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Integrated assessment of four strategies for solving water imbalance in an agricultural landscape

Sandrine Allain¹ · Gregory Obiang Ndong¹ · Romain Lardy¹ · Delphine Leenhardt¹

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Abstract

Water imbalances are an environmental, social, and economic problem in many agricultural watersheds, including those in temperate climates. Structural changes are recommended because crisis management, through water restrictions, is not sustainable. However, the content of these changes is debated, especially because their impacts concern different sectors and stakeholders and are uncertain. MAELIA is an integrated assessment and modeling platform, which combines a multi-agent model with a geographic information system; it represents fine-scale interactions among water, water management, and agricultural systems, accounting for daily irrigation decisions on each field and effects of the corresponding water withdrawals on water flows. In this article, for the first time, we investigated the effectiveness of some of the most popular strategies aimed at solving water imbalances considering environmental, water management, and agricultural indicators calculated with MAELIA. The alternatives we assessed were (i) reducing the irrigated area, (ii) assisting irrigation with decision-support tools, (iii) implementing crop rotations, and (iv) merging water storage into large reservoirs. Simulations were run for the 2001–2013 period on a case-study area, the downstream Aveyron watershed. We show that, in this area, the decision-support tool and crop-rotation alternatives drastically decreased irrigation withdrawals and required fewer restrictions and flow-support releases. However, those two alternatives had different impacts on the environment and farming systems: decision-support tools cost almost nothing for farming systems and improved environmental indicators slightly, while crop rotations had greater potential for long-term environmental preservation but degraded local and farm economies in the current context. The uniqueness of this study comes from using a fine-scale mechanistic model to assess, in an integrated way, the impacts of politically debated water management strategies that were previously only assessed in terms of potential withdrawal reduction.

Keywords Integrated assessment and modeling · Quantitative water management · Irrigated agriculture · MAELIA platform

1 Introduction

Droughts can occur in agricultural areas when low rainfall coincides with low water stocks (in water bodies and soils) and high water needs for crops (Amigues et al. 2006; Erdlenbruch et al. 2013). Droughts that are recurrent rather than episodic reveal a water imbalance, i.e., when water demand structurally exceeds the water supply. These situations are unsustainable: they erode ecosystem functioning (Gordon et al. 2010), induce water-use conflicts (Pimentel et al. 1997), and negatively impact agricultural production (Molden 2007).

At the same time, it is well acknowledged that land use, especially agricultural practices and water storage, have significantly modified surface and ground-water hydrology (Trout 1999; DeFries and Eshleman 2004); hence, agricultural and water systems must be considered as a nexus.

Crisis measures, such as water-use restrictions, are considered inappropriate for resolving structural water imbalances; thus, profound changes in agricultural water management and governance are recommended (Pahl-Wostl et al. 2007; Erdlenbruch et al. 2013; Murgue et al. 2015). They include reconsidering the approach (participatory, prospective, integrated, adaptive, etc.) and the orientation (demand management, agroecology, locally adapted cropping systems, etc.) of agricultural water-management practices. However, such changes are difficult to implement for a variety of reasons, one of which is insufficient knowledge about potential effects of large-scale agricultural changes.

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The water imbalance in agricultural systems with both rain-fed and irrigated crops is studied much less than that in agricultural systems in arid climates (Amigues et al. 2006). However, it can be a “hot topic” in temperate regions that polarizes pro-supply and pro-demand perspectives (Fig. 1). Even within each perspective, different visions oppose each other, for instance, between strategies to improve water efficiency and strategies to design ecologically intensive farming systems (Duru et al. 2015). Mixed rain-fed/irrigated agricultural systems also reflect probable future shifts in agricultural practices, given that climate change (Olesen and Bindi 2002) and population growth (Turrall et al. 2011) are expected to generate water imbalances in new areas. Therefore, we investigated ways to improve the quantitative status of water in these areas to address the current local issue and to be prepared for future challenges in other areas.

Agronomic studies of crop-management strategies under water-limited conditions (e.g., deficit irrigation, conservation agriculture, drought-tolerant cultivars (Debaeke and Aboudrare 2004; Davies et al. 2011) have helped to explore concrete solutions to water imbalances at the field or farm scale. In parallel, landscape-scale and regional water management strategies (e.g., agricultural changes, new infrastructure, incentives, regulations) have been considered with input from

stakeholders and/or experts, both from academia (Murgue et al. 2015; Figureau et al. 2015) and water institutions (e.g., Adour-Garonne Water Agency 2017). Some strategies have even been modeled into existing platforms to test their impacts on a water system (e.g., Ullrich and Volk 2009) and integrated models have been developed to better understand the links between farming practices and hydrology at multiple scales (Bergez et al. 2012).

Despite those progresses, assessment of water management strategies has yet to simultaneously (i) include spatial (watershed, agricultural landscape) and temporal (multiyear) scales large enough for decision-making and sustainability issues; (ii) consider complex interactions among farming, water and water management systems, including at fine resolutions (day, field); and (iii) produce indicators diverse enough to reflect the variety of stakeholder interests and the three pillars of sustainability. Generally, scholars who consider the multiple interrelations and flows between water and agricultural systems adopt a macroscopic nexus perspective (Bazilian et al. 2011; Bizikova et al. 2013), which produces knowledge remote from local debates (e.g., about landscape planning). To the contrary, the effort to develop models coupling farming practices to water systems at fine resolutions has not yet produced assessments of water management strategies that really integrated environmental, economic, and regulatory dimensions

Fig. 1 Irrigation under temperate climate (here, in Southwestern France). Cropping systems requiring high water inputs, such as maize monocrops, and water-storage infrastructure symbolize “pro-supply” agricultural water management, which now attracts strong criticism. Photos: Delphine Burger-Leenhardt (up) and Jérôme Molena (down)



(Lardy et al. 2016; Robert et al. 2018); hence, there is still a gap to close between modeling advances and their application to real-world issues. To close this gap, we used an integrated multi-agent model, representing daily water withdrawals, crop management on each field, and irrigation restrictions and water releases from reservoirs, in order to assess, in an integrated way, four contrasting alternatives for agricultural water management. The effects of those alternatives were assessed using environmental, water management, and agricultural indicators calculated for a case-study area—the downstream Aveyron watershed, southwestern France. Results of these simulations contribute to current debates about landscape planning for sustainable water management and the understanding of social-ecological processes linking water users, resources, and management at the landscape scale.

2 Materials and methods

2.1 Study area

The study area is located in the Adour-Garonne hydrographic basin (southwestern France), many of whose watersheds experience structural water imbalances. They consequently follow specific water-use policies to meet the good status requirement for water bodies. In addition, climate change is expected to reduce the flow of all the main rivers of the basin, by 20 to 40% in 2050, given temperature raise, more erratic rainfall, and increasing evapotranspiration and to modify hydrologic regimes (Adour-Garonne Water Agency 2014).

Our study focuses on the downstream portion of the Aveyron watershed (Fig. 2). Between 2000 and 2013, precipitations averaged 780 mm per year and evapotranspiration 850 mm. The year 2011 was the driest, with 940 mm of evapotranspiration for only 570 mm of rainfall (data calculated using the SAFRAN database of Météo France). Of the 800 km² of the study area, half is agricultural and mainly covered with field crops, among which mono-cropped maize requires the most water. Large patches of fruit crops and seed maize crops also exist, which provide high added-value but require secure water inputs. We estimated approximately 13,000 ha of irrigable area (according to the French Land Parcel Identification System) and withdrawals of approximately 12 hm³ per year (calculation based on the Adour-Garonne Water Agency withdrawal estimates for each withdrawal point, available on request). Although the agricultural population has decreased, irrigation withdrawals do not appear to have done so.

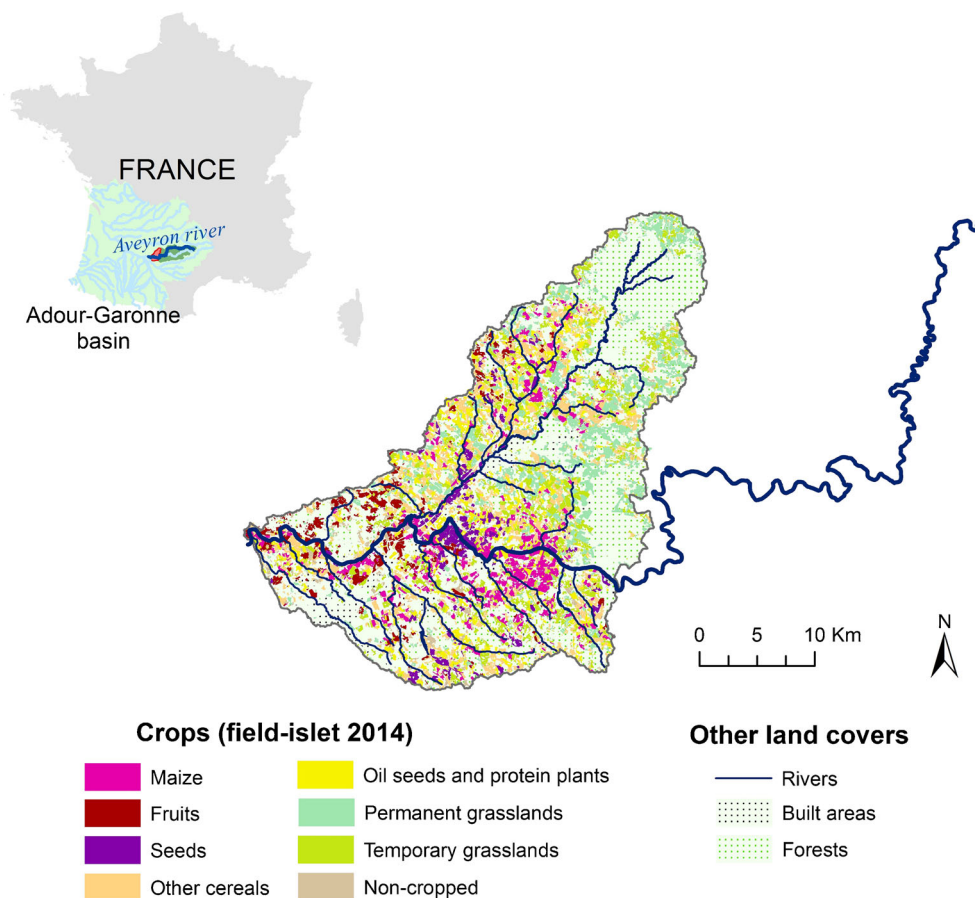
In the case-study area, water quantitative crises are frequent, showing a situation of water imbalance. Those crises occur when river flow falls below a specific threshold (the low-water regulating flow, LWRF), established by the watershed's Water Management Plan, in application of the Water

Framework Directive (Directive 2000/60/EC), with the objective to ensure the proper functioning of the water environment and the satisfaction of all water uses. To help comply with LWRF, water restrictions and flow-support releases are the main tools that public agents can use. Water releases from public reservoirs support the flow of the Aveyron and sections of its northern tributary (the Lère River); they can be supplemented with releases from hydropower dams, paid by the local community to the electricity company. Restrictions are set at the scale of specific administrative units (distinguishing sectors with flow support from sectors without it) after the meeting of a “drought committee”; they can range from 1 day per week to a complete prohibition to irrigate. From a social perspective, water restrictions tend to exacerbate conflicts between agricultural and other water uses, such as recreational activities (fishing, swimming, and canoe-kayaking) and use by aquatic ecosystems. The downstream Aveyron watershed is therefore an illustrative case of water imbalance situations in which low water inputs combine with high agricultural water demand.

2.2 The modeling platform: MAELIA

MAELIA (multi-agent for environmental norms impact assessment, maelia-platform.inra.fr) is a simulation and modeling platform originally created to study environmental, economic, and social impacts of water-regulation options at the watershed scale (Gaudou et al. 2013). It consists of three main modules: agricultural, reflecting farmers' behavior and plant growth; hydrological, simulating water flows (based on SWAT-model equations, Arnold et al. 1998); and regulatory, representing water releases and restrictions. Farmers are modeled as agents who implement crop-management decisions (tillage, sowing, irrigation, harvest, etc.) at the field scale depending on vegetation stage, environmental conditions, available equipment, and workforce. Crop-management decision rules are defined for each combination of soil type × crop × crop sequence × irrigation equipment and are based on “if-then” causal chains reflecting farmers' reasoning. For instance, irrigation is launched according to the calendar date, the duration since the last irrigation, the vegetation stage, the past and forecast rainfalls, and the status of water resources (availability and absence of restrictions); therefore, it reflects observed practices and not the optimal water needs of plants. The resulting plant growth is based on plant characteristics, development stage, and soil humidity (AqYield model, Constantin et al. 2015). Irrigation decisions produce water withdrawals that are modeled at each withdrawal points on a daily basis, therefore modifying water flows in the hydrological module. Reversely, water flows are computed every day at the measurement points, which can trigger water releases or irrigation restrictions (regulatory module).

Fig. 2 Main crops in the study area (downstream portion of the Aveyron watershed) according to the Land Parcel Identification System (LPIS) 2014. The LPIS is a national geographic information system based on farmers’ declarations for each group of fields (islets) they use. The LPIS shows that islets with the main irrigated crops (maize, fruits, and maize seeds) are located along the banks of the Aveyron River



MAELIA can output, at multiple scales, the values of most of the variables simulated, especially water flows, withdrawals, agricultural production, gross margin, releases from reservoirs, water restrictions, and the workload of crop-management operations. One main application of the model is to assess effects of changes, e.g., in water management or climate. Studied changes are translated into modified model inputs, e.g., new crop-management rules, crop distributions, water regulations or climate data, and the simulation outputs specified by the model user are compared to those of the reference situation. However, MAELIA has never been used to assess in an integrated way the impacts of water management alternatives. Former works concentrated on calibrating the model to reproduce the low-water period (Lardy et al. 2014, with a sensitivity analysis performed as a preliminary step), instantiating the model for the case-study area (Murgue et al. 2016), testing the impacts of the water storage infrastructure on river flows (Lardy et al. 2016) and developing a user-friendly interface for advisory services (Lacroix et al. 2018).

2.3 Water management alternatives studied

By analyzing the gray literature, we identified several strategies that are traditionally suggested as able to solve water-imbalance problems. Considering MAELIA characteristics,

we selected strategies that could be transcribed into input files for the modeling platform and which impacts could be a priori modeled in a reliable way. For instance, we excluded strategies based on economic or political incentives, as behavioral changes are not modeled in MAELIA. We then organized a workshop with a group of eight local stakeholders (from State agencies, local communities, and the civil society) to select four water management strategies that they were “more eager to learn about” (rather than the most realistic or desirable alternatives). Using our own expertise, stakeholder comments, and results of previous studies (Murgue et al. 2015), we converted the narrative and qualitative expression of these four strategies into quantitative descriptions adapted to our study area. The resulting four alternatives are described below.

2.3.1 Alternative 1: reduced irrigated area

Reducing the irrigated area is the most straightforward mechanism to reduce the amount of water withdrawn from the environment. It can be done by increasing the area of rain-fed cropping systems, either on each farm or in certain zones of the watershed. Stakeholders preferred the latter approach based on environmental concerns, aiming to reduce water use in areas with natural hydrology (i.e., without flow support) by stopping withdrawals there and to favor water purification by

re-introducing grassland. This alternative was implemented in MAELIA as follows:

- All fields withdrawing water from flow-supported zones (the Aveyron River and southern Lère River) and collective reservoirs were not modified
- The steepest 50% of remaining fields (by area) were converted into permanent grasslands (rain-fed)
- The remaining fields kept their initial crops but became rain-fed. The only exception was seed-crop fields. Since irrigating them is a contractual obligation, they were converted into straw cereal fields (rain-fed)

As a result, 22% (2800 ha) of the initial irrigated area of the study area became rain-fed, mainly in the north and in patches in the southern hillsides.

2.3.2 Alternative 2: decision-support tool

Optimizing irrigation by managing water inputs better (“the right amount of water at the right moment”) is one of the strategies most frequently recommended to reduce withdrawals within an efficiency paradigm (Duru et al. 2015). Decision-support tools combined with humidity sensors can help farmers to more closely match irrigation with crop water needs.

We mimicked tool-assisted irrigation by activating a theoretical irrigation strategy in MAELIA (described in detail (in French) on the MAELIA website: <http://www.maeliaplatform.inra.fr/modeles/processus-agricoles/regles-de-decisions-sir/irrigation/>). According to this strategy, irrigation is launched based on a water-need satisfaction index (real transpiration/maximum transpiration) calculated by AqYield each day. Irrigation is delayed until the satisfaction index falls below a threshold that depends on the vegetation stage, with a maximum of 0.9 around flowering. This theoretical irrigation strategy changed only the moment at which irrigation was launched (not the amount applied) and was applied to all irrigated field crops (11,000 ha).

2.3.3 Alternative 3: large substitution reservoirs

The study area has more than a thousand small individual reservoirs, which are criticized because they intercept a large quantity of water, including that from summer storms; are not used optimally; and are unregulated. Stakeholders suggested modeling the merger of these storage capacities into large disconnected reservoirs that are filled during winter by pumping in the Aveyron River (substitution reservoirs) to reduce pressure on the low-water period and improve the ecological and physicochemical quality of most rivers. This idea was not presented as a realistic option for the future but as

insight into the debate about storage infrastructure and the only supply management alternative.

To implement this alternative, we simulated an increase in the storage capacity of two existing reservoirs to the south of the Aveyron River, creation of a new large reservoir to the north, and removal of all individual reservoirs (as if they had been naturally filled with sediments after being abandoned). The storage capacity added (southern) or created (northern) equaled the total storage capacity of all individual reservoirs in each area. The existing southern reservoirs gained a total of 2.7 hm³ of water (for a total capacity of 9.3 hm³) and the new northern reservoir contained 3.9 hm³. All direct withdrawals from rivers and aquifers remained unchanged. In this alternative, 4000 ha of cropped area became connected to a substitution reservoir.

2.3.4 Alternative 4: crop rotation

To reduce irrigation withdrawals, water-demanding crops can alternate with crops that demand less water over time. Crop rotation is an agroecological practice that is recommended not only to reduce irrigation but also to preserve soil quality and reduce pest damage within a biodiversity-based or ecological intensification paradigm (Duru et al. 2015). We implemented this alternative in MAELIA by converting all mono-cropped maize fields (grain or seed), i.e., approx. 3700 ha, to a 4-year crop rotation that is already applied in the area: sunflower–straw cereal–oilseed rape–maize. The first-year crop differed among the fields of each farm to balance agricultural production over the years.

2.4 Simulation and analysis

We ran MAELIA for all alternatives and the reference situation for the period 2001–2013. Climate data were obtained from the SAFRAN dataset of Météo France (Vidal et al. 2010). Most agricultural input data for fields and islets came from the database developed by Murgue et al. (2016). To update the crop and crop-sequence data for each field, we applied the same procedure as Murgue et al. (2016) with the then-most-recent version of the French Land Parcel Identification System geographic database. We also updated economic data (sale prices and charges) using 2015 data from agricultural support services (available on demand) and the regional union for seed-maize breeders (personal communication).

We used MAELIA simulations to generate a series of trend and dynamic indicators and to compare each water-management alternative to the reference situation. All trend indicators were inter-annual means (from 2001 to 2013) of single annual values (e.g., water returns to the environment, crop yields), daily sums (e.g., water withdrawals), or daily means (for flow estimates) for the entire calendar year or only

the low-flow period (June–September). Results for trend indicators were calculated as the percentage change from the reference situation. For water withdrawals and river flows, we calculated dynamic indicators (i.e., time series) as 10-day means of daily values.

The simulation period 2001–2013 allows to capture some climate variability, with two peculiarly dry years (2003 and 2011) but does not offer insight into climate change impacts. Climate projections were not used because we could not model the upstream Aveyron flow entering the study area in accordance with the rainfall given that the upstream portion of the Aveyron watershed is karstic. For the 2001–2013 simulation period, the upstream Aveyron flow was forced using observed data (HYDRO dataset—available at <http://www.hydro.eaufrance.fr/>—and records of water releases provided on demand by local State agents).

2.4.1 Water management indicators

The amount of water withdrawn is the key constraint in water management. The higher and longer the peak of withdrawals, the more difficult it is to manage the water resource. In addition, because areas with water imbalances must reduce the amount of water withdrawn (decree no. 2007–1381 of the French Environmental Code), a decrease in annual withdrawals also means better compliance with regulations. Consequently, we calculated cumulative withdrawals (*CW*) on an annual basis to obtain a general view and calculated withdrawals on a 10-day basis to investigate their dynamics.

The volume of water released from reservoirs (*RR*) to support river flows is another indicator useful for water management. It indicates the extent to which the water system has been altered by humans and is a proxy for water-management costs, since flow-support costs (building and maintaining public infrastructure and contracts with power companies) are financed with public money. It is an output variable of MAELIA that was simulated at a daily time step and summed for the entire year.

The duration of river flow below LWRP (*CR*), calculated as the number of days per year below LWRP, enables water management to be assessed in the face of water regulations and water-use conflicts, since LWRP is a legal norm, and river flow below it is synonymous with water restrictions.

2.4.2 Environmental indicators

LWRP is also an environmental norm used to assess the quantitative water status of rivers. The longer that river flow falls below LWRP per year, the more the water imbalance is structural (as opposed to being episodic), with long-term consequences for river functioning and associated ecosystems. Indicator *CR*, the number of days per year below LWRP,

was used to assess the influence of alternatives on the frequency of environmental crises.

Another environmental indicator considered was mean flow (*M*). MAELIA has been validated for the low-flow period, which is the most critical period and the one that concentrates the most water uses (agricultural and recreational). We simulated daily flows at the Aveyron outlet and calculated a trend indicator (mean of the entire low-flow period) and a dynamic indicator (10-day means of daily values). Indicator *M* thus complements indicator *CR*, which focuses on critical episodes.

To consider effects on the hydrological cycle, we calculated a third indicator (*RE*), which corresponds to the volume of rainwater returned to the environment, i.e., to water tables, lakes, and rivers. *RE* equals the annual balance of water entering water bodies (drainage (*D*) and runoff (*R*) from fields (calculated by AqYield) minus the water leaving water bodies (irrigation withdrawals (*I*)).

Although *RE* is considered an important indicator of sustainability (Amigues et al. 2006), farmers may also consider it an indicator of wasted rainwater (i.e., available but not used).

2.4.3 Agricultural indicators

Agricultural indicators were calculated only for field crops, i.e., those grown for grain. Other crops (trees, grasslands, and maize silage) were excluded from indicator calculation because AqYield, used to estimate agricultural production, was not calibrated or validated for them and/or because their economic value was difficult to estimate.

We calculated agricultural production (*P*), in tons, as the sum of the production of all field crop in the study area to assess effects on the agricultural sector and local economy.

Field-crop yield (*Y*), in tons per ha, was calculated as *P* divided by the total area of field crops (*A*) in the study area.

The gross margin is an accounting value common at the farm scale; at the landscape scale, it reflects the average benefit that farmers as a group receive from farming, but not the economic health of their farms. We calculated *GMH*, in Euros per ha, as the sum of gross margins generated by all field crops (*GM*) in the study area divided by *A*.

3 Results and discussion

3.1 Effects on water management

Compared to the reference situation, cumulative withdrawals significantly decreased with crop rotations (alternative 4, –42%), decision-support tools (alternative 2, –33%) and, to a lesser extent, reduced irrigated area (alternative 1, –12%) (Table 1). Crop rotation and reduced irrigated area flattened the withdrawal peak during the irrigation season because the

Table 1 Comparison of four contrasting water management alternatives to a reference situation using trend indicators (inter-annual means) from 2001 to 2013

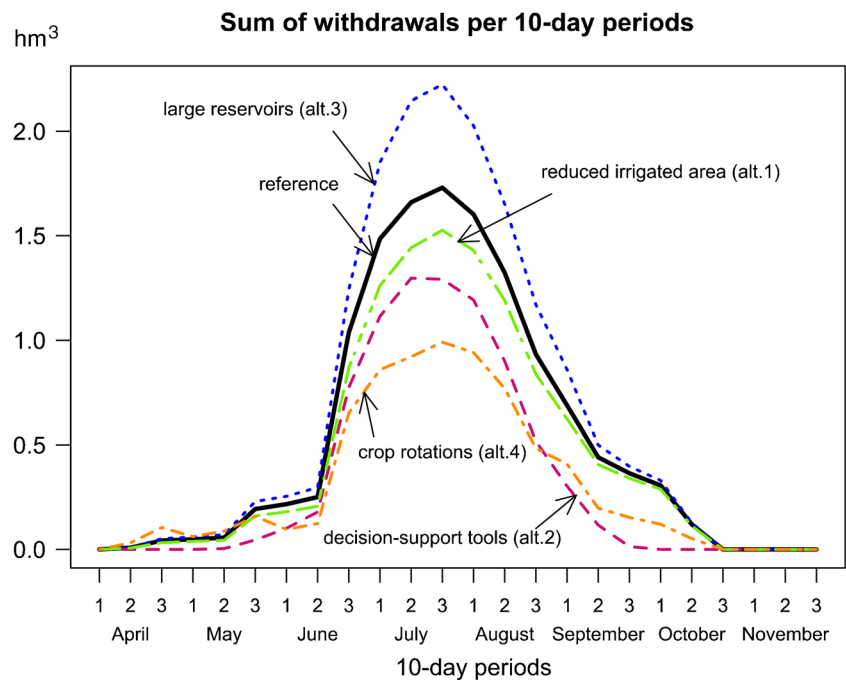
Indicator	Calculation	Period considered	Reference situation	Alternatives				
			Inter-annual mean	1. Reduced irrigated area	2. Decision-support tool	3. Large reservoirs	4. Crop rotation	
<i>Water management</i>	<i>CW</i>	Sum of daily withdrawals	Entire year	13.4 hm ³	- 12%	- 33%	+ 24%	- 42%
	<i>RR</i>	Sum of daily reservoir releases	Entire year	5.3 hm ³	- 2%	- 18%	- 6%	- 26%
	<i>CR</i>	Number of days below LWRF	Entire year	43 days	- 1%	- 11%	- 6%	- 14%
<i>Environment and hydrology</i>	<i>M</i>	Mean of daily flows	Low flow (June-Sept.)	11.8 m ³ /s	+ 0.1%	+ 1.7%	+ 1.3%	+ 2.7%
	<i>RE</i>	Annual value of D + R-I	Entire year	274 mm	+ 1.1%	+ 2.3%	- 1.8%	+ 6.0%
<i>Agriculture</i>	<i>P</i>	Sum of field-crop production	Entire year	119,030 t	- 11%	- 0.4%	+ 3.5%	- 12.0%
	<i>Y</i>	Annual value of P/A	Entire year	5.6 t/ha	- 3.9%	- 0.4%	+ 3.5%	- 12.0%
	<i>GMH</i>	Annual value of GM/A	Entire year	505 €/ha	- 2%	- 1%	+ 9%	- 9%

Indicators related to water management (*CW*, *RR*, and *CR*) changed more than other indicators. The crop rotation alternative had the largest trade-offs between water management/environmental indicators and agricultural indicators.

new cropping systems required less water (Fig. 3). Decision-support tools reduced the intensity and duration of withdrawals (from mid-May to September) because, outside of this period, soils were wet enough to satisfy most water needs. The large-reservoir alternative (alternative 3) increased withdrawals by 24%. Since the water pumped into reservoirs in winter was available to all farmers who irrigated, the storage capacity of their individual reservoirs no longer limited withdrawals, and the demand for agricultural water was met more easily.

Decision-support tools (alternative 2) and crop rotations (alternative 4) significantly reduced the quantity of flow-supporting releases. Annual flow-support depends on the number of days below LWRF, which triggers a water release. It also uses estimated agricultural water needs to determine the amount to release. Crop rotation reduced both factors (water needs and number of days below LWRF), while decision-support tools influenced flow-support mainly by reducing the number of days below LWRF (*CR*, Table 1). The decrease

Fig. 3 Cumulative volume of water withdrawn for irrigation per 10-day interval (2001–2013 inter-annual mean). The “large reservoir” alternative increased the peak of water withdrawals compared to the reference situation. Conversely, the “decision-support tools” and “crop rotation” alternatives were the most effective to decrease irrigation withdrawals



in flow-support releases was small when irrigated area was reduced (alternative 1), since the decrease in withdrawals was both small and far from the Aveyron River. Likewise, large reservoirs (alternative 3) reduced the number of days below LWRF without changing water needs, which limited the reduction of flow support.

Restricting use is another strategy for managing water. The alternatives' effects on restrictions (approximated by CR, Table 1) logically followed the observed trend in flow support, with crop rotation and decision-support systems restricting water use the least.

In sum, crop rotations and decision-support tools reduced farmers' water demand and consequently their withdrawals, eased water management, and reduced its cost. The effects of reducing the irrigated area on withdrawals were too localized to reduce the use of water management tools (water releases and restrictions). The large-reservoir alternative significantly increased withdrawals without increasing restrictions or the quantity of flow support (and even decreasing them a little). This alternative could have advantages from a water quantity viewpoint when food security is an issue and is limited by water inputs. Conversely, it seems counterproductive in contexts in which the focus is to reduce water consumption (as in the study area).

3.2 Effects on the environment

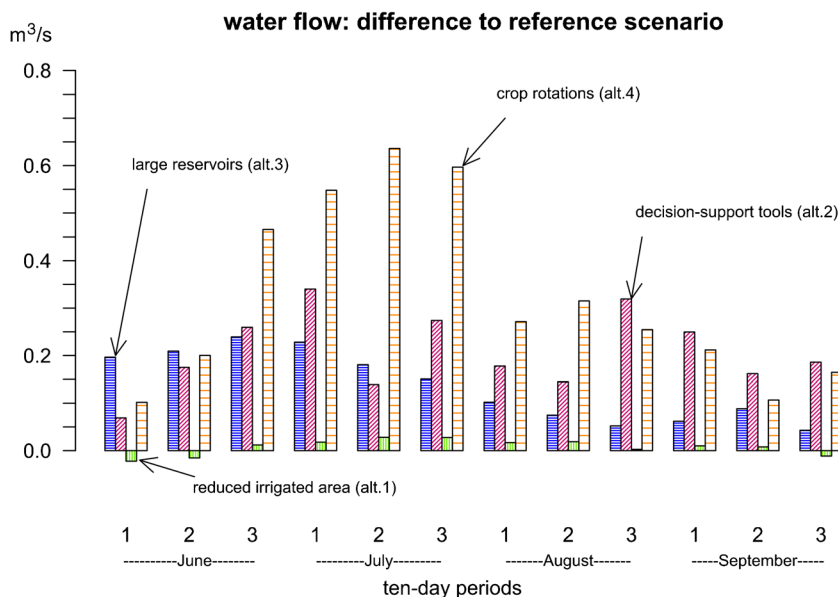
Alternatives had little impact (a 0–3% increase from the reference flow, Table 1) on the mean water flow during summer simulated at the Aveyron outlet. Impacts on withdrawals and impacts on flows differed because the Aveyron is large and long, and its flow depends mainly on upstream processes and less so on downstream processes. Crop rotation had the strongest impact on the Aveyron flow (+2.7%), followed by

decision-support tools (+11.7%) and large reservoirs (+1.3%). These impacts were far greater on the number of days below LWRF due to threshold effects: a relatively small increase in river flow could cause it to exceed the LWRF.

Alternative 4 reduced maize cropping by 75% in fields that were initially mono-cropped (due to the four-year rotations), which were located mainly in the Aveyron alluvial plain. Consequently, this alternative had a direct and relatively large impact on flow of the Aveyron in summer. This impact was even larger from the end of June to the end of July (Fig. 4), i.e., when maize requires the most water. In comparison, the effect of reducing the irrigated area (alternative 1) was negligible. Although this alternative implies drastic changes to certain fields, the area converted to rain-fed crops had a small cumulative water demand and lay far from the flow-measurement point (the Aveyron outlet). In alternative 2, decision-support tools were applied to all irrigated fields, regardless of crop species. Water needs varied over time among crops, and therefore among fields. Consequently, this alternative induced a relatively small and constant increase in flow of the Aveyron (+0.2 to +0.3 m³/s) from mid-June to September (Fig. 4). In late summer, when flow is usually lowest, this alternative outperformed crop rotations because irrigation was stopped early. In the large-reservoir alternative (alternative 3), storage occurred in winter and was geographically concentrated. The rainwater that filled the small reservoirs during summer in the reference situation flowed into rivers instead, which explains the slight increase in flow during this season (Table 1; Fig. 4).

Crop rotations returned the most water to the environment (+6%, Table 1), mainly by reducing withdrawals (Sect. 3.1). Decision-support tools, although they also reduced withdrawals, decreased drainage, which caused the amount of water returned to the environment to increase only slightly (+2.3%). This agrees with studies on water optimization

Fig. 4 Change in the mean flow of the Aveyron River for each simulated water management alternative from the reference situation per 10-day interval (2001–2013 inter-annual mean). Alternatives 4 crop rotation and 2 decision-support tools increased the flow in summer more than alternatives 1 “reducing the irrigated area” and 3 “large reservoirs”



technologies, such as that by Ward and Pulido-Velazquez (2008), who warned that the decrease in drainage can negatively affect the gain obtained by reducing withdrawals, especially when associated economic benefits cause the irrigated area to increase, which depletes return water flows. The large-reservoir alternative was the only one that decreased slightly (-1.8%) the amount of water returned to the environment, due to more withdrawals, a trend that could erode the resilience of the water system over time.

On the whole, crop rotation and decision-support tools seem suitable alternatives to reduce the occurrence of critical episodes in the water environment. In addition, crop rotations have a non-negligible positive effect on other hydrological indicators (*RE* and *M*), which could induce long-term improvements when crop rotations are part of an agroecological cropping system (e.g., with intercrops and reduced tillage) (Hobbs et al. 2008; Thierfelder and Wall 2010). This alternative could also postpone the beginning of the low water period because it significantly increases river flow in the first month of summer. Effects of the large-reservoir and reduced-irrigated-area alternatives on the environment, although small from a quantitative point of view, deserve further investigation. More particularly, these alternatives were designed to address aquatic biodiversity and water quality issues, both of which are beyond the scope of MAELIA and therefore were not assessed.

3.3 Effects on agriculture

Production of field crops was not influenced by the decision-support tool alternative (alternative 2) but was increased slightly ($+3.5\%$) by the large reservoir alternative (alternative 3) because farmers more easily met the demand for water. Economically, the gain in production induced by the latter alternative was larger ($\Delta GMH = +9\%$), due to the added-value of seed maize and maize crops, which benefits most from a more secure access to water. This securing effect on the economy is confirmed by the simulation results of Rey et al. (2016) under more humid climates.

The unchanged level of production observed with the decision-support tool alternative was due to the theoretical irrigation strategy used in the model. This strategy adjusts irrigation operations to the needs of plants to meet their potential yields (calculated by AqYield) when the water resource is sufficient and available, i.e., when the workforce is available and no restrictions occur. Testing crop irrigation based on the theoretical strategy in experiments would help to confirm the potential of the decision-support tool alternative to maintain high yields. Like production, the gross margin of field crops was also maintained, but this result should be treated cautiously. First, if a fixed cost (resource access fee) is considered, economic losses could increase, because it is far more expensive than water use fees (around 0.005 €/m^3). Second, the revenue simulated by the model considers only the quantity produced, not its quality.

Reduced irrigation for certain crops, such as wheat, can decrease the quality, e.g., protein content (Guttieri et al. 2000), and reduce the gross margin derived from growing them.

Reducing the irrigated area and implementing crop rotations (alternatives 1 and 4) decreased the production of field crops by more than 10% (Table 1). This decrease could impact the local economy because the downstream Aveyron watershed is a zone of maize and seed production that benefits from established supply chains in the region. For the crop-rotation alternative, production decreased because the new crops alternated with maize produced less ($\Delta p = \Delta Y = -12\%$, Table 1). From the farm-economy perspective, the loss of maize and seed areas is detrimental ($\Delta GMH = -9\%$) because they generate the highest gross margins among field crops. For the reduced-irrigated-area alternative, most of the decrease in field-crop production was due to converting field crops into grasslands (which were not considered in the *P* indicator). Unlike production, field-crop yields decreased less (-3.9%). This small decrease was caused by seed fields converted into straw-cereal fields and stopping irrigation of some grain-maize crops. Although the gross margin of field crops decreased only slightly (-2%), the gross margins of farms that convert fields into grasslands would likely decrease, especially because natural grasslands are not greatly valued in a context of declining livestock farming.

In the end, the large-reservoir alternative was the only one able to maintain the agricultural economy at the current level in the current context. Decision-support tools can help maintain high yields, but they can also decrease crop quality. Crop rotations and reduced irrigated areas have substantial negative effects on field-crop production and decrease farm and local economies. However, if the agricultural water tariff were to change (e.g., with higher use fees and smaller access fees), as the European Commission and the French General Accounting Office recommend, the gross margin could increase for the least water-consuming alternatives (crop rotations and decision-support tools). Additionally, if contracts for seed production became less attractive or maize prices collapsed, the negative economic results for the crop-rotation alternative would require revision. On the whole, economic results are the most sensitive to exogenous changes and should not be assumed to remain consistent in the long term.

3.4 Key insights from the method and perspectives for improvement

Results of our integrated assessment depend on the case-study area, the modeling choices we made, and the reference situation to which results are compared. For instance, the average demand for water is high and well satisfied in the case-study area, so water savings can also be high when implementing crop rotations or using decision-support tools. By contrast, the case-study area covers only a little portion of the Aveyron watershed, which explains that important efforts for reducing irrigation withdrawals

do not translate into similarly important improvements on the Aveyron flow. The area affected by changes is also variable among alternatives, ranging from 2800 to 11,000 ha, so the effectiveness of the different alternatives is relative to the area on which changes are implemented (this area being context-dependent) and not absolute. However, agricultural land use in the case study is similar to many other irrigated watersheds, with most of the irrigated field crops located in the alluvial plain. Therefore, the spatial extent of the different strategies we modeled reflects real-world situations and is an important dimension to address at the landscape scale.

Our integrated modeling approach identified a “no-regrets” alternative: the decision-support tool. This alternative appeared beneficial to the water management system and, to a lesser extent, to the environment, at nearly no cost to the agricultural economy. However, this conclusion depends greatly on the initial gap between current irrigation practices and crop water needs. In addition, this alternative can increase the irrigated area (not considered in the model). The accuracy of the theoretical irrigation strategy for different crops has not been tested in practice.

The crop-rotation alternative had the most contradictory results since it was the most promising for the environment and water management but the most detrimental to the economy. These negative economic results, however, may need to be reconsidered given the volatility of agricultural prices, potential changes to the water tariff, and future climate variability (not investigated). In addition, the environmental performance of crop rotations could improve when they are combined with other agro-ecological techniques (currently under study for modeling in the MAELIA platform). Unlike optimization strategies, such as the use of decision-support tools, implementing crop rotations provides great potential for addressing diverse environmental challenges and not only improving river flows.

Results for the large-reservoir alternative indicated that merging storage capacities increases water availability and hence withdrawals. The increase in withdrawals contradicts the orientation of water policies but secures the production of crops with high added-value (maize and seeds) and consequently maintains the agricultural economy without negative impacts on low-flow hydrology and management. However, this alternative has the highest uncertainties, which MAELIA cannot address in its present state. Uncertainties include water storage issues (Carluer et al. 2016), such as physicochemical and ecological qualities of water, as well as hydrological dynamics throughout the water cycle, including the high-water period and flooding episodes. In addition, this alternative is the least realistic because it implies connecting each irrigated field to a reservoir using kilometers of pipes.

The reduced-irrigated-area alternative had the smallest effect on the indicators studied, although it was the only one that stopped irrigated agriculture in certain parts of the watershed. This alternative also suffered most from limits of the model's

domain of validity. Since SWAT model estimates of water flows have been calibrated/validated only for large rivers, we could use river-flow predictions only for the Aveyron outlet. We thus excluded impacts on upstream areas and small rivers, which are influenced the most by the stopping of irrigation. Additionally, because the AqYield submodel of plant growth was created only for field crops, we could not use its production estimates for grasslands or trees; consequently, our agricultural indicators were only partly relevant for this alternative.

On the whole, our integrated assessment method helps to understand potential quantitative outcomes of contrasting agricultural water-management strategies. Nonetheless, it does not investigate how to implement the alternative strategies and does not completely explore the range of their potential impacts. Therefore, results of our assessment should not be perceived as recommendations for designing policies, but as new insights in the current debate on the sustainability of mixed irrigated/rain-fed farming systems (Debaeke and Aboudrare 2004; Amigues et al. 2006) and on the relevance of different forms of agricultural modernization (Duru et al. 2015), from the perspective of water resources. This is the first time that strategies drawing much political attention for future quantitative water management are challenged by a fine-resolution multi-agent model like MAELIA and their impacts assessed in an integrated way.

4 Conclusion

Structural changes are needed to recover water balance in certain watersheds and to anticipate the future risk of imbalance in others. We used MAELIA to develop and implement an integrated assessment method to explore impacts of four water management alternatives in an agricultural watershed that experiences water imbalances. The four alternatives—reducing irrigated area, assisting irrigation with decision-support tools, merging storage capacities into large auxiliary reservoirs, and implementing crop rotations—were assessed based on eight indicators that considered effects on water management, the environment, and agriculture.

All alternatives except the large-reservoir alternative significantly reduced cumulative water withdrawals, sometimes drastically, but the impacts of these water economies on other indicators varied greatly. The decision-support-tool alternative, which represents an efficiency paradigm for agriculture, seems a no-regrets alternative because it has a positive influence on water management and the environment at nearly no cost to the agricultural system.

Conversely, the crop-rotation alternative, representing an ecological intensification paradigm, has the most contradictory results: the highest performance for water management and the environment but the lowest performance for agriculture. This alternative, however, could encourage other agro-

ecological practices and provide greater environmental benefits in the long term.

The reduced-irrigated-area and large-reservoir alternatives provided the most debatable results, given model limitations and the context of the watershed studied.

Overall, we provided new insights into the debate on the most sustainable strategies to address water imbalances, as four of those strategies were for the first time assessed using a multi-agent model coupling hydrological, agricultural, and water management processes from the field to the landscape. The method could be further developed and applied to new areas and alternatives to deepen our understanding of farming systems' abilities to adapt to future challenges.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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