in agent trajectories can be linked to changes in the option-set of the agents. We proposed mobilizing the concept of Affordance to make explicit the operational option-set of each agent at each daily time step. We applied the WatASit model based on this concept to a typical gravity-fed network of Southern France under two model configurations (i.e. network coordination or not), and over a collective irrigation campaign from May to September, with year 2017 as reference. Agent option-sets provided an intermediate level of information for interpreting agent trajectories in each model configuration. At the collective level, the absence of irrigation options relates to an insufficiency of water in the downstream branches of the network that causes irrigation abandons in the model configuration in which the network is not coordinated. At the individual level, the options of the farmer agents inform on the different nature of their irrigation abandons in each of the two model configurations, and for each farmer situation. The model configuration in which the network is not coordinated leads to an overload situation due to the collective behavior of the farmers: overload is maximal if all the farmers irrigate at the same time. However, the model configuration in which the network is coordinated leads to a different situation. Irrigation is no longer dictated primarily by the behavior of other farmers, but by the number of plots of a farmer to be flooded during the same irrigation time slot. As part of sensitivity analysis, agent option-sets help interpret the threshold effects of model forcing or parameters. Irrigation options are more sensitive to the number of rainy days when the network is coordinated, making this model configuration more interesting to reduce the irrigation abandons up to a certain number of rainy days. Visualizing the option-set of the agents is also useful to take a step back on what the model does and how agents are represented in it. In WatASit, agents are not surprisingly limited in terms of anticipation as the Affordance concept was mobilized to clarify agent possibilities of actions they directly perceive in their environment, and not as a substitute for agent decision-making.

5.6 Acknowledgments

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Part III

Coupling with agro-hydrological models

Abstract of Part 3

The second part of the thesis focused on the modeling of short-term interactions at the scale of a collective irrigation network, without simulating the biophysical processes such as plant growth and hydrology.

In the following chapter, we proposed the COPAT framework to address the management of irrigation when it depends on a collective water network, and the potential impacts on crop water stress due to the network operational constraints under coordination scenarios. COPAT relies on the coupling of a crop model at the plot level with an ABM at the network level.

To make communicate these two models during the course of the simulation, we had to derive the crop model into a daily function, which made it possible to run it as a slave model of the ABM, and thus to give daily irrigation orders at the plot level according to the collective sharing of water in the ABM. We illustrated the framework on the Aspres-Sur-Buëch case study on which COPAT allowed considering the network specific constraints and comparing two coordination scenarios.

Simulation results suggest the importance of tackling the network level as plant water stress could be underestimated when simulated at the plot level because specific network constraints are missed. In particular, earlier average plant water stress and maximum stress severity when irrigation is not coordinated, while network coordination tends to limit the impact, notably for the plots located in the most downstream part of the network. COPAT also provides access to a tactical assessment of the spatial variability of plant water stress occurring during a collective irrigation campaign.

In the next chapter, we investigated a coupling methodology to locally consider the mutual influences between natural water resources and collective irrigation at the operational level. We proposed four daily coupling stages allowing to take into account the hydrological constraint at the network intake in WatASit, and to incorporate water from irrigation into the hydrological units and river reaches of the hydrological model.

The key was the derivation of the hydrological model into a daily version to force the hydrological model on a daily basis while keeping the distributed spatial routing from the upstream hydrological units to the units or river reaches downstream of the basin.

We had to make the farm plots spatially consistent with the hydrological units to keep homogeneous their hydrological processes. Modifying spatially the hydrological model was not easy because it refers to a set of physical processes whose meaning are linked to their explicit spatial representation. By deriving farm plots as hydrological units of the hydrological model, we assumed that irrigation processes on farm plots have topological connections with the original hydrological units.

However, this derivation could have impacted the vertical flow processes of the hydrological units, in particular the computation of the base-flow. An important follow-up of this work is therefore to test the impact of the coupling methodology on the water balance components of the catchment. For future research, the representation of the river reaches at the catchment scale in the ABM opens up possibilities for assessing the impact of several collective irrigation networks on natural hydrology at the operational level.

Chapter 6

COPAT: coupling plant and agent trajectories

Contribution to the thesis project: In the previous part of the thesis, we have investigated the use of the Affordance concept in ABM to represent short term interactions between irrigators and the water network due to their operational possibilities. The representation of the biophysical components of the system, in particular the plants and the water resources, was limited as plant growth and hydrological processes were not simulated. In this chapter we focus on the coupling with a crop model to better represent plant dynamics interacting with the irrigator operations. The key point of this chapter is that the coupling of a crop model at the plot level with an ABM at the network level allow accounting for specific operational constraints at the network level when simulating irrigation on each plot. This chapter reproduces a paper ([Richard et al., 2020b](#)) which has been submitted to *Agricultural Water Management*. This work has also been presented in the 10th International Congress on Environmental Modelling and Softwares (iEMSs) on September 14, 2020.

A framework for coupling plant and agent trajectories (COPAT) to support collective irrigation coordination

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Abstract Crop models provide optimal irrigation strategies at the plot level. However, in many places irrigation is managed collectively in order to coordinate water supply at the network level with potential feedback on plant dynamics. To capture these feedbacks during a collective irrigation campaign, we proposed the COPAT framework for coupling a crop model (Optirrig) at the plot level with an agent-based model (WATASit) at the network level. The key was the derivation of the crop model into a daily function. It made it possible to give daily irrigation orders on each plot and to recover their agro-hydrological variables (i.e. *LAI*, *WSI*). Applied on an illustrative case study in Southern France, COPAT allowed considering the network operational constraints to capture feedbacks on plant water stress by comparing coordination scenarios. Simulation results suggest the importance of considering the network level as plant water stress could be underestimated when simulated at the plot level because specific network constraints are missed. In particular, the absence of network coordination can lead to earlier plant water stress during the irrigation campaign than when simulated at the plot level, while network coordination tends to limit the impact. COPAT also provides access to a tactical assessment of the spatial variability of plant water stress, as the most severe water stress was observed for the crops located furthest downstream of the network in the absence of coordination. The contribution of the framework also lies in an explicit representation of irrigation operations allowing tracing-back, for instance, the missed irrigations due to insufficient network flow. For future research, validating quantitatively the model output could be done by directly collecting observations of irrigation on each plot, or by comparing with *LAI* retrieved from remote sensing techniques.

Keywords model coupling ; irrigation coordination ; crop model ; agent-based model ; water stress ; WSI.

Résumé en français Les modèles de culture fournissent des stratégies d'irrigation optimales au niveau de la parcelle. Toutefois, dans de nombreux endroits, l'irrigation est gérée collectivement afin de coordonner l'approvisionnement en eau au niveau du réseau avec des rétroactions potentielles sur la dynamique des plantes. Pour saisir ces rétroactions lors d'une campagne d'irrigation collective, nous avons proposé le cadre COPAT pour coupler un modèle de culture (Optirrig) au niveau de la parcelle avec un modèle à base d'agents (WatASit) au niveau du réseau. La clé était la dérivation du modèle de culture en une fonction quotidienne. Elle a permis de donner des ordres d'irrigation quotidiens sur chaque parcelle et de récupérer leurs variables agro-hydrologiques (c'est-à-dire *LAI*, *WSI*). Appliqué à un cas d'étude illustratif dans le sud de la France, COPAT a permis de prendre en compte les contraintes opérationnelles du réseau pour capter les rétroactions sur le stress hydrique des plantes en comparant des scénarios de coordination. Les résultats de la simulation suggèrent que le stress hydrique des plantes pourrait être sous-estimé lorsqu'il est simulé au niveau de la parcelle du fait que des contraintes spécifiques au réseau d'irrigation soient omises. En particulier, l'absence de coordination du réseau peut entraîner un stress hydrique des plantes plus précoce au cours de la campagne d'irrigation que lorsqu'il est simulé au niveau de la parcelle, alors que la coordination du réseau tend à limiter l'impact. COPAT donne également accès à une évaluation tactique de la variabilité spatiale du stress hydrique des plantes: le stress hydrique le plus grave a été observé pour les cultures situées le plus en aval du réseau en l'absence de coordination. L'apport du cadre COPAT réside également dans une représentation explicite des opérations d'irrigation permettant de retracer, par exemple, les irrigations manquées en raison d'un débit insuffisant au niveau de la parcelle desservie par le réseau. Pour les recherches futures, la validation quantitative des résultats du modèle pourrait être faite en collectant directement les observations de l'irrigation sur chaque parcelle, ou en les comparant avec des données de *LAI* récupérées par télédétection par exemple.

Mots clefs couplage de modèles ; coordination de l'irrigation ; modèle de culture ; modèle à base d'agents ; stress hydrique ; WSI.

6.1 Introduction

Crop models simulate crop growth and agricultural yields according to the climate-soil-plant interactions. Therefore, they are useful to evaluate or optimize irrigation management scenarios at the plot level. In recent years, several simulation platforms have been developed firstly to facilitate the automation of crop models, but also to better take into account context-dependent constraints at other levels than the plot level.

Scholars have explored various ways for associating agent-based models (ABMs) with crop models for two decades, leading to modeling and simulation environments embedding biophysical, economics or socioeconomic components (Belcher et al., 2004, Berntsen et al., 2003). Aquacrop (Raes et al., 2009, Steduto et al., 2009) was combined with an economic model (García-Vila and Fereres, 2012). STICS (Brisson et al., 2003) was implemented in the RECORD platform to represent farming practices into agro-ecosystems. APSIM (Keating et al., 2003, McCown et al., 1995) or DSSAT (Jones et al., 2003) have been embedded in the (HarvestChoice, 2010) platform to nourish regional-scale decision-making. WOFOS (Reidsma et al., 2009, Supit et al., 2012, Wolf and van Diepen, 1995) has been reformulated into the modular Python Crop Simulation Development programming structure (de Wit, 2015). Gaudou et al. (2014) have integrated AqYield (Constantin et al., 2015, Murgue et al., 2016, Nolot and Debaeke, 2003) into the MAELIA multi-agent platform.

Several studies have shown the usefulness of coupling cellular components representing a landscape with an agent-based simulator at the household or farmer level with behaviors that alter the landscape (Berger et al., 2006, Parker et al., 2003, Verburg et al., 2004). Such approaches enable to assess the environmental, economic and social impacts of the combined changes in agricultural activities (demography, dynamics of land cover and climate). Thanks to these platforms, organizational constraints of irrigation, such as cropping system, access to water, irrigation inputs cost and availability, have been assessed in terms of their impact on irrigation water use efficiency or productivity ("more crop per drop").

However, irrigation management also depends on strong operational drivers ([Aurbacher et al., 2013](#), [Martin-Clouaire and Rellier, 2009](#), [Merot et al., 2008](#)). For example, [Merot et al. \(2008\)](#) have shown the importance of water distribution constraints or hay-mowing and irrigation inter-related operations to ensure irrigation efficiency in the Crau plain (France). Indeed, once the strategic choices have been made (i.e. crop choice and rotation, irrigation targets for the season), the farmer has to make operational choices: site management on the short term, including an as adaptable as possible resources management strategy, with special emphasis on irrigation and fertilization decisions ([Sebillote and Soler, 1990](#)). Operational management thus highlights inequalities among farmers regarding their structural irrigation constraints ([Richard et al., 2020a](#)).

At the level of the irrigated scheme, the operational constraints include, for example, the variation of flow rate and water availability along the upstream-downstream gradient in the abduction network, according to its withdrawals, seepage and hydraulic limitations. During the irrigation campaign, the possibilities for operational adjustment of irrigators' calendar are thus limited by these constraints and by the behavior of other irrigators influencing the network flow rate. In such context, irrigation coordination is a key factor for sharing the capacity of a common network distributing water in place and time to all the plots during an irrigation campaign. A simulation framework allowing to capture potential feedback of such coordination strategies and associated irrigation constraints at the network level on crop dynamics is missing.

Integrated simulation frameworks that merge models into a unified software package (e.g. [Gaudou et al., 2014](#), [Matthews, 2006](#), [Schreinemachers et al., 2007](#)) are useful to capture the complex human-environment interactions, and shed light on the understanding of the system dynamics with potential entry-points for policy design ([Dragan et al., 2003](#)). However, model simplifications commonly occur when merging modules, especially of environmental processes (e.g. [Schreinemachers et al., 2007, 2010](#)), altering the model's ability to fully capture interactions. A more flexible method, also used by scholars in farming and environmental modeling (e.g. [Bithell and Brasington, 2009](#), [Bulatewicz et al., 2010](#), [Warner et al., 2008](#)), is therefore to couple simulation softwares together rather than integrating individual components in a single modeling and simulation software. The main advantage is that there is no need of recording components and

consequently the users and developers community of each model components may be asked to help with the coupled model (control code, provide and test new modules, ...). However, it involves conceptual and programming developments to ensure compatibility of many characteristics including basic assumptions, spatial and time scales. First it requires making sure that models components and associated softwares have communication features and manage disruption correctly. Last but not least, it requires a clear conceptual and operational framework to organize scheduling between the models and between the simulation softwares.

The objective of this paper is to describe the COupling Plants and Agents Trajectories (COPAT) framework to capture potential feedback of network coordination strategies, and associated specific network constraints, on crop water stress. Thanks to COPAT, we coupled two models, and their software packages, simulating crop growth and crop water stress (Optirrig) at the plot level, and collective irrigation operations (WatASit) at the network level. A case study in France illustrates the added-value of the framework.

In the next section, we present the Optirrig-D version of the Optirrig model specifically developed for the coupling (Section 6.2.1). We also describe the WatASit ABM (Section 6.2.2), using the Overview, Design concepts and Details (ODD) protocol (Grimm et al, 2006). We then present the COPAT framework and describe the coupling processes between the two models (Section 6.2.3). Designed to be as generic as possible, the framework has been applied on 16 cereal plots irrigated by a typical gravity-fed network in Southern France (Section 6.2.4). Model inputs, parameterization and evaluation are presented in Sections 6.2.5, 6.2.6 and 6.2.7. Section 6.3 describes simulation results of the two coordination scenarios, with and without coupling for model verification. We then used these results for discussing the added-value, limitations and outlooks of the proposed framework in Section 6.4.

6.2 Description of the COPAT framework

The purpose of the framework is to assess the potential feedback on crop water stress induced by the management of the collective water network by the coordination, or not,

of these different branches, and according to the specific network constraints. Table 6.1 lists the main characteristics of the two software packages mobilized:

- the framework uses a daily crop model (Optirrig) and the *LAI* (*Leaf Area Index*; Monteith, 1977) as a proxy for crop development and production,
- it complementary uses the hourly and daily WatASit ABM at the network level to generate scenarios of coordination under collective network constraints,
- the crop model simulates climate-soil-plant interactions on a daily basis in which irrigation dates on each plot are forced by the ABM through a daily coupling. The ABM is itself nourished by the state of maturity of the crops, ensuring automated communication between the two models.

6.2.1 Crop dynamics at the plot level: Optirrig-D

The Optirrig model is a two-layer structure in which the inner layer performs hydro-agronomic calculations, having rewritten and modified the concepts originally present in the Pilote model (Feng et al., 2014, Khaledian et al., 2009, Mailhol et al., 1997, 2011) and now termed PiloteR as coded in the R language. The outer layer of Optirrig allows the use of multiple runs for various numerical purposes, e.g. exploratory scenarios of irrigation and fertilization and/or climatic scenarios, uncertainty and sensitivity analysis, model fitting or irrigation optimization either ex-post or in quasi-real-time for current developments. Figure 6.1 gives a simplified view of the structure and main variables of the model, among which the *Water Stress Index* (*WSI*).

The soil module consists of a three-reservoir system (Mailhol et al., 1997, 1996) from soil surface to the maximum rooting depth. The first reservoir (*R1*) depth is of 10 cm and rules the water balance at the soil surface. In this reservoir, evaporation is governed by current *LAI* acting on the partitioning coefficient between transpiration and evaporation. The second reservoir (*R2*) has a depth and capacity increasing with root growth. The third reservoir (*R3*) represents the remaining depth between the current root depth and the maximal root depth, thus vanishes if and when *R2* reaches full extension. Water is first taken from the first reservoir until total depletion by evaporation. Water is then

TABLE 6.1: Main characteristics of Optirrig and WatASit models.

Optirrig	WatASit
<i>Scientific domain</i>	
Irrigation optimization, plant production, soil science	Operational management of collective irrigation, coordination
<i>Type of model</i>	
Process-based crop model	Agent-based simulator of irrigation operations under collective constraints
<i>Main assumptions</i>	
WSI time-evolution is the main control of LAI values	Priority is given to the plot that has not been irrigated for the longest time Maximum irrigations per irrigator to be defined Number of irrigators per farm to be defined
<i>Components</i>	
Soil water balance Plant growth Total dry matter and agricultural yield Crop water stress	Irrigation possibilities simulator Decision-making (operational strategy)
<i>Internal processes</i>	
Soil water reservoirs dynamics Biomass growth Crop management options	Multi-scale irrigation constraints Network flow Network coordination options
<i>Input/parameters</i>	
Climate inputs Land cover inputs Soil parameters	Climate inputs Land cover inputs Network parameters
<i>Temporal resolution</i>	
Daily	Hourly and daily
<i>Spatial resolution</i>	
1D with no explicit representation The nominal scale is plot-scale	Grid-cell based Number of pixel user defined
<i>Simulation platform</i>	
R Software	CORMAS
<i>Programming language</i>	
R	SmallTalk

taken, by plant only, from the second reservoir. Thus, the soil water balance among reservoirs is computed on the basis of field capacity (θ_{fc}) and wilting point (θ_{wp}). Maximal evapotranspiration (MET) is calculated following Eq. 6.1:

$$MET = K_c \times ET_0 \quad (6.1)$$

where ET_0 is the reference evapotranspiration (Allen et al., 1994) and K_c , the crop coefficient as a function of LAI . WSI , the ratio between actual transpiration and maximal transpiration, is calculated by the soil module as a moving average of 10 days.

The crop module is based on the LAI simulation, involving two shape parameters and a vegetative stage parameter (TM) corresponding to the temperature sum (TT) required to reach either the maximal possible LAI value (LAI_{max} , when no stress occurred during the season) or at least the peak of the LAI curve in most cases. The threshold temperature value corresponding to LAI_{max} is tf . TM is derived from the literature. Total dry matter (TDM) is calculated based on Beer's Law, RUE (the radiation use efficiency) being affected by WSI . The required climatic data are precipitations (P), global radiation (R_g), average temperature (T) and ET_0 . The LAI simulation is performed using the following equation:

$$LAI(j) = LAI_{max} \left[\left(\frac{TT(j) - T_s}{tf} \right)^\beta \exp \frac{\beta}{\alpha} \left(1 - \left(\frac{TT(j) - T_s}{tf} \right)^\alpha \right) - (1 - WSI^\lambda) \right] \quad (6.2)$$

where:

$$TT(j) = \sum_{k=1}^{k=j} (T(k) - T_b) \quad (6.3)$$

and subscript j corresponds to a given LAI date, $T(k)$ the averaged daily temperature of day k , T_b the base temperature of the crop, LAI_{max} the maximum value of the LAI and T_s the temperature of emergence, α and β two shape parameters for LAI curves, WSI the water stress factor and δ a parameter governing plant sensitivity to water stress.

Practically, we involved a recent version of the Optirrig model (Cheviron et al., 2016) developed at INRAE G-Eau and aiming at the generation, analysis and optimization of irrigation scenarios. This Optirrig-D version (“D” denotes the specific daily horizon of simulation) allows the external forcing of irrigation instructions for certain time steps, prior to the calculation of model state variables (LAI and WSI among others) which are always passed to the ABM at the end of the daily time step, whether irrigation takes place or not. The optirrig-D version developed in this study is thus a daily function derived from the Optirrig model, which is usually run without interruption from the beginning to the end of the simulation period. In this classical use, irrigation ($I+$, in $\text{L m}^{-2} \text{d}^{-1}$ in legal units, often given as mm) is either scheduled according to decision rules, resulting in an irrigation calendar, or decided from field data and/or model predictions, typically when the amount of water available in the root-zone reservoirs ($R1$, $R2$) goes under a certain threshold. However, as the coupling with the ABM requires to force $I+$ according to agent actions, it is necessary to be able to modify it during the course of the simulation, at each daily time step.

6.2.2 Irrigation at the network level: WatASit (ODD protocol)

6.2.2.1 Overview

Purpose The WatASit ABM is designed to simulate the irrigation operations of irrigators sharing a common water network during a collective irrigation campaign. It explicitly represents the irrigation possibilities left by the operational constraints of the irrigators. The constraints taken into account in WatASit are of the following nature:

- Existence, or not, of daily slot coordination of the network or other coordination modalities,
- Precipitation of the day,
- Maximum irrigation operations at a time per irrigator (number of irrigator per farm to be defined),
- Availability, or not, of the irrigator during the operation duration and daily time window for triggering irrigation operations,

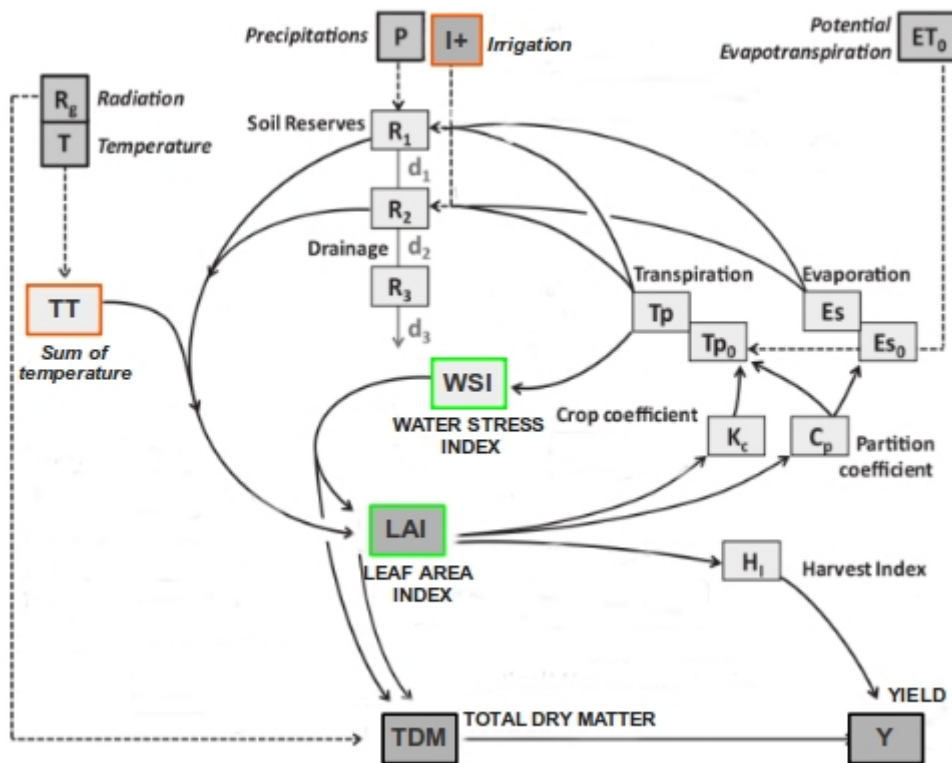


FIGURE 6.1: Simplified view of the Optirrig model (adapted from *Chevion et al., 2016*). Climatic forcing are squares with thick contour lines, intermediate variables are pale grey sketches and key state variables are grey sketches with thick contours: *LAI*, *TDM* and *Y*. Variables specifically used for the coupling are sketches with colored contours : orange for the coupling (*I+* and *TT*) and green for the monitoring of the coupling (*LAI* and *WSI*). Irrigation is noted *I+* to indicate that this model forcing depends on the irrigation scenario.

- Minimum network flow to trigger a flood irrigation.

In WatASit, an irrigation possibility is generated on the plots where these constraints make irrigation possible at a given hourly time step.

State variables and scales WatASit is designed to cover the spatial area of an irrigator union during several months of an irrigation campaign. The model is based on the distinction between the elements that are involved in operations (called operational entities), such as the irrigators, the crops or the irrigation infrastructure, and the areas over which operational entities can operate (called spatial entities). A third kind of entity (called artifact entities) explicitly represents the abstract possibilities of irrigation. Thus, the model has three types of 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. The farm plots are made of one or several pixels and have an area, a crop type and a floodgate attribute (if served by the network). The farm plot spatial level is common to the crop model and is used for the coupling with the crop model. The farms, at which level irrigation decisions are made by the irrigator agents mobilizing their irrigation strategy, 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.

Operational entities Spatial entities are occupied by operational entities that physically represent the irrigator actuators (i.e. the farmers) and passive objects (i.e. crops, floodgates, intake, junction, reject and branches of the network). Each farm plot is occupied by a crop, and also by a floodgate if the plot can be supplied with water by the network. Crop state variables (i.e. *LAI*, *TT* and *WSI*) are used for the coupling with the crop model to monitor the crop growth and crop water stress dynamics at the plot level. Other operational entities include intake, branches and branch junctions and reject points of the gravity-fed network.

Artifact entities WatASit considers artifacts for explicitly representing the possibilities of irrigation and the effective actions of irrigation. Possibilities of irrigation result from the interactions between an irrigator actuator and a passive object. In a given farm, they can interact according to conditions that define the situation of interaction (see Section 6.2.7). Situations of interaction are managed by an artifact entity called “*situation controller*”. If conditions are fulfilled, the situation controller generates an irrigation possibility on the plot. Among the possibilities, the chosen one becomes an irrigation action.

Process overview and scheduling WatASit scheduling is represented in Figure 6.2. Each day, there is first initialization of the current precipitation, and also of the number of days since the crops have not been irrigated. Then, every hour, the flow rate is updated in the network according to network junction state (i.e. *opened* or *closed*) and ended actions. Irrigation options are then generated on each farm according to the states

of actuators and passive objects. Depending on the actuator's operational strategy, an option can be performed to make an irrigation action or ask for more water in the canal.

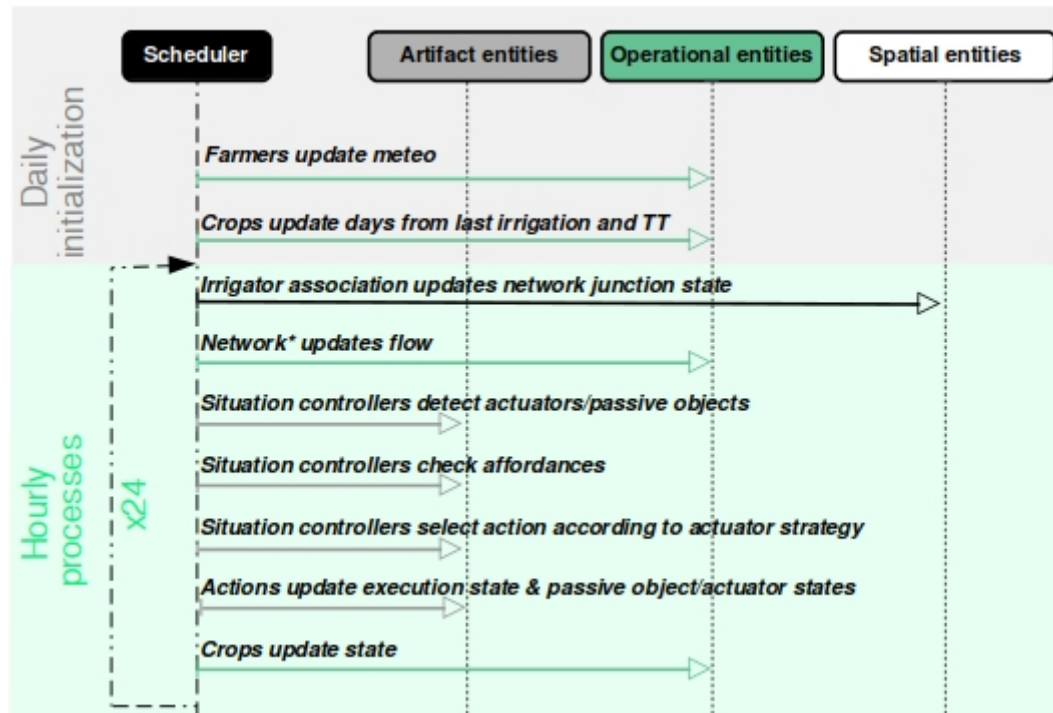


FIGURE 6.2: Sequence diagram of the WatASit model. Black, green and grey arrows indicate methods of the spatial, operational and artifact entities, respectively. *TT* is the temperature sum of the crop.* denotes that the method is performed by both network intake, junction, reject and branches.

6.2.2.2 Design concepts

Basic principles, emergence and adaptations WatASit is based on the theory of Situated Action (Dreyfus, 1972, Suchman, 1987) which represents the phase of execution of actions according to the operational constraints of the actors. In the model, the behavior of the irrigator agents is determined by their possibilities of irrigation, which are re-evaluated at each hourly time step. The agents choose, or not, depending on their operational strategy, to select one of the possibilities to perform it. Irrigation possibilities result from both water availability in the network serving the plot, agent availability to operate irrigation, and climatic forcing. As the water at the floodgate is not always sufficiently available to irrigate a plot, irrigator agents have 3 possibilities:

- irrigate plot with crop needing water and having an irrigation possibility,

- ask for more water in the canal by rising the flow at the canal water intake if maximum flow at intake is not yet reached,
- do no irrigate during this time step.

Fitness, learning, prediction and sensing Agent behaviors follow a set of decision rules representing their operational irrigation strategy. This strategy determines the plot to be irrigated at each hourly time step among all the plots of a farmer. Agents do not predict the consequences of their behavior and do not change their strategy as a consequence of their behavior. However, agents' possibilities of action change according to the context of the moment, forcing them to modify their behavior.

Interactions and collectives WatASit allows direct interactions between the actuators (i.e. the irrigator agents) and the passive objects of their spatial environment (e.g. the floodgates to deliver water to their plot from the collective network). By triggering or not irrigation, irrigator agents thus also interact indirectly with each other by reducing the amount of water available for the irrigators located downstream of the network. Grouping of irrigators is materialized by membership of an irrigator union.

Stochasticity In this study, WatASit does not include stochastic elements as, in particular, the initialization of the cropping systems for each irrigator is made from a geo-referenced data-set and only the 2017 climate forcing data are used.

Observation Simulation output (i.e. dates of irrigation, *LAI*, *TT* and *WSI* on each farm plot) are collected from the two models by recording attributes of WatASit entities (i.e. irrigated state of farm plot entities) and Optirrig-D variables (i.e. cereal *LAI*, *TT* and *WSI*) in the *R* software during the irrigation campaign.

6.2.2.3 Details

Initialization Spatial entities were initialized from the “*Registre Parcellaire Graphique*”¹ (RPG 2017) database using a pre-processing that consists of rasterizing the farm plot

¹available online at <http://professionnels.ign.fr/rpg>

shapefiles. Farm plots belonging to each farm were identified, and crop types were associated to each farm plot. The collective water network (i.e. water intake, junctions, branches and reject points) was initialized using shapefiles from the HYDRA database² (BD Hydra V2). At the initialization, farm plots served by the network were listed for each canal branch. Value of attributes at time $t = 0$ are detailed in Table ??.

Input Daily precipitations come from the French SAFRAN reanalysis (Vidal et al., 2010) from May 31, 2017 to July 31, 2017.

Sub-models The affordance generation sub-model 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.

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*”.

The sub-model representing the flow in the water network is specific to the functioning of gravity-fed irrigation and floodgates. 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 along the network. Detailed description of the network representation is available on the OpenCOMSES at this link: <https://www.comses.net/codebases/0d8dcdf1-8772-4e57-9f03-1f6c062bbe60/releases/1.1.1/>
..

6.2.3 COPAT overview and scheduling

The framework has required the development of an *Application Programming Interface* (API) designed as a set of R functions, and called *RCormas*³, to allow communication

²available online at http://hydra.dynmap.com/index_.php?grFrame=1

³Rcormas is available at <https://gitlab.irstea.fr/cormas-dev/r-cormas>

between the R software in which the crop model is implemented and the CORMAS platform running the ABM. The API also allows to pilot the simulation from a R program that can initialize the model, get and set values from entities and run simulation steps. To assess the feedbacks of network coordination strategy and associated specific constraints on cereals *WSI*, a simulation framework using this API is designed (Figure 6.3).

The framework relies on the crop model at the plot level and the ABM at the network level. If there is a conflict for the use of water in the collective network, the sharing is managed by the ABM and may induce a delay in irrigation for some of the irrigators who would aim to irrigate at the same time. The framework is scheduled as follows:

[a] in the time period from the beginning of the simulation to the beginning of the irrigation campaign, no irrigation is present and the crop-related *LAI*, *WSI* and *TT* variables are calculated by the crop model from the climatic forcing only (Figure 6.3 [a]),

[b] during the irrigation campaign, the coupling between the crop model at the plot level and the ABM at the network level is activated. The daily crop model *Otpirrig-D* keeps the history of all necessary state variables from one day to another, and calculates the state variables according to the daily update of $I+$ transmitted by the ABM on each cereal plot (Figure 6.3 [b]). Each day, first the crop model runs simulates *LAI*, *WSI* and *TT* for each crop. We make the assumption that the crop growth process is slow enough that we do not need to calculate it by the hour. The precipitation P and the sum of temperature *TT* are then transmitted to the ABM. Second, the ABM simulates 24 hourly time steps, generating the set of irrigation actions made by the agents according to their coordination scenario and associated constraints that could modify $I+$ for the current day. Third, $I+$ is collected for each plot and is transferred to the crop model, which integrates them to compute new *LAI* values of cereal crops and their associated *WSI*. This sequence is repeated every day until the end of the simulation period.

In both [a] and [b], if *TT* exceeds the cereal temperature of maturity *TM*, the irrigation campaign is stopped for the cereal plot ($I+$ is null).

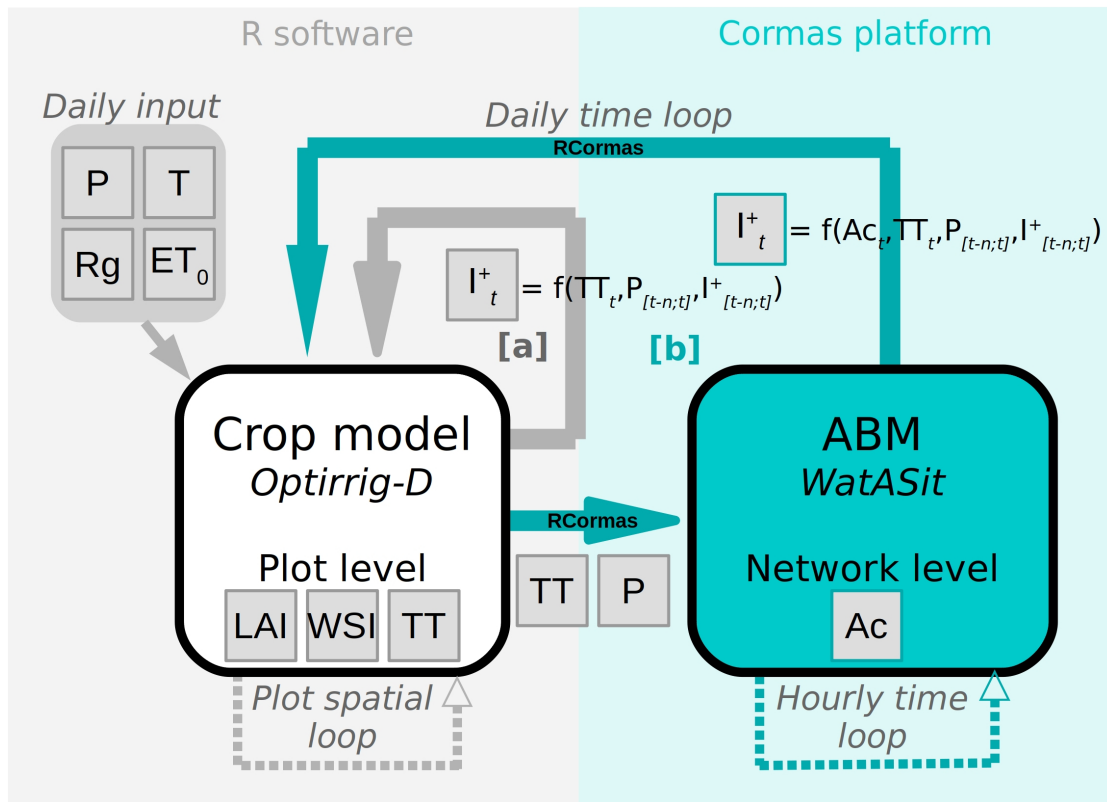


FIGURE 6.3: Scheme of the coupling simulation framework. [a] indicates the simulation processes which shortcuts the coupling with the ABM (grey arrows), whose grey boxes are the main variables. The precipitation, temperature, global radiation and reference evapotranspiration are denoted P , T , Rg and ET_0 , respectively. LAI is the *Leaf Area Index*, WSI the *Water Stress Index* and TT the sum of temperature. I^+ stands for the irrigation, which is denoted with a "+" to indicate it depends on the management options. t is the current time step, whereas $[t-n;t]$ is the time period of the last n days. [b] indicates the simulation chain which integrates the coupling with the ABM at the network level (blue arrows). In this case, I^+ also depends on the actions (Ac) carried out by the agents. $RCormas$ refers to the API used for activation of the coupling and communication between the R software and the CORMAS platform.

6.2.4 Case study: the Aspres-Sur-Buëch gravity-fed network

In order to illustrate the COPAT framework, we selected the Aspres-sur-Buëch case study (Figure 6.4), in which 83 plots can be irrigated by 10 irrigators sharing the gravity-fed network. The case study is located in the Buëch catchment, a sub-basin of the Durance with a surface area of 1490 km² in France. Collective irrigation constitutes by far the use that takes the most from the water resource during the low water period from May to October. 38 irrigator unions are equipped either for gravity-fed irrigation, or for pressure irrigation, or for both. Strategies for coordinating the water networks are thus collectively discussed in this river basin. This discussion is particularly

present in the context of the ongoing program to modernize the gravity-fed networks.

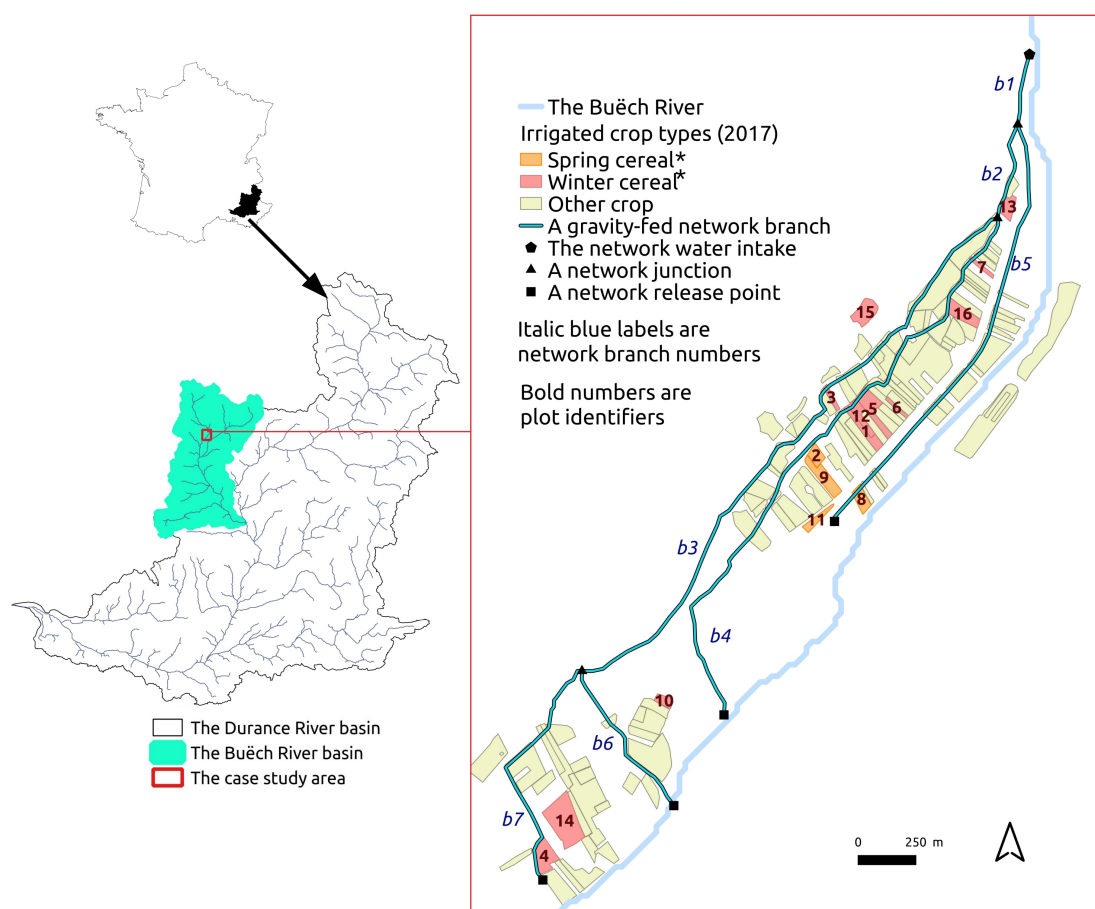


FIGURE 6.4: Presentation of the Aspres-Sur-Buëch study area (red box) located in the Buëch River basin (in blue), sub-basin of the Durance. Within the study area, the colors represent the types of crops irrigated by the gravity-fed irrigated network (source: BD Hydra V2 and RPG 2017). Bold numbers on the plots correspond to their identifiers, while italic blue labels are network branch numbers.* denotes crops simulated by Optirrig-D.

The total simulation period runs from 15 October or Day Of Year 1 (DOY 1), when the winter cereals are sown, to the end of the cereal season on July 31 (DOY 289). The coupled simulations start at the beginning of the irrigation campaign on May 1st (DOY 198), when irrigators of Aspres-Sur-Buëch water their network each year. 2017 is taken as reference for the climatic forcing. During this year, gravity irrigation accounted for 7.3% of the irrigable areas for 44.7% of the authorized water withdrawal volumes, of which one third of the crops were cereals (29.7%). The Aspres-sur-Buëch gravity-fed network is fairly representative in terms of location (in the upstream part of the basin), irrigable area (with 75 ha whereas the average is 50 ha in 2017), and crop rotation

(23.7% cereals in 2017).

In this study, the modeled landscape is represented in the ABM by a grid of 54 by 44 pixels with a resolution of 75 m, with 83 plots served by the network. However, for practical reasons of crop model parameterization, we focus on 16 cereals plots (Figure 6.4) made of 12 winter cereals and 4 spring cereals, that belong to 6 of the 10 irrigators sharing the gravity-fed network. Table 6.5 sums up the crop type, plot area and irrigator identifiers of the 16 cereal plots. Irrigation on the other plots served by the network is thus not driven by TT to be stopped at the end of the simulation period. In addition, each farm is occupied by a unique irrigator (the farmer) which is able to carry only one irrigation at a time due to the specificity of the gravity-fed system of the case study.

6.2.5 Inputs

As for WatASit, Optirrig-D inputs are the climatic forcing (precipitation, temperature, global radiation and reference evapotranspiration) and were obtained from the French SAFRAN reanalysis (Vidal et al., 2010) from January 1, 2017 to December 31, 2017.

6.2.6 Parameterization

Parameters of both models are specified in Tables ?? (for Optirrig-D) and ?? (for WatASit). Concerning Optirrig, typical parameters of winter soft wheat have been considered for all winter cereals. Parameters for spring cereals are based on typical spring oat parameters. For a given crop, literature (e.g. Cox and Joliff, 1986, Howell et al., 1996) can provide some parameters such as the LAI_{max} , tf , and the TM parameter. All these parameters are linked to the base temperature Tb parameter, which is also given in relevant literature (see Mailhol et al., 1997). Sowing DOY are average dates reported by irrigators during the 2016-2017 crop campaign. Available water reserve (AWR) and maximum profile and rooting depth ($Pmax$) are from the *PACA Regional Soil Reference System*. Moreover, AWR in the soil of the plots in the study area were calculated from the *PACA Regional Soil Reference System*, described in Braud et al. (2013), using a method presented in Manus et al. (2009).

Concerning WatASit, field surveys in the form of observation of irrigation practices and semi-directive interviews were conducted to collect information about the 2017 irrigation campaign concerning the specific network constraints, the network coordination and the irrigation strategy of the irrigators. The President of the Aspres-Sur-Buëch water network, its technician in charge of the technical management, and 3 irrigators were interviewed. According to field surveys, irrigators have abandoned, over the past 15 years, the network coordination by daily slots. The irrigation strategy (Figure 6.5) and the scenarios (Section 6.2.7) have been specified in accordance with the information provided by the irrigators. The irrigation strategy consists to irrigate crops after a number of days without irrigation or sufficient precipitation inputs to contain as much as possible a maximum of successive non-irrigated days. Cereals which have not been irrigated over a long period (i.e. more than N consecutive days, see Table ??) are considered as abandoned for irrigation and irrigation is not possible on them any more during the remainder of the irrigation campaign.

In addition, the network specific constraints have been specified (Table 6.2). For instance, an irrigation continues until reaching a target plot flood duration. As flow rate of the floodgate (Q_{flood} , see Table ??) is fixed, it is equivalent to inject a fixed irrigation dose ($Idose$, see Table ??). Other parameters are specific irrigation operations and gravity-fed network characteristics mentioned by the irrigators. In particular, the reference flow rate at the network intake (Q_{ref} , see Table ??) was determined by the irrigators to avoid overflow and comply with the river abstraction rules during the 2017 low-flow period (also note that no irrigation restrictions came into effect during the 2017 cereal campaign).

6.2.7 Scenario and model evaluations

The potential feedback induced by the scenarios of coordination and collective irrigation constraints at the network level are evaluated by comparison of irrigation dates and cereals WSI with simulations at the plot level (i.e. bypassing WatASit and its associated network level constraints). The level of the collective network may prevent irrigators from applying their irrigation strategy to the plot in the same way as if it did not depend

TABLE 6.2: Specification of the network specific constraints.* indicates that when this constraint is the only one which is not fulfilled, a “missed” irrigation is recorded.

Network constraint	Specification
Number of irrigator per farm	<i>One irrigator per farm</i>
Number of simultaneous irrigations per irrigator	<i>One irrigation at a time per irrigator</i>
Plot flood duration	<i>Fixed</i>
Target irrigation dose	<i>Fixed</i>
Required branch canal flow rate serving the plot floodgate	\geq <i>plot flood rate (Q_{flood})</i>
Functioning of the network while raining	<i>Irrigation is not triggered if there is precipitation</i>

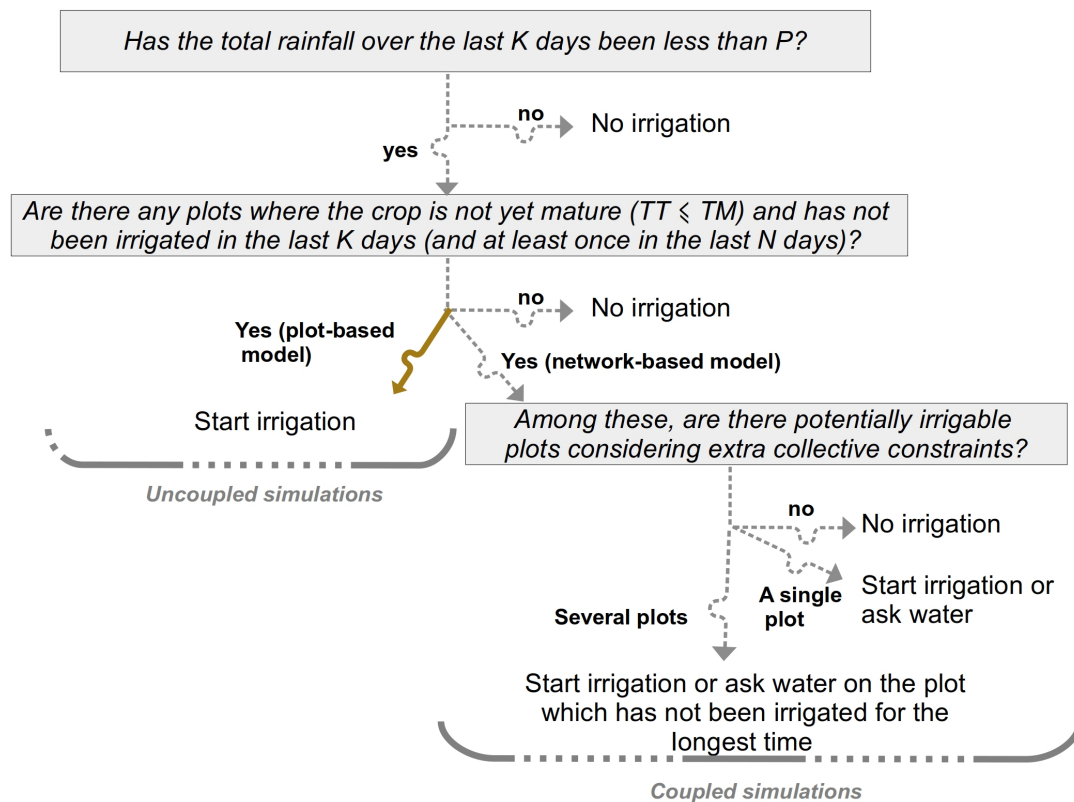


FIGURE 6.5: Irrigators' strategy considered for the case study. Typical values are $K=12$ days, $P=120$ mm, $N = 45$ days and $TM = 1200^\circ\text{C}$ for spring cereals and 1700°C for winter cereals.

on a common functioning.

We called "Ref_NoSlots" the simulation in which irrigators optimally apply their irrigation strategy at the plot level without any constraints due to the common network. Irrigation is simulated by the model at the plot level without coordination strategy. This simulation thus shortcuts the WatASit model during the whole simulation period (including the irrigation campaign). Ref_NoSlots does not consider any possibility of conflict between irrigators for the collective use of water. Irrigation strategy is then equivalent to a regular plot-based calendar of irrigation dates and doses (*Idose*) injected on the plots. We called "Network_NoSlots" the scenario in which irrigation is simulated by the model at the network level without coordination strategy. Water is distributed to each plot via the collective network but the network flow is not coordinated from one branch to another. The water flows simultaneously in all the branches of the canal during the irrigation campaign (Table 6.3). The sharing of water between irrigators is mainly constrained by the network capacity that cannot distribute water everywhere at the same time.

We called "Ref_DailySlots" the simulation in which irrigators optimally apply their irrigation strategy at the plot level and follow a daily slots coordination strategy (Table 6.3). Irrigation is simulated by the model at the plot level and irrigation dates are constrained by daily slots which are directly generated in the Optirrig-D model. Finally, "Network_DailySlots" is the scenario in which irrigation is simulated by the model at the network level with a daily slots coordination strategy. It depicts flow coordination using daily slots for each network branch, constraining temporally irrigation operations. In this scenario (Table 6.3), the branches of the canal are watered according to 4 time slots (A, B, C and D). These four time slots are due to the four water reject points of the network (Figure 6.4). For each slot, water flows in only some branches of the gravity-fed network (e.g. branches 1 and 2 for slot A), and the different daily slots follow one after the other in a 10-day coordination, which begins again with each new ten-day period.

When irrigation is thought of at the individual plot level, it is difficult to make assumptions about the functioning of the infrastructure that carries the water (i.e. whether

TABLE 6.3: Collective strategies of network coordination considered in the study, and extra irrigation constraints. The seven canal branches of the canal are denoted $b1$ to $b7$. For example, in the Network_DailySlots scenario, water network coordination is done in 10-day periods. Thus, canal branches $b1$ and $b5$ are flowing during the first three days of each 10-days period, then $b1$, $b2$, $b3$ and $b6$ are flowing during the third following days, etc

Coordination scenario	Slot A	Slot B	Slot C	Slot D
Network branches	b1+b5	b1+b2+b3+b6	b1+b2+b3+b7	b1+b2+b4
Network_NoSlots				
Day(s)	<i>always</i>	<i>always</i>	<i>always</i>	<i>always</i>
Plot(s)	<i>all plots</i>	<i>all plots</i>	<i>all plots</i>	<i>all plots</i>
Network_DailySlots				
Day(s)	<i>days 1, 2, 3</i>	<i>days 4, 5, 6</i>	<i>day 7</i>	<i>days 8, 9, 10</i>
Plot(s)	<i>plot 8</i>	<i>plots 3, 10, 13, 15</i>	<i>plots 3, 4, 13, 14, 15</i>	<i>plots 1, 2, 5, 6, 7, 9, 11, 12, 13, 16</i>

or not the capacities of the network are exceeded), and these constraints are generally given little consideration. The Network_NoSlots and Network_DailySlots scenarios of coordination are associated with network specific constraints of the collective gravity-fed functioning of the case study. Thus, in the coupled simulations, an irrigation is triggered according to these specific constraints (Table 6.2). Moreover, we called a “missed irrigation” an irrigation that could not be triggered solely because the minimum flow rate served by the canal at the plot floodgate was not met.

6.3 Result

Illustrative results are presented in this section. Indeed, as we focus on the differences in outputs between coupled (i.e. irrigation simulated by the coupled model at the network level) and uncoupled simulations (i.e. irrigation simulated by the uncoupled model at the plot level), we do not evaluate quantitatively the performance of the coupled model in this study. However, we verified certain qualitative observations made during the field surveys to ensure that potential feedback was realistic and not due to modeling artifacts. While we were unable to collect irrigation dates for all cereal plots, we observed that the plots downstream of the gravity-fed network (cereal plots 10, 14 and 4) were not irrigated at all during the 2017 campaign. In addition, the irrigators mentioned 6 irrigation dates by plot at maximum during the cereal campaign. In sections 6.3.2 and .3.3, we also

indicate outputs from an extreme simulation run called “NoIrri”, without any irrigation inputs during the irrigation campaign.

6.3.1 Irrigation dates and model verification

This section presents the irrigation dates of the 16 cereal plots simulated by the network-based model (i.e. the `Network_NoSlots` and `Network_DailySlots` network coordination scenarios), with respect to the reference simulation of the plot-based model (i.e. the `Ref_NoSlots` and `Ref_DailySlots` simulations).

6.3.1.1 When irrigation is not coordinated

The two top lines of Figure 6.6 correspond to irrigation dates when the network is not coordinated. With the plot-based model (`Ref_NoSlots`), the plots are irrigated simultaneously on a regular 12-days basis until maturity temperature is reached (materialized by the green lines). This is not the case with the network-based model (`Network_NoSlots`) in which we observed significant delays between the series of irrigation, and no irrigation for the most downstream plots 10, 14 et 4. For instance, 28 days separate the series of irrigation between DOY 207 and DOY 235. In Figure 6.7, the irrigation possibilities and missed irrigations of the irrigator agents are traced back from the ABM. The irrigation possibilities appear to be limited during this period due to the precipitation. Moreover, irrigations of plots 4, 10 and 14 were missed (Figure 6.7 “missed irrigation” for `Network_NoSlots`), meaning that the network flow was insufficient at their level to trigger irrigation. Taking into account the network specific constraints thus leads to both the abandonment of the most downstream plots (i.e. plots 4, 10 and 14) and significant delays in series of irrigation. As a consequence of irrigation delays, maturity of the crops is reached later for some of the crops (e.g. 3 and 4 for plots 15 and 16, respectively) with the network-based model (`Network_NoSlots`) than with the plot-based model (`Ref_NoSlots`).

6.3.1.2 When irrigation is coordinated

The two bottom lines of Figure 6.6 correspond to irrigation dates when the network is coordinated. Irrigation operations simulated by the plot-based model (`Ref_DailySlots`)

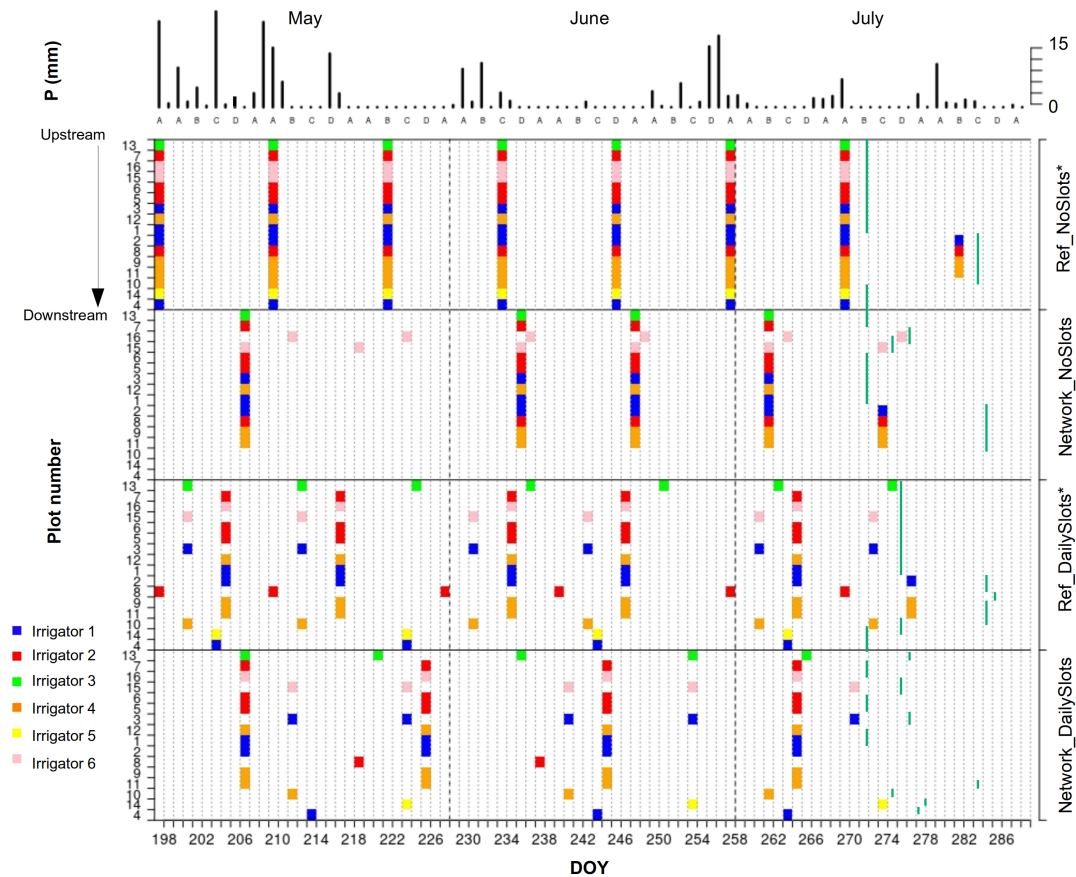


FIGURE 6.6: Irrigation dates within the 16 cereal plots from May 1st (DOY = 198) to July 31 (DOY = 289). Ref.NoSlots and Ref.DailySlots are simulations at the plot level. Network.NoSlots and Network.DailySlots depict coordination scenario at the network level. * indicates the simulation does not imply the coupling framework. Colors are irrigators'identifiants, black ticks are precipitation (P , in mm). "A", "B", "C" and "D" labels indicate daily slots. Green ticks show when the maturity is reached by the plant.

are distributed differently over time from one plot to another, and form a pattern driven by the four A, B, C and D slots that irregularly repeats until the maturity temperature is reached. When irrigation is simulated at the network-base model (Network_DailySlots), the pattern is not exactly repeated, which is explained by the fact that irrigation possibilities are constrained both by daily slots and precipitation of the day (Figure 6.7 "irrigation possibility" for Network_DailySlots). However, reaching the plant maturity is not necessarily penalized, and happens even earlier on some plots (2, 5, 6, 10 and 16). Comparing the two coordination scenarios, the plots are almost always irrigated at the same time when irrigation is not coordinated (Network_NoSlots). But the absence of network coordination leads to significant delays from a series of irrigation to another, and a lack of irrigation in the most downstream plots, which is prevented by the coordination of the network (Network_DailySlots).

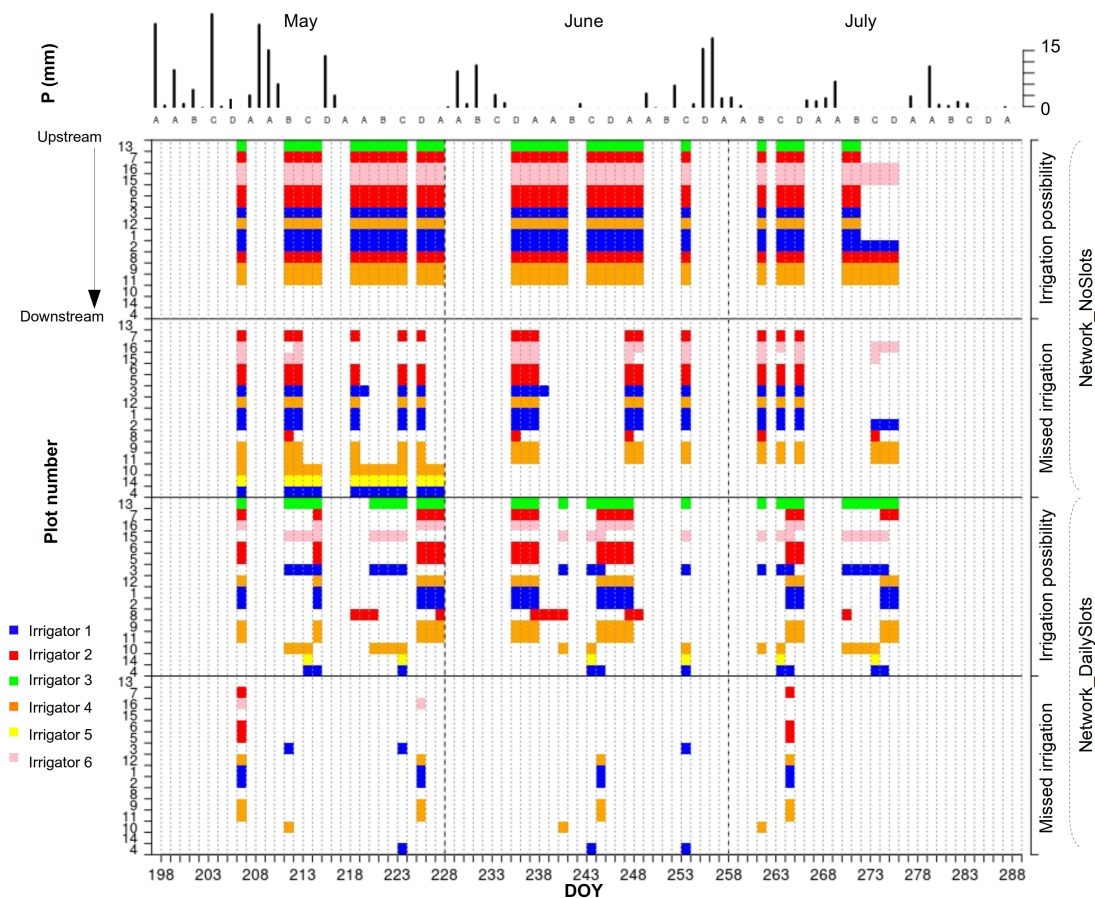


FIGURE 6.7: Dates of irrigation possibilities and missed irrigation within the 16 cereal plots considered in the study during the irrigation campaign from May 1st (DOY = 198) to July 31 (DOY = 289). Network_NoSlots and Network_DailySlots depict coordination scenario at the network level. Colors are irrigators' identifiers, black ticks are precipitation (P , in mm). "A", "B", "C" and "D" labels indicate daily slots.

6.3.2 Spatial distribution of cereal stress severity

In this section, we measure the water stress severity of a cereal plot as the greatest stress level undergone by this cereal over a simulation. As in Optirrig-D the time-evolution of WSI values is the consequence of both rain and irrigation events from the 10 past days, WSI is the main control over LAI values and it's thus a good candidate for evaluating the impact of the network specific constraints. To facilitate comparisons, we use 4 WSI classes which are presented in Table 6.4. WSI equals 1 is corresponding to low plant water stress. Since severe stress has an exponential impact on biomass growth, it makes sense to locate it during the irrigation campaign.

TABLE 6.4: Value ranges of the 4 *WSI* classes.

<i>WSI</i> range	Stress severity
0.75 - 1	<i>Low</i>
0.5 - 0.75	<i>Medium</i>
0.25 - 0.5	<i>High</i>
0 - 0.25	<i>Very high</i>

Figure 6.9 locates maximum stress severity within the 16 cereal plots. When irrigation is simulated by the plot-based model without coordination (Ref_NoSlots), cereal maximum stress is low (blue plots) for all spring cereals and is high (orange plots) for all winter cereals. This difference is due to parameterization of the Optirrig-D model that differentiate this two cereal types, especially the sowing period. When coordinated, irrigation simulated by the plot-based model (Ref_DailySlots) induced few differences in cereal stress severity than without coordination (Ref_NoSlots): three plots move from high to medium stress (Figure 6.8, yellow plots). It means that daily slot coordination has a slight beneficial impact when irrigation is simulated by the plot-based model. In the absence of irrigation (NoIrri), winter cereals have dropped one class of maximum stress, from high to very high (Figure 6.9, the red plots), and spring cereals have dropped two classes, with high stress (Figure 6.9, the orange plots).

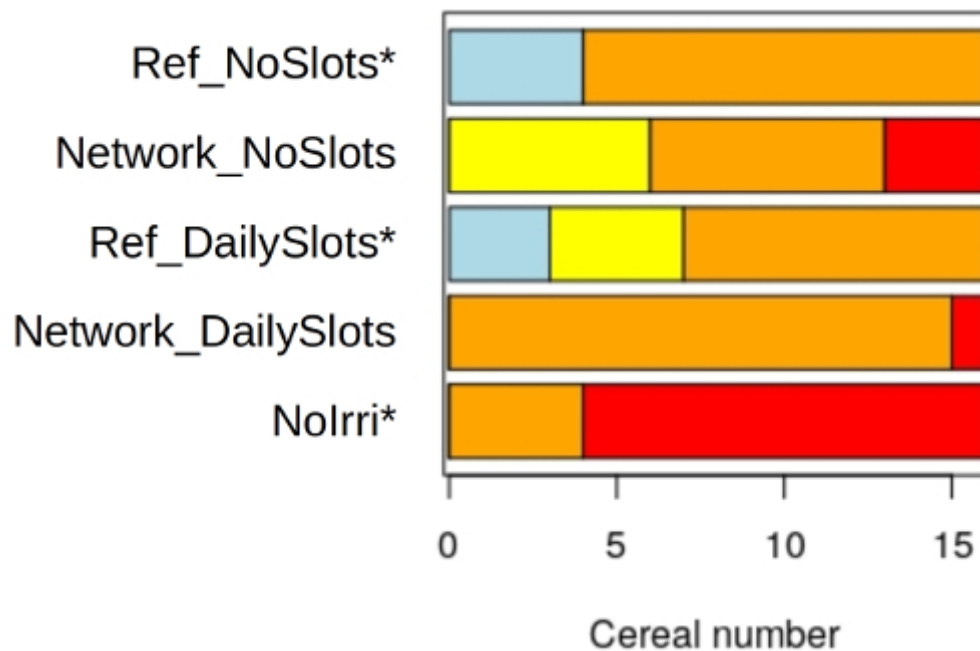


FIGURE 6.8: Cereal number for each water stress severity level. Blue, yellow, orange and red colors denote low, medium, high and very high stress, respectively.

The key point appears when irrigation is simulated by the network-based model without coordination (Network_NoSlots). A spatial dichotomy appears between the upstream part of the network, where stress severity is medium to high, and the downstream part, where all three cereal plots have very high maximum stress (Figure 6.8 and Figure 6.9, Network_NoSlots). This dichotomy is not observed when irrigation is simulated by the plot-based model (Ref_DailySlots), and is less obvious when irrigation is simulated by the network-based model with daily slot coordination (Network_DailySlots). In addition, maximum water stress globally occurs earlier when the network is not coordinated (Figure 6.9, Network_NoSlots).

6.3.3 Average stress dynamics of cereals

This section focuses on average water stress time-series integrated over the irrigation campaign (Figure 6.10).

When simulated by the network-based model, the absence of network coordination (Figure 6.10, *WSI*, green line) leads to earlier medium stress in average (i.e. 10 days earlier) than when the network is coordinated (orange line). The absence of coordination also induces an impact on cereal growth: maximum of average *LAI* (Figure 6.10, *LAI*, green line) is reached 12 days earlier and about 1 point lower than when the network is coordinated (green line). This is because irrigation operations are less frequent and less distributed over time in the absence of coordination (Figure 6.10, irrigation number). It means that the network specific constraints significantly impact average crop water stress when the network is not coordinated, while network coordination tends to limit the impact of the network specific constraints.

6.4 Discussions

In this section, we propose to first discuss the added value of the proposed framework to capture potential feedbacks on crop water stress due to specific irrigation constraints in place when sharing water depends on a collective network. Then we consider several limitations of the study with possibilities of improvement and key follow-up.

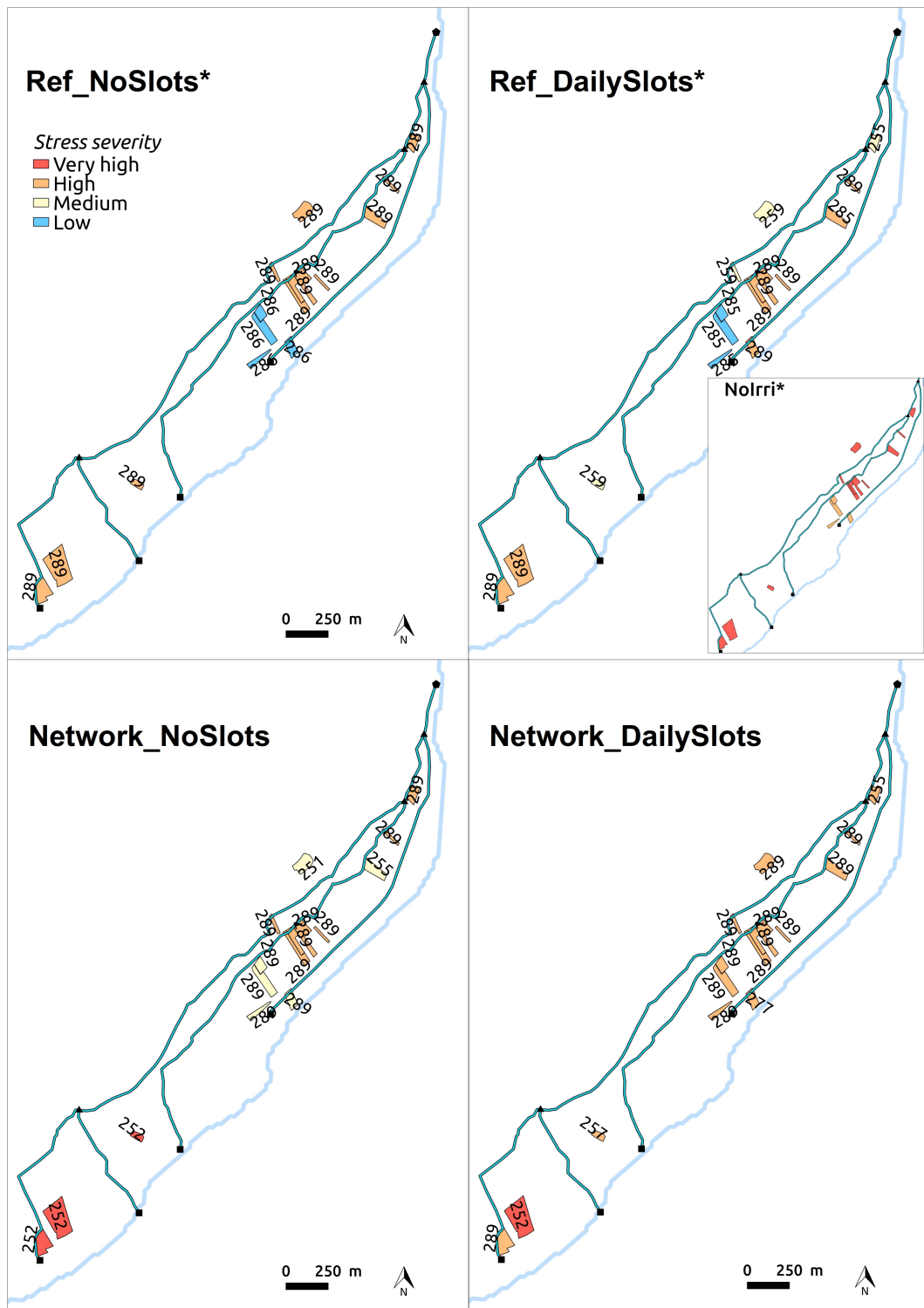


FIGURE 6.9: Localization of maximum stress severity within the 16 cereal plots, according to Network_NoSlots and Network_DailySlots scenarios with respect to Ref_NoSlots and Ref_DailySlots simulations, respectively. Bold numbers are Days Of Years of occurrence of the maximum stress.* indicates the simulation does not imply coupling.

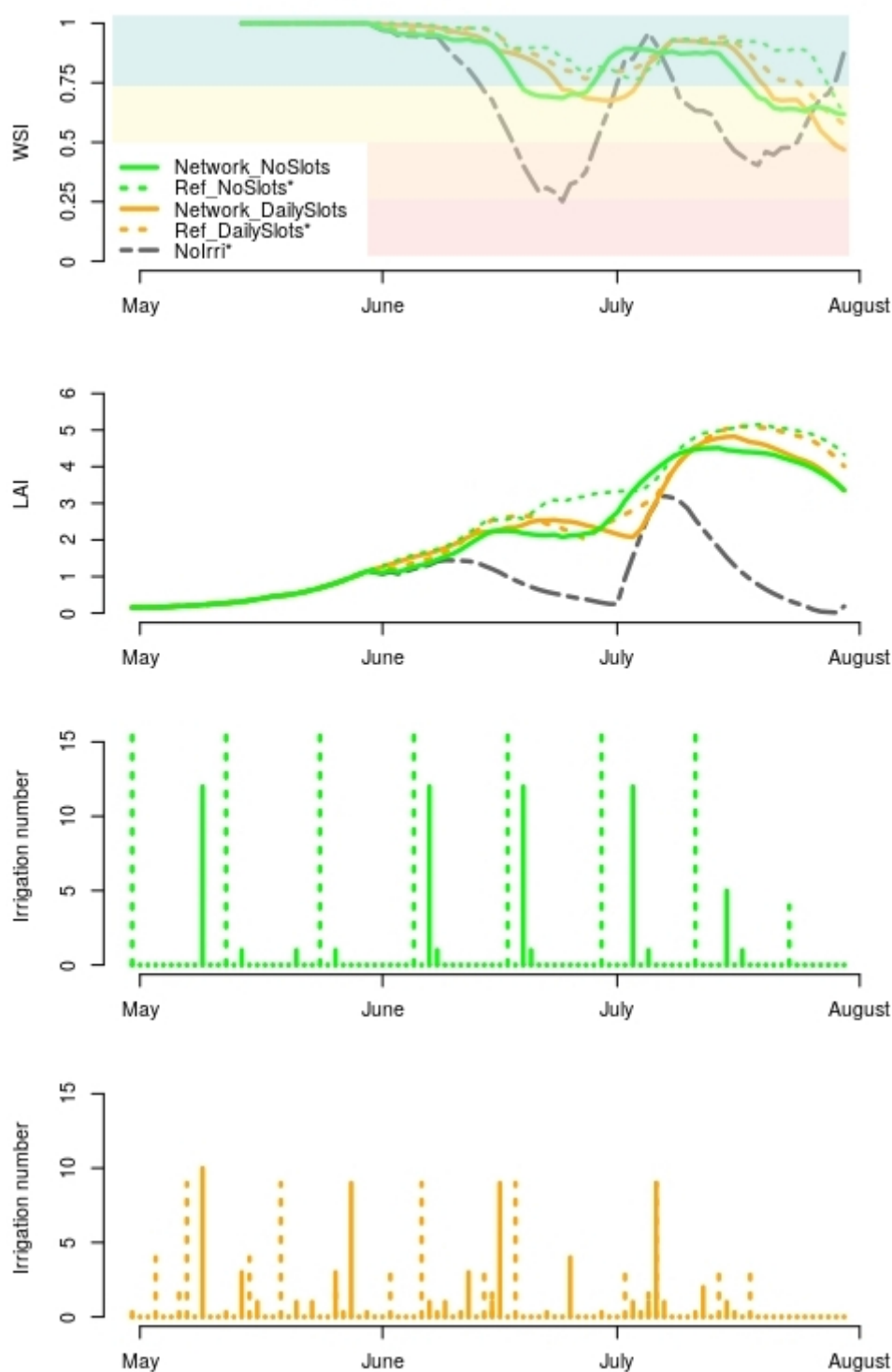


FIGURE 6.10: *LAI*, *WSI* and irrigation number evolutions for all cereals during the irrigation campaign from May 1st to July 31. Green and orange lines are the Network_NoSlots and Network_DailySlots scenarios, respectively. Dotted green and orange lines are the Ref_NoSlots and Ref_DailySlots simulations, respectively.* indicates the simulation does not imply coupling. Background blue, yellow, orange and red colors indicates low, medium, high and very high plant stress severity, respectively.

6.4.1 Added value of the COPAT framework

As related by several researchers, most ABMs driving agriculture or irrigation scenario in the literature focus on decision making rather than on operation (Cros et al., 2004, Garcia et al., 2005, Guerrin et al., 2016, Johnston et al., 2005, Snow and Lovatt, 2008). Applied on an illustrative case study in Southern France, COPAT allowed considering the network operational constraints to capture feedback on plant water stress. The COPAT contribution lies in a complementary explicit representation of irrigation at the operational level, allowing tracing back, for instance, the missed irrigations denoting the situations where the insufficient network rate is the cause for not triggering simultaneous irrigation at multiple locations. Compared to the first approach developed in Richard et al. (2020a) with the ABM alone, the framework makes it possible to tackle the impact on some crop variables (i.e. *WSI*, *LAI*) widely used in agricultural system studies. In particular, simulation results alert on potential underestimation of plant water stress when simulated at the plot level when plants depend on a collective irrigation network for sharing water at multiple plot locations.

The framework also allows comparing coordination scenarios, and provides access to a tactical assessment of the spatial variability of plant water stress occurring during a collective irrigation campaign. Not surprisingly, simulation results highlight that network coordination tends to limit the impact of its specific constraints by delaying average plant water stress and increasing maximum average plant growth with respect to simulation at the plot level. Indeed, the network coordination reduces the effect of network flow along its upstream-downstream gradient, limiting missed irrigation for the most downstream plots, and thus reducing severe stresses on them.

In addition, most approaches in the literature are merging crop model into a unique integrated simulation platform (e.g. Belcher et al., 2004, García-Vila and Fereres, 2012, Raes et al., 2009). As experienced by Marohn et al. (2013), coupling individual models prevented simplifying a number of dynamics that are exogenous to the coupled model. For example, the precocity of plant water stress when the network is not coordinated, as a result of irrigation delays caused by the network specific constraints, could not have

been represented by either model individually. COPAT therefore enables developing individual models simultaneously and independently, with people yet familiar with them.

6.4.2 Limitations and outlook

As described by [Letcher et al. \(2013\)](#), the coupling of individual models is only possible under certain conditions:

- Individual model components do not necessarily work on the same space and time scale, but disaggregation or aggregation must often be applied to link models. In our approach, the water network results from aggregation in the ABM of the elementary spatial entities (the plots). In addition, the ABM has also a double time scale (hourly and daily). These double space and time scales make it possible to link daily irrigation at the plot level in the crop model, with the constrained operations at network-scale.
- Individual model components may be adapted specifically to work together without extensive recording. Indeed, the coupling between the two models was only made possible because the crop model was adapted to a daily function, allowing it to run as a slave model of the ABM. Using COPAT with another crop model could be envisaged at this condition.
- The level of detail should be appropriate for a specific purpose otherwise the coupled model could be overly complex, with difficulty to identify feedback drivers, and over-parameterization. In our approach, the chosen parameterization has been kept as simple as possible. It distinguishes only two classes of crops, summer and winter cereals, whereas it could be specific to each cereal variety (barley, wheat, etc.).

Moreover, the proposed coupling is bi-directional, but the coupling from the crop model to the agent model is probably less impacting than the coupling from the agent model to the crop model. Indeed, we dictated crop dynamics by forcing irrigation from the agents. But only precipitation and the sum of temperature come from the crop model to drive the behaviors of the agents. Reinforcing the coupling from the crop model to the agent model could be achieved by integrating, for example, the *WSI* variable in the

irrigation strategy, as a proxy for crop stress. However, rather than looking at *WSI* which is an elaborated variable, and that corresponds to a conceptual representation, we could also reason in percentage of *AWR* which is a phenomenological variable and concretely observable (sensors in the ground). This would avoid the *WSI* threshold phenomenon: when *WSI* decreases from 1 to X , no effect, then effect is exponential when *WSI* decreases from X to 0 (especially if we reason on *WSI* averaged over time, and even more so over long periods). This is why we used *WSI* classes in this study rather than comparing values directly.

For future research, explaining and validating quantitatively the relevance of model output remains a challenge. It can be done by directly involving the stakeholders and collecting observations of irrigation on each plot. Another way could be to compare simulated *LAI* with *LAI* retrieved from optical or remote sensing techniques (e.g. [Zheng and Moskal, 2009](#)). In addition, the inter-related operations between hay-mowing, garden watering and irrigation have not been considered but could have a significant impact on gravity-fed irrigation ([Merot et al., 2008](#)). This could be achieved by adding an explicit representation of garden watering and mowing operations in the WatASit model, or using a crop model representing such operations. Coupling further specialized models to the system, as for example the SIC hydraulic model ([Baume et al., 2005](#)), could also be useful for the modeling in the study area where the representation of flow in the network is a key issue. Deploying the framework to another case study means that detailed information is required to set up the model parameters, potentially limiting the spatial scale. The conceptual structure of the ABM, designed to be as generic as possible, allows changing the major structural constraints. However, the use of different irrigation strategies may require specific crop indicators to be coupled. For instance, in systems where irrigation is finely controlled, evapotranspiration or *AWR* are often used to pilot irrigation. Such variables could be easily retrieved from the crop model.

The COPAT framework also entails some quantification of the differences among coordination scenarios according to plant water stress. Another follow-up of this work could be to assess variants of the daily slots scenario to determine optimal coordination conditions for minimizing crop water stress during the irrigation campaign. It may be also an interest to quantify, at least in terms of order of magnitude, the differences in water

withdrawals and discharges related to each of the coordination scenarios. Finally, as agricultural yield can be simulated by the crop model with extra parameters (e.g. plot density) it is possible to establish the link between the maximum plant water stress that has occurred during an irrigation campaign and the final yield obtained. This could be also of interest to make a cost-benefit analysis of different solutions for irrigation.

6.4.3 Conclusion

In this study, we proposed the COPAT framework to tackle the management of irrigation when it depends on a collective water network, and the potential impacts on crop water stress due to the network operational constraints under coordination scenarios. COPAT relies on the coupling of a crop model at the plot level with an ABM at the network level. To make communicate these two models during the course of the simulation, we had to derive the crop model into a daily function, which made it possible to run it as a slave model of the ABM, and thus to give daily irrigation orders at the plot level according to the collective sharing of water in the ABM. We illustrated the framework on a gravity-fed network in Southern France on which COPAT allowed considering the network specific constraints and comparing two coordination scenarios. Simulation results suggest the importance of tackling the network level as plant water stress could be underestimated when simulated at the plot level because specific network constraints are missed. In particular, earlier average plant water stress and maximum stress severity when irrigation is not coordinated, while network coordination tends to limit the impact, notably for the plots located in the most downstream part of the network. COPAT also provides access to a tactical assessment of the spatial variability of plant water stress occurring during a collective irrigation campaign, and an explicit representation of irrigation operations allowing tracing-back, for instance, the missed irrigation operations due to insufficient network flow. Validating quantitatively the model output could be done by directly involving the stakeholders and collecting observations of irrigation on each plot, or by comparing with *LAI* retrieved from optical or remote sensing techniques.

6.4.4 Acknowledgment

The authors would like to thank the *Zone Atelier Bassin du Rhône (ZABR)* and *Agence de l'Eau Rhône-Méditerranée-Corse* for funding the RADHY Buëch project to which

TABLE 6.5: Characteristics of the 16 cereal plots

Plot id	Crop group	Crop type (2017)	Plot) area (ha)	irrigator id
1	Winter cereal	Triticale	0.55	1
2	Spring cereal	Oat	0.41	1
3	Winter cereal	Triticale	0.22	1
4	Winter cereal	Soft wheat	1.06	1
5	Winter cereal	Oat	1.01	2
6	Winter cereal	Oat	0.17	2
7	Winter cereal	Soft wheat	0.2	2
8	Spring cereal	Oat	0.52	2
9	Spring cereal	Oat	0.87	3
10	Winter cereal	Soft wheat	0.3	3
11	Spring cereal	Oat	0.37	3
12	Winter cereal	Triticale	0.56	3
13	Winter cereal	Soft wheat	0.55	4
14	Winter cereal	Barley	2.33	5
15	Winter cereal	Spelt	0.83	6
16	Winter cereal	Spelt	0.77	6

this work contributes. They also *AgroParisTech* for the funding of the PhD of the first author. We thank the *Société du Canal de Provence* for giving access to the soil database, and we thank *Météo-France* for providing the SAFRAN reanalysis. Authors are also grateful to the irrigators of Aspres-Sur-Buëch, all state services and associated structures of the Hautes-Alpes County, Claire Distinguin, for providing help during field surveys, and Jean-Claude Mailhol, for his explanations of the PILOTE model.

6.4.5 Appendices

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Chapter 7

COWAT: coupling water resources and agent trajectories

Contribution to the thesis project: In this previous chapter, we coupled the WatASit model with a crop model to simulate plant water stress at the plot level according to specific operational constraints for the sharing of water at the network level. In this chapter, which is a paper in preparation, we propose a method for coupling the WatASit model with a distributed hydrological model to account for the hydrological constraints at the network intake, and to integrate the impact of irrigator operations on the local hydrology. As we still have some tests to perform before this method is operational, we only present the method without examples of simulations. However, we identify the main issues of such a coupling and propose solutions to overcome them.

A method for coupling natural water resources and agent trajectories (COWAT) to consider their local interactions due to collective irrigation

7.1 Introduction

Among the various water uses, irrigation is often described as an important cause of water withdrawals (Foley et al., 2011, Godfray et al., 2010). Mutual influences of natural water resources and irrigation within a catchment relies in particular on multiple and diffused local interactions between hydrological processes and irrigation activities.

In the vein of “socio-hydrology”, several scholars have investigated the coupling between water resources and human activities to capture their mutual influences. Most studies are limited to unidirectional coupling, e.g. human activities towards water availability, or vice versa (Troy et al., 2015). When two-way coupling is implemented, it is in a continuous way and for a long-term simulation period (e.g. Fernald et al., 2015, Kandasamy et al., 2014, Pande and Ertsen, 2014). In such studies, modeling the local interactions with hydrology by considering the dynamic of human activities in a way that is not spatially centralized remains an open question (Sivapalan et al., 2012, Troy et al., 2015).

Hydrology involves natural processes that do not have necessarily the same geographical boundaries as human activities (Ehret et al., 2014). This is particularly the case for irrigation which results from networks of individuals operating at the level of the farm plot, the farm or the irrigation scheme. Cross-scale interactions with hydrology also imply various time scales from sub-daily to pluri-annual time steps (Sivapalan, 2015). Natural hydrological processes do not therefore necessarily match with the scales meaningful for irrigation, with a variety of heterogeneous spatio-temporal scales to be considered (Blair and Buytaert, 2016). In recent years, the Hydrology community has developed numerous distributed models to better integrate the spatial heterogeneity of the natural processes due to their physical aspects. Such models allow taking into consideration local biophysical specificity such as hydro-geology, land use, soil type or climatic forcing. Their emergence represents an important step forward in terms of coupling possibilities in the various locations where irrigation activities evolved differently over time, but not separately from hydrological processes.

As agent-based models (ABMs) are valuable tools to tackle local human activities, researchers make extensive use of ABMs to model human interactions with natural resources (An, 2012, Bousquet and Le Page, 2004, Filatova et al., 2009, 2013). Besides, the joint use of ABMs allowing a local representation of human activities, with distributed hydrological models representing locally the natural hydrological processes, is a promising approach clearly identified in the literature (Vogel et al., 2015), and still in infancy.

Over the past decade, few scholars have investigated it. Among them van Oel et al. (2010) have provided a good example of an ABM integrating a semi-distributed hydrological modeling approach for tackling the feedback between water resource availability and water use in the semi-arid Jaguaribe River Basin (Brazil). Indeed, the ABSTRACT model (Agent-Based Simulation Tool for Resource Allocation in a Catchment), developed with the Common Pool Resources and Multi-Agents System (CORMAS) platform for agent-based modeling and simulation (Bousquet et al., 1998), represents the river by a sequence of branches. Each branch receives water from its upstream river branch or branches and from irrigation grid cells that provide runoff and return flows. A water balance, expressed as mass conservation equation, is simulated on each grid cell and takes into account the soil and crop characteristics. Water demand by farmers on each irrigation grid cell is computed at a 10-days time step, in the same way as for the CatchScape model developed by Becu et al. (2003). Three irrigation areas were considered: upstream irrigation area, downstream irrigation area and floodplain irrigation area. Each irrigation area contains a collection of farm household. Farming household agents of each irrigation area shared similar crop distribution, decision-making and irrigation technology, as, on the local scale, the exact geographical location of agricultural activities was unknown. In addition, upstream irrigation area relied on an irrigation scheme of which the canal network had not been represented explicitly. The model allowed representing local water use of farmers that both respond to and modify the spatial and temporal distribution of water resources in a river basin. However, specific network constraints operating at the daily or sub-daily time step could be missing for other case studies in which the sharing of water strongly depends of the internal network functioning (e.g. Richard et al., 2020a).

In this context, the objective of this chapter is to propose a method to locally consider the mutual influences between natural water resources and collective irrigation at the operational level. Rather than integrating individual model components in a single modeling and simulation software, we opted for a more modular coupling method already explored for coupling an ABM with a crop model (Richard et al., 2020d). The main advantage is that there is no need of recording components that can lead to model simplifications (e.g. Berger et al., 2007, Schreinemachers et al., 2007) and could alter the model's ability to fully capture interactions. Therefore, we used the WatASit ABM, used for example in Richard et al. (2020a) to simulate irrigation operations of a gravity-fed network during a collective irrigation campaign, and the distributed hydrological model J2000 (Branger et al., 2013, Krause et al., 2006).

J2000 is a distributed model developed at the University of Jena, Germany, and usually used with a daily fixed time step. It relies on the *Hydrological Response Unit* concept (HRU, see Flügel, 1995) for making space discrete and to split the river in river reaches. Indeed, J2000 is fully distributed, as distinct from lumped or semi-distributed models that are also commonly used, such as SWAT (Bormann et al., 2009, Miller et al., 2002), HEC-HMS (Ali et al., 2011, Beighley et al., 2003) or HSPF (Brun and Band, 2000, Im et al., 2003). J2000 also gives access to the components of flow (e.g. surface runoff, base-flow) at each time step. This is particularly interesting to provide local modifications of the hydrographic network due to irrigation withdrawals and discharges simulated at the same location by WatASit. In addition, J2000 and WatASit are freely available and open-source, within the JAMS modeling platform (Kralisch et al., 2007) and the CORMAS multi-agent platform (Bommel et al., 2015) respectively. In fact, JAMS has a good potential of customization for coupling purposes due to its modular design.

The chapter first presents the material: the two models to be coupled (Section 7.2.1) and application site and available data (Section 7.2.2). Second, the concept of the coupling is described (Section 7.3) before detailing the models' spatial modifications (Section 7.4) and time modifications and scheduling (Section 7.5) to make communicate the two models together. Then, we discuss the ability of the method to locally entail the mutual influences between natural water resources and collective irrigation (Section 7.6) before concluding.

7.2 Material

7.2.1 Models

7.2.1.1 J2000

The basic principle of J2000 is to cut out a watershed into a partition of place units supposed to be homogeneous in terms of hydrological processes called the *Hydrological Response Units* (HRU) and to simulate hydrological processes on these HRUs. The geographical part of the HRUs are represented by irregular polygons delineated by geographical information system (GIS) analysis from biophysical properties of the watershed such as topography, soils, geology, precipitation and land cover using an in-depth hydrological systems analysis (Flügel, 1995). The HRUs preserve the three-dimensional heterogeneity of the drainage basin (Flügel, 1995). The J2000 distributed hydrological model (Krause, 2002) used in this study is implemented within the JAMS modeling framework (Kralisch et al., 2007) and available under an open-source license.

JAMS has a modular architecture base on contexts and components. A context gathers a list of variables and an ordered sequence of components (or other contexts). A component specifies a set of reading and writing variables and two functions *init* and *run* that specify a set of operations to perform on writing variables at initialization of the model and then at each call of the component respectively. Building a JAMS model starts by assembling components in contexts and for each component of a context, making a link between variables of the context and variables of a component so that the component has access in reading or writing to some of the variables of the context it is included in.

A set of components are used in J2000. They may implement either a generic operation related to software engineering and dedicated to be specialized (such as the *Precip-DataReader* component that specializes the *DataReader* component and is used at each time step to read climate input for instance) or a physical process (such as the *VegetationInterception* component) that can also be modified if needed. During the simulation

execution, components are called in the specified order and state variables of each context are modified accordingly.

Three special kind of contexts are used in J2000: the model context, the temporal context and the spatial context. The model context is the most general context that groups all other contexts of the model and contains global variables. The temporal context is used for iteration within a defined time interval (*time loop*). Then, within the temporal context, the spatial context is used for iteration over spatial places. Two kinds of spatial context are used, one for HRUs (the iteration over HRUs is called the *HRU loop*) and one for the reaches (the iteration over HRUs is called the *reach loop*). The execution of spatial context is organized from upstream to downstream and specific *dataTransfer* components are used to transfer outflow from the spatial context of an upstream entity into inflow of the spatial context of the corresponding downstream entities. Components and contexts of J2000 are presented in Figure 7.1. We see that the *HRU loop* is performed first so during the *reach loop*, when iterating on a reach, inflow from the upstream reach and from the neighboring HRUs can be used to compute the reach outflow. With this architecture, the hydrological processes such as *vegetation*, *soil* or other biophysical processes are specified as J2000 components of the HRU context.

J2000 uses five components based on physical processes as shown in Figure 7.2: *vegetation*, *snow*, *soil water*, *groundwater* and *flow routing*, which are described in details in Krause (2002) and Krause et al. (2006). In this study, we used the version previously used and described by Horner et al. (2020) at the daily time step. The vegetation module distinguishes net rain from snow and from precipitation intercepted by the plant for transpiration according to a *LAI* lumped parameter specific to the land cover class of the HRU. The soil water module is made of two storage compartments partitioning the soil porosity into the middle pore storage (*MPS*) and the large pore storage (*LPS*). The infiltrated water is distributed in these two storage compartments according to the *MPS* saturation level and a distribution coefficient. Water in the *MPS* can only be transpired by the plants. Water in the *LPS* flows with gravity and can be distributed to the *MPS* according to a diffusion coefficient and the *MPS* saturation. The groundwater module is made of a storage representing fast and slow reacting groundwater compartments. Percolation water is distributed in these storage compartments according to the

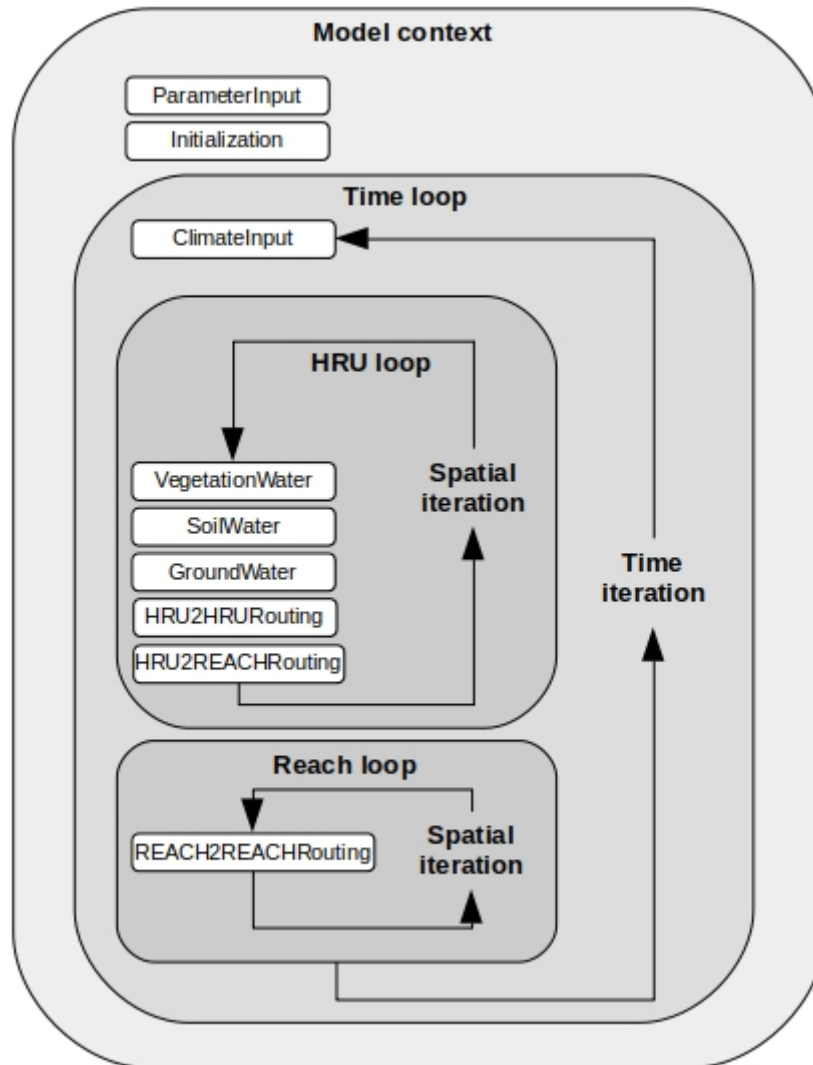


FIGURE 7.1: The J2000 components within spatial and temporal contexts.

HRU slope and a distribution coefficient. The flow components distinguish direct surface runoff ($RD1$) resulting of saturation excess or infiltration excess, interflow ($RD2$) which is the sub-surface flow by excess of percolation, and baseflow (RG). At each time step, the outflows of each HRU are routed laterally to the connected neighboring HRU according to the spatial routing scheme, until the channel network is reached. The flow routing module then transfers water from reach to reach using a simplified kinematic wave approach. J2000 also allows the identification of flow components at each HRU and each point of the river. Another version of J2000 including water uses exists but was not used in this work.

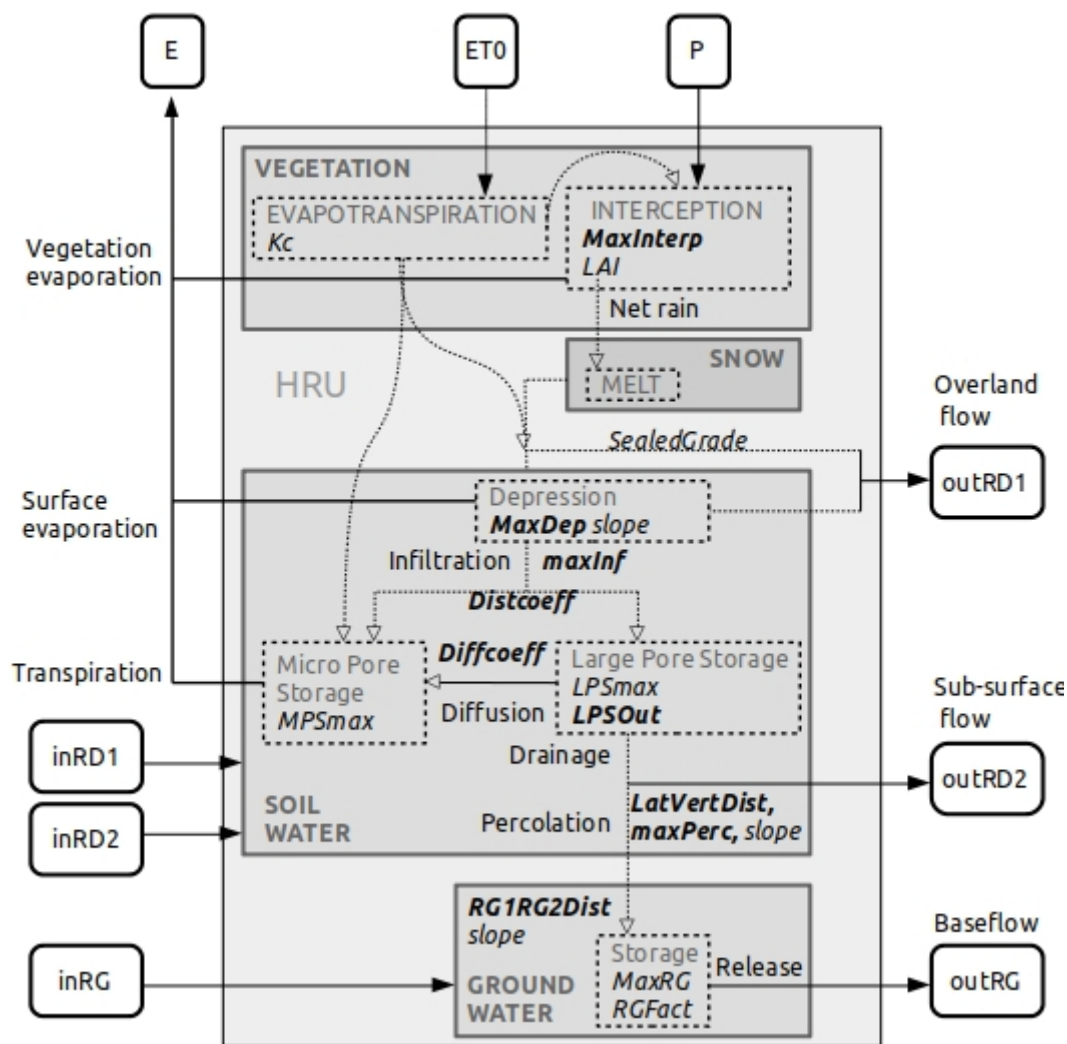


FIGURE 7.2: Schematic of the J2000 model showing the two storage, the input and output flows for one HRU and the main parameters (italic). Parameters indicated in bold are lumped (1 value for the whole catchment), whereas the other parameters are distributed.

7.2.1.2 WatASit

The WatASit ABM is designed to simulate the irrigation operations of irrigators sharing a common water network during a collective irrigation campaign. The model is based on the distinction between the elements that are involved in irrigation operations (called operational entities), such as the irrigators, the crops or the irrigation infrastructure, and the areas over which operational entities can operate (called spatial entities). A third kind of entity (called artifact entities) explicitly represents the abstract possibilities of irrigation.

The spatial entities have 4 hierarchical levels (see Figure 4.1). The spatial places represent the smallest landscape unit and thus the elementary spatial level. The farm plots are made of one or several spatial places and have an area attribute. The farms, at which level irrigation decisions are made by the irrigator agents mobilizing their irrigation strategy, 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.

Spatial entities are occupied by operational entities that physically represent the irrigators and passive objects (i.e. crops, floodgates, branches of the network). 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. Actuators are entities that are a source of interaction with a passive object as they can carry out actions. Passive objects are entities that are the target of an interaction with an actuator, which is necessary to carry out an action. The artifact entities explicitly represent abstract things of the real world such as action possibilities (called “affordances”) and actions. Possibilities of irrigation thus result from the interactions between the actuator (i.e. the irrigator) and a passive object (i.e. an irrigation equipment). They can interact according to conditions that define the situation of interaction. If conditions are fulfilled, an irrigation possibility is generated. Among the possibilities, the chosen one becomes an irrigation action. Artifacts are reified on each farm by dedicated entities called situation controllers.

The model is based on a double time step. Each day, there is first initialization of the current precipitation and irrigation restriction conditions, and also of the number of days since the crops have not been irrigated. Then, every hour, the flow rate is updated in the network according to network junction state (i.e. opened or closed) and ended actions. Irrigation options are then generated on each farm according to the states of actuators and passive objects. Depending on the actuator operational strategy, an option can be chosen to make an irrigation action or ask more water in the canal.

7.2.2 Application site and available data

The Grand Buëch catchment (336 km²) is located in an area of medium mountains (southern foothills of the Alps range), and close to the city of Gap, France (Figure 7.3). It is part of the French rural areas, with a population density of 14.4 inhabitants per square kilometer (against 105.8 on average in France). The upstream part of the basin is limited by a range of mountains culminating at 2000 m and covered by deciduous and coniferous forest, grasslands, lawns and mineral surfaces on steep slopes. The downstream part is differentiated by the presence of winter and spring crops, and urbanized or commercial areas. The outlet of the catchment is the confluence with the Petit Buëch river at the elevation of 680 m. The geology consists of Jurassic limestone, with fluvial-glacial deposits in the downstream part leading to a limited soil water storage capacity. The Grand Buëch catchment is subject to severe low flow periods, with a minimum monthly flow with a 1/5 probability of not being exceeded ($QMNA5$) of 1.1 m³s⁻¹, and that can lead to water use restrictions (Sauquet et al., 2019). The time it takes for a water particle from the part of the basin that is farthest from the outlet to reach the outlet (concentration time) is 13 hours (Gautier, 1992).

Surface irrigation dominates and consists of irrigator unions managing collective gravity-fed networks of canals. The irrigator union of Aspres-Sur-Buëch is fairly representative of such collective surface irrigation, with an irrigable surface area of 75 ha (the average is 50 ha per irrigator union), and crop types (38.9% meadows, 29.5% fodders and 23.7% cereals), and was chosen as application case. It includes 74 farm plots irrigated within the collective gravity-fed network by 10 irrigators.

The catchment is not permanently gauged, as there is no fixed hydrological station but gauges are installed temporarily during low-flow periods between May and September since 2017 (their data are not yet validated). For climatic data, the SAFRAN reanalysis database (Vidal et al., 2010) was obtained from *Météo-France* on an 8*8 km² grid from 2005 to 2017. The GIS data used in this study are a digital elevation model (DEM) with 25 m resolution from IGN BDTopo database, a soil map described in Braud et al. (2013) from the *PACA Regional Soil Reference System* (RSRS), and geology map described in Wasson et al. (2002) in the scale of 1:250,000 from the Hydro-eco-region database

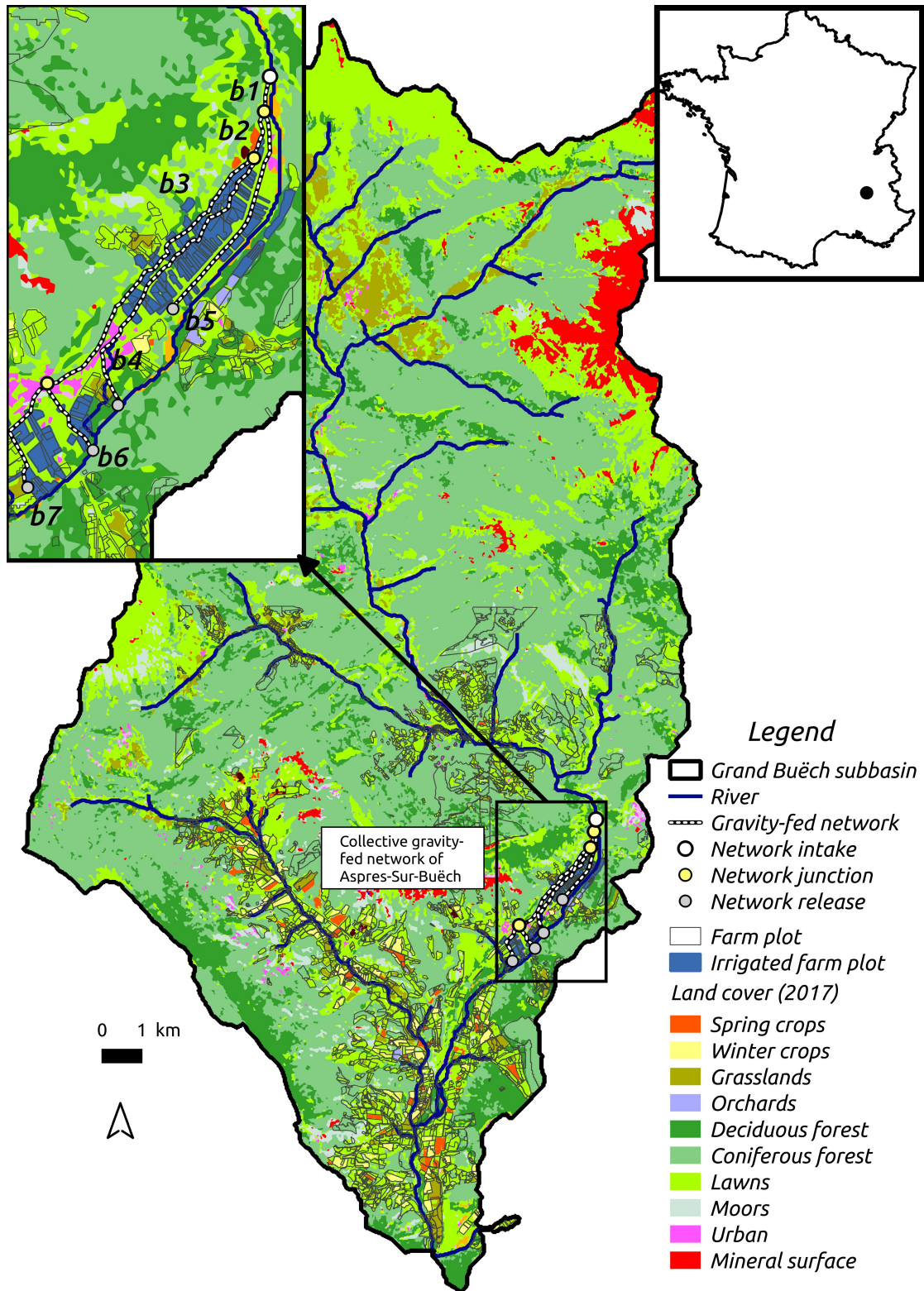


FIGURE 7.3: Situation map of the Grand Buëch catchment, representing landcover from Sentinel-2 data at 10m resolution, the river from BD Carthage, the irrigator union and gravity-fed network of Aspres-Sur-Buëch (see the zoom in the insert at the top left) from BD Hydra and the farm plots from RPG (2017). *Italic bolder labels $b1$ to $b7$ indicates the canal branches.*

(HydroEco). The river network was obtained from the French national database BD CARTHAGE. Land cover was furnished through the Sentinel-2 database at 10 m resolution. The farm plots shapefiles and crop types are derived from the 2017 French “*Registre Parcellaire Graphique*” database. This data-set has been crossed with the *HYDRA database* (HYDRAv2 2015), which contains irrigator union shapefiles (i.e. irrigated perimeter areas) and hydraulic network shape files (i.e. network intakes, branches, junctions and rejects) to identify farm plots served by the collective irrigated perimeters.

The WatASit ABM has been already deployed on the Aspres-Sur-Buëch case study (Richard et al., 2020a) in which the model and the parameterization for the case study is fully detailed.

7.3 Concept of the coupling

7.3.1 Coupling objectives

The coupling between the models has three objectives:

- To take into account the local hydrological constraint at the level of the water intake of the irrigation network represented in WatASit in relation with the hydrology at the basin scale,
- To take into account in J2000 the diversion of part of the river flow by the irrigation network and its consequences on the different components of the HRU and reach flow (i.e. *RD1*, *RD2* and *RG*),
- To observe the influence of the plot flooding and irrigation returns for the recharge of soil water and groundwater on the reach flow.

7.3.2 Coupling stages and requirements

We implemented the coupling (Figure 7.4) at the daily time step through 4 stages.

Figure 7.4 [1] shows that first stage: at the beginning of each time step, first, natural hydrology is simulated in J2000 according to the HRU to HRU, HRU to reach and reach to reach topological links.

In the second stage, the daily flow simulated by J2000 of the reach interacting with the intake of the water network is set in WatASit (Figure 7.4 [2]). It requires to specify a new type of spatial entity in WatASit to represent the river reach and to constrain the intake flow depending on its flow. It also requires to be able to transfer information from J2000 to WatASit at each daily time step, and thus to stop and restart J2000 during the course of the simulation without losing in memory the values of the model's state variables. This is not possible with the current version of the model as developed by its authors.

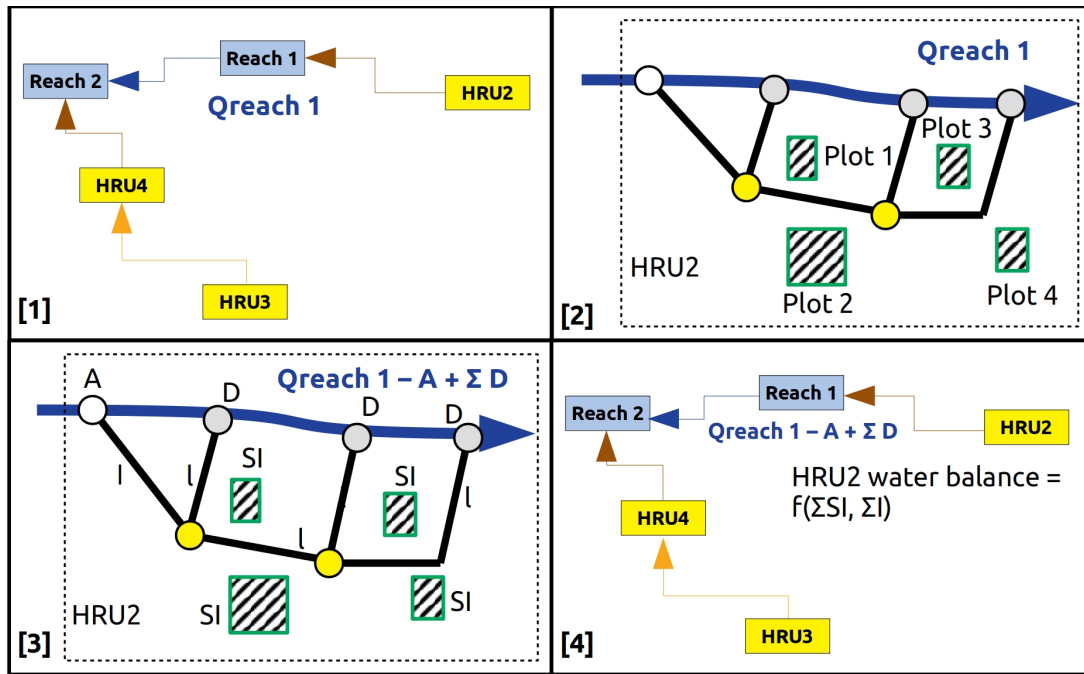
At the third stage (Figure 7.4 [3]), the WatASit model simulates 24 hourly sub-step of the day, and computes daily sums of network abstraction (A) from the river network, surface irrigation (SI) at the level of each plot, network discharge to the river (D), and infiltration seepage (I) of each network branches. It requires to assume that the river flow is constant during the day, and that all water withdrawals by the network either became irrigated or infiltrated, or returned to the river, in order to verify:

$$A - (\sum SI + \sum I + \sum D) = 0 \quad (7.1)$$

Note that the evaporation of water within the irrigation network could not be represented due to the simplified network representation in the WatASit network sub-model. After this step, the new daily flow of the river reach is modified as follows:

$$Qreach_{new} = Qreach - A + \sum D \quad (7.2)$$

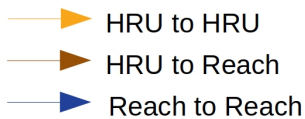
During the last stage (Figure 7.4 [4]), we inform each entity of J2000 of the perturbations they are subjected to for this new daily time step: *river reaches* must include in and out water flows from WatASit canals, and HRUS must include the I and SI inflows in their water balance. Then, the $Qreach$ computed in the first stage of the next daily step



J2000 concepts :



Topology type :



WatASit concepts :

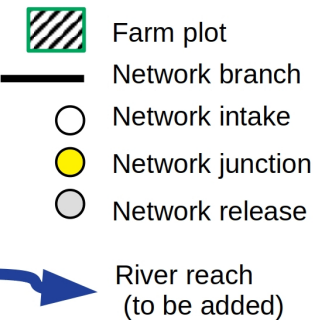


FIGURE 7.4: Schematic view of J2000 and WatASit concepts in the four coupling stages (i.e. [1], [2], [3] and [4]) to be realized at each daily time step. Qreach is the sum of reach flow components $RD1$, $RD2$ and RG . A is the network abstraction. SI is the surface irrigation at each plot level. I is the infiltration due to branch seepage. D is the network discharge to the river.

(Figure 7.4 [1]) will include both natural and irrigation related processes. Note that Figure 7.4 is a schematic representation as HRU2 might not be the only one interacting with the irrigation scheme. It requires being able to transfer information from WatASit to J2000. In addition, the model must be modified so that it becomes possible to change the variables of the HRU water balance without changing its operating mode. Overall, the concept of HRU relies on homogeneous hydrological processes over a spatial unit. However the farm plots are not homogeneous in terms of hydrological processes and daily irrigation computed at their level cannot simply be transferred to the HRU where they are located. In order to maintain homogeneous hydrological processes at the plot

TABLE 7.1: Name, type and unit of the coupling variables with respect to each model definitions. Arrows show the direction of the transfer of information for each variable.

	J2000	Coupling direction stage	WatASit
<i>Variable name</i>	Runoff	[2] →	Q
<i>Unit</i>	L d ⁻¹		m ³ s ⁻¹
<i>Model component/class and context</i>	REACHtoREACH Routing Reach loop	← [4]	RiverReach Spatial entities
<i>Variable name</i>	netRain	← [4]	irriDailyDose
<i>Unit</i>	mm		mm
<i>Model component/class and context</i>	Vegetation HRU loop		Farm plot Spatial entities
<i>Variable name</i>	infiltration	← [4]	seepage
<i>Unit</i>	L d ⁻¹		m ³ s ⁻¹
<i>Model component/class and context</i>	SoilWater HRU loop		Network branch Operational entities

level where irrigation is computed, HRUs must be defined consistently with the WatASit plots. This requires refining the HRUs in the J2000 model.

7.3.3 Coupling variables

Table 7.1 presents the variables to be coupled for implementing the four stages presented in the section above. At stages [1] and [4], *Runoff* is the variable in J2000 representing, in each river reach, the total flow resulting from the sum of the *RD1*, *RD2* and *RG* components (see Figure 7.2). At stage [4], *net rain* is the variable in J2000 representing the precipitation after retrieving the part intercepted by the vegetation. We assume that surface irrigation by flooding a plot is not intercepted by the vegetation cover and we therefore consider it as net rain. *Infiltration* is the variable in J2000 representing the amount of water entering into the soil. We considered the seepage from the network branches as part of the water infiltrating the soil.

7.4 Models' spatial modifications

7.4.1 Overview of J2000 and WatASit spatial editing

Figure 7.5 presents the key steps for the spatial editing of the two models. At step 2 of the J2000 editing (blue boxes), the original SENTINEL-2 land cover map contains 17 classes that were reclassified to have common classes with RPG crop classes used in the WatASit model. We obtained 14 common land classes presented in the following in Figure ?? (a). Each class requires monthly *Leaf Area Index (LAI)* parameters and crop coefficients (Kc). Kc were obtained from FAO (1998), and LAI from the ECOCLIMAP database (Faroux et al., 2013). Step 3 of the J2000 editing for generating the HRU mesh and the HRUs/river reach topology is presented in detail in the next section. Note that each soil class (Figure ?? b) requires information about the soil depth, porosity and field capacity. These parameters were estimated using a method presented in Manus et al. (2009) and are described in Braud et al. (2013). In addition, river reach width was set up according to the IGN CARTO database, which includes river sections different from river reaches of J2000 and which indicates for each section a width class (0 to 15 m and 15 to 50 m). We considered a width of 7.5 m or 32.5 m for the river reaches of J2000 that were superimposed on a section of the IGN base having a 0 to 15 m width class or 15 to 50 m, respectively. Step 2 of the WatASit editing is also further detailed in Section 7.4.3.

7.4.2 HRU delineation in J2000

In order to keep the hydrological model mesh consistent with the spatial scale of irrigated farm plots in WatASit, we investigated two methods for HRU delineation: size reduction and the concept of HRU-plot.

7.4.2.1 HRU delineation method 1: size reduction

In this section we investigate the influence of HRU delineation key parameters for having HRU areas coincident with farm plots areas. First, natural sub-basins were delineated using a classic stream burning algorithm as described in Branger et al. (2013). We then operated an overlay of land use, geology, soil and DEM GIS layers (Table 7.2) to

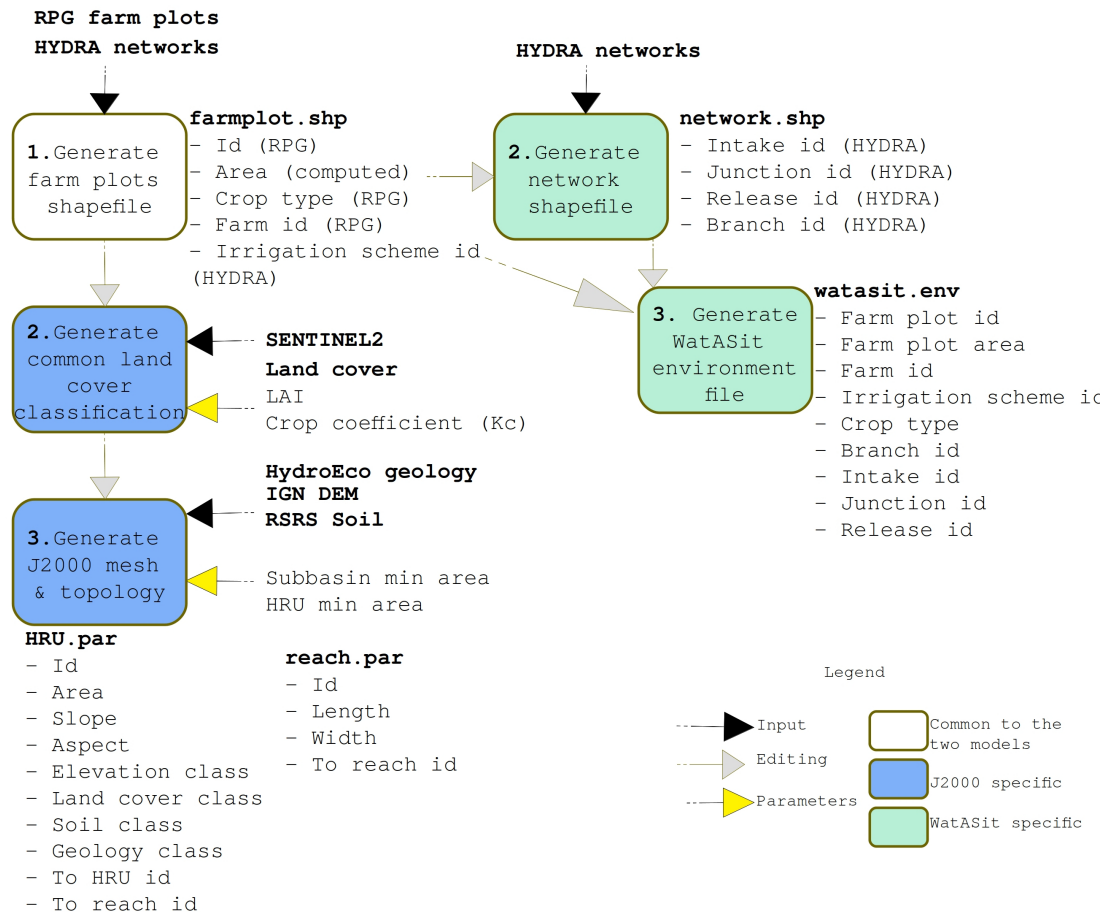


FIGURE 7.5: Key steps of J2000 and WatASit spatial editing.

delineate HRU. This overlay operation is mainly controlled by two parameters: *subbasin_min_area* and *HRU_min_area*. We compared resulting mean HRUs area of each case while modifying one parameter at a time (Table 7.3).

Figure 7.6 shows the resulting box-plots of HRUs area for each delineation case with respect to the farm plots area. The lowest median area of 0.18 km² was obtained for case 8 (see Table 7.3 for case description) but was still much larger than the farm plots median area (about 0.02 km²). Moreover, several delineation errors were observed (i.e. topological gaps) in cases 4, 7 and 8 (Figure 7.6) and it was not possible to make other cases with finer spatial delineation. Consequently, it was not possible to get HRU size converging with farm plot areas. In the following, we use the case 6 which has the most finest HRU delineation without topological errors. Case 6 has 495 original HRUs covering the Grand Buëch basin with an average area of 0.65 km².

TABLE 7.2: SIG layers for the overlay operation to delineate HRUs.

Layers to be overlaid	Data source
DEM	IGN 25m resolution
Land use	SENTINEL 2 (13 classes) 10m resolution
Geology	HydroEco (8 classes) 1:1 000 000
Soil	SRSR (8 classes) 1:250 000

TABLE 7.3: Experience plan for HRU delineation according to *subbasin_min_area* and *HRU_min_area* parameters of overlaying processes.

Case	<i>subbasin_min_area</i> (A) (km ²)	<i>HRU_min_area</i> (B) (km ²)
Case 1	A = 5	B = A / 2
Case 2	A = 5	B = A / 5
Case 3	A = 5	B = A / 10
Case 4	A = 5	B = A / 20
Case 5	A = 2.5	B = A / 2
Case 6	A = 2.5	B = A / 5
Case 7	A = 2.5	B = A / 10
Case 8	A = 2.5	B = A / 20

7.4.2.2 HRU delineation method 2: concept of HRU-plot

As it was not possible to get HRUs having similar sizes as the farm plots areas, we present in this section the concept of HRU-plot to describe farm plots of WatASit as HRUs in J2000. For the original HRUs obtained in case 6 (see previous section) containing farm plots, each farm plot became a HRU that we called HRU-plot. These HRU-plots are topologically connected to the original HRU from which they inherited (Figure 7.7 top). We thus assume that HRU-plots drain into their original HRU. We distinguish two cases:

- If a farm plot is contained in a HRU, it inherits the characteristics (i.e. elevation, slope, aspect values and geology, land cover and soil classes) of the HRU except the area. This is the case of plots 1, 2 and 3 in Figure 7.7 (bottom),
- If a farm plot crosses two original HRUs, the farm plot is divided into two separate HRU-plots. Each new HRU-plot inherits the characteristics of its original HRU, except area. This is the case of plot 4 in Figure 7.7 (bottom).

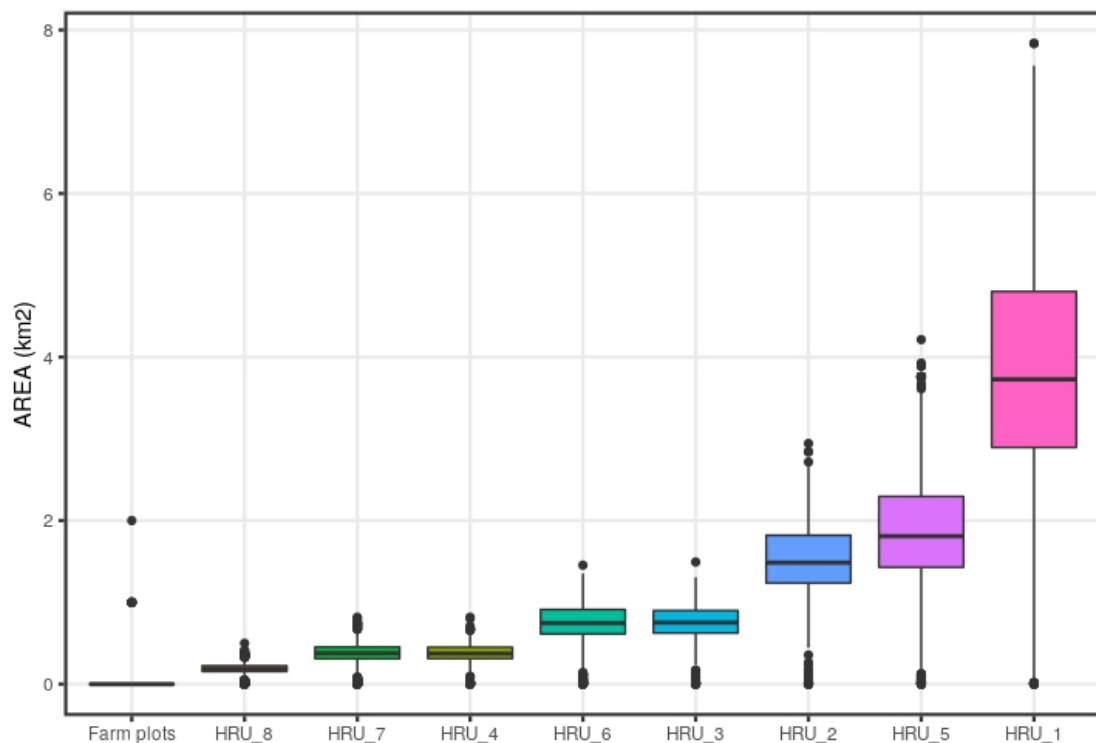


FIGURE 7.6: Boxplots of farm plots and HRUs areas for each of the 8 delineation cases.

The original HRUs were reduced to their part that does not contain a farm plot, called “HRU-truncated”, which sometimes resulted in dividing the original HRU into several truncated HRUs. New areas of truncated HRUs and HRU-plots were computed. HRUs not containing farm plots remained unchanged.

Truncated HRUs and HRU-plots were then merged to get a new mesh taking into account the spatial limits of the farm plots. We obtained a total number of 3297 HRUs of which 2802 were HRU-plots with an average area of 0.02 km^2 . The river network was also made discretized into 162 reaches with an average length of 0.89 km. Having smaller reaches helps to account for the water intake location of the irrigation network. The truncated HRUs were connected topologically to the downstream original HRUs or river reach they drain into. The final HRU and river reach map is shown in Figure ?? with their characteristics (i.e. land use, soil, geology and slope classes) from original GIS layers are shown in Figure ??.

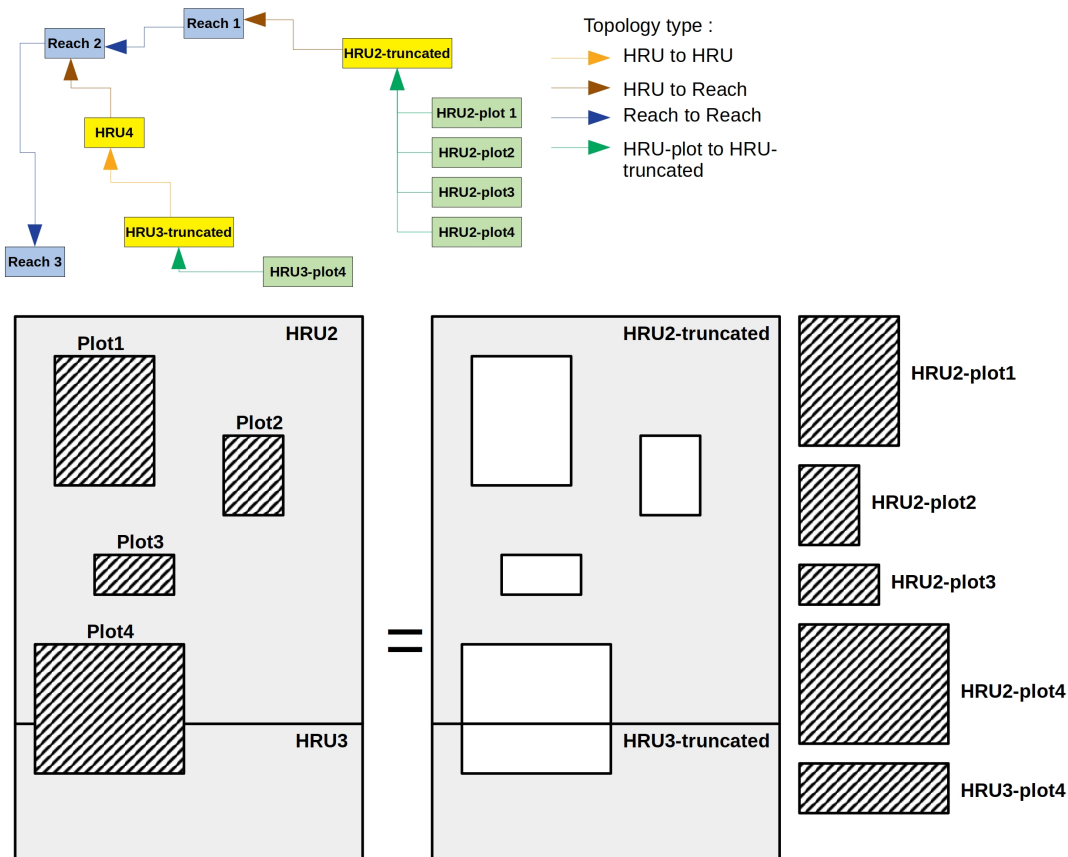


FIGURE 7.7: The HRU-plot concept. Top: the topology types integrating the new HRU-plot to HRU-truncated topological link. Bottom: View of the HRU and plot transformation due to the HRU-plot and HRU-truncated concepts.

7.4.3 Specification of a new spatial entity in WatASit

In order to represent in WatASit the river reaches conceptualized in J2000, we specified a new type of spatial entity in the WatASit model (Figure ??). To encompass all the river reaches of the Grand Buëch catchment, we had to modify the size of the cellgrid to comply with the basin size. We used a grid of 452x561 cells (Figure ??), instead of 54x44 in the original WatASit version, with a resolution of 50m, by aggregating twice the initial resolution of the river reaches used in J2000 (25m), as it was not technically possible to keep such resolution due to the CORMAS platform limitations in terms of graphic representation. Doing this, we missed some of the farm plots smaller than 50x50 m², which are representing less than 10% of the farm plots within the catchment, with three of them located in the Aspres-Sur-Buëch irrigation area.

To constrain the flow entering the network at the intake, we also wrote a new method of the Network intake class in WatASit. In order to maintain aquatic and riparian life, the flow at the entrance of the network is limited to the 9/10 of the flow of the river reach. Thus the flow at the entrance of the network is computed as the minimum between an optimal flow value calibrated empirically by the irrigators at the water intake and the 9/10 of the flow of the river reach where the water intake is located.

7.5 Model's temporal modifications and coupling scheduling

7.5.1 From J2000 to J2000-D

As stages 2 and 4 require to make communicate J2000 and WatASit, it must be possible to modify the state variables values of both models during the course of the simulation. For WatASit, the *Rcormas*¹ *Application Programming Interface* (API) allows getting and setting values of model attributes without stopping the course of the simulation in CORMAS. But this is not the case for J2000 which is usually used without interruption over the whole simulation period.

In order to allow forcing or retrieving J2000 state variables at each daily time step while a stimulation is running, we developed the J2000-D (D for daily) version of the model. Figure ?? shows the modifications made in J2000-D with respect to the original J2000 model architecture. It mainly relies on the addition in the model context of the *CouplingCommunication* module in the time loop context. This module can access the HRU and reach sub-spatial contexts through specific modules called in each spatial context (*HRUVariablesChanger* and *REACHInOutChanger*). This allows modifying and retrieving HRU and reach variables at any time. It also enables, via a socket communication protocol², to import and export information with an external source as required for stages 2 and 4 of the coupling (see Table 7.1).

¹Rcormas is available at <https://gitlab.irstea.fr/cormas-dev/r-cormas>

²A detailed description can be found at <https://gitlab.irstea.fr/watasitdev/j2k-coupling/-/wikis/home>, and the java code is available at <https://gitlab.irstea.fr/watasitdev/j2k-coupling/-/tree/master/modules>

In addition, we added the *ExternalSurfaceIrrigationApplication* module in the *HRU loop context*. This module links the *irriDailyDose* variable of the *Farm plot* entities of WatASit to the *netRain* variables of the HRU units in J2000, as required for stage 4 of the coupling. We also added the *ExternalInfiltrationApplication* module in the HRU loop context to connect the *seepage* variable of the *Network branch* entities of WatASit with the *infiltration* variable of HRU units. Finally, we added the *BuechReachInOut* in the *reach loop* spatial context in order to connect the WatASit flows at the network intake and releases to the *runoff* variable of J2000 reaches. Since these modules represent disruptions to the natural hydrological processes we call them disruption modules in the following.

7.5.2 Scheduling of the coupling

A daily time step was chosen for the hydrological model simulations and for the coupling time step with the WatASit model. Although WatASit incorporates an hourly time step, it has only informative value for distributing the duration of the irrigation operations, but cannot correspond precisely to a schedule of the day. If the hourly processes in WatASit are indeed necessary as an internal time step, the simulated irrigation correspond to daily balances at the level of each plot. In addition, the flow entering into the network intake is mainly constrained by low river flow of which significant variations are seasonal (Sauquet, 2015) and not infra-day. It would therefore make little sense to use the hourly time step in the two models to make them communicate with each other. In addition, it would require significant adaptations in the J2000 model.

To schedule the 4 coupling stages, we chose to use the ABM as a daily sub-model of the hydrological model. We designed an API called *Rcoupler*³ (Figure ??) under the R software (RCoreTeam, 2018). The API allows to pilot both models. First, J2000 runs to simulate natural runoff during one daily time step (Figure ?? [1]). Second, *Rcoupler* interrupts the simulation and set runoff in the *River Reach* entities of WatASit (Figure ?? [2]). Third, WatASit simulates surface irrigation over 24 sub-daily time steps and computes daily balances for each reach and farm plots (Figure ?? [3]). Finally, *Rcoupler* sends instructions to the J2000 *CouplingCommunication* module in order to

³Available at <https://gitlab.irstea.fr/watasitdev/watasitrcoupler>

integrate daily irrigation doses (through the *dailyIrriDose* variable of WatASit) of farm plots and infiltration of network branches into equivalent HRU-plot of J2000, and the inflow and outflow from the WatASit network branches to the corresponding reaches in J2000 (Figure ?? [4]). To do this, the *CouplingCommunication* module first stores all these disruptions, for each HRU and each reach. Then, it runs the next daily time step of J2000. During the time step execution, each time a disruption module is called in its context, it refers to the *CouplingCommunication* module in order to get the value to apply for this time step for the entity of the spatial context. This allows respecting the upstream / downstream sequencing of operations representing hydrological processes, which is necessary to maintain the consistency of the model.

7.6 Conclusions and discussion

In this chapter, we investigated a coupling methodology to locally consider the mutual influences between natural water resources and collective irrigation at the operational level. We proposed four daily coupling stages allowing to take into account the hydrological constraint at the network intake in the ABM, and to incorporate water from irrigation into the HRU units and river reaches of the hydrological model. As discussed by [Cumming et al. \(2006\)](#), the modeling of interactions between "human" and "natural" components requires choosing the appropriate spatial and temporal scales.

Temporally, we assumed that the hydrological constraint of the network flow was mainly due to low flows with daily or longer dynamics. We therefore used a daily time step for updating the river reach flow interacting with the irrigation scheme in the ABM. By using a double time step, the ABM allowed complying with both the irrigator operations at the hourly time step and the network-river interactions at the daily time step. This temporal flexibility of the ABM to tackle short-term processes while representing human-nature interactions at another time-step is one of the challenge of the emergent "socio-hydrology" to address interactions between slow and fast processes including humans as endogenous to the system ([Sivapalan and Blöschl, 2015](#)). However, as we chose to couple the two models without merging their components, we had to make them communicate. The key was the derivation of the hydrological model into a daily version. It

required important modifications facilitated by the JAMS modular architecture. Without such architecture, it might not have been possible to force the hydrological model on a daily basis while keeping the distributed spatial routing from the upstream HRUs to the HRUs or river reaches downstream of the basin.

Spatially, we had to encompass three scales: the catchment scale for representing runoff drained from HRU units and river reaches of the whole catchment area into the local river reach, the irrigation scheme interacting with the local river reach and HRUs located at the same place, and the farm plots in which irrigation is operated. The concept of river reach from the hydrological model has been spatially represented in the ABM thanks to the specification of a new spatial entity type in the ABM. It allowed linking the world of agent-based modeling with an external concept coming from the world of hydrology to address local interaction between human (i.e. the irrigation scheme and its water intake) and nature (the river flow). Such flexibility of ABMs to encompass the various spatial scales of irrigated systems has been already highlighted by [Berger and Troost \(2014\)](#) while developing climate change mitigation options for agriculture. However, we had to make the farm plots spatially coherent with the HRUs to keep homogeneous their hydrological processes. Modifying spatially the hydrological model was not easy because it refers to a set of physical processes whose meaning are linked, in the case of HRUs, to their explicit spatial representation. By deriving farm plots as HRU-plots, we assumed that irrigation processes on farm plots have topological connections with the original HRUs. However, this derivation could have impacted the vertical flow processes of the HRUs, in particular the computation of the base-flow.

An important follow-up of this work is therefore to test the impact of the coupling methodology, in particular the concept of HRU-plots, on the water balance components of the catchment. In order to estimate the impact of the HRU spatial modifications, we could first compare the water balance terms with the original J2000 model at the catchment scale between a simulation with the initial HRU mesh and a simulation with the modified mesh including the HRU-plots. A further test to assess the impact of the temporal modifications could be to compare a coupled simulation (using the COWAT methodology between J2000-D and WatASit) without irrigation input with an uncoupled simulation (using only J2000-D with similar HRU mesh and topology). This could be

directly piloted from the *Rcoupler* API as the coupling with the ABM can be deactivated to pilot the hydrological model alone. For future research, the representation of the river reaches at the catchment scale in the ABM opens up possibilities for assessing the impact of several collective irrigation networks on natural hydrology at the operational level.

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used for tackling short-term interactions within entangled spatial scales (Section 8.2.1) and for documenting human and natural links by the interpretation of ABM outputs (Section 8.2.2). We also detailed their key limitations (Section 8.2.3). We carry on by discussing the specific requirements of model coupling (Section 8.3) before to come back to the case study (Section 8.4) to discuss the contribution of our work to irrigation management, and also the contribution of the case study to the design of our work. We also come back to the question of the interdisciplinarity in "socio-hydrology" and the positioning of our work in relation to this research community (Section 8.5). Finally, we propose some perspectives for improving or integrate our work with other existing approaches (Section 8.6).

8.2 A modular approach at the crossroad of irrigation scales and disciplines

8.2.1 Using complementary tools for addressing short-term interactions between irrigation and agro-hydrological processes within entangled spatial scales

The simulation of the mutual influences between human actions and natural resources such as water has progressed a lot over the last decades. The dynamic representation of these influences over time is one of the challenges facing the hydrological research community, notably under the aegis of the *International Association of Hydrological Sciences* (IAHS) (Montanari et al., 2013), but also of many other movements more or less far away in terms of scientific discipline and whose reflections share the same principles of integrated natural resource management. If long-term interactions, in a logic of foresight, are increasingly better represented and described, short-term interactions remain little explored.

In several fields, such as agriculture, there are many short-term interactions that can also impact the co-evolution of humans and natural resources. This is notably the case of interactions between water and agricultural activities, especially irrigation, in situations that are difficult to predict in advance during a crop campaign (Reynaud, 2008) and that

can significantly affect harvests. In such situations, the short-term interactions of irrigation actions and natural elements - plants, soils, local rainfall, local water availability - depend on the very local condition of the environment. Conversely, the state of these natural elements depends on the frequency and intensity of irrigation operations, but not only. Indeed, they are rooted in natural processes that are more widely distributed in space and that contribute to local modification of natural elements, and the human actions that depend on them.

These are, for example, processes that take place at the level of a plot and that condition the water available for plants and the plants' need for water (Jones, 1992). In Chapter 6 (see Figure 8.1, left-side), we have investigated such processes in the case of gravity-fed irrigation: the water available to plants at plot level results from the actions of the irrigators within the canal network, the processes of organizing these actions at the network level are also important. But the water received by the plant also depends on the plant processes, which in turn refers to the water cycle at the watershed scale. In addition, the network collects surface water in the river, which also results from the water cycle at the watershed scale. Representing dynamically in the short term the mutual influences between irrigation and the different components of the agro-hydrosystem in which it is inserted requires in fact to apprehend the local situations by taking into account the different scales of space and time of the natural processes and organization of the human actions on which they depend.

In this work, we first proposed to represent some short-term irrigation actions, at the operational level, i.e. at the moment when the decision confronts the range of possibilities according to the context of the moment. In order to represent this range of possibilities, we reviewed the approaches to the representation of human actions within ABM, which are widely used to represent the interactions between man and nature. Among the different approaches that exist (Chapter 2, see also Figure 8.1), some of them, still rather confidential, are interested in the possibilities perceived by an actor, according to the place where he is, the state of the objects present in this place with which he can interact, his understanding of these objects, and his capacities to act with them. This is the case of the concept of Affordance mobilized within the framework of the Theory

of Situated Action.

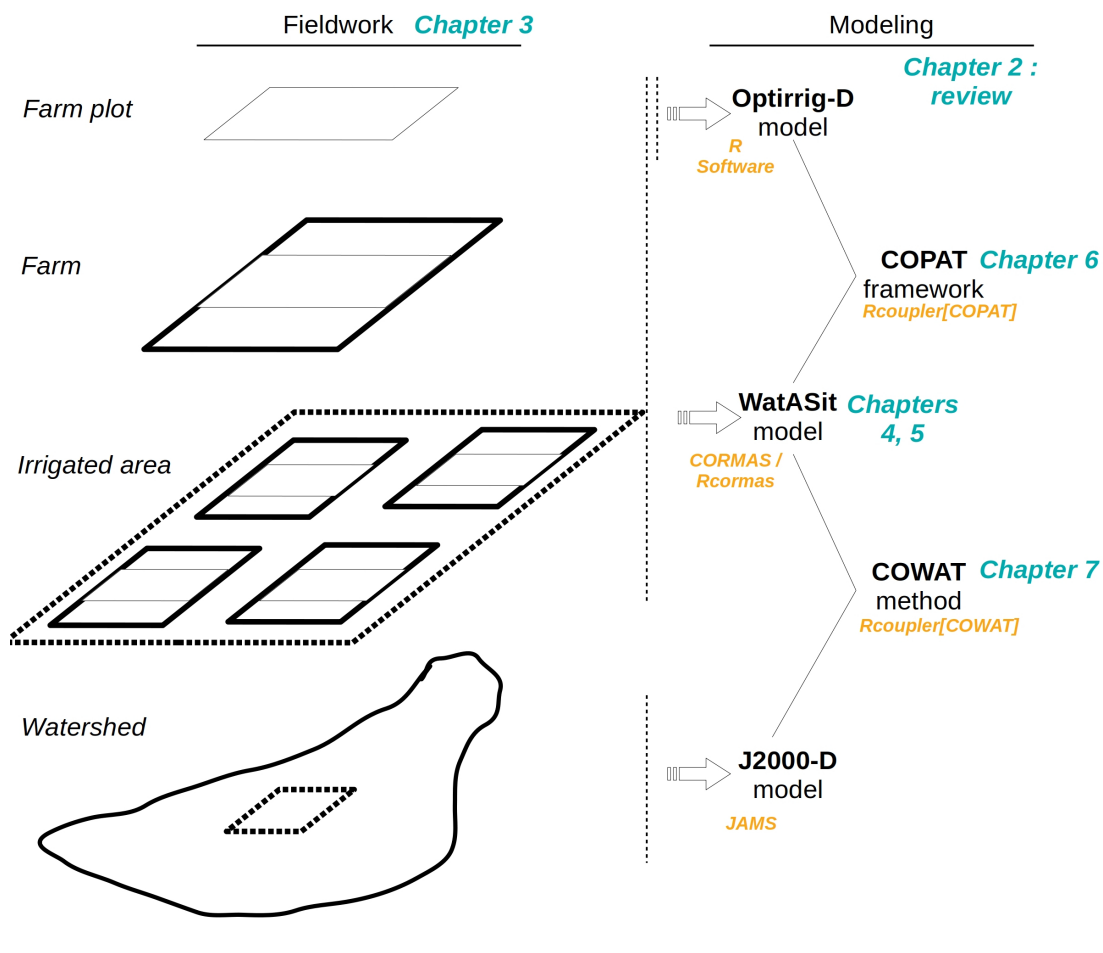


FIGURE 8.1: Overview of irrigation scales and the various tools used in the thesis work.

We have proposed the WatASit agent-based model that mobilizes this concept to clarify the operational possibilities of irrigators sharing their access to water through a common gravity-fed network (Chapters 4 and 5). The simulation of these possibilities during a representative irrigation campaign of a year with a low number of rainy days gave access to an intermediate level of agent trajectory analysis. Indeed, the simulation results are generally interpreted from indicators of the actual behavior of the agents during the simulation disregarding the possibilities they had. The analysis of possibilities provides information on the nature of the situations that led to the action. For example, we have observed that when the irrigator agents do not coordinate the common irrigation network, as is the case today in the case study we have explored in the Buëch River basin, irrigation difficulties are linked to a reduction in the possibilities of irrigation due to the insufficiency of the water resource supplied by the irrigation network in relation to

the surface area the network served. On the other hand, when the irrigators coordinate the network, the difficulties do not come from a lack of water, because the irrigation possibilities exist, but from an overload of work preventing the irrigator from operating all these possibilities in a short period of time (Chapter 5). In one case, the main constraint is thus spatial, whereas in the other it is rather temporal. In addition to helping in the interpretation of agents' trajectories, this intermediate level is a form of dynamic representation of agents' adaptations at the operational level over time. More precisely, it dynamically represents the range of possibilities with which the actor is confronted at the moment of acting. This range evolved during the simulation by increasing or decreasing at each simulation time step according to the biophysical conditions of the agent's environment. Therefore, it constitutes a first form of mutual interaction with the agent and reflects the potential of operational adaptation.

After having represented the trajectories of the agents with the WatASit model, we tried to represent the trajectories of the plants in a more realistic way. For this, we proposed the COPAT coupling framework (Chapter 6, see also Figure 8.1). This framework allowed to represent both the trajectories of the irrigating agents and the irrigated plants in a linked way. Indeed, each day the trajectories of the plants depend on the irrigation operations of the agents, and the irrigation of the agents took into account the history of the water inputs received by the plants of each plot (rainfall and irrigation), as well as their state of maturity to determine the end of irrigation. We thus related two complementary spatial scales: that of the plot and that of the irrigation network. This allowed us to take into account the organizational (coordination) and physical (water flow) constraints specific to the irrigation network, and to show the feasibility of evaluating their impact on the dynamics of some characteristics of the plants, such as water stress, during an irrigation campaign. In particular, an evaluation of the spatial distribution of stress (on each plot served by the network) at each daily time step, and at the end of the campaign, was made possible, depending on the coordination mode of the chosen network. To ensure the temporal consistency of the coupling between the two models, we had to derive the crop model as a daily function of the agent-based model.

We finally proposed the COWAT method to represent the trajectories of the agents considering the dynamics of the water resources (Chapter 7, Figure 8.1). On the one hand,

we wanted to take into account the influence of hydrological processes at the watershed scale on the water available at the catchment of the network in the river. On the other hand, we integrated the water transfers related to this catchment and to irrigation operations in the representation of water trajectories. While we have only proposed COWAT as a potential method, without supporting simulations, we have put forward points of vigilance for the coupling at a fine spatial scale of a distributed hydrological model and an agent-based model. In particular, a key difficulty is the local modification of hydrological units while preserving the upstream-downstream routing of these units at each time step. A second difficulty concerns the coherence of the concepts of each model for elements shared by the coupling. For example, we had to explicitly represent the plots in the hydrological model that did not represent them, reconciling their addition with the concept of homogeneous spatial units used by the hydrological model to describe the hydrological processes. We make a proposal around the hybrid concept of HRU-plot.

In the end, we have mobilized in this work concepts from several scientific disciplines, such as the concept of Affordance from cognitive sciences, and the concepts of plant water stress and hydrological response unit from agronomy and hydrology, respectively, which each bring a representation at their specific scale.

8.2.2 Documenting anthropogenic and natural causal links by (partially) facilitating the interpretation of ABM outputs

Among the specificities of the tools we used, we have based our representation of human behavior on an agent-based modeling approach which is sometimes penalized by the complexity and opacity of these models ([Turchin, 2003](#)). In particular, the trajectories of the agents, recorded through probes or indicators, can be due to multiple interactions among them or with elements of their environment, making the interpretation of the results difficult ([Janssen and Ostrom, 2006](#)).

We have made efforts for interpretation, notably concerning the visualization of the trajectories of the agents, which is one of the elements that can facilitate the interpretation of ABM outputs ([Lee et al., 2015](#)). Recording and visualizing the agent possibilities of action represented by the model over time helped us to take a step back from what

the model was doing and how we had represented our agents. According to [Bergez and Lacroix \(2008\)](#), it is important to better understand the framework of farmers' constraints and possibilities in order to integrate irrigation into their complexity of management. From this point of view, the WatASit model has enhanced the integration of some specific constraints of gravity-fed irrigation at individual level (e.g. location and number of plots to be flooded) and collective level (e.g. water availability in the network due to the behaviors of the upstream irrigators). The visualization of the agent possibilities also helps to understand the spatial complexity of irrigation management at the operational level. In [Chapter 5](#), we observed spatial inequalities in terms of irrigation possibilities between the upstream and downstream parts of the Aspres-Sur-Buëch network, which had consequences in terms of plant water stress ([Chapter 6](#)). Such spatial analysis of the irrigator options is probably also possible with other modeling approaches. Considering planned approaches, it requires the combination of multiple plans describing the variety of situations possibly occurring and the use of algorithms for the choice of the possible plans in a given time and space.

The possibilities of irrigator agents have been translated into differences in operations, such as the absence of irrigation on some plots. We also tried to document the trajectories of the irrigator agents (e.g. date and nature of irrigation operations) in relation to the options available to them according to the agro-hydrological conditions, such as the water available in the network, the rainfall received by the plant, and the maturity of the plant. We then tried to document the influence of management alternatives (only dealing with network coordination in our study) on plant growth and water stress. COWAT has also proposed a method to account for the influence of irrigation operations into water balance components at the catchment scale. In this sense, we participated in the challenge of better documenting the various interactions and feedback between anthropogenic and natural causal links within an agro-hydrosystem, which is one of the challenges of the modeling of such systems to take into consideration the human footprint ([Vogel et al., 2015](#)).

8.2.3 Key limitations

We have focused on some specific constraints for the sharing of water when it depends on a collective irrigation network. However, farmer behavior is known to be influenced by many other constraints and factors than the ones taken into account in the WatASit model.

One of these other factors is the economic environment (e.g. [Berger and Ringler, 2002](#)), in which the crop prices can evolve for many reasons. It is likely that national and global market evolution also influence the use of technologies for irrigation. This is why the WatASit model is first designed to simulate an irrigation campaign when the structural elements resulting also from the economic context (i.e. irrigation technology, choice of crops and rotations) are already in place. Typically, the simulation period is the irrigation campaign because it is unlikely that these structural elements will be modified during the course of the campaign. This means that if the model is to be used as a foresight tool over several years, it would require to take into account crop rotations from one year to the next as well as potential changes in technology (e.g. purchase of sprinklers or drip irrigation) and human resources (e.g. employment of labor involved in irrigation operations). Urbanization and agricultural decline are also phenomena that structurally affect irrigation and that should be taken into account. In addition, it is possible that irrigation strategy changes due to the structural change in the farming system or in the environmental conditions experienced by farmers. However, several ABMs, such as MAELIA ([Gaudou et al., 2014](#)), are better equipped to represent the evolution of structural constraints to make pluri-annual prospective simulations concerning the impact of irrigation on water resources, in particular on a regional or watershed scale. Our work might be of interest for focusing on complementary scales and associated issues, in particular the difficulties for collective irrigation at the irrigation scheme scale during specific irrigation campaign time windows.

A further factor is the access to information by farmers (e.g. [Paget et al., 2019](#)) that can also influence the operational management of irrigation. While daily access to weather information is now less unequal from one farmer to another due to the multiplicity of

information sources, the accuracy and frequency of information on the agronomic condition of the plot (e.g. water stress at important stages of development and for each crop location) can vary according to the level of technological instrumentation on the farm. If this instrumentation was relatively undeveloped on all the farms in our case study (i.e. Aspres-Sur-Buëch), the question could arise for other case studies and would also require to have heterogeneous irrigation strategies in adequacy with the farmer's level of information.

The institutions also have a role in the regulation, especially operational, of irrigation, particularly through water restrictions and compliance with low-water target flows. Concerning water restrictions, we have made a hypothesis specific to our case study, namely that the irrigators of the gravity-fed network of Aspres-Sur-Buëch are not restricted for the irrigation of the plots served by the network. However, we differentiated irrigation taking place during or outside the restricted periods (i.e. *illegalFlood* and *legalFlood* affordances in the WatASit model), which showed that irrigation abandons took place before restrictions in our model. For other cases where it could be necessary to restrict irrigators, it would be easy to deactivate the *illegalFlood* affordance. However, water restriction management strategies of irrigators are a sensitive topic that is difficult to investigate in the field. This is why it seems more reasonable to use extreme scenarios (all irrigators respected or not) or "symbolic" restrictions. Such symbolic representation is used in MAELIA for example, where a hundred or so randomly selected farmers are inspected. They take a "violation ticket" at that time, but they are not subject to real sanctions as these are little known in reality. A phenomenon that could however be very interesting to represent is the anticipation character of irrigators when a restriction is announced, for example one week in advance following the meeting of the drought committee. Many irrigators have testified that they irrigate in anticipation of restrictions, sometimes more than necessary. To use a metaphor from one irrigator: "*it's the same as when you announce a fuel shortage, everyone rushes to fill up*". In a work carried out prior to the thesis, a water restriction simulator was developed (Sauquet et al., 2019). It could be used to help take into account such behaviors.

Our representation of the operational management of irrigation relies on a fixed availability of irrigators over time to operate irrigation. However, some working periods are

more intense than other ones. For instance, [Merot et al. \(2008\)](#) have considered some factors that could influence the availability of irrigators, such as interactions between the grassland cropping system and the sheep rearing system, or the inter-related operations between hay mowing and irrigation. Irrigation options in WatASit are likely to be overestimated due to the influence of such factors. Although specific affordances can be added in WatASit to explicitly represent the hay mowing and other agricultural operations, what we had first done, it requires to manage a lot of crossed-calendar issues and to specify generation rules for each affordance. We made the choice of a unique availability parameter to prevent over-parameterization. However, it could be beneficial to modulate the availability parameter in WatASit according to the key workload periods.

Finally, the WatASit model is infra-annual by representing an irrigation campaign of several months and this limits its use as a foresight tool. We can however propose initial states of the model that seem plausible in the future, to be co-constructed with the stakeholders for example.

8.3 Coupling or not coupling, that is the question

8.3.1 What are the coupling requirements to tackle interactions at fine spatio-temporal scales ?

Model coupling is one of the forms of integrated modeling which is based on the articulation and coherence of objects which, unlike merging, remain distinct on the theoretical, conceptual and software levels ([Varenes and Silberstein, 2013](#)). In our work, we have identified several requirements to ensure this coherence in order to couple models at fine spatio-temporal scales.

Temporally, we are in the case where the WatASit, Optirrig and J2000 models have a non-continuous time formalism made of regular time steps, which [Letcher et al. \(2013\)](#) call "*dynamic, quasi-continuous*". Model outputs are produced at each time step, which can be as small as needed, over a specified period of time. Optirrig and J2000 have a

daily time step, and WatASit has a double hourly and daily time steps.

Spatially, WatASit is a grid-based spatial model which provides outputs on a uniform grid-based representation. The grid elements or cells can have some similar characteristics and can be aggregated. For instance, in WatASit a farm plot entity is an aggregation of grid cells having the same farm plot id but that are not necessarily neighbors. The farm and irrigation scheme entities are spatial aggregations of the farm plot entities. Optirrig is a lumped spatial model that generates a set of output at the scale of a farm plot. J2000 is a region-based, also called compartmental spatial model. J2000 outputs are provided on homogeneous sub-areas (called hydrological responses units) of the total area.

As put forward by [Letcher et al. \(2013\)](#), the coupled model does not necessarily have the same time step as the individual models. However, a first element of coherence that must be ensured is the presence in each of the individual models of coupling variables aggregated at the same time step. In our case, it is the WatASit agent-based model that provides aggregated variables at the daily time step common with the Optirrig and J2000 biophysical models. Then, having a common time step is not enough, because it is also necessary to be able to read and write the coupling variables at each coupled time step, in particular according to information external to each individual model. In addition to make communicate software written in heterogeneous languages, it is necessary to ensure temporal continuity. It means the conservation of the values from one time step to another, of the unmodified state variables, and of the conservation of the history of all the state variables. For this, it is first necessary to distinguish at the conceptual level the target variables of the coupling, those which are dependent on these coupled variables, and the other variables which do not depend on them in each of the individual models. The coupled variables must also represent at the theoretical level the same physical quantities if they are quantitative, or the same definitions if they are qualitative.

In the case of the coupling between WatASit and Optirrig-D, ensuring temporal continuity is sufficient because the coupled variables represent the same spatial object: a farm plot. The crop model then provides a finer level of detail with the representation of the

agronomic processes of each plot. At the software level, it must be possible to call it in a loop, where each spatial iteration corresponds to a plot of the irrigation scheme level. It requires an interface that allows the piloting of each individual model, the storage in a buffer table of values at each time step to be communicated between the models, and above all that ensures sequencing between models. Indeed, an important point is that an individual model must have finished all the methods of the time step before moving on to the other individual model. A specific test, which returns a signal at the end of the last method executed in each model, is made in the *Rcormas* and *Rcoupler Application Program Interfaces* (API) to ensure such sequencing.

In the case of the coupling between WatASit and J2000, two additional points of attention are to be taken into account. The first is that there is no spatially consistent object. Indeed, J2000 represents units considered homogeneous in terms of hydrological processes and WatASit represents, among others, agricultural plots that do not necessarily share the same spatial boundaries or physical characteristics and are not homogeneous in terms of hydrological processes. There is therefore a first conflict that concerns theoretical integration. The proposal we have made consists of a hybrid concept of HRU-plot, homogeneous from the point of view of hydrological processes and sharing the same spatial boundaries as the farm plots entity present in the agent model. Second, the temporal and spatial continuities are directly entangled because of the spatial representation: it must be possible to modify a spatial entity in J2000 after the processes on upstream entities have been computed, and before they are computed on downstream entities. This requires adaptations that are intertwined at the conceptual and software levels that consist of punctual requests, "on demand", when it is the turn of the hydrological entity, to search for information stored upstream of the spatial loop in a buffer table (that we called J2000-D).

In the end, the spatial and temporal scales are to be considered more or less jointly according to each case of coupling. The feasibility of coupling does not depend only on the articulation at the software level, but also on the flexibility and the existing margins of adaptations at the three levels of theoretical, conceptual and software integration. The risks of incoherence, especially theoretical, are probably higher than in the case of a model merging approach. Such merging approach however requires the designer to be

expert of several theoretical domains, at the risk of creating inconsistencies or oversimplifications himself. Coupling also requires being able to embrace different theoretical domains, but allows interaction with the designers of each individual model in order to directly make adaptations by themselves or to better assess the feasibility of the coupling. If such interactions are not possible, it is less interesting to couple the models rather than merge them.

8.3.2 What are the needs of coupling in terms of parameterization ?

Although coupling requires the adaptation of time and space scales, it does not add so many parameters. In COPAT, they concern the simulation time management to distinguish the whole simulation period from the coupled simulation period with a specific *start irrigation date* parameter. In COWAT, they concern the *RiverReach* spatial entity specifically added for the coupling (i.e. *Id* and *flow* attribute of each *RiverReach*).

The agent-based model in itself is data intensive because it is necessary to collect a lot of field information on the real actions and constraints of farmers to parameterize affordances. But it is not specific to the WatASit model as a lot of ABMs based on other approaches, such as empirical, planned or economic, are also data intensive (An, 2012). Concerning the hydrological model that we deployed, it does indeed need more data than the initial model because, among other things, the mesh has been refined. In particular, we need to use both SENTINEL-2 and RPG data to generate the HRU-plots, but at least in France these data are available and remote sensing can help.

We also need more parameters because the purpose of coupling was to represent more processes that could be ignored in the initial models. For example, vegetation growth was not represented in WatASit, and interdependent operations at the network level were not represented in Optirrig or J2000. More processes necessarily means more parameters, whether in coupling or merging approaches.

8.3.3 What are the generic potentials of the COPAT and COWAT coupling methodologies ?

We have not tested the generic character of the COPAT and COWAT coupling methodologies. Their potential deployment with other models, for example, would require certain conditions.

In order to consider using another crop model than Optirrig in the framework of COPAT, or another hydrological model than J2000 in the framework of COWAT, these models would at least have to share the same temporal formalism with constant time steps. The time steps can be different if aggregated variables allow bridges to be built between their different time scales. They should also be flexible enough at the formal and software levels to be derived as daily functions, which is the main condition to articulate them dynamically with the agent-based model. Otherwise, it could be better to investigate merging models.

Choosing another hydrological model would require paying particular attention to its distributed and conceptual formalism (Figure 8.2). CLSM (Ducharne et al., 2000), ISBA (Noilhan and Planton, 1989) or ORCHIDEE (Krinner et al., 2005) are surface diagrams that calculate the vertical transfers of water and energy and COWAT is therefore not adapted to these models as it relies on the concept of HRU. SWAT (Arnold et al., 1998), which uses the concept of HRU, could be a good candidate if it can be derived as a daily function.

On the other hand, Optirrig and J2000, or rather their daily versions Optirrig-D and J2000-D, could be considered with models other than WatASit. In fact, they can communicate with any external source capable of providing irrigation doses over time at plot scale.

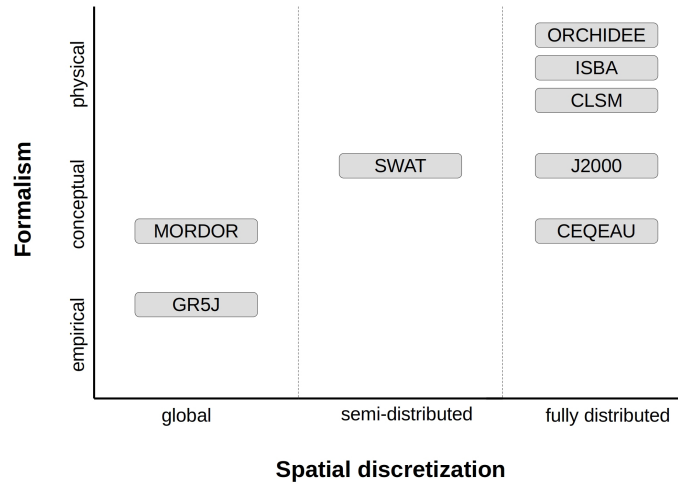


FIGURE 8.2: Formalism and spatial discretization of several hydrological models.

8.4 Back to the case study

8.4.1 Contribution in relation to the case study

Human societies face difficult choices in the development of future water uses and associated policies, recognizing the need to preserve a common good that is essential to human sustainability and well-being (Castelletti et al., 2012). This is reflected in new water-sharing objectives that encourage irrigation, and more particularly collective gravity-fed irrigation in the Buëch River basin, to reduce their withdrawals from the river. If such objectives are not achievable, specific programs aim to develop measures to transform these systems.

The Buëch water resources management program was launched at the end of 2019, and has been notably devoted to the creation of water reservoirs and conversion to sprinkler systems. The Aspres-Sur-Buëch irrigator union is a typical example of a gravity-fed network that is facing a structural choice for its future to adapt its operational functioning. It is an example of a structure where operational functioning is no longer adapted to current irrigation management requirements, in particular: 1) it faces an historical decrease in the number of farmers and more generally professionals who have an interest in sharing collective maintenance tasks and their cost (e.g. Loubier and Garin, 2013), 2) it has difficulties for piloting finely the resource and reporting on the actual volumes withdrawn, out of step with the new structural water management policies in force, 3)

it has a low reactivity to water restrictions in periods of drought.

Generally speaking, the farmers in the case study mention a lesser interest in the services provided by the collective gravity-fed network due to the accumulation of new regulations targets with historic operational difficulties. Such accumulation has gradually participated to the disappearance of the fundamental forms of cooperation that made its added value: disappearance of coordination by water time slots, calls for a service provider for cleaning the canals and watering them at the beginning of the irrigation campaign, cancellation of meetings that were as many discussion arenas. Our work provides some points of vigilance brought by such situation.

Applied to the study of the gravity system of Aspres-Sur-Buëch, the analysis of affordances highlighted the duality between temporal and spatial operational constraints. Indeed, if the abandon of the network coordination allows a greater number of irrigation slots (i.e. more affordances), it is accompanied by an increase in the importance of the spatial constraint resulting in greater inequalities among the irrigators in terms of the number of irrigation possibilities, as well as the abandon of a greater number of plots by some farmers rather than by others (Richard et al., 2020a). The abandon of network coordination therefore does not have the same impact on irrigators in terms of irrigation capacity, and therefore production, and raises the question of the decision-making process for this change in organization. Did the irrigators most impacted by the change have participated in this choice? Interviews of irrigators who have definitively abandoned irrigation in the most under-served downstream plots inform that they are fairly aware of these imbalances. In particular, they mention the advantage of the owners of plots located upstream of the network, who are always sufficiently served in terms of water whatever the sharing method adopted. In addition, they mention the lack of human and financial resources for network maintenance, which penalizes the flow in the most downstream branches of the network. Such arguments are also found in other associations of gravity-fed irrigators in the Buëch basin, and it would be interesting to investigate other watersheds. Thus, the transition to a more "flexible" mode of water sharing responds to a set of increased constraints, accentuating the internal imbalances in the irrigator network. Affordance might be an indicator of such internal imbalance and of the behavioral complexity faced by an irrigator in a given situation he operates in.

Deploying the approach to other case studies would allow the influence of the model data to be assessed further. In particular, a need for irrigation that is scarcer or more frequent depending on the amount of rainfall influences the number of affordances considered in the irrigation strategy, and thus the number of irrigation possibilities simulated.

The COPAT framework also provides a spatial assessment of crop water stress at the network level resulting from the abandon of network coordination (Chapter 6). The recent testimonies collected in the field on the perimeter as well as on the scale of the catchment area show a tendency towards the development of individual margins of leeway for operational irrigation management (Chapter 3). For example, individual pumping stations and retention basins have been set up, and new sprinkler irrigated area have appeared, particularly at Aspres-Sur-Buëch on the other side of the river to cultivate orchards, even though the area is often subject to frost. They participate to make individual behaviors less constrained by the collective functioning of the gravity-fed network.

In a technical way, our work questions us on the local meaning of water savings for the needs of the environment. One of the main confusion is between gross withdrawals (at the water intake) and net withdrawals (after taking into account returns to the environment). Gross and net withdrawals from the river were not the subject of this study, but their integration might allow a first comparison of the water efficiency of each mode of irrigation (i.e. pressure, gravity-fed and mixed). It also raises questions about the level of geographical detail that needs to be understood to analyze the situation. For example, if the irrigators mentioned water returns to the river, these returns are always made downstream of the water intake of the network. There is therefore a reach of river short-circuited by the irrigation network in which the question of ecological continuity may arise during low-flow periods. The COWAT method might help to represent the impact of irrigation on local river reaches during low-flow periods.

8.4.2 The use of a real application case also leads us to think about hydrology in a different way

By looking at a real application case, we were led to think about hydrology in a different way, within a certain limit.

Indeed, we have not questioned the concept of HRU used in the J2000 model for example, but we have modified its spatial dimension to make it coincide with an object external to the model, the plot. This allowed us to make the link with the scale of the irrigation network, composed in particular of several plots. This scale was the starting point of the WatASit model because it seemed fundamental to represent the observations made during the field surveys. Thus, the modeling of hydrological processes does not have the central place in our approach, any more than those of agronomic processes. We were only interested in it when taking into account the hydrological constraint at the entrance of the irrigation network in link with hydrology at the catchment scale. Although we did not assess the mutual impact of irrigation operations and hydrological processes, we pointed out the physical processes directly interacting with them, such as interception by vegetation and infiltration at ground level.

In addition, the identification of the determinants and effects of the possibilities of action that condition the operational interactions between an actor and his biophysical environment has required thinking jointly human actions and water resources. It was the case in particular of the modification over time of plant water inputs, and over space of hydrological processes according to non-biophysical factors such as the coordination of the actors between them. Finally, the integration of human representation into hydrological design challenge the emphasis on physical processes as the key predictor of hydrology.

8.5 Back to interdisciplinarity in “socio-hydrology”

8.5.1 “Socio-hydrology” emanates above all from hydrologists, with a vision centered on modeling, and with sociological aspects that remain limited

[Sivapalan et al. \(2012\)](#) have advocated “socio-hydrology” as a “*new interdisciplinary science of people and water*”. Although, as [Sivakumar \(2012, p. 3788\)](#) argues, “socio-hydrology” is rather a recycled and reformulated “hydro-sociology” with reference to the

work of [Falkenmark \(1979\)](#) in the late 1970s, the contemporary debates it generates are interesting within hydrology in general. In particular, they make it possible to take stock of the limits of the classical hydrological approach in the presence of human influence. The fundamental contribution surely lies in the way of representing the co-evolution between water resources and human or societal behavior in the long term, which is no longer a fixed scenario on a given horizon, but an endogenous component of the system ([Pande and Sivapalan, 2017](#)).

The contribution in terms of interdisciplinary collaboration is less obvious. Indeed, [Seidl and Barthel \(2017\)](#) conducted a questionnaire survey of a sample of hydrological researchers ($N = 353$) to explore the extent to which the social sciences are integrated into hydrological research, particularly within the framework of "socio-hydrology". Their results show that hydrologists would like to learn from the social sciences in order to integrate a "sociological" component into their work themselves. [Seidl and Barthel \(2017\)](#) estimate that 95–98% of all articles published in *Water Resources Research* or *Hydrology and Earth System Sciences*, where the vast majority of "socio-hydrology" articles are published, were written by mono-disciplinary teams, and they could not detect a strong development of interdisciplinary collaboration.

As [Wesselink et al. \(2016\)](#) explain in their comparison between "socio-hydrology" and "hydrosocial" research (a branch of human geography also coming from Falkenmark's "hydrosociology"), "socio-hydrology" focuses on quantitative methods and computer modeling, while "hydrosocial" approaches focus on understanding and theorizing. Although sociological methods are increasingly solicited, they remain less used than numerical modeling in "socio-hydrology", and are limited to field surveys such as questionnaires and semi-structured interviews (e.g. [Nüsser et al., 2019](#), [Ogilvie et al., 2019](#)). According to [Seidl and Barthel \(2017\)](#), "socio-hydrology" is still dominated by hydrologists with a hegemonic attitude towards interdisciplinary collaboration with social scientists.

From our point of view, "socio-hydrology" is very useful for the evolution of hydrology within coupled human-water systems, but it still emanates mainly from hydrologists, with a vision focusing on modeling, and with sociological aspects that remain limited.

A mutual reflection of hydrologists and sociologists to contribute to interdisciplinary collaboration has not yet been well developed in the current vein of "socio-hydrology", and should also account for other approaches that are not represented in the main currents of thought. An important point to think about the process of interdisciplinary collaboration, stemming notably from our participation in meetings and works (e.g. [Collard et al., 2020](#), under press) of the "socio-hydrology" team of UMR G-Eau, is the place given to the methods of each discipline in a more global approach, centered neither on one or the other discipline. The methods, whether they come from the social sciences or the hydrological sciences, can benefit from joint reflection on their limits. If [Melsen et al. \(2018, p. 1435\)](#) claimed that models are "*uncertain, subjective and a product of the society in which they were shaped*", this is certainly partly true, but it is surely also valid for a large number of other methods (e.g. field observations and interviews, article writing, cartography) that involve the interpretation and representation of reality. This type of remark shows that the centrality of the model in the current "socio-hydrology" is a hindrance to strengthening collaborations with the social sciences. There is probably a need for better reflection on the model role, prerogatives and the appropriate time to call upon model as an aid to the complementary analysis of other approaches on the same level, sometimes accepting not to use modeling. An interesting entry point for strengthening collaborations seems to be the sharing of fieldwork ([Riaux and Massuel, 2015](#)), which could also facilitate the decentralization of the model's role.

Our work has not involved more collaboration with sociologists, but efforts have been made to use concepts totally outside the world of hydrology or agronomy, as the Affordance concept, and has led us to think about hydrology in a different way, within a certain limit.

8.5.2 The Affordance concept connects hydrology to the interdisciplinary debate of socio-ecological feedback mediated by the environmental cognition

The Affordance concept refers to the interdisciplinary debate on human/animal representation in its environment, in particular the notion of perception. For the ecological approach (e.g. [Gibson, 1977](#)), the perception of the environment by an actor (in the

meaning of the subject of an action) is direct, meaning the capture of information during the action to adapt to its environment. Perception and action are therefore indivisible. For proponents of the cognitive approach, perception is indirect because it is the product of a mental construction (Luyat and Regia-Corte, 2009). For them, the ecological approach gives too much importance to the environment to the detriment of the actor's intentions and the cognitive processes that result from them.

For Norman (1998), the notion of affordance refers to the necessary instructions for interaction transmitted to actors, during an exclusively perceptual contact. This would lead to a distinction, unlike Gibson, between perceived and actual affordances. In other words, Gibson considered affordance perception being the result of a neutral process, whereas Norman imposed a separation between a world composed of actual affordances and a world of perceived affordances resulting from cognitive processes linked to cultural and social conventions. Finally, Norman (2007) will consider under the influence of De Souza (2005) an affordance as the result of a communication process between the actor and an object of the external world via its visual interface, involving a cognitive process.

According to Raudaskoski (2003), objects may have affordances that the actors cannot perceive or, on the contrary, may not have affordances that, for the actors, are present. This would reinforce the argument that affordances are a communication process and that their perception depends on a historical and cultural process. In this perspective, the "affordances" generated in the WatASit model are constructed affordances that could differ from affordances actually perceived by the actors.

In addition, Zhang and Patel (2006) mobilize the theory of distributed cognition to no longer limit the existence of affordances independently of actors, as Gibson and Norman's approaches implied. According to them, the structures and information present in the environment determine an external representation space, while biological, perceptual and cognitive processes specify an internal space. The affordances are the conjunctions between the possible actions of the two spaces.

According to [Morgagni \(2011\)](#), the question of the coupling between the role of the bio-physical environment and the contribution of cognitive and cultural processes must be read in terms of a dynamic loop, as the possibilities for interaction with objects cannot be developed in a punctual time. Affordances could be seen as responses to practical actions made possible by the cognitive habits retained by the actors. These habits are included in a system of practices and knowledge that presupposes a specific and situated horizon of action. [Morgagni \(2011\)](#) then takes up the famous example of Gibson's mailbox: *"If we did not know about the postal service, the object mailboxes would not tell us anything about the affordances they may have in this respect, whereas our social organization and our previous experiences put us in a position to access these actions, to perceive them as conceivable, thus giving us access to this particular type of affordance made available by any sign mailbox. This possibility of action will be available until such time as the mailbox, the postal service or another semiotic actor inserted in this social context, informs us that these affordances are no longer available"*.

Affordances would then be the manifestations of a much broader process, which must be approached more generally to describe the links between action and interpretation, but also the objects capable of transmitting in a distributed way cognitive elements and culturally established habits.

8.6 Perspectives

8.6.1 Endowing our farmer agents with better decision-making abilities in WatASit

In WatASit, farmer agents are not endowed with anticipation and learning abilities for decision-making, as highlighted in [Chapter 5](#). Indeed, we focused more on their capacity to choose an action in a reactive way to adapt to their current options, especially in situations that cannot be planned in advance. For example, a farmer wanted to irrigate a plot but could not because of insufficient water flow in the canal at his level due to withdrawals upstream of the canal by other farmers. To specify the "possible" character of an operation, in our work, requires knowing the physical determinants of an action (lack of water for example) but also certain determinants from the actor's point

of view. This means specifying the variables and indicators observed by the actor that condition, according to him, whether the action is possible or not. For example, rain does not fundamentally make irrigation impossible, but as a precaution the irrigators in our case study do not (or very little) consider the possibilities of irrigation when it rains in the reality, and thus in our simulations we don't consider any possibility of irrigation when it rains. Thus, we considered some physical variables (the flow rate necessary for gravity-fed irrigation, the availability of the agent) and from the irrigator's point of view (rainfall, insufficient flow) to generate possibilities of action among which the agent applied a thought scheme to choose the one to be carried out. In doing so, the agent no longer considered in this decision-making process the rain of the moment or the flow in the canal, these variables already controlling the field of possibilities on which he is reflecting. At the moment of choice, he considers only the information necessary to compare, separate and prioritize the possibilities in relation to each other. A transfer of these variables from the decision-making mechanisms to the operational mechanisms takes place. Thus, we have considered a decision to choose the action to be carried out among all the possible actions. This decision is based in our work on the water inputs (irrigation and precipitation) of each plot during the past days, giving priority to the actions on the plots with the least inputs. Thinking about the possibilities of action also sends us to think about their effects on the simulation environment. These effects depend on physical parameters in particular (irrigation mechanisms, irrigation doses, flow in the network) that we have only considered in a simplified way. In WatASit, agent trajectories are therefore mainly based on a perception-action loop, in line with [Afoutni \(2015\)](#) and [Guerrin et al. \(2016\)](#), without calling for complex decision algorithms.

However, anticipation and learning are important abilities mobilized by the farmers in real farming and irrigation management for a lot of other situations including operational situations. Indeed, anticipatory processes are also part, along with reactive processes, of the dynamic character of decision making when the actor's environment is uncertain or dynamic ([Robert et al., 2016a](#)). If in the long term anticipation is difficult, in the medium term, the new information available on the state of the environment facilitates pro-active processes such as the adjustment of the technical management of the farm by partial modifications of the cropping system ([Robert et al., 2016a](#)). In the short term,

i.e. at the operational level, this may involve, for example, canceling, postponing, substituting or adding farming operations. Learning aspects are also commonly used in the literature on adaptation processes in agricultural decision-making (Robert et al., 2016a). They enable the integration over time of knowledge from environmental observations, for example with feedback loops (e.g. Stengel, 2003).

In addition, humans actively re-evaluate their beliefs, values, and functioning (Filatova et al., 2013) that are directly linked with their anticipation and learning abilities. An important follow-up of this work could be to extend the WatASit model to a triple perception-cognition-action loop, using for instance elaborated “*Belief-Desire-Intention*” (*BDI*) agent architecture, as done for operational decision-making by Martin-Clouaire (2017) and for structural decisions in MAELIA. In MAELIA, each farmer agent establishes annually a cropping plan through rotations that are chosen according to a set of criteria based on a *BDI* architecture (Taillandier et al., 2012). This allows the farmer agent to make a decision even in the absence of complete information, based on four criteria: profit maximization, similarity to the last cropping plan, minimization of financial risks and workload. Such *BDI* architecture could be nourished by the simulated affordances of agents to make evolve their beliefs and intentions during the simulation.

8.6.2 Quantitative validation of the COPAT framework

We applied our modeling work to a real-world case study, which helped to design the WatASit agent model, the COPAT framework and the COWAT method, and to interpret their outcomes in line with current operational issues. As we have not quantitatively validated our simulation results, they are only informative and should not be used for decision support purposes for example. However, such quantitative validation could be envisaged in several ways.

First, a precise follow-up of an irrigation campaign could be planned to collect observations about irrigation operations on each plot (i.e. irrigation dates and doses on each plot, or even crop yields). Considering directly crop yields, they could be simulated by Optirrig but would require extra parameters, such a crop density. We could also instrument some plots to follow the evolution of *LAI* which is simulated on each plot

by the Optirrig model in order to validate the coupling with the WatASit within the COPAT framework. The validation could only work if there are significant differences in the irrigation schedule from an ideal schedule. *LAI* is defined as one half of the total leaf area per unit of horizontal ground surface area (Chen and Black, 1992). Several field measurement methods of *LAI* exist, such as digital hemispheric photography, direct destructive sampling method, plant canopy analyzers or even the *PocketLAI* smartphone applications (Bréda, 2003). *Available Water Reserve (AWR)* of the soil could be an alternative by instrumenting a few plots with soil moisture sensors. Such field measurement methods are however facing spatial and temporal heterogeneity issues when considering large areas made of several plots. In addition, it requires a close long-term partnership that can be difficult to set up. Indeed, time availability of the irrigators is limited due to their day-to-day calendar management, and it seems that such an extensive collection of information is not immediately feasible, at least in our case study.

A further way could be to compare simulated *LAI* with *LAI* retrieved from optical or remote sensing techniques (e.g. Zheng and Moskal, 2009). Indeed, such studies have shown a good potential for the estimation of multi-species *LAI* from satellite data (e.g. Zhang et al., 2020). Crop coefficients, which are simulated by the Optirrig model, are the ratio of actual and reference evapotranspiration, and could also be compared with crop coefficients derived from time series of satellite image (e.g. Mateos et al., 2012). We have also participated upstream of the thesis work in the development of the *SAMIR (SAteellite Monitoring of IRrigation)* tool that could be useful for simulating evapotranspiration from remote sensing products together with land-surface modeling (Jarlan et al., 2015). However, such approaches often required some field experiments for calibration purposes that rely on advanced field instruments such as gas analyzers to measure actual evapotranspiration.

In addition to field measurements, it might be interesting to directly involve the irrigators represented in the WatASit model to discuss its design and results. Some authors, such as Farolfi et al. (2010) in the vein of *Companion Modeling*, have proposed an iterative methodology to formalize the modeling in interaction with local stakeholders. In particular, the last step is a reflection stage to criticize the model and propose new improvements. The WatASit model could be a good candidate for such a reflection because it explicitly represents elements of the irrigators' world, such as floodgate among

others, which could perhaps facilitate the transposition between the abstract world of modeling and their real world. A workshop with the irrigators of Aspres-Sur-Buëch was planned during the thesis, but was finally canceled due to the COVID sanitary crisis.

8.6.3 Scaling-up the COWAT method at the basin-scale

In fact, the management of an irrigation network is inseparable from basin-scale water management for water allocation, regulation and dam management. Due to lack of time, our work focused on a single irrigation scheme and we took the management at the basin scale into account by the way it was translated locally. In particular, the flow at the inlet of the network water intake is not influenced by upstream dam or reservoir and corresponds to the flow calibrated by the irrigators to respect the monthly water volume allocated by the State Services.

A representation of water management on a basin scale would however be necessary, for example to deploy the COWAT methodology at the whole Buëch catchment scale including many irrigation networks. For this, we could draw inspiration from other work that provides for such management arrangements. Thus in MAELIA (Gaudou *et al.*, 2014), the "State services" entity annually allocates a volume to the reservoir of the "Basin manager" entity. During the low water period, the flow is measured daily at hydro-metric stations. The "State services" entity bases its action on the comparison of the measurements at the hydro-metric stations with management thresholds. Priority is given to the preservation of the low-water level via water releases from the dams. A function optimizes the in-stream flow downstream of the dam to maintain the low water level objective flow by taking into account a transfer time from the dam to the measuring station due to the morphological characteristics of the river. This requires the anticipation of agricultural withdrawals and therefore a daily estimate of the water needs of the crops. When the preservation of these objective flows is not possible in spite of dam releases, the "State services" entity decrees a drought restriction. We could integrate such basin-scale entities by developing a larger version of WatASit that would represent the several irrigation networks of the Grand Buëch. But we could also consider directly integrating the operational representation of irrigation of the WatASit model

in a platform like MAELIA, in order to benefit from its already operational capacities to represent water management on the scale of the whole basin in particular in the long term. In addition, we could also use the COWAT method as MAELIA is based on the HRU concept for the representation of hydrology.

Chapter 9

Conclusion

In our introduction, we mentioned two general research questions. In the first one, we wondered how to represent the actions of irrigators in space and time in order to dynamically take into account their short-term interactions with the agro-hydrological components of the system.

In the first part of the thesis we started by reviewing the literature on the different approaches used to represent human actions in agent-based models (Chapter 2). This literature review highlighted the existence of the situated approach and the concept of Affordance as a good candidate for representing human actions at the operational level.

In the second part of the thesis, we mobilized the Affordance concept in an agent-based model to represent the short-term interactions between irrigation operations and the local biophysical state of the environment (Chapter 4). As a proof of concept, we simulated at each time step the possibilities of action of an agent resulting from the local constraints (e.g. availability of water resources, plant growth) it encounters to operate irrigation within a gravity-fed network (Richard et al., 2020a). The operational constraints that were taken into account for the triggering of irrigation at the level of each plot are the availability of the water resource in the irrigation network, the availability of the irrigating agent to act and the meteorological constraints. The short-term interactions that have been represented mainly concern the irrigators and the equipment pieces of the irrigation network, notably the floodgate of each plot. The main contribution of

this model lies in the direct consideration of the state of the environment (i.e. water availability at the floodgate, meteorology) and the state of the agent (i.e. availability of the farmer agent), at a given location in the simulation space and at a given time step, to generate all their possible interactions in this situation. Moreover, the updating of this set of possible interactions is done from one time step to another without using complex algorithms.

In Chapter 5, we explored in more detail the links between the agents' behaviors during the simulation and the set of interactions that were possible for them. Furthermore, we tested several parameter values for the same model. This allowed us to better understand what our model was doing, and to take a step back on the way our agents were represented, for example concerning their anticipation capacity. Moreover, by integrating the possibilities of the agents in the sensitivity analysis of the model to inputs and parameters, we observed that our indicator of irrigation abandonment was biased, especially in rainy years. We then sought to directly represent the dynamics of the plants irrigated by the agents through the evolution of their water stress during the irrigation campaign.

Thus, in the third part of the thesis, in Chapter 6, we proposed a coupling framework between a crop model at the plot scale (Optirrig), and the WatASit model at the irrigation network scale. This framework allowed to 1) take into account the constraints of water sharing at the collective network level in the simulation of irrigation at the level of each plot, and 2) compare irrigation network coordination scenarios. The short-term interactions simulated in the WatASit model could then be represented in terms of plant water stress. Moreover, plant maturity was taken into account when the agents triggered irrigation to update their possibilities of irrigation only for plants that were not yet ready to be harvested, which was not the case with the WatASit model alone. The COPAT framework showed the complementarity of the two models at different spatial scales, but the need to adapt their temporal functioning. The key lay in deriving the crop model into a daily function of the agent model in order to be able to force the irrigation received by each plot in the crop model according to the actions of the agents at each time step in the agent model. At this stage, the water at the inlet of the irrigation

network was not considered as being possible to be limiting the possibilities of irrigation.

In Chapter 7, we proposed the COWAT method to represent, using a distributed hydrological model (J2000), the flow in the river reach where the network collects water. The method also takes into account the discharge of water from the network into the river reach, and the modification of the water flow at the level of the *Hydrological Response Units* according to the irrigation operations in the WatASit model at the level of the irrigated plots. Compared to the coupling with the Optirrig crop model, this coupling includes an additional difficulty. As the hydrological model is distributed, it is difficult to maintain the effect of the flow topology from one hydrological unit to another while modifying the flow locally at the level of some units only. For this reason, we propose to modify the hydrological model at the software level by incorporating components that allow both communication with another software, but also the management, through a buffer environment, of the information exchanged for integration at the required time step on the hydrological unit. In addition, the modification of processes at the level of the hydrological units requires the preservation of their homogeneity. For this purpose, we have proposed a hybrid concept of hydrological unit of the size of the irrigated plots (called *HRU-plot*), which allows the link between the concept of hydrological units of the hydrological model, and the plot entities of the agent model. As the impact of the COWAT method on the water balance in the hydrological model has not yet been evaluated, we have not illustrated the potential contribution of the method.

The second research question that we asked in the introduction concerned the contribution of the tools to discussions on water management in the Buëch River basin. In the first part of the thesis, we conducted field surveys in the Buëch River basin for: 1) characterizing the variety of irrigated systems at the scale of the case study catchment and identifying the irrigation problematic, in particular how the irrigated systems are challenged by the operational management of irrigation involving short term interactions between irrigators and their environment (i.e. the crop, the water resources), and which irrigation networks from the variety of systems are challenged, 2) describing the functioning of such networks with a particular attention given to the elements involved in the short-term interactions of irrigation and 3) presenting the Aspres-Sur-Buëch local case study as representative of the gravity-fed networks in terms of operational problematic

such as the abandon of the traditional coordination of the water network through daily slot coordination, which is the object of the WatASit model developed in Chapter 4, as it could potentially impact farmer possibilities of irrigation (Chapter 5), and could interfere with plant dynamics (Chapter 6) and with natural hydrology (Chapter 7). We made an agrarian diagnosis to identify the irrigated systems the most challenged by the operational management of irrigation. The gravity-fed networks were particularly challenged by the fine piloting of their water withdrawals. During the semi-directive interviews we made with the local stakeholders and from the meeting attended, a large part of the ongoing discussion required in-depth understanding of the operational constraints and possible alternatives of their functioning. There was a need of identifying the potential practices that are not optimal for the piloting of water withdrawals or for ensuring equality between irrigators in terms of their ability to irrigate. In this context, the modeling of the short-term interactions between current irrigators' practices and the water resources by comparison with alternative practices was a stake for local managers, as the potential feedback on the plant dynamics. At the basin scale, identifying precisely the locations where the natural river flow was modified or could be insufficient for the preservation of ecosystems was also a key point for the design of future irrigation and water policies.

to characterize its irrigated systems and identify the difficulties related to irrigation management on the short term (Chapter 3). We observed some difficulties in the operational management of collective irrigation, particularly in the gravity-fed irrigation network of Aspres-Sur-Buëch which we chose to study. We then asked ourselves the question of the contribution of using the concept of Affordance mobilized in an agent-based model for the description of these difficulties. We made the hypothesis that the application to a typical collective irrigation network can make it possible to compare situations as before and after the abandonment of network coordination by daily water slots.

In Chapter 4, we designed the WatASit model and we then applied it to the gravity-fed network of Aspres-Sur-buëch which abandoned the historical sharing of water by water daily slots. Simulation results show that the abandonment of coordination by daily slots highlights the inequalities between irrigators in terms of irrigation capacity (Richard et al., 2020a). The change in organization does not impact all irrigators in the same way, depending on their location, especially downstream of the network, and the number

of irrigable plots each irrigator has.

In Chapter 5, we explored how changes in the trajectory of agents in a model such as WatASit can be linked to the evolution of their possibilities of action, before and after the abandonment of daily slot coordination. The simulation of the irrigation possibilities of the agents gave us information on the meaning of their behavior in certain situations. For example, the abandonment of irrigation observed in the simulations at the level of the most downstream plots of the network only appears due to the insufficiency of the water resource when the irrigation network is not coordinated. In our simulations, network coordination greatly reduces irrigation abandonment, but the difficulty then comes from the individual situation of each irrigating agent to satisfy all irrigation needs simultaneously during a reduced time window. In Chapter 6, the COPAT framework for coupling with the Optirrig crop model further showed that potentially a lack of coordination leads to earlier water stress, on average, than when the network is coordinated.

Finally, the last chapter (Chapter 8) highlighted the modularity of the tools used to apprehend different spatial scales: the plot, the farm, the irrigation network and the watershed. In general, the approach is at the interface of several disciplines: hydrology, agronomy, modeling, and have links with cognitive sciences with the concept of Affordance. The main limitations concern some irrigation constraints, particularly economic ones, that we have not take into consideration. Moreover, the WatASit model is essentially infra-annual, which requires adaptations to the initial state of the model in order to consider its use as a foresight tool.

In the end, as we step back from this work, we see that it leads to a certain way of thinking jointly about the representation of human actions and water resources. On the one hand by identifying the determinants of the possibilities of action that condition the operational interactions between an actor and the water resource. On the other hand, by the modification over time of plant water inputs and hydrological processes according to non-biophysical factors such as the coordination of the actors between them. In general, we have proposed a hybrid approach, which starts from field observations and then uses different modeling tools to help shed light on them.

Appendix A

Complementary description of the case study

A.1 The context of water management in the Durance River basin in France

A.1.1 Hydrological studies in the Durance River basin: future quan- titative water sharing in question

According to [Santoni \(2014\)](#), after several decades of balance between supply and demand, water resources of the Durance region have been subject to tensions since the 1990s due to the growth of tourist uses and environmental concerns. Supply depends both on the natural availability of the resources and their abstraction for human uses. Spatially, the *R2D2 2050* project ([Sauquet, 2015](#)) has highlighted the diversity of natural hydrological regimes in the Durance River basin (Figure [A.1](#)). The Upper Durance is governed by a snow-fed regime with a winter low flow period. In the Middle Durance, the rain- and snow-fed regime induces a later low flow period. Finally, the Lower Durance extends downstream with a rainfall regime that results in a marked low flow in August and September, but limited during the winter. These regimes reflect an altitudinal and climatic gradient from the Northeast of the river basin to the Southwest. Temporally, the *R2D2 2050* project put forward a marked alternation during the 20th century of

periods of high water (e.g. 1910-1920) and low water (e.g. 1940-1950).

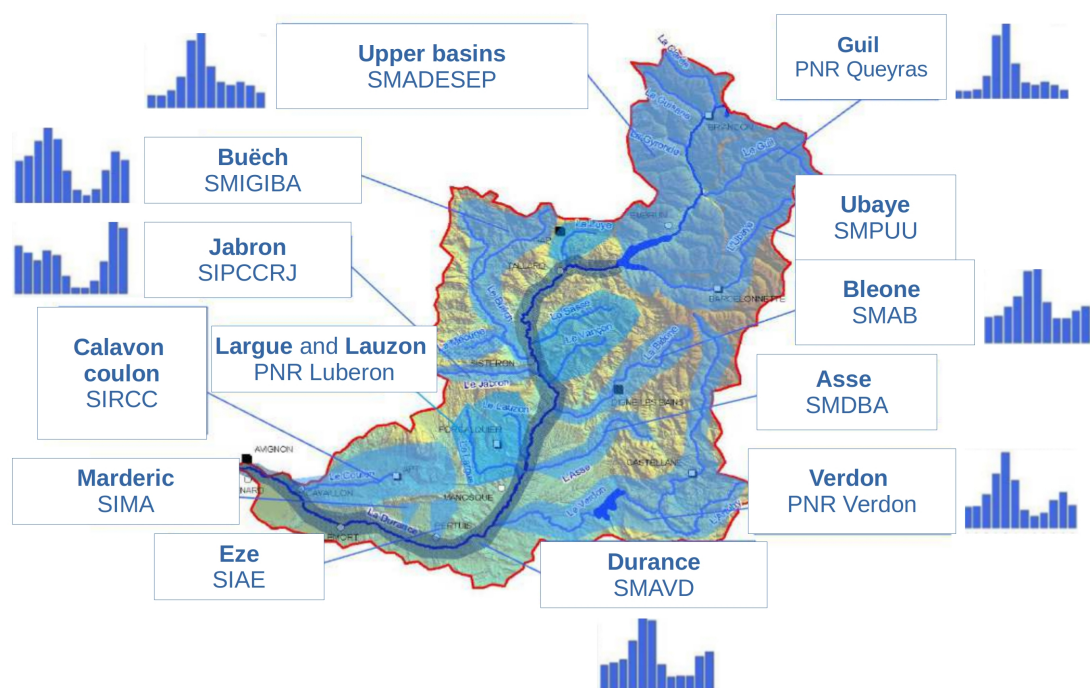


FIGURE A.1: The Durance River Basin and its sub-catchment areas. Capital letters denotes the managing institution. Histograms represent average flow over the last 30 years for the twelve month of the year (sources : *PACA Region, 2010* and *Hydro database*.)

In terms of prospective, the [RegionPACA \(2010\)](#) makes the following assumptions for 2030: (1) "A 10 to 15 % decrease in rainfall supply to water resources", (2) "A 25 % reduction in snow cover" and (3) "A decrease in summer low water flows". The *R2D2 2050* project ([Sauquet, 2015](#)) confirms a decrease in water resources by 2050, but reminds us that the climate factor could appear secondary to the socioeconomic trajectories concerning the uncertainties on water uses, notably for:

- Drinking water supply with 5.4 million inhabitants in 2030 for the trend hypothesis ([RegionPACA, 2011](#)),
- Agricultural withdrawals because "water availability is a determining factor [...] and will be even more so in the future in a context of climate change" ([RegionPACA, 2011](#)), with significant withdrawals through canals ("Canal de Provence", "Canal de Manosque", "Canal Saint-Julien..."),

- Hydro power through the presence of 14 dams, 32 power stations and a drift canal towards the *Etang de Berre* (RegionPACA, 2011),
- Tourism accounting for 35 % of employment in 2009 according to the *SDAGE 2009-2015*.

The diagnostic study of water resources conducted by the DrealPACA (2008) reports on the withdrawals and volumes used for the above-mentioned uses, at the scale of each catchment area. At peak periods, only 14 of the 26 basins did not appear to be in deficit, which may result in tensions for the sharing of the resource locally but also downstream of critical points. Thus the *R2D2 2050* project considers that with unchanged territory, the demand on the Serre-Ponçon dam should increase and that the agricultural reserve part of water would more frequently be insufficient (Sauquet, 2015). Considering the unsecured territories, i.e. dependent on the only local resource, the project foresees a more critical situation with restriction decrees more frequently used (Sauquet et al., 2019) and the need to implement quantitative adaptation measures.

A.1.2 A multitude of governance scales

Several groups of stakeholders (Figure A.2) can be distinguished according to the spatial scales with which they are associated. State services and local authorities largely consider management perimeters corresponding to administrative districts at different scales (region, county, commune and inter-municipal). However, the water agencies and the river basin managing institution use the perimeters of the hydrographic districts and catchment areas, respectively. In addition, the industrial actors (e.g. EDF, SCP, SEM) manage more specifically at the level of their water networks. Another group can be made up of stakeholders who use ecological zoning (e.g. "NATURA 2000", blue and green corridors, natural reserves), which are characterized by their trans-territoriality (Salles, 2006). These various perimeters overlap among them and with the different administrative scales. Thus the PACA Regional Council works on a regional perimeter which is a portion of the *Rhone-Mediterranean-Corsica* hydrographic district and which includes the county, communal and inter-communal perimeters, each of which contains parts of watersheds, canals and ecological zoning. It leads to a very large number of managers being involved in the decision-making process. Moreover, the emergence of

new leisure uses and new environmental concerns has led to the creation of consultation bodies such as river basin or river committees, which reveal a territorial collision of perimeters, procedures and stakeholders giving the image of a political-administrative mosaic. However, for each stakeholder, the defense of its perimeter aims to establish its territorial legitimacy (Santoni, 2014).

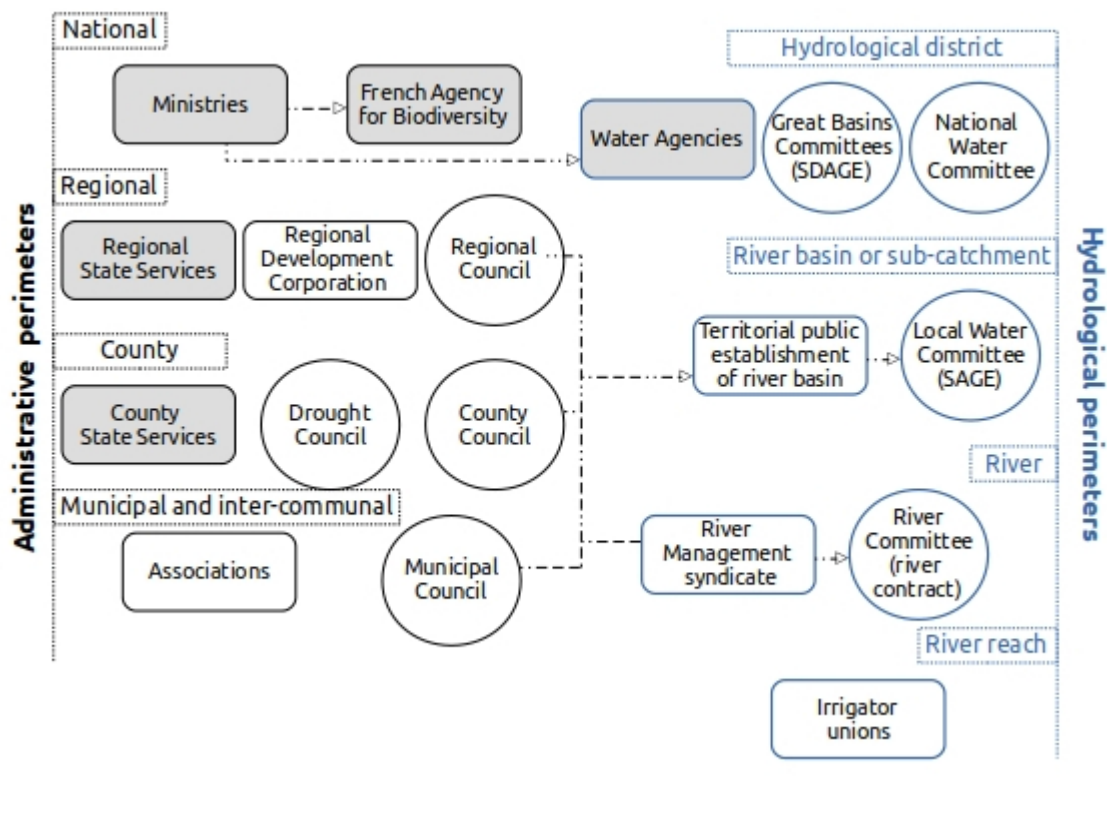


FIGURE A.2: Administrative and hydrological perimeters of water management in France (adapted from Santoni, 2014). Grey boxes are State Services while white boxes are from civil society. Blue contourlines denotes a water management entity acting at an hydrological perimeter.

A.1.3 Environmental preoccupations through the prism of technical debates and operational problems

The accumulation of scientific studies has legitimized environmental concerns (Salles, 2006), which has resulted in an evolution of the historical hydraulic management to gradually take into account the needs of the environment. Indeed, the catchment area was adopted as the key water management perimeter, and through an approach of bottom-up conciliation, to correct the negative effects of the authorizations of water exploitation infrastructures delivered by the State to develop water supply during the second half of the

20th century (Aubin, 2007). Water resource management thus slightly moved to water demand management. Indeed, industrial holders of water infrastructures have deployed canal agreements to achieve water savings for aquatic environments. These agreements create mainly environmental and participatory entries for water management, and favor a form of downstream-upstream solidarity between water users. For example, the *EDF-SMADESEP* agreement of 16 June 2008 explicitly recognizes the tourist uses of water. However, Santoni (2014) underlines that technical negotiations are not within the reach of all stakeholders. Indeed, at the level of the technical committees, scientific language can disarm some stakeholders such as the elected representatives, in particular of the smallest structures. The main technical variables evoked in these agreements are the *Instream Flow* ("*Débit Réservé*" in French) at the level of dams and reservoirs, the *Low-Water Target Flow* (*DOE* standing for "*Débit d'Objectif d'Etiage*" in French) to reconcile withdrawals and aquatic ecosystems, as well as the thresholds used for water management during water low-flows (table A.1).

Finally, water management in the Durance River basin is marked by the rise of legislation to take into account the quantitative tensions observed in particular during the low-flow or drought periods (e.g. 2003, 2007), and the development of scientific arguments legitimizing environmental considerations. Within this trend, irrigation is a key factor of uncertainty for the prevention of future water crisis (Paydar and Qureshi, 2011), and its evolution faces technical and operational mutations to comply with new water management norms.

A.2 Description of the irrigated systems of the Buëch River basin from the agrarian diagnosis point of view

As part of the RADHY Buëch project, a 6-month internship was realized by Distinguin (2019) from March to August 2019 to investigate the variety of the irrigated systems of the Buëch River basin by mobilizing an agrarian diagnosis approach. This multidisciplinary approach mobilizes several disciplines such as agronomy, economics, sociology and others to understand the functioning of a complex reality by studying farming systems within a historical dynamic in a given agro-ecological context (Cochet et al., 2007).

TABLE A.1: Structural and low-flow water management objectives, instruments, variables and regulatory frameworks (compilation by the author).

STRUCTURAL WATER MANAGEMENT

Objective :

Quantitative equilibrium between water demand and resource.

Maintenance of the Low-Water Target Flow (DOE) 4 years out of 5.

Regulatory instruments :

The SDAGE and SAGE to classify the river basins with quantitative water imbalance.

The ZRE to give a special status to basins that are not in quantitative equilibrium by modifying in particular the monitoring of withdrawals and their taxation.

Contractual instruments :

The quantitative water resources management plan (PGRE) to identify the measures to achieve the quantitative objectives determined in the study of withdrawal volumes (EVP).

Variables :

The DMB : minimum flow rate to allow the maintenance of aquatic life.

The DOE : DMB + withdrawals downstream of the measuring point.

The DOE will have to be reached after implementation of PGRE actions.

The Target Flow : It corresponds to an intermediate flow rate to be reached before the implementation of the actions of the PGRE.

The Instream Flow¹ to specify the amount of water downstream of the water infrastructures. DR are reduced to Target Flow pending implementation of the PGRE.

Regulatory framework :

2006 LEMA.

WATER LOW-FLOW MANAGEMENT

Objective :

Water restrictions 1 year out of 5 on average.

Regulatory instruments :

County drought framework decree to specify the modalities and levels of water restrictions.

Variables :

The vigilance, alert, enhanced alert and crisis flow thresholds.

Crisis threshold can be defined in relation to DMB, and alert threshold in relation to DOE.

Regulatory framework :

The environmental code of laws that prioritizes water uses.

The approach is based on the concept of an agrarian system, which is defined as "*a historically constituted and sustainable mode of exploitation of the environment, adapted to the bio-climatic conditions of a given space, and responding to the social conditions and needs of the moment*" (Mazoyer and Roudart, 1987). In particular, the approach makes it possible to account for the constituent elements of the agrarian system, such as production systems and their biophysical and socioeconomic environments. The production system allows to describe the dynamics and relations between production units, crop and livestock systems in order to provide a richer systemic reading than the technical approach (Cochet et al., 2007). It also provides an account of agricultural practices, farmers' strategies, past developments and ongoing processes. Concretely, an important bibliographical review of the history of agriculture and irrigation in the Buëch River basin was carried out, supplemented by numerous interviews on the farm trajectories over the last century. Several landscape readings in different points of the basin then made it possible to characterize the land use according to the natural vegetation, the nature of the soils and reliefs, the climate, the main types of crops and especially their irrigation. Numerous interviews were also conducted to collect the schedules of agricultural and irrigation practices and their main constraints. The main limitation concerns the lack of economic analyses that could not be integrated into the diagnosis, as well as the difficult quantification of the representativeness of the information collected in the absence of cluster analysis.

The agrarian diagnostic has provided an overview of the irrigated systems in the Buëch River basin due to the major changes that have led to the current state of irrigated agriculture which represents 362 farms covering a total of 32418 ha, with 89 ha per farm in average (statistics for the year 2017). Perennial crops are about 10.6 ha per farm compared to 11.8 ha per farm for the Hautes-Alpes county. 26 % of these farms have orchards which are mainly located in the downstream part of the catchment where water access is secured by the Saint-Sauveur dam. 68 % have livestock, of which 49 % are sheep or goat farms and 19 % are cattle farms. The average size of a cattle herd is 16 units compared to 77 in the entire Hautes-Alpes county. The diagnosis identifies three major periods (Figure A.3) of water resource development that shaped the agrarian systems of the Buëch basin.

From the 18th century until the first half of the 20th century, the transport of water

was ensured by gravity-fed canals, which had various functions: agricultural irrigation, feeding mills for the production of oil or flour, driving force for dyeing fabrics, forge hammers or sawmills (Ghiotti, 2001). The distribution of water among users was carried out by means of secondary or tertiary canals connected to the main canal, and was often difficult to manage. In the 1850s, Napoleon III undertook a modernization of the management of these irrigated perimeters by creating irrigator unions by the law of 21 June 1865. The most common form within the Buëch River basin are irrigator unions. They are public administrative structures whose creation, statutory modifications and dissolution are pronounced by decree of the county Prefecture. During this period agricultural systems were mainly based on crop-sheep farming (Figure A.3). Sheep were valued for the maintenance and fertilization of the land with their manure, as well as for their wool for clothing. The south-facing slopes downstream from the river basin were shaped by vineyards. Cereals and natural meadows were the main crops. Fodder plants consisted of clover, alfalfa and sainfoin, and were used for animal feed. The cereals produced were mainly wheat, oats and rye. Plantations of fruit trees (apple, pear, walnut, almond, plum, and cherry) were rare and were mainly used to delineate the landscape. Wetlands close to the fields were exploited for hemp cultivation. Along the watercourses, the riparian areas structured the borders of the Buëch River basin by the presence of forests and moors composed of poplars and willows useful for the supply of firewood and building materials. They also helped to limit the damage caused by floods to cultivated land. To face these natural hazards (e.g. torrential floods, land movements) the Buëch River basin was the subject of several developments such as the construction of dikes as early as 1830. Thus, until the 1960s, agriculture was characterized by small farms of 10 to 15 hectares (Ghiotti, 2001).

From the 1960s, the market for sheep farming experienced a great boom in the Southern Alps region (Berthet-Bondet, 1980). It was favored by the abandonment of livestock breeding for manure production in other regions of France in favor of chemical fertilizers. The collapse of the wool market, however, led the breeders of the Hautes-Alpes county to further develop meat production (Hubert, 1991). The post-war context of food shortages led to an increase in agricultural production through modernization programs based on land consolidation (increase in average surface area, reduction of agricultural sprawl), the generalization of motorized tools and fodder intensification. 85 % of the

agricultural land in the Hautes-Alpes county has thus been regrouped (Durbiano, 1989) to bring together all the small parcels of land parceled out by farmers in order to promote productivity gains and facilitate working the land. This period had a strong impact on the village's inhabitants, who regularly mentioned it during interviews. According to speeches by farmers of the Buëch valley, the land consolidation process gave rise to numerous neighborhood quarrels, some of which still persist today. However, the generalization of tractors from the 1960s allowed farmers to plow fallow land in favor of wheat sowing and intensive fodder (Houssel, 2006). Nevertheless, the rural exodus continued, resulting in the gradual closure of the landscape by reforestation of the mountain slopes (Girel, 1993). Moors and forests represented 90 % of the surface area in 1977 instead of 60 % at the beginning of the century (Thepot, 1977). The commune of Veynes went from 12,948 inhabitants in 1826 to 7,400 inhabitants in 1968 (Streifeneder et al., 2007). However, the availability of agricultural land has enabled farmers to extend fodder production and to make crop rotation more complex by planting leguminous plants (sainfoin, alfalfa, etc.). It was at this time that agriculture upstream of the watershed began to distinguish itself from that downstream of the river basin. The upstream part was rather based on cereal and hay production and transhumant sheep breeding, while the downstream part started tree farming in addition of sedentary sheep breeding (Figure A.3). Many farmers who cultivated orchards as a secondary activity gradually made it their main crop. In 1976, there were 1,050 farms with an average size of 30.5 ha. 430 farms had a herd of sheep and 380 farms had an orchard, 50 of which made it their main activity throughout the basin (CEMAGREF, 1982). As early as 1975, studies were undertaken on the transport of water from the Buëch into the inlet canal of the Sisteron plant in order to study the possible construction of a hydroelectric dam. The project was favorably received on the condition that the irrigation systems were modernized: pressure irrigation began to appear (Figure A.3).

From the 1980s, a new mode of pastoral management and resource development developed through the installation of fences on pastoral land. 200 breeders in the Hautes-Alpes county submitted a grant application to benefit from it, quickly realizing the advantages of these new arrangements in terms of work organization: easier herding (the herd can use the resource for longer periods of time), resource exploitation (better

management of the resource) and management of the farm's production systems (rotation of plots of land). The farmers then had less need to call on a shepherd or a family member to keep the herd. At the same time, scientific studies showed the negative impact of the dikes on the functioning of the Buëch braided riverbed shape. The reduction of the width of the riverbed and the increase in the ripisylve modified the riverbed dynamics, creating sinking of the alluvial floor along the entire basin (Gautier, 1992). This was the beginning of a more "balanced" management of the water resources of the Buëch watershed (Figure A.3). The droughts of 1989 and 1990 helped to rethink the relationship to water and its protection. The 1990s marked a real turning point in water management, particularly in the Buëch valley. Water management became a major economic and political issue that required a reorganization of the areas of intervention. From 1990, the construction of the Saint-Sauveur dam and the Riou reservoir (Figure ?? C) marked the first phase of land use planning and the beginning of a long period of development and construction of structures. The Riou reservoir is essentially fed by water from the Saint-Sauveur dam transported by a concrete canal (Figure ?? A and B). These two structures will contribute to the agricultural and tourist development that lead to the current organization of the irrigated systems of the Buëch River basin.

As in many other places (Sanchis-Ibor and Molle, 2019), the construction of the Saint-Sauveur dam has been accompanied by a modernization of the irrigation system infrastructures in the downstream part of the catchment, allowed by a permanent access to water. It led to an extension of the irrigated land downstream of the basin, that concerned particularly orchards. The modernization of irrigation was carried out under the condition of quantitative water resource saving through the development of sprinkler irrigation and the abandonment of gravity-fed canals (Durbiano, 1989). The switch to sprinkler irrigation was subsidized up to 95 % for all the works. These hydraulic developments have transformed the agricultural landscape of the river basin and its social relations (Ghiotti, 2001). As a corollary, irrigated areas increased by 25 % downstream of the basin following the construction of these hydraulic works. The irrigated perimeters of the downstream Buëch extended, with an irrigated area increasing from 10 ha on average to about 16 ha. The widespread use of sprinkler irrigation downstream of the basin has led to the development of intensive tree production (Figure ??), in addition

to the production of large cereal and oil seed. According to data from the Hautes-Alpes General Council, between 1980 and 1995, the orchard surface area increased by 65.2 % from 2040 ha to 3370 ha. Gaps have widened between the intensification of tree-growing with pressure irrigation practices downstream and upstream gravity-fed agriculture (Figure ??), which has remained based on polyculture-sheep farming where gravity-fed irrigation persists (Figure A.3).

In the end, the agrarian diagnosis made it possible to highlight the major changes in the irrigated systems of the Buëch catchment area, which have gradually led to greater specialization downstream of the basin due to secure access to water through the dam. Today, it is the upstream part that is in turn at the heart of water management programs, and in particular the gravity-fed irrigation systems still in operation.

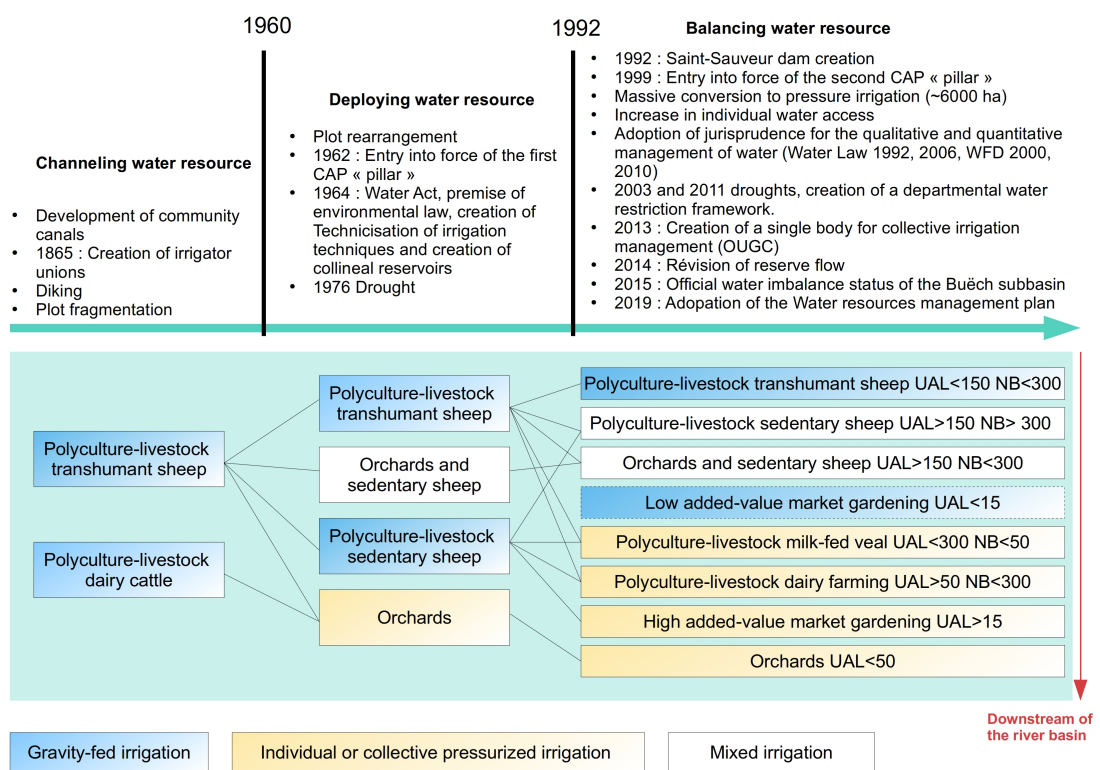


FIGURE A.3: Farming systems evolution of the Buëch River basin from of the agrarian diagnosis point of view (Adaptation from an original work realized by C. Distinguin). Boxes are farming systems, arrows show their differentiation processes over time. Box with dotted contour-line is a new farming system. Gravity-fed, pressure and mixed irrigation technology are denoted by blue, yellow and white colors. UAL is the "surface agricole utile" in French, and NB for the number of animals in the herd.

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Appendix B

Interview guides

B.1 Interview guide with irrigators (original French version)

B.1.1 L'exploitation aujourd'hui (10 min)

Pouvez-vous vous présenter ? Relances : Date d'installation ? Formation professionnelle ? Autre activité professionnelle ? Appartenance à un syndicat agricole ?

Pouvez-vous présenter votre exploitation agricole ? Relances : Statut de l'exploitation ? Type de conduite ? Labels ? Nombre d'ouvrier(s) permanent(s) et temporaire(s) ? Surfaces totale, utile et irriguée ? Performance économique globale de l'exploitation (marge nette, revenu agricole, coût de l'irrigation) ? Productions et sous-produits (transformation, débouchés, exportation) ? Contexte économique (subvention, tendance du marché) ? Assurances spécifiques ?

Évolution de l'exploitation ? Relances : Type d'exploitation avant guerre ? Évolution à partir des années 50 ? Évolution du matériel en particulier pour irriguer ? Évolution des productions agricoles et de l'élevage ?

B.1.2 Les productions végétales et animales (30 min)

Quelles étaient les principales cultures de votre exploitation en 2017 ? Relances : Surfaces (ha) ? Volumes d'auto-consommation et de vente ?

Quelles sont les cultures irriguées ? Relances : Type d'irrigation ? Stratégie d'irrigation ? Opérations d'irrigation ? Dose d'irrigation ? Nombre de coupe(s) de foin/luzerne en moyenne et en 2017 ? Appartenance à une ou plusieurs associations d'irrigants ?

Pouvez-vous me décrire la composition de votre cheptel actuel (si élevage) ? Relances : Nombre de bêtes ? Opérations de conduite du troupeau ? Montée en estives (quand et comment) ?

Quel est votre calendrier de travail au cours de l'année (exemple de l'année 2017) et quelles sont les périodes les plus chargées ? Relances : Itinéraires techniques et principales opérations (travail du sol, fertilisation, protection, récolte, irrigation) ?

B.1.3 La gestion de la campagne d'irrigation (30 min)

En tant qu'agriculteur, quel rapport avez-vous à l'eau ? Relances : Sources d'eau de l'exploitation ? Aménagements spécifiques à l'irrigation (bassin de rétention, pompage) ? Selon vous comment a évolué l'état de la ressource au niveau quantitatif depuis l'époque de vos parents et grand-parents ?

Comment se déroule une campagne d'irrigation (en général et en 2017 plus particulièrement) ? Relances : Matériel utilisé ? Dates des opérations d'irrigation (en général et en année sèche) ? Quelles observations pour décider d'irriguer une parcelle ? Comment choisissez-vous les parcelles à irriguer ? Notamment lorsque vous avez plusieurs opérations à réaliser en même temps, sur quel(s) critère(s) choisissez-vous l'opération à faire en priorité ? Quelle est la durée des opérations pour un hectare de culture ? Combien d'irrigations par cultures ? A quels moments ? Jusqu'à quand ?

Quelles sont les contraintes rencontrées en période d'irrigation ? Relances : Inconvénients des différents types d'irrigation (gravitaire, aspersion, localisée) ? Dépendance aux autres agriculteurs qui utilisent l'eau ? Si organisation en tour d'eau : comment êtes-vous prévenu que vous pouvez irriguer à votre tour ? Est-ce que vous avez des difficultés pour irriguer certaines parcelles ? Lesquelles ? Pouvez-vous irriguer plusieurs parcelles en même temps ? Quel sont les coûts d'installation et de fonctionnement de l'irrigation ? Avez-vous déjà manqué d'eau ?

Qu'est-ce qu'une sécheresse pour vous ? Relances : Indicateur(s) de l'arrivée d'une sécheresse ? Date de la dernière sécheresse ? Sécheresse(s) qui vous ont marqué(es) ? Pourquoi ? Impacts pour les productions agricoles ? (si pas de sécheresse évoquée, mentionner l'année 2017)

Comment gérez-vous les périodes de basses eaux et de sécheresse ? Relances : Faites-vous des ajustements particuliers dans votre manière d'irriguer ? Êtes-vous amené(e) à abandonner des cultures ? Comment les choisissez-vous ? Quel impact des restrictions sur l'irrigation ? Avez-vous changé des choses au niveau de l'exploitation ou au niveau du pilotage de l'irrigation des parcelles suite à ces périodes ?

Comment voyez-vous l'évolution future de votre exploitation ? Relances : Augmentation des surfaces cultivées, irriguées, du cheptel ? Investissement foncier ou matériel ? Changement du mode de conduite de l'exploitation ? Arrêt ou reprise de l'exploitation ?

B.2 Interview guide with institutional actors (original French version)

B.2.1 Caractéristiques de l'usage "besoin en eau des milieux"

Quelles sont les principales caractéristiques des milieux naturels du Buëch ? Relances: Sont-ils remarquables sur certains aspects ? Sont-ils connectés avec d'autres milieux naturels hors du Buëch ? Comment décririez-vous l'écoulement naturel des cours d'eau

du Buëch ? Quelle est leur évolution d'après-vous ? Quelles sont vos missions dans ce cadre ? Comment se traduisent-elles sur le Buëch ? Y a-t-il une saisonnalité de ces missions ? Personnellement, êtes-vous impliqué dans des associations de défense de l'environnement ?

B.2.2 Perception des autres usages de l'eau

Quels sont les autres usages de l'eau au sein du bassin du Buëch ? Relances: Sont-ils connectés avec l'usage "besoin en eau des milieux" ? Si oui, par quels processus ? Est-ce que le partage de mêmes ressources entre différents usages est sujet à des tensions ? Si oui, pour quel type de ressources en eau, superficielles ou souterraines (ou les deux) ? Est-ce qu'il existe une répartition des tensions éventuelles au sein du bassin? Quels sont les principaux acteurs pour la gestion du partage de ces ressources sur le Buëch ? Est-ce que cette gestion sort du cadre du seul territoire du Buëch et si oui quelles échelles spatiales de gestion sont impliquées? Est-ce qu'il y a des liens entre les ressources en eau du Buëch et celles d'autres bassins versants (transferts d'eau) ?

B.2.3 Expérience des sécheresses

Quel est l'historique des sécheresses sur le bassin versant du Buëch ? Relances : En terme d'intensité et de dégâts pour les milieux naturels, quelles sécheresses vous ont particulièrement marqué ? Comment se positionne l'année 2017 dans cet historique ? Comment s'est déroulée l'année 2017 dans le cadre de vos activités professionnelles ?

B.2.4 Mesures d'adaptation

Quelles sont les mesures d'adaptations que vous cherchez à mettre en place pour la protection des milieux naturels du Buëch face au manque d'eau ? Est-ce un enjeu pour vous ? Relances : A quelles échelles spatiales et temporelles? Avec quels objectifs et quels horizons visés ? Quelles sont les connaissances associées à ces mesures ? Ces mesures ont-elles fait leur preuve ? Dans quel contexte ? Ces mesures sont-elles en lien avec d'autres acteurs ? Comment et à quel moment prend-ton conscience qu'une sécheresse s'établit sur le bassin ? De quelles informations disposez-vous et à quels moments ? Est-ce que vous pouvez identifier une (ou plusieurs) zone(s) fortement impactée(s) par

le manque d'eau lors de l'été 2017 ou d'une autre année ? Comment avez-vous géré la période d'étiage de l'année 2017 ? Quelles étaient ses caractéristiques par rapport aux autres années ?

B.2.5 Déterminants potentiels

De manière générale, quelle est votre perception de la situation hydro-climatique à venir dans les prochaines années sur le Buëch ? Relances: Est-ce que vous identifiez des changements dans la gestion des besoins en eau des milieux naturels du Buëch qui soient dus à des dynamiques collectives faisant suite à un manque d'eau ? Que pensez-vous de la situation actuelle des milieux naturels du Buëch en comparaison à celle de 2003 par exemple ?

Appendix C

Paper

This paper was published as an article ([Richard et al., 2020a](#)) in *La Houille Blanche*. We reproduce here the original french version. It was also presented at the *UNESCO/SHF International Conference for Drought, Low-flow and Water deficit* held from 11 to 13 December 2019, in Paris, France.

L'abandon des tours d'eau et ses conséquences opérationnelles sur les systèmes collectifs d'irrigation. Une approche multi-agents situationnelle appliquée à un canal gravitaire de moyenne Durance (France).

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Résumé Le fonctionnement des réseaux d'irrigation collectifs est de plus en plus contraint par l'introduction de nouveaux dispositifs de gestion de la ressource en eau visant à réguler leurs demandes en eau. Certains réseaux collectifs s'adaptent en modifiant leur mode d'organisation pour le partage de l'eau entre irrigants, de manière à rendre l'irrigation plus flexible dans le temps. Cette étude propose d'évaluer l'impact d'un tel changement à l'échelle d'un réseau gravitaire ayant abandonné le mode de partage historique par tours d'eau. L'approche mobilise le modèle multi-agents WatASit qui, basé sur le concept d'affordance, permet d'intégrer une représentation du niveau de gestion opérationnelle durant une campagne d'irrigation. Le concept d'affordance clarifie les possibilités d'actions offertes aux acteurs. Les résultats de simulations montrent que si l'abandon du mode de partage par tours d'eau permet effectivement une augmentation des créneaux d'irrigation, il met en exergue les inégalités entre irrigants en termes de capacité et d'abandons d'irrigation. Le changement d'organisation n'impacte pas tous les irrigants de la même façon, selon la localisation, notamment en aval du réseau, et le nombre de parcelles irrigables de chacun.

Mots clefs irrigation collective ; réseau gravitaire ; modélisation agents ; action située ; affordance.

Abstract (english) The operation of collective irrigation networks is increasingly constrained by the introduction of new water resource management devices aimed at

regulating their demand. Some collective networks are adapting by modifying the way they organize the sharing of water between irrigators in order to make irrigation more flexible over time. This study proposes to evaluate the impact of such a change on the scale of a gravity-fed network that has abandoned the historical mode of sharing by water daily slots. The approach mobilizes the WatASit multi-agent model which, based on the Affordance concept, allows to integrate a representation of the operational management level during an irrigation campaign. The affordance concept clarifies the possibilities of actions offered to the actors. The results of simulations show that if the abandonment of the mode of sharing by water daily slots effectively allows an increase in irrigation slots, it highlights the inequalities between irrigators in terms of capacity and irrigation abandonment. The change in organization does not impact all irrigators in the same way, depending on their location, particularly downstream of the network, and the number of irrigable plots of land each irrigator has.

Keywords collective irrigation ; gravity-fed network ; agent-based modelling ; situated action ; affordance.

C.1 Introduction

Les réseaux collectifs d'irrigation sont de plus en plus contraints par l'introduction de nouveaux dispositifs visant à réguler leur demande en eau. Dans de nombreux bassins versants, l'irrigation est décrite comme une part majeure des besoins anthropiques en eau (Foley et al., 2011, Godfray et al., 2010), et les fonctionnements de ces réseaux, souvent hérités de règles ancestrales (Plusquellec, 1988, Sheridan, 1985), sont régulièrement pointés du doigt en termes d'efficience. En France, les réseaux collectifs d'irrigation sont principalement constitués d'associations de propriétaires fonciers (ASA) et de sociétés régionales de gestion de l'eau (SAR) (Schlüter et al., 2017). Les ASA sont souvent issues d'anciens systèmes d'irrigation ou de drainage datant parfois du Moyen Âge, dont un quart gère de petits réseaux gravitaires desservant quelques dizaines d'hectares. Réglementairement, la loi sur l'eau de 2006 a défini un volume maximal prélevable pour l'irrigation dans chaque bassin hydrographique où un déséquilibre important subsiste

entre l'offre et la demande. Sur la base de ce volume, une autorisation unique valable pour plusieurs années est accordée à un Organisme Unique de Gestion Collective de l'irrigation (OUGC) dont le rôle est de répartir la ressource entre les agriculteurs (Schlüter et al., 2017). Ce partage se traduit par un prélèvement maximal autorisé pour chaque structure d'irrigation. La gestion structurelle de l'eau n'est pas la seule à évoluer, puisque suite à la sécheresse de 2003, des dispositifs de restrictions ponctuelles en période de sécheresse ont également été mis en place (Sauquet et al., 2019).

Or ces contraintes réglementaires nouvelles s'ajoutent à d'autres contraintes des agriculteurs : les contraintes organisationnelles et opérationnelles (figure C.1). Nous appelons contraintes organisationnelles les contraintes dues aux choix stratégiques faits par les agriculteurs en amont de la campagne d'irrigation, qui déterminent l'organisation de leurs exploitations et les investissements pour les années à venir en fonction de leurs visions à long terme (Janssen and van Ittersum, 2007). Un bon exemple est le mode d'accès à l'eau qui peut difficilement changer au cours d'une campagne d'irrigation (Koundouri et al., 2006). Ces choix stratégiques étant faits, l'agriculteur doit piloter l'irrigation (Sebillote and Soler, 1990) en fonction des contraintes opérationnelles évoluant au jour le jour telles que la météo, l'état des cultures, la disponibilité en eau, entre autres. Cette gestion opérationnelle, en plus d'avoir des conséquences sur la production de l'année en cours (Martin-Clouaire, 2017), est importante car elle influe sur la qualité de vie des irrigants, et met en avant des effets de seuils non visibles au niveau organisationnel. À l'échelle du réseau d'irrigation, le niveau opérationnel comprend par exemple le débit en entrée du réseau en fonction des demandes en eau des irrigants, du quota de prélèvement et des limites hydrauliques du réseau pour éviter qu'il ne déborde notamment. En cours de campagne d'irrigation, les possibilités d'ajustement opérationnel du calendrier d'irrigation des agriculteurs sont ainsi déjà limitées par les contraintes organisationnelles, et doivent également prendre en compte les contraintes réglementaires. Par exemple, en situation de restriction, l'application par les agriculteurs de leur stratégie d'irrigation peut être difficile, conduisant à des fréquences d'irrigation moindres des cultures. Des modifications organisationnelles sont alors opérées allant dans le sens d'une plus grande flexibilité et autonomie opérationnelle de chaque irrigant pour pouvoir notamment réagir et s'adapter aux nouvelles contraintes réglementaires (restrictions en eau, gestion plus fine du volume alloué). Il s'agit, par exemple, de se décharger des

contraintes liées au mode collectif de partage de l'eau comme les tours d'eau hérités des traditions passées. C'est notamment le cas de l'ASA d'Aspres-Sur-Buëch, dans le bassin du Buëch, affluent de la Durance, qui a utilisé ce mode de partage pendant des siècles avant de l'abandonner progressivement au cours de ces dernières années.

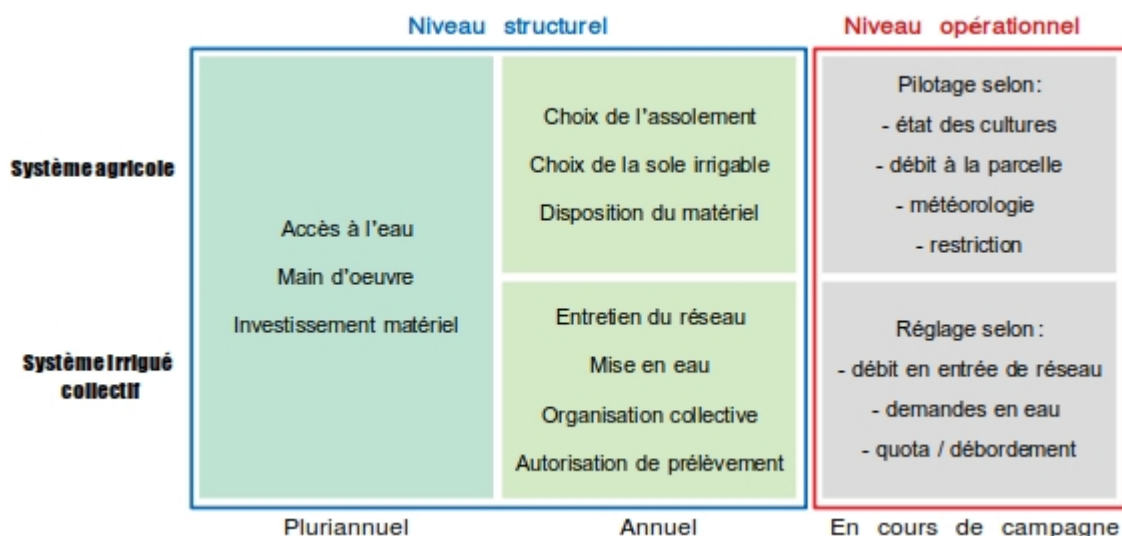


FIGURE C.1: Les niveaux structurel et opérationnel de l'irrigation (adapté de *Sebillote et Soler, 1990*).

Cette étude propose d'étudier l'impact, au niveau opérationnel, de l'abandon du mode de partage par tours d'eau, sur un système gravitaire typique de moyenne Durance. Pour cela, nous proposons une approche multi-agents permettant de représenter la gestion opérationnelle de ces systèmes irrigués. Dans la littérature, la grande majorité des modèles à base d'agents sont fondés sur des plans d'actions conçus a priori, bien adaptés au niveau organisationnel, mais qui prennent difficilement en compte le contexte du moment, qui nécessiterait de prévoir à l'avance l'ensemble des situations à venir et d'avoir un plan pour chacune d'elles. Or il existe des approches basées sur la théorie de l'action située qui représentent la situation au moment d'agir via ses différentes possibilités opérationnelles, appelées affordances. Dans cette étude, nous proposons de mobiliser le modèle conceptuel WatASit basé sur le concept d'affordance, pour mieux comprendre l'impact de l'abandon du mode de partage par tours d'eau en représentant explicitement le niveau opérationnel de gestion au cours d'une campagne d'irrigation. La plupart des plans d'expériences réalisés sur des modèles d'exploitations agricoles visent à étudier

les impacts de forçages climatiques ou de mode de gestion sur des indicateurs agro-économiques. Notre objectif est ici d'utiliser l'action située via le concept d'affordance pour aller plus loin dans l'analyse de la chaîne causale : scénario de gestion (avec ou sans tours d'eau), possibilités d'irrigation offertes aux agents au cours de la simulation, actions finalement réalisées par les agents et conséquences sur les indicateurs. Après avoir décrit le cas d'étude et les données utilisées, nous présentons le modèle WatASit-Aspres dédié au cas d'étude. Nous explorons ensuite les résultats de simulation et discutons l'apport des affordances, avant de conclure.

C.2 Matériel et méthodes

C.2.1 Le cas d'étude

Le bassin versant du Buëch (figure C.2), d'une superficie de 1490 km², s'étend principalement sur le département des Hautes-Alpes, en France. Orienté nord/sud, ce sous-bassin de la Durance est un territoire de moyenne montagne et de transition entre les Alpes et la Provence, dont la confluence avec la Durance se fait à Sisteron. En termes d'usages de l'eau, le bassin est classé en Zone de Répartition des Eaux (ZRE) signifiant qu'une insuffisance est constatée entre la ressource et les besoins. Les usages de l'eau ont d'ailleurs été restreints deux années sur trois en moyenne sur la période 2003-2017. L'irrigation collective constitue de loin l'usage qui prélève le plus sur la ressource en eau durant la période d'étiage, entre mai et octobre, avec 38 associations d'irrigants de type Association Syndicales Autorisées (ASA) équipées soit pour l'irrigation gravitaire, soit pour l'irrigation sous-pression, ou pour les deux. En 2017 l'irrigation gravitaire représentait 7,3% des superficies irrigables pour 44,7% des volumes prélevés autorisés, avec comme principales cultures les prairies (43,6%), suivies des céréales (29,7%) et des fourrages (22,2%).

L'ASA d'Aspres-sur-Buëch a été choisie comme cas d'étude car elle est assez représentative en termes de localisation (dans la partie amont du bassin), de surface irrigable (avec 75 ha alors que la moyenne est de 50 ha), et d'assolement (avec 38,9 % de prairies, 29,5 % de fourrages et 23,7 % de céréales). La zone d'étude comprend 83 parcelles irrigables via un canal gravitaire (figure C.2) par 10 agriculteurs irrigants. Des enquêtes de terrain ont

été menées afin de recueillir des informations sur les différentes contraintes d'irrigation durant la campagne 2017 (tableau C.1). Selon ces enquêtes, les agriculteurs de la zone d'étude ont abandonné progressivement, au cours des 15 dernières années, l'organisation historique par tours d'eau journaliers pour se libérer de sa contrainte temporelle.

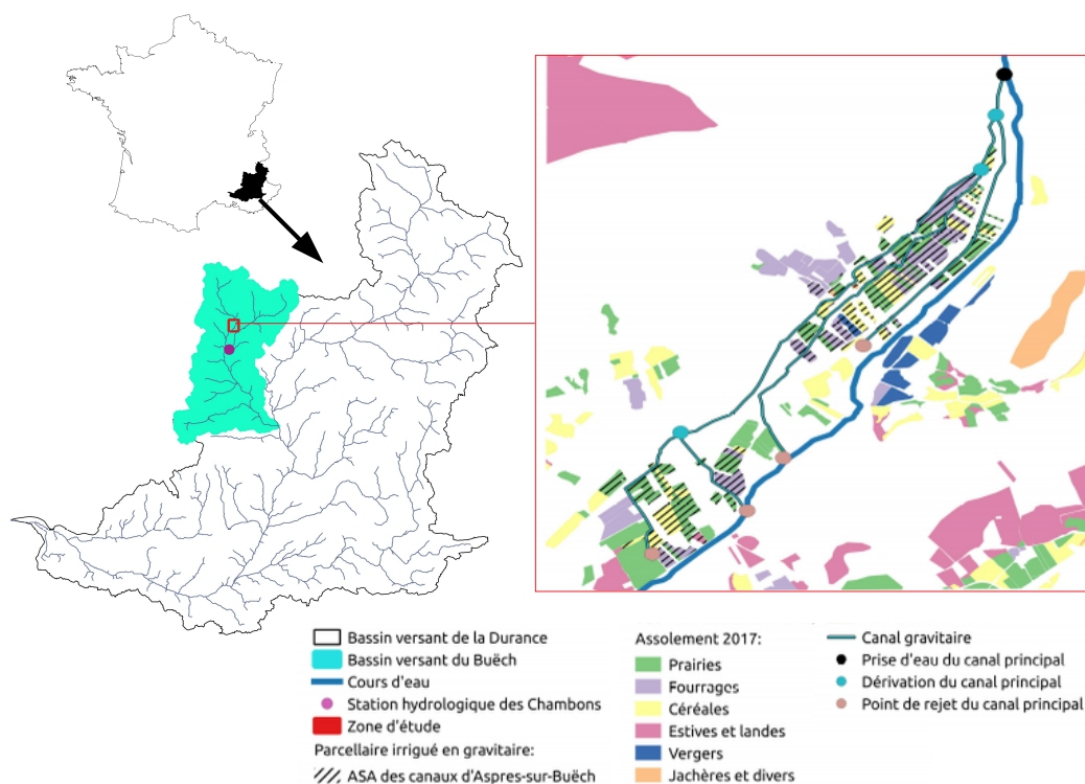


FIGURE C.2: Présentation de la zone d'étude (encadré rouge) située dans le bassin versant du Buëch (en bleu), sous-bassin de la Durance. Au sein de la zone d'étude, les couleurs représentent les types de cultures, et le périmètre irrigué en gravitaire de l'ASA d'Aspres-sur-Buëch apparaît en rayé (source: BD Cartage, BD Hydra et RPG 2017 consultés en mars 2019).

C.2.2 Les données

C.2.2.1 L'occupation du sol

Le Registre Parcellaire Graphique (RPG) est une base de données d'informations géographiques utilisée comme référence pour l'examen des aides de la politique agricole commune (PAC). Il fournit chaque année à l'échelle de la France les limites des parcelles agricoles et leur principale culture. Les données de 2017 ont été utilisées.

C.2.2.2 Les infrastructures d'irrigation

La base de données Hydra développée en 2015 (BD Hydra V2) fournit des données géographiques sur l'ensemble de la région Provence-Alpes-Côte-d'Azur (PACA) à différentes échelles. Les données utilisées dans l'étude concernent les fichiers de forme du périmètre et du réseau d'Aspres-Sur-Buëch (téléchargés en 2019 à cette adresse: <http://www.crige-paca.org/>).

C.2.2.3 Les conditions météorologiques

Les données météorologiques quotidiennes ont été obtenues à partir de la réanalyse française SAFRAN (Vidal et al., 2010) sur une grille de 8 km du 1er janvier 2017 au 31 décembre 2017.

C.2.2.4 Les restrictions en eau

Les restrictions d'utilisation de l'eau adoptées dans la zone d'étude au cours de l'année 2017 proviennent de la base de données nationale PROPLUVIA (<http://propluvia.developpement-durable.gouv.fr>), qui fournit les dates d'entrée en vigueur et le niveau de restriction associé. Leurs conséquences sur l'irrigation sont expliquées dans le Plan directeur de lutte contre la sécheresse des Hautes-Alpes (<http://www.hautes-alpes.gouv.fr/le-plan-cadresecheresse-a1895.html>), qui prévoit la limitation de l'irrigation deux jours par semaine (jeudi et dimanche pour notre cas d'étude) si le niveau de restriction est "alerte", le niveau qui a été adopté sur le cas d'étude en 2017.

C.2.3 Le modèle à base d'agents WatASit

C.2.3.1 Cadre théorique

Plusieurs théories peuvent être mobilisées pour représenter les comportements d'acteurs. Alors que la théorie de l'action planifiée considère que toute action est déterminée par un état à réaliser et un plan pour y parvenir (Miller, 1960a), la théorie de l'action située (Dreyfus, 1972, Suchman, 1987) est apparue en réponse à une question fondamentale :

comment le plan, qui est une représentation abstraite de la réalité conçue a priori, peut-il être lié aux modalités concrètes de mise en œuvre d'une action ? En représentant la phase d'exécution en fonction de ses contraintes opérationnelles, le comportement de l'acteur est alors déterminé par ses possibilités d'action lorsqu'il agit, et pas seulement par les processus de décision. Ces possibilités d'action, appelées *affordances* (Gibson, 1977), changent continuellement en fonction du contexte du moment, obligeant l'acteur à s'y adapter. Ainsi, l'action ne résulte pas seulement d'une représentation abstraite (en tant que plan) mais provient d'un sous-ensemble limité d'actions possibles (i.e. les *affordances*) se produisant dans un lieu précis à un moment donné. À un pas de temps donné, les acteurs peuvent choisir, ou non, en fonction de leur stratégie opérationnelle, de sélectionner une des *affordances* présentes dans leur environnement à ce pas de temps pour l'exécuter en tant qu'action.

Précédemment, les travaux de Guerrin (2009) ont porté sur la modélisation des actions situées dans les systèmes agricoles en adoptant une approche de dynamique des systèmes, sans tenir compte de la dimension spatiale. Les premières mentions d'*affordances* dans les modèles à base d'agents se trouvent dans Cornwell et al. (2003) et Raubal (2001). Courdier et al. (2002) ont proposé un modèle à base d'agents incluant la notion d'objets situés. Afoutni et al. (2014) ont travaillé sur un premier modèle conceptuel focalisant sur la représentation de l'action située en utilisant notamment le concept d'*affordance*. Néanmoins ce modèle conceptuel n'a pas été déployé sur un cas d'étude réel.

C.2.3.2 La structure du modèle WatASit

Nous présentons simultanément dans cette section la structure du modèle conceptuel WatASit et sa spécification sur le cas d'étude. La structure du modèle est basée sur la distinction entre les éléments qui sont impliqués dans les opérations, appelés entités opérationnelles, et les zones spatiales sur lesquelles les entités opérationnelles peuvent opérer, appelées entités spatiales. Les entités opérationnelles sont organisées selon l'idée proposée par l'approche IODA (Interaction-Oriented Design of Agent simulations) (Kubera et al., 2011), qui distingue les entités qui effectuent des actions, des entités qui subissent des actions. Dans notre approche, nous suivons l'organisation inspirée de l'approche IODA proposée par Afoutni (2015):

- Les opérateurs sont des entités qui sont source d'interaction avec un objet passif, car ils peuvent mener des actions,
- Les objets passifs sont des entités qui sont la cible d'une interaction avec un opérateur, qui est nécessaire pour réaliser une action.

La structure des modèles à base d'agents peut être représentée aisément à l'aide d'un diagramme de classe UML (*Unified Modeling Language*) qui synthétise les différents types d'entités du modèle ainsi que leurs relations (Le Page and Bommel, 2005). La figure C.3 présente les types d'entités principales du modèle WatASit.

Les classes blanches représentent la zone spatiale considérée : elle est composée de plusieurs entités spatiales, le réseau d'irrigation, les exploitations agricoles et les parcelles qui sont des spécialisations de la classe des entités spatiales (liens en violet avec des flèches). Les parcelles ont quatre états possibles : "non irriguée", "irriguée", "irriguée en période de restriction" ou "abandonnée". Le réseau d'irrigation et les exploitations agricoles sont représentés comme un ensemble de parcelles agricoles, qui peuvent être irriguées ou non, selon qu'elles soient desservies ou non par le réseau. La capacité hydraulique et l'organisation collective représentent les contraintes du réseau d'irrigation héritées des choix stratégiques faits par les agriculteurs. De même, une exploitation agricole est associée à un système de culture et à une main-d'œuvre (i.e. un nombre de personnes en capacité d'irriguer).

Les classes vertes représentent les entités opérationnelles qui sont localisées sur les entités spatiales (figure C.3, cases vertes). Elles représentent physiquement les opérateurs (les irrigants) et les objets passifs (les infrastructures, les cultures) situés sur la zone spatiale. Chaque exploitation est occupée par un agriculteur unique. Les opérateurs disposent d'une stratégie opérationnelle qui leur permet de choisir entre les affordances disponibles simultanément, et qui est conforme aux principales règles de fonctionnement mentionnées par les agriculteurs lors des enquêtes de terrain (tableau C.1). Ces règles donnent la priorité aux parcelles n'ayant pas été irriguées au cours des 12 derniers jours. S'il existe de telles parcelles et qu'il a plu moins de 120 mm au cours des dix derniers jours (ce qui est considéré comme suffisant par les agriculteurs pour éviter

d'avoir à irriguer), l'opérateur choisit parmi ces parcelles celle qui n'a pas été irriguée depuis le plus longtemps. Lorsqu'une parcelle est choisie pour être irriguée, son état devient "irriguée" ou "irriguée en période de restriction", selon l'action réalisée et durant la durée d'exécution de cette action. De plus, les parcelles dont le nombre de jours écoulés depuis la dernière irrigation dépasse 45 sont considérées comme abandonnées pour l'irrigation par les agriculteurs. Ce délai correspond approximativement au délai entre deux fauchages de prairie, le principal type de culture du cas d'étude. L'état des parcelles devient alors "abandonnée" de manière irréversible.

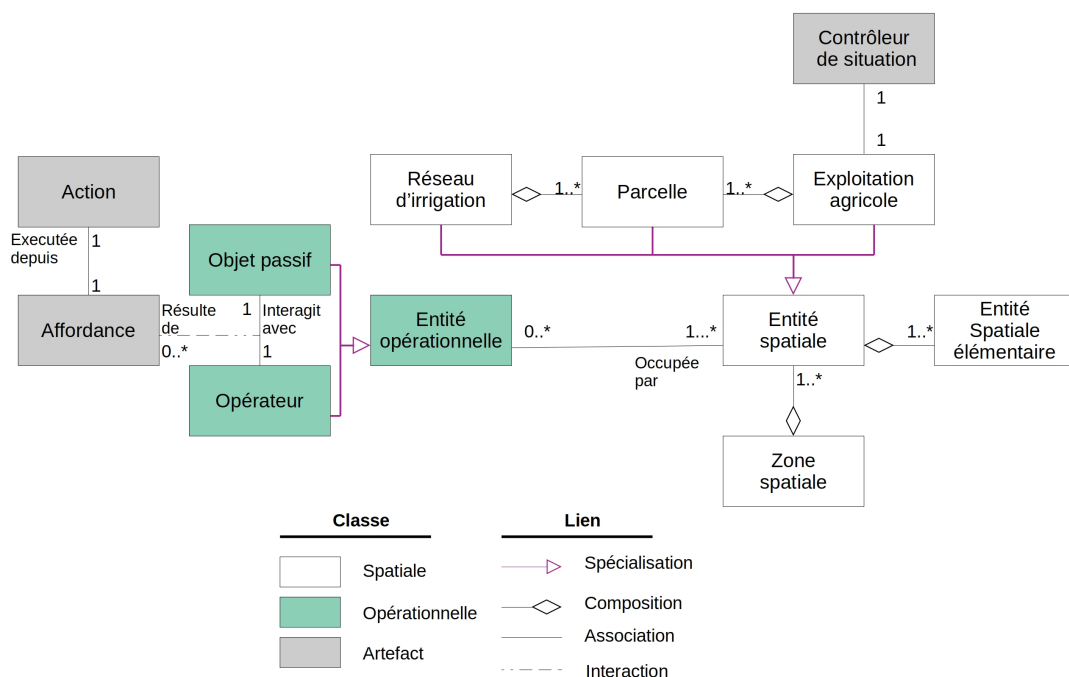


FIGURE C.3: Diagramme de classe UML du modèle WatASit. Chaque boîte aux contours solides représente un type d'entité : une Classe. Les classes blanches sont des entités spatiales, les classes vertes sont des entités opérationnelles, et les classes grises sont des entités artefacts. Les liens commençant par des losanges représentent des compositions (par exemple, une exploitation est composée de une ou plusieurs parcelles), les liens mauves avec des flèches signifient qu'un type d'entité est une spécialisation d'un autre (par exemple, une exploitation et une parcelle sont deux entités spatiales particulières), les liens en pointillés sont des interactions entre les classes, et les autres liens représentent toutes les autres relations, appelées associations (par exemple en entité opérationnelle est située sur une ou plusieurs entités spatiales, qui sont elles-mêmes associées à zero ou plusieurs entités opérationnelles).

Les classes grises concernent les artefacts nécessaires à l'approche située. Nous considérons trois types d'artefacts : les affordances, les actions et les contrôleurs de situation.

Selon la définition de Stoffregen de l’affordance comme une propriété émergente du couple acteur-environnement (Stoeffregen, 2003b), les affordances résultent des interactions entre les opérateurs et les objets passifs. Sur une entité spatiale donnée, le contrôleur de situation vérifie si un opérateur est présent, et s’il peut interagir avec un objet passif. Si les conditions d’interaction sont remplies, une affordance est générée. C’est pourquoi les affordances sont représentées dans notre modèle par une classe d’interaction impliquant une entité opérationnelle jouant le rôle d’un opérateur, et une entité opérationnelle jouant le rôle d’un objet passif (figure C.3, cases grises et lien en pointillés). Comme une affordance représente une possibilité d’action, une action est liée à une affordance unique et partage la même localisation et la même origine temporelle. Les conditions d’interaction pour la génération des affordances considérées dans le modèle WatASit-Aspres sont présentées dans le tableau C.2, ainsi que les conditions d’exécution, la durée potentielle et les effets de l’action correspondante.

Les affordances de mise en eau des parcelles - i.e. *Inonder* et *Inonder (restriction)* - sont générées lorsque l’opérateur est disponible, c’est-à-dire lorsqu’il n’est pas impliqué dans une autre action, et si la parcelle agricole est suffisamment desservie en eau par le canal. Il convient de noter qu’il n’y a pas de génération d’affordances d’irrigation lorsque celles en cours dans la même branche du canal ne permettent pas d’irriguer une nouvelle parcelle agricole en raison d’une insuffisance de débit dans la branche. Cela représente une forme de coordination intra-branche entre les agriculteurs.

C.2.3.3 Le séquençage du modèle WatASit-Aspres

Le séquençage du modèle est basé sur une boucle entre perception journalière et action horaire. Chaque jour, il y a d’abord une mise à jour des contraintes opérationnelles considérées et/ou perçues à ce pas de temps par l’opérateur, notamment les précipitations prévues pour les jours à venir et l’adoption de restrictions d’irrigation au niveau de la zone étudiée. Ensuite, on passe à la phase d’action horaire, l’étape opérationnelle à proprement parler. Chaque heure et sur chaque exploitation, les entités opérationnelles sont détectées par les contrôleurs de situation, puis les affordances sont générées. L’application de la stratégie opérationnelle au niveau de chaque opérateur permet le choix de l’action à chaque pas de temps horaire parmi l’ensemble des affordances générées. Puis l’opération

TABLE C.1: Les affordances du modèle WatASit-Aspres et les couples opérateur/objet passif associés. Pour chaque affordance, les conditions d'interaction pour leur génération sont présentées. Q , Q_{min} et Q_{max} renvoient aux débit, débit minimum et débit maximum dans le canal d'irrigation. $Q_{\text{échelon}}$ correspond à l'augmentation de débit en entrée du réseau consécutivement au relevage de la vanne d'un échelon de mesure

Affordance	Opérateur / objet passif	Conditions d'interaction
Inonder	Irrigant / martellière	Disponibilité de l'opérateur Pas de précipitation Disponibilité de l'opérateur Niveau de restrictions < "alerte" État de l'objet passif ($Q \geq Q_{min}$)
Inonder (restriction)	Irrigant / martellière	Disponibilité de l'opérateur Pas de précipitation Disponibilité de l'opérateur Niveau de restrictions \geq "alerte" État de l'objet passif ($Q \geq Q_{min}$)
Demander	Irrigant / martellière	Disponibilité de l'opérateur Pas de précipitation État de l'objet passif ($Q < Q_{min}$)
Faire autre chose	Irrigant / autre objet passif	Disponibilité de l'opérateur

TABLE C.2: Conditions d'exécution, durée potentielle et effet des actions. Q , Q_{min} et Q_{max} renvoient aux débit, débit minimum et débit maximum dans le canal d'irrigation. $Q_{\text{échelon}}$ correspond à l'augmentation de débit en entrée du réseau consécutivement au relevage de la vanne d'un échelon de mesure

Action	Condition(s) d'exécution	Durée cible	Effet de l'action
Inonder	État de l'objet passif ($Q \geq Q_{min}$)	4 heures/ha	$Q = Q - Q_{min}$
Inonder (restriction)	État de l'objet passif ($Q \geq Q_{min}$)	4 heures/ha	$Q = Q - Q_{min}$
Demander	Aucune	1 heure	$Q = \min(Q_{max}, Q + Q_{\text{échelon}})$
Faire autre chose	Aucune	1 heure	Aucun

choisie est réalisée, et l'écoulement dans le réseau d'irrigation est mis à jour en entrée de parcelle, ainsi que l'état des parcelles.

C.2.3.4 La représentation du réseau d'irrigation gravitaire

Nous utilisons un modèle d'écoulement gravitaire simplifié¹. L'objectif de ce modèle simplifié n'est pas de simuler précisément le débit hydraulique s'écoulant à travers les

¹Sa description est disponible à ce lien <https://www.comses.net/codebases/0d8dcaf1-8772-4e57-9f03-1f6c062bbe60/releases/1.2.0/>

branches du canal, mais de représenter le lien entre l'organisation des irrigants et le débit en eau desservant les différentes parcelles agricoles réparties le long du gradient amont-aval. Pour rendre possible l'inondation d'une parcelle agricole, il est nécessaire, en raison de la taille et du fonctionnement des vannes, d'atteindre et de maintenir un débit fixe à leur niveau. Ce fonctionnement a aussi été observé en Crau sur des réseaux similaires (Hong, 2014). Cela signifie que l'inondation d'une parcelle agricole n'est pas possible si elle est desservie avec un débit inférieur. Lorsqu'une irrigation est déclenchée, c'est-à-dire lorsqu'une action *Inonder* ou *Inonder (restriction)* est exécutée par un agent agriculteur, le débit d'inondation est soustrait du débit de la branche correspondante du canal. Si des irrigations simultanées sont lancées au même moment, le nombre maximum d'irrigations simultanées est déterminé par le débit de la branche qui doit permettre de desservir toutes les parcelles irrigables par celle-ci. La durée d'inondation est ajustée en fonction de la taille de la parcelle agricole, le temps d'irrigation empirique par hectare ayant été recueilli auprès des agriculteurs interrogés. Le débit dans chaque branche du canal est obtenu en fonction du débit de la branche amont et d'un coefficient de division à chaque embranchement. Un taux d'infiltration par unité de longueur de chaque branche est également pris en compte à partir de mesures effectuées par Charton (2001). La mise en eau du canal se fait au 1er mai, selon le cahier des charges de l'ASA. En outre, le débit en entrée du canal peut varier lorsqu'une action *Demander* est exécutée, dont l'effet est de relever la martellière en entrée du réseau d'un échelon.

C.2.3.5 L'implémentation du modèle et la paramétrisation de l'état initial

Le modèle est implémenté dans la plateforme de modélisation et simulation multi-agents CORMAS (Bommel et al., 2015). Les parcelles agricoles ont été importées à l'aide d'un prétraitement qui consiste à "rasteriser" les fichiers de forme sur une grille de 54x44 cellules ayant une résolution de 75m. Les parcelles agricoles appartenant à chaque ferme ont été identifiées, ainsi que celles desservies par chaque branche du canal. Le réseau d'irrigation composé de la prise d'eau du canal, de ses branches, de ses dérivations, points de rejet et vannes aux parcelles ont été importées dans la plateforme de modélisation en suivant le même procédé. Les opérateurs ont un attribut de disponibilité maximale de travail de 12 heures par jour, et ne peuvent pas entreprendre une nouvelle opération s'ils sont déjà impliqués dans une autre.

C.2.3.6 Les scénarios et les sorties de simulations

Les deux scénarios envisagés dans l'approche de modélisation concernent l'organisation collective au sein du réseau d'irrigation, avant et après l'abandon par tours d'eau. Le scénario de référence (SR) ne tient pas compte d'une coordination par tours d'eau entre les différentes branches du canal d'irrigation, conformément au fonctionnement actuel du réseau d'irrigation d'Aspres-Sur-Buëch. Cela signifie que l'eau circule simultanément dans toutes les branches du canal. Le scénario alternatif (SA) considère des créneaux journaliers d'irrigation fixes pour chaque branche du canal d'irrigation, tels qu'ils étaient pratiqués il y a encore 15 ans sur la zone d'étude. Dans le scénario alternatif, les branches du canal du réseau d'irrigation s'écoulent une par une dans une programmation de 10 jours. Cela permet d'augmenter le débit délivré aux parcelles agricoles desservies par la branche mais impose aux agriculteurs des créneaux d'irrigation.

Le modèle WatASit-Aspres permet de simuler le nombre d'affordances et d'actions de chaque type durant la campagne d'irrigation, pour chaque agriculteur et sur chaque parcelle. Les résultats du modèle informent donc à la fois sur le nombre de créneaux temporels pour ces opérations, et sur leur distribution spatiale le long du gradient amont-aval du réseau d'irrigation. Un autre indicateur est le nombre de parcelles agricoles dont l'irrigation a été abandonnée pendant la campagne.

C.2.4 Résultats de simulations

C.2.4.1 Impact du mode de partage sur la localisation des irrigations et abandons

Cette section présente la localisation des actions *Inonder* par les irrigants au cours de la campagne d'irrigation simulée entre le 1er mai et le 30 septembre, ainsi que les abandons d'irrigations. Les actions *Inonder* sont géographiquement plus concentrées en amont de la zone d'étude dans le cas du scénario de référence (figure C.4, en haut). Les parcelles de la partie avale n'ont jamais été irriguées, alors que certaines le sont dans le cas du scénario alternatif, notamment celles appartenant aux irrigants 2, 3, 5, 8, 9 et 10.

De manière cohérente avec la localisation des irrigations, les abandons d'irrigation sont plus nombreux dans le cas du scénario de référence (figure C.4, en bas) et concernent les parcelles situées en aval n'ayant pas été irriguées. Dans le cas du scénario alternatif, certaines parcelles ayant été irriguées au cours de la campagne ont quand même été abandonnées. C'est le cas de certaines parcelles situées en aval et appartenant aux irrigants 2 et 9.

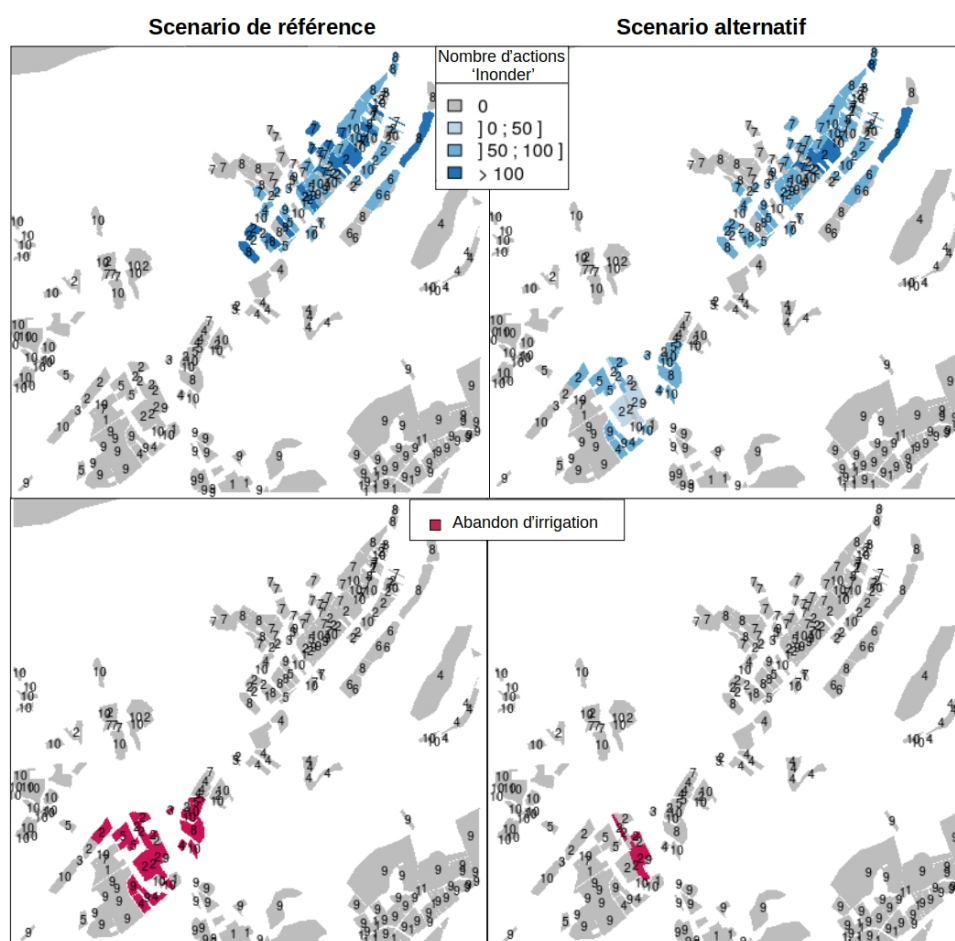


FIGURE C.4: Simulations des actions *Inonder* (en bleu, en haut) et des abandons d'irrigations (en rouge, en bas) dans le cas du scénario de référence (à gauche) et du scénario alternatif (à droite). Un abandon d'irrigation correspond à une parcelle n'ayant pas été l'objet d'une action *inonder* ou *inonder (restriction)* pendant plus de 45 jours. Les chiffres sur chaque parcelle désignent les identifiants des irrigants propriétaires.

C.2.4.2 Impact sur le nombre de possibilités d'actions et d'actions

Cette section présente le nombre cumulé des trois types de possibilités d'actions (i.e. d'affordances) et d'actions d'irrigation (*Inonder*, *Inonder (restriction)*, et *Demander*,

voir tableau C.2) simulées au cours de la campagne, selon le scénario de référence (SR) et le scénario alternatif (SA).

Le nombre d'affordances *Inonder* est très supérieur dans le cas du scénario de référence (figure C.5 A), traduisant un plus grand nombre de créneaux pendant lesquels les irrigants ont la possibilité de déclencher une irrigation. Seul l'irrigant 4 a plus de créneaux dans le cas du scénario alternatif (en bleu). Le nombre de créneaux d'irrigation pendant une période de restriction est également supérieur (i.e. les affordances *Inonder (restriction)*), figure C.5 B). Dans le cas de l'affordance *Demander*, témoignant d'une irrigation potentiellement manquée du fait que la quantité d'eau dans le canal n'est pas suffisante pour irriguer une parcelle qui en a besoin, tous les irrigants ont un nombre de demandes supérieur dans le cas du scénario de référence.

Contrairement au nombre d'affordances *Inonder*, le nombre d'actions du même type n'est pas systématiquement supérieur dans le cas du scénario de référence (en vert, figure C.5 A'), mais seulement pour les irrigants 7 et 8. Cela signifie que le nombre d'irrigations effectives est supérieur dans le cas du scénario alternatif pour les irrigants 2, 3, 4, 5, 9 et 10. Certaines possibilités d'irrigation du scénario de référence n'ont donc pas donné lieu à des irrigations, traduisant le fait qu'à certains moments des agents pouvaient irriguer une parcelle mais ne l'ont pas fait. Cela s'explique soit parce qu'ils ont choisi d'irriguer une autre parcelle à ce moment-là car celle-ci n'était pas prioritaire, soit parce que trop d'agents en amont ont déclenché des actions d'irrigations à ce moment précis et ont épuisé la capacité du canal. Concernant l'action *Inonder (restriction)*, leur nombre montre qu'il y a un plus grand nombre d'irrigations qui sont réalisées en période de restriction sécheresse dans le cas du scénario alternatif (en orange, figure C.5 B'). Ceci signifie que les irrigants n'ont pas pu irriguer ces parcelles précédemment, et qu'ils ne peuvent pas retarder l'irrigation au risque de dépasser le délai de 12 jours depuis la dernière irrigation de la parcelle, ce que leur stratégie d'irrigation cherche à éviter. C'est notamment le cas des irrigants 2, 7, 8 et 10. Le nombre cumulé d'actions *Demander* est quant à lui très largement supérieur dans le cas du scénario de référence (en vert, figure C.5 C'), montrant que le mode de partage sans tours d'eau conduit à un bien plus grand nombre de situations où il aurait fallu irriguer la culture d'après la stratégie

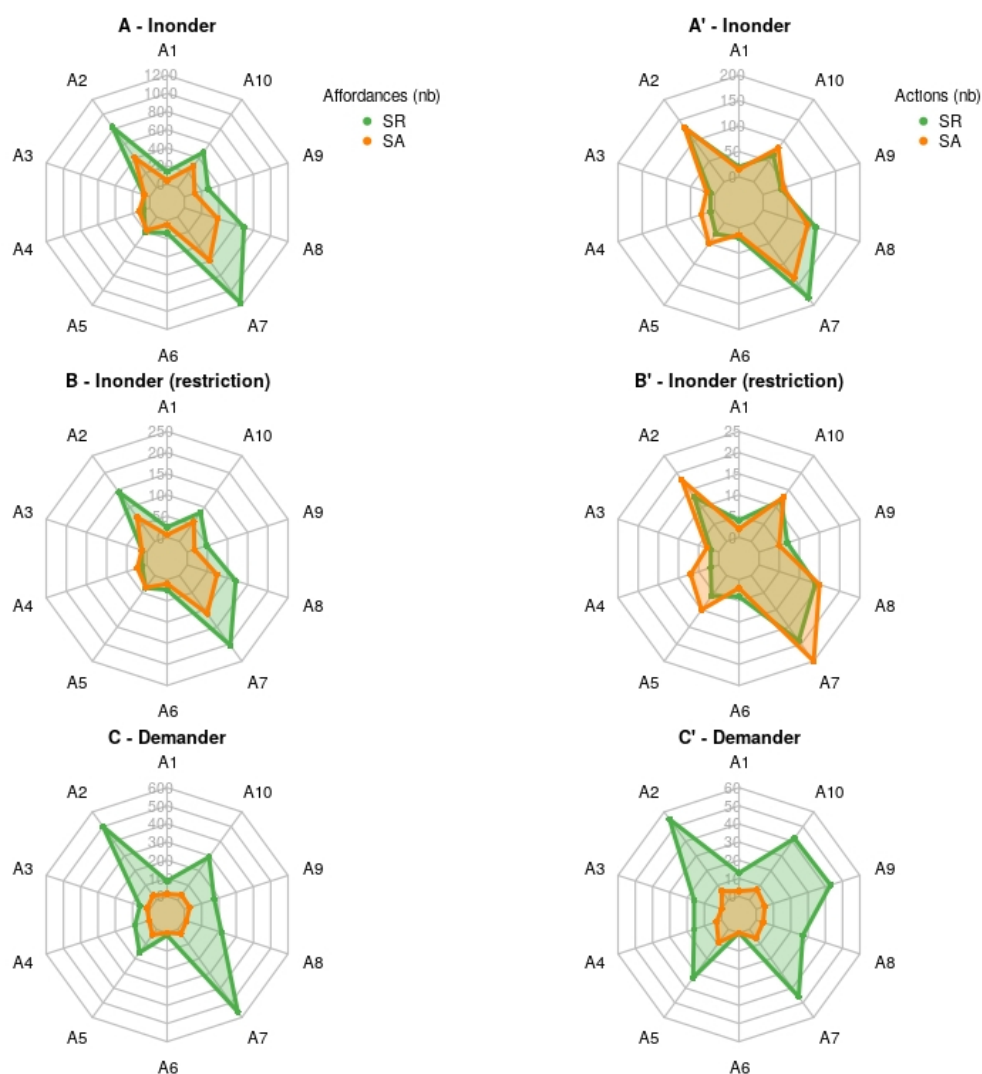


FIGURE C.5: Nombre cumulé d'affordances (à gauche) et d'actions (à droite) pour chacun des 10 agriculteurs irrigants (A1 à A10) au cours de la campagne d'irrigation dans le cas du scénario de référence (SR) et du scénario alternatif (SA). A, B et C renvoient aux affordances *Inonder*, *Inonder (restriction)* et *Demander*. A', B' et C' renvoient aux actions respectives. Les échelles entre les affordances et les actions ne sont pas les mêmes.

d'irrigation mais que c'est impossible du fait d'un débit insuffisant dans le canal.

De manière générale, l'absence de tour d'eau (scénario de référence) conduit à un plus grand nombre de créneaux temporels pendant lesquels l'eau s'écoule dans les branches du canal en alimentant suffisamment, ou non, les parcelles pour les inonder. Cependant, cet écart important dans le nombre de créneaux temporels entre les deux scénarios ne se traduit pas dans les nombres d'actions *Inonder* ou *Inonder (restriction)*. Ce résultat s'explique par le nombre plus important de parcelles irriguées en aval dans le cas du

scénario alternatif, car desservies avec un débit suffisant pour être inondées, qui permet à un plus grand nombre de possibilités d'irrigation d'être effectuées lorsque les irrigants appliquent leur stratégie opérationnelle.

C.2.4.3 Les capacités d'irrigation des agriculteurs rendues plus inégales par l'abandon des tours d'eau

Quel que soit leur type, les écarts en termes de possibilités d'irrigation entre irrigants sont nettement plus prononcés dans le cas du scénario de référence. Ainsi pour l'affordance *Inonder*, l'écart entre le minimum (A3, 100 affordances) et le maximum (A7, 1200 affordances) de possibilités des agriculteurs est d'un facteur 12 dans le cas du scénario de référence, alors que ce facteur ne dépasse pas 6 dans le cas du scénario alternatif (figure C.5 A). Au total, le scénario de référence conduit à 1807 créneaux de plus que le scénario alternatif où l'irrigation est possible (i.e les affordances *Inonder*). Ce faisant, il conduit aussi à 289 créneaux de plus en période de restrictions (i.e. les affordances *Inonder (restriction)*), et 1935 irrigations manquées potentielles (i.e. les affordances *Demander (restriction)*), et 1935 irrigations manquées potentielles (i.e. les affordances *Demander* (tableaux C.3 et C.4)). En moyenne, cela représente 180,7 possibilités d'irrigation de plus par irrigant dans le cas du scénario de référence, 28,9 en période de restriction, et 193,5 irrigations manquées potentielles supplémentaires. Les écarts-types (i.e. la dispersion entre irrigants) sont nettement supérieurs dans le cas du scénario de référence : +189,9 par rapport au scénario alternatif pour les possibilités d'irrigation, +30,7 pour celles en période de restriction, et +173 concernant les irrigations manquées potentielles.

Si la somme et la moyenne par irrigant des possibilités d'irrigation sont similaires dans le cas des deux scénarios, l'écart-type est supérieur dans le cas du scénario de référence (+12,9). Il est cependant légèrement inférieur concernant les possibilités d'irrigation en période de restriction. Quant à la somme des abandons d'irrigation, elle est 6 fois supérieure dans le cas du scénario de référence, se rapprochant fortement du nombre d'abandons observés lors des enquêtes de terrain sur le mode de partage sans tours d'eau du scénario de référence appliqué actuellement par les irrigants. L'écart-type des abandons d'irrigation est également légèrement supérieur dans le cas de ce scénario (+0,4). De plus, la moyenne du nombre de possibilités d'irrigation par parcelle irriguée

TABLE C.3: Somme, moyenne et écart-type de la différence des abandons d'irrigation entre le scénario de référence (SR) et le scénario alternatif (SA). OBS renvoie aux observés lorsqu'ils sont disponibles. ND signifie non disponible

SR	SA	OBS
30	5	29
3	0,5	ND
2	1,6	ND

TABLE C.4: Différence (SR - SA) entre le scénario de référence (SR) et le scénario alternatif (SA) de la somme, la moyenne et l'écart-type des affordances et des actions. OBS renvoie aux observés lorsqu'ils sont disponibles. ND signifie non disponible

		Inonder	Inonder (restriction)	Demander
<i>Somme</i>	Affordances	+1807	+289	+1935
	Actions	0	-17	+248
<i>Moyenne par irrigant</i>	Affordances	+180,7	+28,9	+193,5
	Actions	0	-1,7	+24,8
<i>Écart-type entre irrigants</i>	Affordances	+189,9	+30,7	+173
	Actions	+12,9	-1,9	+14,7

est presque 2,5 fois supérieure dans le cas du scénario de référence. La moyenne du nombre d'irrigations par parcelle irriguée atteint 10,7, proche de l'observée lors des enquêtes (10), et représentant 139 % du nombre dans le scénario alternatif. Autrement dit, il y a moins de parcelles abandonnées dans le scénario alternatif mais chaque parcelle reçoit plus souvent de l'eau dans le scénario de référence.

Pour mieux évaluer les écarts entre irrigants en termes de possibilités opérationnelles selon chacun des scénarios, une analyse en composantes principales, centrée, et normée pour éviter les effets de taille des variables, a été réalisée à partir du nombre par irrigant de chacune des affordances, et également du nombre de parcelles irrigables de chaque irrigant, et de la distance maximale de ces parcelles par rapport à la prise d'eau du réseau d'irrigation (figure C.6). L'axe des abscisses est principalement défini par les variables *Distance* et *Demander*, qui sont fortement corrélées. Vers la gauche, le nombre d'affordances *Demander* augmente ainsi en même temps que la distance maximale des parcelles irrigables d'un agriculteur. L'axe des ordonnées est lui principalement défini par le nombre de parcelles irrigables des agriculteurs, qui augmente en allant vers le haut. La variable d'abandons d'irrigation est autant corrélée au nombre qu'à la distance

des parcelles irrigables, et augmente en même temps que ces deux variables. Les variables *Inonder* et *Inonder (restriction)* sont très corrélées. Dans les mêmes conditions de nombre et de distance des parcelles irrigables, les individus irrigants apparaissent nettement plus dispersés dans le cas du scénario de référence (en vert) que dans le cas du scénario alternatif (en orange). En particulier, l'ellipse des individus est plus étalée le long de l'axe des abscisses dans le cas du scénario de référence, traduisant un effet "distance" plus important.

Au final, l'écart entre les individus irrigants en termes de possibilités d'irrigation est plus faible avec l'organisation par tours d'eau (scénario alternatif), dénotant un nombre de créneaux d'irrigation moins variable d'un irrigant à l'autre que lorsqu'ils ne s'organisent pas par tours d'eau. De plus, les irrigants 4, 9 et 10 apparaissent les plus touchés en termes d'abandons d'irrigation par l'organisation sans tours d'eau, avec les distances entre points les plus importantes pour un même individu, le long de l'axe de la variable *Abandons*. L'irrigant 2 est le seul à avoir eu des abandons de parcelles dans le scénario alternatif, et c'est par conséquent le seul qui soit remonté le long de l'axe vertical avec le scénario alternatif, car il a eu moins de possibilités d'irrigation (hors et pendant les périodes de restrictions) dans le scénario alternatif.

C.2.5 Discussion

Le concept d'affordance mobilisé dans l'approche a permis de mettre en lumière un niveau d'analyse intermédiaire du système étudié. Généralement, les analyses se basent sur des indicateurs finaux, par exemple biophysiques ou économiques, qui synthétisent l'impact des actions réalisées. La mise à disposition dans les résultats de simulations des artefacts d'affordances permet l'étude de l'ensemble des possibles à l'origine des indicateurs finaux.

Appliquée à l'étude du système gravitaire d'Aspres-Sur-Buëch, l'analyse des affordances a permis de mettre en avant la dualité entre les contraintes opérationnelles temporelles et spatiales. Si l'abandon du mode de partage par tours d'eau permet un plus grand

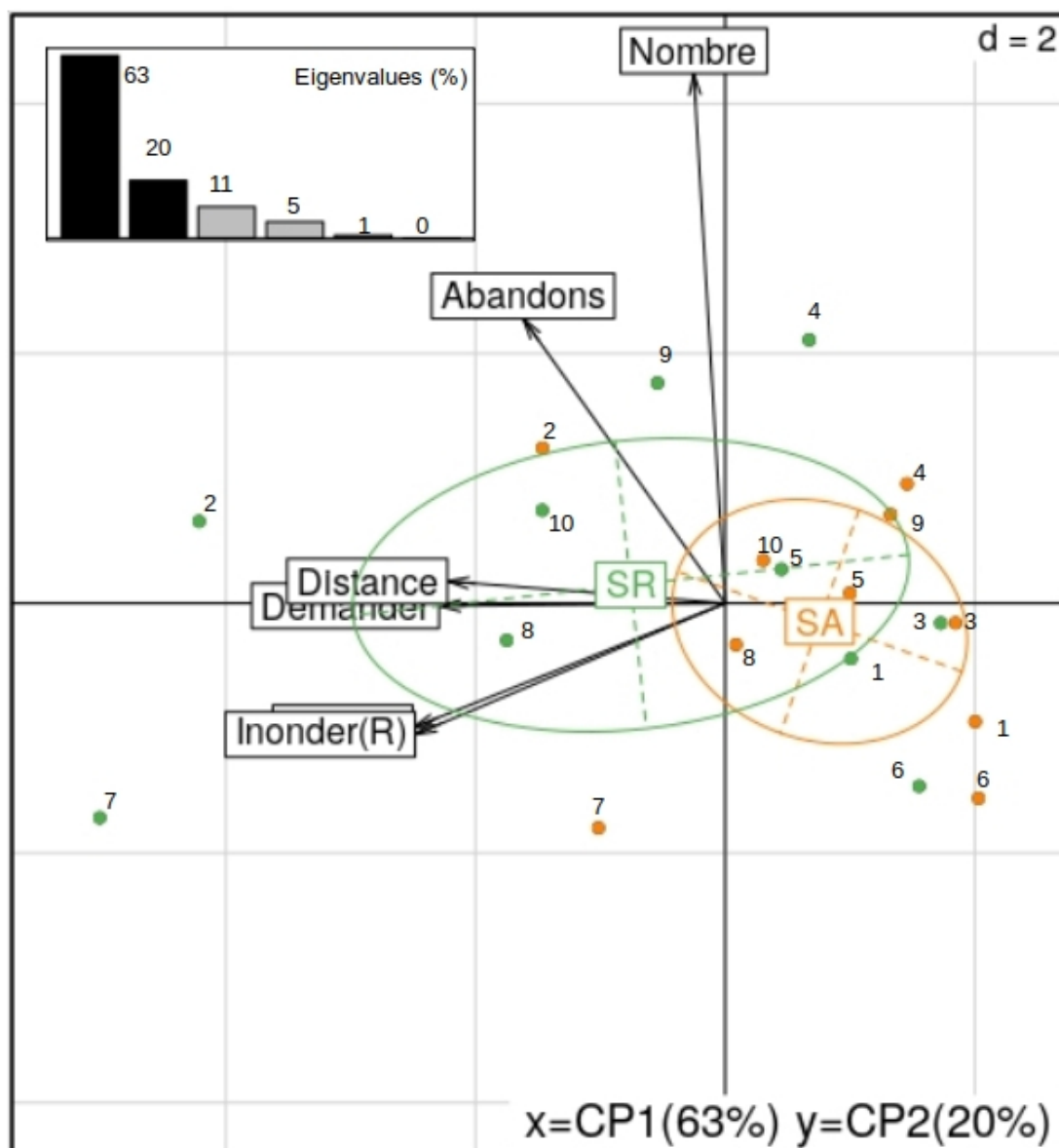


FIGURE C.6: Analyse en composantes principales, centrée et normée, avec ellipses des individus. Chaque point représente un individu irrigant dans le cas du scénario de référence (SR) en vert ou du scénario alternatif (SA) en orange. *Inonder*, *Inonder(R)* et *Demander* sont les variables représentant le nombre d'affordances de chaque type. *Nombre* et *Distance* correspondent au nombre de parcelles irrigables de chaque agriculteur, et à la distance maximale de ces parcelles par rapport à la prise d'eau du réseau d'irrigation. Les chiffres indiquent les identifiants des individus irrigants. L'encadré présente les valeurs propres en pourcentage de l'inertie totale (eigenvalues) pour chaque composante principale.

nombre de créneaux d'irrigation (i.e. plus d'affordances), il s'accompagne d'une augmentation de l'importance de la contrainte spatiale se traduisant par de plus fortes inégalités parmi les irrigants en termes de nombre de possibilités d'irrigations, ainsi que l'abandon d'un plus grand nombre de parcelles par certains plutôt que par d'autres. Le choix de l'abandon des tours d'eau n'impacte donc pas de la même manière les irrigants en termes de capacités d'irrigation, et donc de production, et pose la question de la prise de décision de ce changement d'organisation. Les irrigants les plus impactés par le changement ont-ils pesé dans ce choix ? Les enquêtes auprès des irrigants ayant abandonné définitivement l'irrigation dans les parcelles en aval les plus mal desservies montrent qu'ils sont assez conscients de ces déséquilibres. Ils évoquent notamment l'avantage des propriétaires de parcelles situées en amont du réseau, qui sont toujours suffisamment desservies en eau quel que soit le mode de partage adopté. Ils incriminent fortement la contrainte des restrictions en eau. Celle-ci, cumulée avec celle de la météorologie (pluie, vent) rend difficile la gestion du stress hydrique et nécessite de trouver plus de créneaux d'irrigation en dehors des plages restreintes, comme la nuit, ce qui est difficilement compatible avec le maintien des tours d'eau fixes. De plus, ils évoquent le manque de moyens humains et financiers pour l'entretien, en particulier le curage, qui pénalise l'écoulement dans les branches les plus en aval du réseau. De tels arguments se retrouvent aussi au niveau d'autres associations d'irrigants en gravitaire du bassin du Buëch, et il serait intéressant d'enquêter sur d'autres bassins versants. Ainsi, le passage à un mode de partage de l'eau plus "flexible" répond à un ensemble de contraintes accrues, accentuant les déséquilibres internes au réseau d'irrigants, mais assurant un service minimum.

Déployer l'approche sur d'autres cas d'étude permettrait aussi d'évaluer l'influence des données du modèle. Notamment, un besoin d'irrigation plus rare ou plus fréquent selon la quantité de pluie considérée influe sur le nombre d'affordances considérées dans la stratégie d'irrigation, et donc sur le nombre de possibilités d'irrigation (i.e. d'affordances) générées. Les valeurs de débits sont également spécifiques au cas d'étude et à la capacité d'épuisement de son canal. Les prélèvements bruts et nets sur la ressource n'étaient pas l'objet de cette étude, mais leur intégration permettrait de comparer l'efficacité en eau de chaque mode d'organisation. Les données météorologiques et les restrictions étant disponibles sur d'autres années, il serait intéressant de comparer la tendance moyenne des affordances et des actions, ainsi que leur écart-type, d'une année

sur l'autre. Le suivi du stress hydrique des cultures permettrait par ailleurs un meilleur suivi biophysique des plantes au cours de la campagne d'irrigation.

C.2.6 Conclusions

Pour étudier l'impact de l'abandon des tours d'eau et l'autonomisation de l'irrigation associée sur les capacités à irriguer des différents agriculteurs partageant un réseau collectif, le modèle multi-agents WatASit basé sur le concept d'affordance a été appliqué au périmètre gravitaire d'Aspres-Sur-Buëch. L'approche a permis de représenter une campagne d'irrigation au niveau opérationnel, en plus des contraintes organisationnelles héritées des choix réalisés par les irrigants en amont de la campagne. En particulier, deux scénarios concernant le mode de partage de l'eau ont été explorés. Un scénario de référence, qui correspond au partage sans tours d'eau tel qu'il est pratiqué actuellement, a été comparé à un scénario alternatif, représentant l'organisation par tours d'eau qui a été abandonnée au cours des dernières années.

Les résultats de simulations ont mis en avant les difficultés à desservir en eau de manière suffisante les parcelles les plus en aval du réseau lorsque l'organisation par tours d'eau est abandonnée. Un deuxième niveau d'analyse permis par la lecture des affordances a montré : (1) une augmentation des créneaux d'irrigation associée à l'abandon des tours d'eau, corrélée à (2) une augmentation des inégalités entre irrigants en termes de possibilités et d'abandons d'irrigation, notamment selon la localisation et le nombre de parcelles irrigables de chaque irrigant.

Le choix qui consiste à organiser le partage de l'eau avec ou sans ce type de tours d'eau fixes au sein du réseau d'irrigation revient à donner la priorité soit à la réduction de la contrainte temporelle, soit à la réduction de la contrainte spatiale. Il semblerait que les nouvelles contraintes réglementaires participent, avec le manque de ressources humaines et financière, à opter pour une réduction de la contrainte temporelle au détriment de la capacité de production des agriculteurs les moins bien lotis géographiquement.

C.2.7 Acknowledgements

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Appendix D

List of publications

Publications related to the thesis work

Articles

Richard, B., Bonté, B., Barreteau, O., Braud, I., 2020. The abandonment of water daily slot and its operational consequences on collective irrigated systems. A situational multi-agent approach applied to a gravity-fed canal of Middle-Durance (France). *La Houille Blanche - Revue Internationale de l'Eau*. 4: 43–55. <https://doi.org/10.1051/lhb/2020033>

Richard, B., Bonté, B., Barreteau, O., Braud, I., 2020. Using the Affordance concept to help interpret agent trajectories in ABMs: application to collective irrigation coordination. *Socio-environmental Systems Modelling*. Under review.

Richard, B., Bonté, B., Delmas, M., Braud, I., Barreteau, O., Cheviron, C., Veyssier, J., 2020. A framework for coupling plant and agent trajectories (COPAT) to support irrigation coordination strategies. *Agricultural Water Management*. Under review.

Richard, B., Barreteau, O., Bonté, B., Braud, I., 2021. Representations of human action in agricultural agent-based models: A review. *Agricultural Systems*. In preparation.

Richard, B., Bonté, B., Veyssier, J., Braud, I., Barreteau, O., Branger, F., 2021. A method for coupling natural water resources and agent trajectories (COWAT) to consider their local interactions due to collective irrigation. *Water Resource Research or Journal of Hydrology*. In

preparation.

Presentations

Richard, B., Bonté, B., Barreteau, O., Braud, I., Delmas, M., Cheviron, B., 2020. A software coupling framework to assess coordination strategies of collective irrigation. *International Environmental Modelling and Software Society (iEMSs) 2020 Conference*. Brussels, Belgium, 14-18 September, 2020.

Richard, B., Bonté, B., Barreteau, O., Braud, I., 2019. Representing the collective irrigated systems at the operational level in situation of tension for the local sharing of water. *UNESCO-SHF International Conference on Drought*. Paris, France, 11-13 December, 2019.

Other publications made during the thesis period

Collard, A-L., Riaux, J., Massuel, S., Bonté, B., Laurenceau, M., Richard, B., Rivière-Honegger, A., 2020. Construire un regard socio-hydrologique (3). Expérimenter un canevas pour engager la négociation interdisciplinaire. *Nature Sciences et Sociétés: vie de la recherche*. Under press.

Bouras, E., Jarlan, L., Er-Raki, S., Albergel, C., Richard, B., Balaghi, R., Khabba, S., 2020. Linkages between rainfed cereal production and agricultural drought in Morocco through remote sensing indices and a Land Data Assimilation System. *Remote Sensing*. Under press.

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Sauquet, E., Richard, B., Devers, A., Prudhomme, C., 2019. Water restrictions under climate change: A Rhône-Mediterranean perspective combining bottom-up and top-down approaches. *Hydrological and Earth System Sciences*. 23: 3683–3710. <https://doi.org/10.5194/hess-23-3683-2019>

Hajhouji, Y., Simmoneaux, V., Gascoin, S., Fakir, Y., Richard, B., Chehbouni, A., Boudhar, A., 2018. Rainfall-runoff modeling and hydrological regime analysis of a semi-arid snow-influenced

catchment: Case of the Rheraya River (High Atlas, Morocco). *La Houille Blanche - Revue Internationale de l'Eau*. 3:49-62. <https://doi.org/10.1051/lhb/2018032>

Appendix E

Résumé long en français

Résumé de la thèse intitulée :

Couplage de la modélisation basée sur les agents et de la modélisation agro-hydrologique pour représenter les actions humaines au sein d'un agro-hydrosystème. Application à l'irrigation collective dans le bassin versant du Buëch (France).

Préparée au sein de l'école doctorale 981 ABIES (AgroParisTech) et des laboratoires INRAE G-eau à Montpellier et RiverLy à Lyon.

Par

Bastien RICHARD

L'eau étant utilisée à de nombreuses fins - les besoins humains fondamentaux, la production d'énergie et d'autres industries, les besoins des écosystèmes -, la gestion des ressources en eau devient de plus en plus complexe dans de nombreuses régions où l'approvisionnement en eau est dépassé par des demandes croissantes. Les défis sont différents selon leur localisation et la période de temps considérée, en fonction de la diversité des contextes hydrologiques, climatiques et sociaux qui évoluent simultanément mais à des rythmes différents. Dans ce contexte, la communauté de recherche en hydrologie, notamment à travers l'Association internationale des sciences hydrologiques (AIISH), s'interroge sur la pertinence de ses modèles, plutôt adaptés pour simuler et prévoir les processus hydrologiques dans des bassins versants peu anthropisés. Paradoxalement, la littérature est pleine de prévisions concernant le cycle de l'eau face au changement climatique, et la complexité des processus modélisés concerne surtout l'hydrologie, en particulier avec l'émergence de modèles hydrologiques spatialisés. Mais les impacts liés aux activités humaines, comme l'irrigation, ont jusqu'à présent été principalement évalués par des approches basées sur des scénarios dans lesquelles la société était simulée en supposant une structure fixe dans le temps. Comme le souligne l'AIISH, il est nécessaire de mieux documenter les diverses

interactions et rétroactions dues aux actions humaines dans les agro-hydrosystèmes.

Spatialement, les processus naturels et anthropiques se superposent à différentes échelles. Chaque cas d'étude doit être considéré individuellement avec des échelles spatiales potentiellement hétérogènes au sein d'un même modèle. Au cours du temps, des processus avec des régimes temporels différents coexistent. Cependant, la plupart des modèles dédiés à la représentation des actions humaines au sein des systèmes agricoles assimilent l'action humaine à sa phase de décision, faisant souvent fi du niveau opérationnel. Or, une fois que les choix stratégiques ont été faits (c'est-à-dire le choix et la rotation des cultures, les objectifs d'irrigation pour la saison), l'agriculteur doit faire des choix opérationnels : gestion du site à court terme, y compris une stratégie de gestion des ressources aussi adaptable que possible, avec une attention particulière donnée aux opérations d'irrigation et de fertilisation. Ainsi la gestion de l'irrigation dépend également de facteurs opérationnels qui peuvent impacter significativement la campagne en cours voir l'organisation de l'exploitation à long terme. L'importance des contraintes de distribution d'eau, ou des opérations de fauchage du foin et d'interrelation avec l'irrigation pour assurer l'efficacité de l'irrigation, ont été montré par exemple dans la plaine de la Crau (France). Si la "socio-hydrologie" émergente s'est beaucoup intéressée aux phénomènes qui pourraient émerger à long terme, la gestion opérationnelle à court-terme permet de mettre en évidence des effets de seuils qui ne sont pas toujours visibles à long terme, en particulier en contexte hydro-climatique incertain.

Ainsi, les questions générales explorées dans la thèse est la suivante: Comment pouvons-nous représenter les actions des irrigants dans l'espace et le temps pour prendre en compte de manière dynamique leurs interactions à court terme avec les composantes agrohydrologiques du système ? Que pourrait apporter cette représentation aux discussions sur la gestion de l'eau d'une étude de cas spécifique ? Comme les modèles basés sur les agents permettent de représenter des comportements distribués dans l'espace, les chercheurs les utilisent couramment pour modéliser les interactions entre les activités humaines et l'environnement, notamment les ressources comme l'eau et les plantes. Pour prendre en compte l'influence des activités humaines sur l'état de l'environnement, et vice versa, le couplage des modèles basés sur les agents avec des modèles biophysiques est une approche clairement identifiée dans la littérature. Si la plupart des études empruntant cette voie reposent sur des approches planifiées bien adaptées au niveau stratégique, d'autres approches semblent particulièrement intéressantes pour représenter le niveau opérationnel en interaction avec l'environnement. De manière plus appliquée, nous nous interrogeons dans la thèse sur la possibilité de construire un modèle qui représenterait les situations (y compris leurs enjeux et les possibilités d'actions) des irrigants individuels et des associations d'irrigants dans un contexte tendu pour l'équilibre quantitatif des ressources en eau ? Que pourrait apporter un tel modèle

aux discussions sur la gestion de l'eau à l'échelle de chaque individu, de l'association, voir d'un bassin versant ?

Une première partie de la thèse est consacrée à l'état de l'art et à la description des enjeux de la gestion de l'eau, notamment opérationnelle, dans le cas d'étude : le bassin du Buëch en Durance. Dans le premier chapitre, une revue des formes de représentation de l'action humaine dans les modèles à base d'agent traitant des systèmes agricoles est menée. Nous observons que ces représentations sont principalement basées sur des théories économiques ou psychologiques qui conceptualisent l'action humaine comme une prise de décision, souvent planifiée à l'avance. Cependant, la Théorie de l'Action Située est apparue en réponse à une question fondamentale : comment le plan, qui est une représentation abstraite de la réalité conçue a priori, peut-il être lié aux modalités concrètes de la mise en œuvre d'une action ? En proposant de se concentrer directement sur les modalités d'exécution de l'action plutôt que sur les mécanismes de décision, le comportement des acteurs est alors déterminé par son sous-ensemble de possibilités spatialisées, et en constante évolution. L'acteur est alors obligé de choisir entre ces possibilités et donc de s'y adapter. Nous faisons alors l'hypothèse que la Théorie de l'Action Située associée au concept d'Affordance peut permettre de représenter les contraintes opérationnelles spécifiques aux systèmes irrigués collectifs en contexte de tension sur la ressource en eau. Nous pensons également que la représentation explicite de ces alternatives peut, d'une part, faciliter le traçage des liens de causalité entre les sorties de simulations et la structure d'un modèle à base d'agents. Ce point est important pour l'interprétation des résultats de ce type de modèle, interprétation souvent décrite comme difficile de fait de la complexité des simulations. D'autre part, nous pensons que cette représentation peut faciliter les interactions spatio-temporelles à court-terme avec des modèles de cultures ou hydrologiques, pour mieux documenter les influences des opérations humaines sur l'état des agro-hydrosystèmes. Dans le second chapitre, nous décrivons les enjeux de la gestion quantitative de l'eau dans le bassin du Buëch, qui est soumis à un déséquilibre entre les besoins en eau et les ressources disponibles depuis une quinzaine d'années. Un travail important a été mené sur le terrain pour enquêter, auprès des irrigants comme des gestionnaires, sur l'évolution des pratiques d'irrigation des périmètres irrigués du Buëch. Après avoir caractérisé les systèmes agricoles de ce bassin, nous décrivons comment l'évolution des contraintes d'irrigation a contribué à leur spécialisation vers des systèmes irrigués hétérogènes, chacun avec son ensemble spécifique de contraintes opérationnelles. Des facteurs de différenciation sont mis en évidence, tels que le partage d'un réseau d'irrigation collectif, la technique d'irrigation utilisée, le niveau de sécurité de l'accès à l'eau, ou encore le niveau d'organisation et de coordination entre ses irrigants. La recherche de l'autonomie opérationnelle au sein de systèmes collectifs jugés obsolètes par de nombreux irrigants contribue à leur transformation par la mise en place de programme de modernisation. L'irrigation gravitaire pratiquée au sein d'associations collectives

principalement situées en amont du barrage, est ciblée par ces programme, et désignée comme la clé d'ajustement du déséquilibre entre offre et demande du bassin. Les difficultés de gestion opérationnelle au sein des réseaux gravitaires hérités de configurations ancestrales, entraîne des changement brutaux, récemment opérés. Ils concernent notamment la maintenance et la coordination du réseau d'irrigation, comme l'abandon de la coordination par tour d'eau au cours des quinze dernières années.

Dans une seconde partie, nous proposons un modèle à base d'agent développé dans cette thèse pour représenter l'irrigation gravitaire au niveau opérationnel, et discutons son apport pour la représentation et la compréhension des changements de gestion observés. Ainsi dans le troisième chapitre, nous décrivons d'abord le modèle WatASit. Nous proposons un modèle basé sur le concept d'Affordance qui rend explicite les possibilités d'action disponibles pour chaque agent. L'approche permet de générer, pour chaque agent et pour chaque pas de temps, un ensemble d'options spatialement réparties qui conditionnent les trajectoires des agents sans faire appel à une re-planification ou à des algorithmes de décision complexes. L'approche tire aussi parti de la mise à jour systématique de l'ensemble des options pour les faire correspondre aux différents échelles spatio-temporelles des contraintes opérationnelles, telle que la disponibilité de l'eau en plusieurs endroits du réseau. Comme preuve de concept, le modèle WatASit a été appliqué au fonctionnement d'un réseau gravitaire collectif du bassin du Buëch qui a abandonné le partage historique de l'eau par tours d'eau. Les résultats de simulations montrent que si l'abandon de la coordination par tours d'eau permet effectivement une augmentation du nombre de possibilités d'irrigation, il met également en exergue les inégalités entre irrigants en termes de capacité à irriguer et d'abandons d'irrigation. Le changement d'organisation n'impacte pas tous les irrigants de la même façon, selon la localisation, notamment en aval du réseau, et le nombre de parcelles irrigables de chacun. Dans le chapitre 4, nous explorons comment les changements de trajectoire des agents dans un modèle tel que WatASit peuvent être liés à l'évolution de leurs possibilités d'action, avant et après l'abandon de la coordination par tour d'eau. Les résultats de la simulation montrent que l'approche fournit un niveau intermédiaire de visualisation et d'analyse. Dans notre exemple, la valeur ajoutée de ce niveau réside dans l'information qu'il fournit sur la nature des trajectoires simulées. En effet, lorsque le réseau d'irrigation n'est pas coordonné par les agents irrigants, les options d'irrigation existent et ne sont pas la cause des abandons de l'irrigation, qui sont dues au manque d'eau au niveau des parcelles les moins bien desservies par le réseau. Dans nos simulations, la coordination du réseau réduit fortement les abandons d'irrigation pour ces parcelles, mais la difficulté vient alors de la situation individuelle de chaque agent irrigant pour satisfaire tous les besoins d'irrigation simultanés pendant une fenêtre de temps réduite. La mobilisation du concept d'Affordance permet également de prendre du recul par rapport à la façon dont les humains sont représentés dans le modèle, avec par exemple un

manque d'anticipation des agents lorsque le réseau d'irrigation n'est pas coordonné.

La troisième partie de la thèse propose d'aborder le couplage du modèle WatASit avec deux modèles biophysiques. L'objectif du chapitre 5 est d'abord de montrer la faisabilité d'un couplage entre un modèle à base d'agent horaire à l'échelle d'un périmètre irrigué (WatASit), avec un modèle de culture journalier à l'échelle de la parcelle (Optirrig), pour mieux prendre en compte les contraintes spécifiques à la gestion du réseau gravitaire. En effet, les modèles de culture fournissent des stratégies d'irrigation optimales au niveau de la parcelle. Toutefois, dans de nombreux endroits comme dans le bassin du Buëch, l'irrigation est souvent gérée collectivement afin de coordonner l'approvisionnement en eau au niveau de chaque réseau, avec de potentiels effets de rétroaction sur la dynamique des plantes. Pour saisir ces rétroactions lors d'une campagne d'irrigation collective, nous avons proposé l'approche COPAT (COupling Plant and Agent Trajectories). L'élément clé de l'approche est la dérivation du modèle de culture en une fonction quotidienne, ce qui a permis d'exécuter cette version quotidienne comme un modèle esclave du modèle à base d'agents, et donc de permettre le couplage au pas de temps journalier. Ce couplage a permis de donner des ordres d'irrigation journaliers au niveau de chaque parcelle en fonction de nouvelles contraintes spécifiques au réseau collectif d'irrigation gravitaire, comme l'écoulement nécessaire dans le canal, et de récupérer les variables agro-hydrologiques des parcelles (i.e. Leaf Area Index, Water Stress Index). Il s'agit aussi en effet d'illustrer l'influence mutuelle des trajectoires des agents et des trajectoires des cultures irriguées. Les résultats de simulations, illustratif sur un cas d'étude et une campagne d'irrigation, montre que potentiellement l'irrigation simulée par le modèle couplé a un impact sur le stress hydrique moyen et la gravité du stress lorsque les plantes sont réparties dans l'espace selon un gradient amont-aval le long du réseau. Dans ce cas, une absence de coordination entraîne un stress hydrique plus précoce, en moyenne, que lorsque le réseau est coordonné. Dans le chapitre 6, nous proposons d'identifier les modifications nécessaires à la fois sur le modèle WatASit et sur un modèle hydrologique spatialisé journalier (J2000), pour les coupler à l'échelle d'un sous-bassin du Buëch. Comme pour le couplage avec le modèle de culture Optirrig, la difficulté réside dans le forçage de l'irrigation en cours de simulation, le modèle hydrologique étant prévu pour simuler une période sans interruption à chaque pas de temps. Mais cette fois un obstacle supplémentaire existe, lié au routage du modèle entre les unités hydrologiques (i.e. les Hydrological Response Unit, HRU) spatialisées. Lors d'un même pas de temps journalier, il faut être capable de modifier localement le bilan hydrologique de chaque unité tout en conservant leur topologie d'écoulement du ruissellement et des flux de sub-surface et souterrain d'une unité à l'autre. L'astuce proposée dans l'approche COWAT (COupling Plant and Water Trajectories) consiste à considérer chaque parcelle irriguée du modèle agent comme une "HRU-parcelle" ayant son propre bilan dans le modèle hydrologique. Cela permet, chaque jour, de forcer les bilans de chaque HRU-parcelle par l'irrigation simulée dans le

modèle WatASit, puis de simuler l'hydrologie perturbée par l'irrigation à l'échelle du sous-bassin en conservant la même topologie d'écoulement des flux hydrologiques.

Finalement, le dernier chapitre revient sur les hypothèses qui ont été faites et nous discutons aussi plus généralement le positionnement de la thèse dans les travaux de la communauté, notamment ceux réalisés sous la bannière de la "socio-hydrologie" émergente. Ils permettent de questionner les géographies et les temporalités des influences humaines au sein des agro-hydrosystèmes, éléments fondamentaux pour la compréhension de la diversité de leurs contextes et de leurs défis pour la gestion de l'eau.

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Title : Coupling agent-based and agro-hydrological modeling to represent human actions within an agro-hydrosystem. Application to collective irrigation in the Buëch catchment (France).

Keywords : collective irrigation; operational management; agent-based model; crop model; distributed hydrological model; Buëch.

Abstract : The mutual influences between human activities and natural resources are at the heart of societal debates. The challenges of water management depend on these interdependences differently according to the local situation. In this context, the hydrology research community is investigating the relevance of its models to represent human activities interacting with water resources. The literature counts many studies in which the complexity of modelled processes concerns hydrology. But human activities such as irrigation are represented in a more or less aggregated way and in a trend or even stationary way over time. As shown by the reflections in progress within "socio-hydrology", it is necessary to better document the various interactions and feedbacks due to irrigation within agro-hydrosystems. Short-term interactions are particularly under-explored. However, in the short term, irrigation management is based on operational constraints, such as those inherent to water distribution, which can significantly impact the future state of crops and harvests. Conversely, the state of crops influences the frequency and spatial distribution of irrigation operations that locally modify the state of water resources. Moreover, most approaches to representing human actions within these systems conceptualize action with its decision phase, often ignoring the operational level. Thus, the question explored in the thesis is the following: How can we represent at the operational level the actions of irrigators in space and time to take into account in a dynamic and situated way their interactions with the agrohydrological components of the system? And what could this representation bring to the water management discussions of a specific case study? We first propose to mobilize the Affordance concept to build an agent-based model (WatASit) explicitly representing the possibilities of action of irrigators in situations of tension for water sharing. Applied to a typical gravity-fed network of the Buëch catchment in the Durance region (France), we show that the trajectories of the agents depend on the evolution of their possibilities during the irrigation campaign and that the analysis of these possibilities helps in the interpretation of individual and collective behaviours. In particular, the consequences of the abandon of the coordination by daily slots of the network, observed during the field surveys, does not seem to impact all the irrigators in the same way by reinforcing the spatial inequalities between the upstream and downstream parts of the network. We then propose the COPAT (COupling Plant and Agent Trajectories) framework to couple a crop model at the plot scale (Optirrig) and the WatASit model at the irrigation network scale. The temporal consistency of the coupling is based on the derivation of the crop model as a daily function. At each daily time step, the irrigation received by each plot is determined by the operations of the agents constrained by the sharing of water within the collective network. An earlier water stress is observed compared to irrigation that would not depend on such sharing, but the coordination of the network by daily slots tends to limit this stress. Finally, we propose COWAT (COupling Water and Agent Trajectories) as a coupling methodology with the spatialized hydrological model J2000 and highlight some points of vigilance to ensure spatial coherence at a fine scale. In the end, the Affordance concept connects with a wider interdisciplinary debate on the representation of human actions and hydrology is thought in interaction with these actions and the operational issues of water management.

Titre: Couplage de la modélisation basée sur les agents et de la modélisation agro-hydrologique pour représenter les actions humaines au sein d'un agro-hydrosystème. Application à l'irrigation collective dans le bassin du Buëch (France).

Mots-clés: irrigation collective ; gestion opérationnelle ; modélisation à base d'agents ; modèle de culture ; modélisation hydrologique distribuée ; Buëch.

Résumé: Les influences mutuelles entre les activités humaines et les ressources naturelles sont au cœur des débats sociétaux. Les défis à l'égard de la gestion de l'eau en dépendent différemment selon les situations locales. Dans ce contexte, la communauté de recherche en hydrologie s'interroge sur la pertinence de ses modèles pour représenter les activités humaines en interaction avec les ressources en eau. La littérature est riche en études dans lesquelles la complexité des processus modélisés concerne l'hydrologie. Mais les activités humaines comme l'irrigation sont représentées de façon plus ou moins agrégée et de manière tendancielle voire stationnaire au cours du temps. Comme en témoignent les réflexions en cours au sein de la « socio-hydrologie », il est nécessaire de mieux documenter les diverses interactions et rétroactions dues à l'irrigation au sein des agro-hydrosystèmes. Les interactions à court terme sont particulièrement peu explorées. Or, à court terme, la gestion de l'irrigation repose sur des contraintes opérationnelles, comme celles inhérentes à la distribution de l'eau, qui peuvent impacter de manière significative l'état à venir des cultures et des récoltes. *Vice versa*, l'état des cultures influence la fréquence et la répartition spatiale des opérations d'irrigation qui modifient localement l'état des ressources en eau. De plus, la plupart des approches de représentation des actions humaines au sein de ces systèmes assimilent l'action à sa phase de décision, faisant souvent fi du niveau opérationnel. Ainsi, la question explorée dans la thèse est la suivante: Comment pouvons-nous représenter au niveau opérationnel les actions des irrigants dans l'espace et le temps pour prendre en compte de manière dynamique et située leurs interactions avec les composantes agro-hydrologiques du système? Et que pourrait apporter cette représentation aux discussions sur la gestion de l'eau d'un cas précis? Nous proposons d'abord de mobiliser le concept d'Affordance pour construire un modèle à base d'agents (WatASit) représentant explicitement les possibilités d'actions des irrigants en situation de tension pour le partage de l'eau. Appliqué à un réseau gravitaire typique du bassin du Buëch en Durance (France), nous montrons que les trajectoires des agents dépendent de l'évolution de leurs possibilités au cours de la campagne d'irrigation et que l'analyse de ces possibilités aide à l'interprétation des comportements individuels et collectifs. Notamment, les conséquences de l'abandon de la coordination par tours d'eau du réseau, observé lors des enquêtes de terrain, ne semble pas impacter tous les irrigants de la même façon en renforçant les inégalités spatiales entre l'amont et l'aval du réseau. Nous proposons ensuite le cadre COPAT (COupling Plant and Agent Trajectories) pour coupler un modèle de culture à l'échelle de la parcelle (Optirrig) et le modèle WatASit à l'échelle du réseau d'irrigation. La cohérence temporelle du couplage repose sur la dérivation du modèle de culture en fonction journalière. À chaque pas de temps journalier, l'irrigation reçue par chaque parcelle est déterminée par les opérations des agents contraints par le partage de l'eau au sein du réseau collectif. Un stress hydrique plus précoce est observé par rapport à une irrigation qui ne dépendrait pas d'un tel partage, mais la coordination du réseau par tours d'eau tend à limiter ce stress. Enfin, nous proposons une méthodologie de couplage COWAT (COupling Water and Agent Trajectories) avec le modèle hydrologique spatialisé J2000 et mettons en évidence certains points de vigilance pour assurer la cohérence spatiale à une échelle fine. Au final, le concept d'Affordance permet d'inscrire la modélisation des actions humaines dans un débat interdisciplinaire plus large sur leur représentation et l'hydrologie est pensée en interaction avec ces actions humaines et les enjeux opérationnels de la gestion de l'eau.