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Integrated modeling of crop and water management at the watershed scale: optimizing irrigation and modifying crop succession

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Keywords

Water; modeling; watershed; withdrawals; irrigation; scenarios

1 Introduction

Due to population growth and the expansion of the agricultural, energy, and manufacturing sectors, the demand for water has increased. Water scarcity has become a major concern for the future of sustainable food production and the conservation of important ecosystem functions (Rosa et al., 2020). Climate change is further exacerbating water scarcity and is expected to increase the frequency of extremely dry periods in Europe (Lelieveld et al., 2012). In southern Europe, precipitation levels declined 20% during the 20th century, additionally contributing to water supply issues (Caballero et al., 2007).

Hydrological droughts occur when there are “inadequate surface and subsurface water resources for the established water uses of a given water resources management system” (Mishra and Singh, 2010). This definition underscores that drought occurrence, like other natural events requiring management, is not only affected by resource levels, but also by usage patterns (i.e., needs and practices) and management approaches, including operational water management and water use regulations. Worldwide, over the past 50 years, cultivated irrigated surfaces have almost doubled in area, and 70% of freshwater withdrawals are devoted to irrigation (Foley et al., 2011). This situation has placed additional stress on water bodies and aquifers. The proliferation of irrigated, water-intensive crops, such as maize, has increased soil drying and water scarcity in many watersheds with large areas dedicated to irrigated crops (Liu et al., 2015).

Given climbing drought risks, it is crucial to consider how water management in cropping systems can be improved in irrigated watersheds. In the scientific literature, agronomic studies at watershed scale and on water management are mainly based on coarse farm typologies and focus on withdrawals volume for irrigation and crop needs (e.g. Clavel et al., 2012; Neupane and Guo, 2019). These studies generally do not include hydrological issues, such as rivers flows. Conversely, there is plentiful studies on the hydrology of watersheds, but the functioning of crops and farming systems are often represented very roughly (e.g. Francesconi et al., 2016; Van Emmerik et al., 2014). Furthermore, most studies focus only on one issue in particular, such as drainage (e.g. Ale et al., 2012) or irrigation (e.g. Clavel et al., 2012).

Another type of approach is to implement integrated assessment and modelling which accounts for the complex interactions among cropping systems, farming systems, water resources, and water management within watersheds both within and across years (Mazzega et al., 2014; Therond et al., 2014). Integrated modelling is a useful method for functionally exploring the impacts of most of these factors (Alcamo et al., 2003; Jakeman et al., 2006; Letcher et al., 2006; Therond et al., 2014; Zhang and Guo, 2016). It can be used to evaluate and compare alternative agricultural and/or water management systems at the watershed scale (March et al., 2012). It is essential to explicitly model anthropogenic management strategies and their consequences to properly simulate the hydrological dynamics of highly entropized basins (Martin et al., 2016). In irrigated watersheds, it is crucial to represent the multiple ways in which different cropping systems (i.e., rainfed vs. irrigated) can affect water resource dynamics and, if relevant, reservoir releases and water use regulations (Martin et al., 2016; Mazzega et al., 2014).

MAELIA is an integrated assessment and modeling platform representing fine-scale spatiotemporal interactions among agricultural practices (e.g., crop succession and management strategies), the hydrology of different water resources, and water resource management approaches (e.g., reservoir releases, water use restrictions) within watersheds (Gaudou et al., 2014; Therond et al., 2014). To properly perform such agent-based modeling, it is necessary to integrate scientific and practical knowledge, local expertise, and large-scale census data (see Murgue et al., 2016, for example). This integrated modeling platform could be very useful to test and evaluate the impact of agricultural scenarios on water dynamics at larger scale.

The objectives of this study was to assess the impacts of three contrasting, realistic scenarios for managing water use in irrigated maize agricultural systems on water dynamics at the field and watershed scales, using MAELIA. We aimed to evaluate how much irrigation withdrawal volumes could be lowered via strategies to reduce water deficits, which are traditionally recommended in France (Mayor et al., 2012).

2 Materials and Methods

2.1 General approach

We first evaluated MAELIA predictions on withdrawal volumes and river flow rates at the watershed scale over several years for the current situation of our studied system. We then designed and analyzed the effect of three scenarios to enhance water management in irrigated maize systems on environmental, water management, and agricultural indicators. These three alternative scenarios were compared with the benchmark scenario based on actual irrigation management practiced in the watershed. In the first, maize irrigation efficiency was optimized based on crop’s water requirement.

In the second, maize monocultures were replaced by a wheat/maize succession. In the third, the two previous scenarios were combined.

2.2 Study system

For this study, we choose the downstream Aveyron watershed, located in southwestern France because it experiences strong and recurrent water deficits (Martin et al. 2016). This watershed is around 800 km² large and is located in the Adour-Garonne basin, which is the basin with the greatest structural water deficit in France. It contains numerous irrigated farming systems that account for up to 80% of total anthropogenic water consumption during the area's low-flow period, from June to September (Mazzega et al., 2014). The Aveyron watershed is among the most irrigated watersheds in France and has the greatest annual water deficit: 7 hm^3 on average. It is a prominent example of a water-imbalance situation, in which low water inputs co-occur with high agricultural demands. Two main rivers cross the watershed: the Aveyron and the Lère. The flow rate of the Aveyron River frequently drops below the target regulatory threshold, which was established to guarantee aquatic ecosystem health. This low-flow threshold is 4 $m^3.s^{-1}$ and 0.1 $m^3.s^{-1}$ for the Aveyron and Lère Rivers, respectively. Furthermore, the flow of the smaller rivers connected to the Aveyron is also regularly disrupted (Mazzega et al., 2014). In this area, daily river discharge dynamics are strongly determined by irrigation demands and the resulting withdrawals. Flow deficits are managed daily by releasing water from the reservoirs associated with the two main rivers and by the implementation of withdrawal restrictions by regulatory authorities.

Our study focuses on the downstream portion of the Aveyron watershed, an area characterized by the Aveyron terraces and their surrounding clay-limestone slopes. The watershed contains an irrigated agricultural landscape which represents 16% of the watershed's surface area but accounts for 80% of its irrigation withdrawals (18 hm^3). In total, around 40,000 ha are under cultivation by 1,150 farms, and approximately 40% of this land may be irrigated (according to the French Land Parcel Identification System, 2014). The area mainly hosts large-scale production systems: maize, grains (wheat and some barley), oilseeds (sunflower and a little bit of soybean), and a few protein crops (peas). The hilly slopes are mainly dotted with fields of rainfed grains and sunflower, while the alluvial plain is covered by irrigated, largely monocropped grain and silage maize, which require the most water. There are also fields of fruit crops and seed maize; the latter has a high added agricultural value but requires a consistent water supply.

2.3 *Climate data*

We obtained daily climate data using SAFRAN (8 × 8 km grid) (Vidal et al., 2010). Over the 10-year study period, 2007–2016, the daily mean minimum and maximum temperatures were 9.0°C and 17.2°C, respectively. Mean cumulative annual precipitation and potential evapotranspiration (Penman-Montheith formula) were 757 mm and 849 mm, respectively, leading to a mean annual water deficit of 91 mm. Over the study period, the years 2011 and 2015 were the driest (547 and 673 mm of precipitation, respectively) and were characterized by an annual water deficit of 300 mm or more (Figure 1). Looking exclusively at the low-flow period, from June to September, the years 2009, 2012, 2015 and 2016 were the driest—low precipitation resulted in a summer water deficit of 300 mm or more.

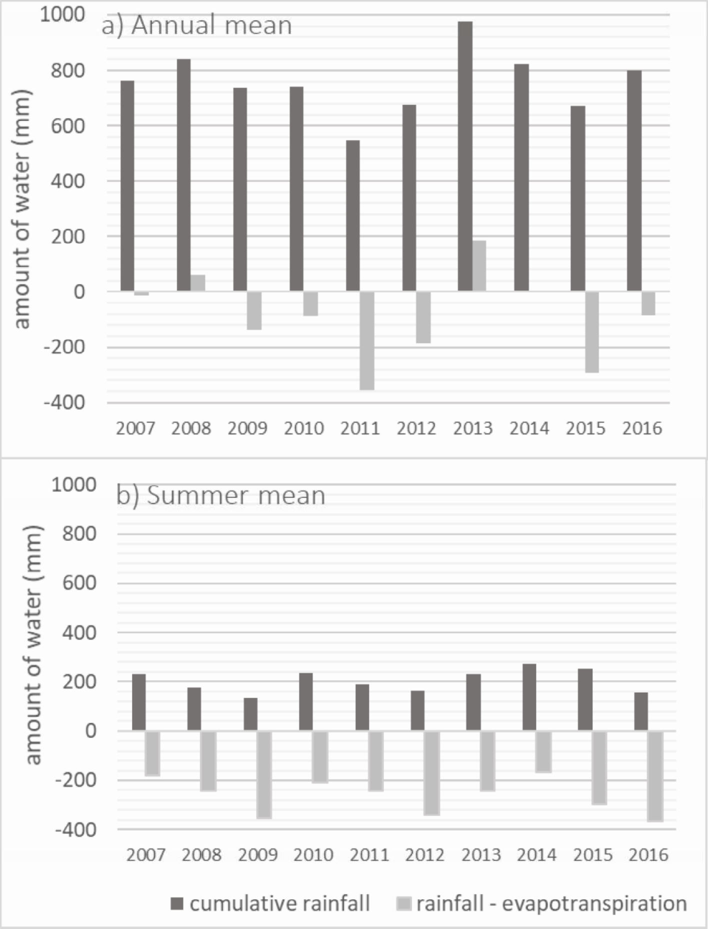

Figure 1. Cumulative rainfall and water deficit levels (rainfall – evapotranspiration) from 2007 to 2016: a) on a yearly basis and b) during the low-flow period (June to September). Depicted are the means for all the SAFRAN data obtained for the downstream Aveyron watershed.

2.4 *The MAELIA model*

2.4.1 *Overview*

MAELIA, a multiagent integrated modeling and assessment platform, was developed to study the environmental and socioeconomic impacts of different combinations of water management and land use strategies (Martin et al., 2016; Murgue et al., 2015, 2014). It employs GAMA® (GIS & agent-based modeling architecture), an open-source generic modeling and simulation environment for building rich, spatially explicit agent-based simulations (Grignard et al., 2013). MAELIA simulates the interactions between four modules:

(i) the agriculture module, which includes a soil-crop model for simulating plant growth, irrigation, and water dynamics at the field level and a farmer-as-agent model for simulating crop management dynamics

(ii) the hydrology module, in which different water resources (i.e., rivers, small reservoirs, large reservoirs, and groundwater) are simulated via the soil and water assessment tool (SWAT) (Arnold et al., 2010)

(iii) the other-water-uses module, in which domestic and industrial water use is simulated via econometric equations (Therond et al., 2014)

(iv) the water-management module, in which withdrawal restrictions and water-release decisions are simulated

The modules interact at different spatial levels at daily time steps; feedback is also incorporated. Field-level water requirements affect farmers' decisions and, consequently, determine irrigation withdrawals from different water resources. There are subsequently impacts on river flow rates, which influence decisions around reservoir releases and/or withdrawal restrictions. The resulting hydrological conditions determine how much water is available for irrigation, which then affects farmers' irrigation levels and crop growth. MAELIA has already been used to explore issues in the downstream Aveyron watershed (Martin et al., 2014; Murgue et al., 2015, 2014). Based on local databases, expert knowledge, and geographic information system (GIS) analysis, each irrigated field in this area is connected to one or more water sources (e.g., river, small reservoir, and/or groundwater). More information about MAELIA can be found in Martin et al. (2016b) and Therond et al. (2014).

2.4.2 Agriculture module and data

Within the agriculture module, the soil-crop model AqYield simulates crop growth, soil water dynamics, and crop yield at the field level. The equations it employs have been previously described (Constantin et al., 2015). Crop development is simulated using the accumulated mean daily effective temperature. AqYield uses a FAO-56 approach to simulate evapotranspiration through a crop coefficient depending on crop development (Allen, 2000). Evaporation and transpiration are daily simulated separately. They are both dependent on a potential, calculated with potential evapotranspiration and crop coefficient, and soil water availability. Soil water dynamics is modelled using a capacity approach. Soil water content levels range from wilting point to 100% field capacity and are calculated for each day by taking the balance of inputs (irrigation, rainfall) to outputs (transpiration, evaporation, drainage, and runoff). The crops represented in the module include the 10 species that, when taken together, cover 100% of the irrigated areas: maize, sunflower, wheat, peas, rapeseed, soybean, temporary and permanent grasslands, orchards, and vineyards. Different parameters are used for grain maize and silage maize; there are six earliness categories for grain maize: from very early to very late. AqYield funnels soil and plant indicators to the farmer-agent and hydrological information (field drainage and runoff) to the hydrology module.

AqYield simulates events in each field for each crop in the crop successions identified via the French Land Parcel Identification System (Murgue et al., 2016; Martin et al., 2016).

In the farmer-as-agent model, crop management strategies are modeled using a set of IF-THEN-ELSE decision rules that represent conditions related to daily soil water content, crop development stage or stress, climate, and/or water resource levels that necessitate technical operations (also simulated), including tillage, seeding, irrigation, and harvesting. They are simulated for each crop based on field (pedoclimatic) and farm characteristics. Farmer-agents carry out technical operations on a daily basis in accordance with these rules, the time available for conducting the work, and the spatial distribution of fields on their farm (i.e., with a view to minimizing distance when changing fields). Each farm and field are individually simulated, taking into consideration their biophysical characteristics (soil, climate) and agricultural characteristics (crop succession, crop management and workload). More details are available elsewhere (Murgue et al., 2014 and Rizzo et al., 2019).

Regarding our case study, farmer's crop management strategies, including irrigation strategies, were modeled according to information collected via a dedicated farm survey (see details in Murgue et al., 2016).

2.4.3 *Irrigation management*

Irrigated fields are organized into islets using the same irrigation materials, resulting in a minimum irrigation rate and volume. This model component makes it possible to simulate how irrigation materials constrain irrigation dynamics. The fields are watered sequentially based on material characteristics. Irrigation decision rules determine the amounts and dates of the water supplied for each irrigated field of each irrigated farm.

2.4.4 *Water-management module*

The water-management module exploits MAELIA's basic framework, via decision rules, to simulate regional policies regarding reservoir releases and withdrawal restrictions (Mazzega et al., 2014; Mayor et al., 2012). These decision rules were determined by obtaining information from regional authorities about their current practices. This module estimates water releases on a daily basis after taking into consideration the hydrological network and filling levels. In the downstream Aveyron watershed, there are four dams (Les Falquettes, Saint-Géraud, Thuriès, and Pareloup) whose reservoirs are available to boost river flow rates. Similarly, the module can simulate withdrawal restrictions using decision rules concerning flow rates at hydrological nodes and water availability in the reservoirs (ibid.).

2.4.5 *Calibration and evaluation*

Calibration and evaluation of MAELIA models were implemented by previous studies. The AqYield model was calibrated and evaluated on several water balance components through time, for various crops at the field scale and over a 7-year succession period (Constantin et al., 2015; Tribouillois et al., 2018). The results highlighted the effectiveness of the model in simulating the different water-related variables, such as soil water content, evapotranspiration, and drainage in irrigated and rainfed systems, with annual crops such as maize, sorghum, sunflower, rapeseed and wheat and on bare soil. The model was evaluated over crop rotation on daily evapotranspiration measured on Eddy covariance and on drainage measured on lysimeters for several years and with or without crop. The results confirmed that the model was able to simulate evaporation during bare soil period and transpiration during crop development. AqYield predicted monthly ET on calibration and validation datasets with a model efficiency of 0.84 and 0.69, respectively. It also predicted soil available water content in the various soil and climate situations with an efficiency of 0.83 (Tribouillois et al., 2018).

Parameters of irrigation decision rules were calibrated to reproduce observed annual irrigation withdrawal volumes provided by the Adour-Garonne Water Agency for the period from 2003 to 2010 (Martin et al., 2016).

The hydrology module was calibrated using an approach similar to that of Lardy et al. (2014), in which simulated and observed flow rates were compared for the two main rivers using a daily time step; irrigation withdrawal volumes were also compared. Water release patterns and water restrictions were calibrated using iterative decision rules, drawing upon regional government records from 2008 to 2010; this information was used to consistently simulate the volumes released annually.

Initial evaluations of model performance concluded that simulated withdrawals at the watershed scale were very satisfactory (Martin et al., 2016; Murgue et al., 2016); they were based on data provided by the Adour-Garonne Water Agency for the period from 2003 to 2010. However, these first evaluations conducted in the previous studies did not provide any statistical performance figures except for an underestimation of 10% on average of the withdrawal. The predictive quality of the model was then entrusted to the appreciation of the field experts in relation to their expertise and knowledge of the expected values and dynamics. They noted a good ability of the model to reproduce annual water withdrawal volumes and interannual differences, particularly in comparison to the observed data, which they also considered not very accurate, with a possible error of 10%. Local experts also validated the results of the simulations of crop management practices (e.g., sowing dates, first and last dates of irrigation). Additionally, they confirmed that, for the same time period, the model accurately reproduced observed flow dynamics during the low-flow season.

To further assess the model, we compared simulated and observed values of withdrawal volumes for irrigation and river flow rates over a 10-year period (2007–2016) in the two main rivers (Aveyron and Lère). The observed data were provided by the water agency. Three statistics were calculated:

(1) the root mean square error (RMSE), which quantifies the difference between predicted and observed values.

(2) the Nash–Sutcliffe efficiency (NSE) coefficient, which was described by Nash and Sutcliffe (1970) and is defined as one minus the sum of the absolute squared differences between the predicted and observed values divided by the variance of the observed values. NSE ranges between −∞ and 1, where the latter is indicative of a perfect fit. When the coefficient value is less than zero, the observed mean is a better predictor than the predicted mean.

(3) the mean bias error (MBE), which reflects the average bias in predicted values.

These three statistics were calculated as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(E_i - O_i)^2}{n}} \qquad (1)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(E_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \qquad (2)$$

$$MBE = \sum_{i=1}^{n}\frac{E_i - O_i}{n} \qquad (3)$$

where E_i = the estimated value, O_i = the observed value, $\bar{O}$ = the mean of the observed values, and n = the number of values.

2.5 *Simulations of the current scenario and three alternative scenarios*

Maize is the main irrigated crop found in the downstream Aveyron watershed. Consequently, we used MAELIA modeling to compare the performance of the current maize management scenario with that of three alternative scenarios to reduce demand for irrigation water and, thus, the overall water deficit in the watershed:

i) The **benchmark scenario** represented current management practices

ii) The **irrigation efficiency scenario** provided water to maize on an as-need basis

iii) The **modified crop succession scenario** replaced maize monocultures with a wheat/maize succession

iv) The **combined scenario** brought together the irrigation efficiency and succession modification scenarios

In the three alternative scenarios, seed maize production was left unchanged because of the crop's economic value. Its importance within the watershed's economy also means it is guaranteed a consistent water supply.

In these four scenarios, the model simulated withdrawal volumes, drainage, river flow rates, the number of days where river flow rates fell below the target threshold, and reservoir releases. The simulations took place over a 10-year period (2007–2016) at the scale of the watershed, in which 1,142 farms with 15,224 crop fields cover a total of 38,880 ha.

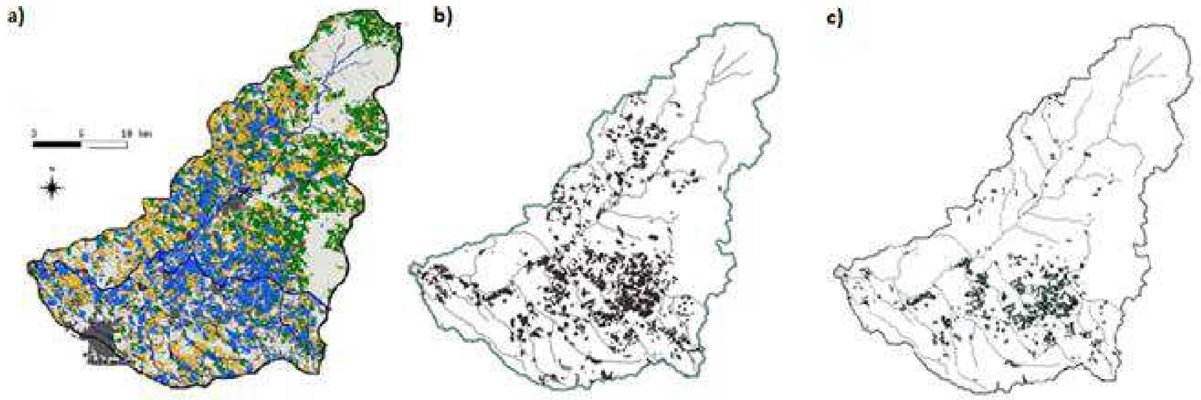

Figure 2. Maps of the fields affected by the different scenarios: a) benchmark scenario, b) irrigation efficiency scenario, and c) modified crop succession scenario. For the benchmark scenario, irrigated fields are in blue, rainfed fields are in yellow, and grasslands are in green. For the irrigation efficiency and modified succession scenarios, the surfaces impacted are in dark gray.

2.5.1 *Irrigation efficiency scenario*

In this scenario, only the irrigation strategy was changed. All other variables were the same as in the benchmark scenario, including farm constraints, crop successions, and irrigation islets as well as tillage, sowing, and harvesting strategies. Instead of irrigation rules based on precipitation and soil moisture used in the benchmark, irrigation was based on plant water requirements, using the water satisfaction index (i.e. ratio between actual and potential transpiration) predicted by AqYield. The threshold value for this ratio to trigger irrigation was fixed between 0.8 and 0.9, depending on crop development (Supplementary Material A). This scenario sought to quantify the gain with optimized irrigation utilizing irrigation decision-making tools. This scenario affect approximately 16% of the watershed's agricultural lands: 2,045 crop fields with at least one maize in crop succession covering 6,365 ha, including 2,820 ha dedicated to maize monocultures and 1,670 ha dedicated to wheat/maize successions (Figure 2b).

2.5.2 Modified crop succession scenario

The modified crop succession scenario was designed based on recommendations made by local stakeholders (Murgue et al., 2015). Maize monocultures and crop successions containing more than 75% maize were replaced by a wheat/maize succession. The hypothesis was that replacing irrigated maize by irrigated wheat would strongly reduce water withdrawals (from about 10 water supplies for maize to 2-3 supplies for wheat) and position them around the wheat flowering that is most often before the intense low-flow season.

We randomly assigned the initial crop to have half of the fields starting with maize and half with winter wheat. The wheat was irrigated if necessary since the farmers already have access to irrigation in those fields. To ensure crop compatibility, the maize was the most common variety used in the watershed (mid-late maize). This choice of maturity also ensures that maize could reach physiological maturity to be correctly harvest before wheat sowing. This scenario affected 7% of agricultural lands within the watershed: 706 crop fields and 2,820 ha of maize monoculture successions (Figure 2c). It led to a 25% decrease in the area covered by maize and a 15% increase in the area covered by wheat.

2.5.3 Combined scenario

In the third alternative scenario, the practices from the two previous scenarios were applied in tandem. As in the irrigation efficiency scenario, approximately 16% of the watershed's agricultural lands (2,045 fields covering 6,365 ha) were affected; this figure included 2,820 ha dedicated to maize monocultures that were converted to the wheat/maize succession and 1,670 ha already subject to a wheat/maize succession (Figure 2).

2.5.4 Data analysis

To assess the irrigation efficiency and modified crop succession scenarios at a small scale, we first selected an example field to explore the main processes influencing water management and balance (i.e., evapotranspiration, irrigation, amount of water in the soil, and drainage). This 2.6-ha field hosted an irrigated maize monoculture (semi-late maize) and was located on deep, clay-limestone soil.

In a second step, irrigation withdrawals, drainage (i.e., percolation across the rhizosphere) and river flow rate were analyzed at the watershed scale over the 10-year period. They were also analyzed on a yearly basis and/or for each low-flow period (i.e. time of the year when natural river flows are lowest and irrigation occurs in June, July, August, and September), depending on the variable.

For withdrawal volumes, we also conducted an analysis on two farms (spanning 24 and 110 ha, respectively) largely dedicated to growing irrigated maize monocultures. We expected that they would show the greatest response to the changes implemented in the three alternative scenarios. The two farms are located on deep soils (clay-limestone and silty soils, respectively).

For drainage, we analyzed it at the watershed scale by taking the mean of all the fields as well as for 20 target islets (blocks of fields), which contained the largest surface areas dedicated to maize monocultures (mean: 92%; range: 71–100%). Their maize monocultures spanned a mean area of 24 ha (range: 16–41 ha). Like the above farms, the target islets were expected to show the greatest response to the three alternative scenarios. This approach allowed us to analyze the maximum effect of the scenarios on annual drainage. The drainage calculation takes into account the soil depth of each field to account for the soil heterogeneity of the watershed. Depending on the fields, this soil depth varies between 50 and 120 cm with an average of 84 cm.

Finally, we evaluated the scenarios' effects on the number of days that river flow rates fell below the low-flow target threshold and, thus, on reservoir releases. The low-flow target threshold is a regulatory standard that helps ensure the coexistence of all uses, the proper functioning of the aquatic environment, and good-quality water conditions. It is defined by the watershed's water management policies. When the river's flow falls below this threshold, restrictions can be applied to irrigation withdrawals.

3 Results

3.1 <u>Evaluation of MAELIA on the actual watershed hydrology</u>

For the study period, the water agency had observed that the mean withdrawal volume was 13.1 hm^3 (range: 9.4–15.9 hm^3). MAELIA performed well in simulating volumes and interannual variation in total annual withdrawal volumes (RMSE = 1.64 hm^3, MBE = -0.78 hm^3 and NSE = 0.43). Predictions were poorest for 2011, which was characterized by atypical climatic conditions (Figure 1), namely a dry spring and a rainy July (88 mm). As a result, in real life, significant volumes were withdrawn early on, and no adjustments were made to the wetter summer. Since this withdrawal pattern was not modeled, poorer predictions resulted.

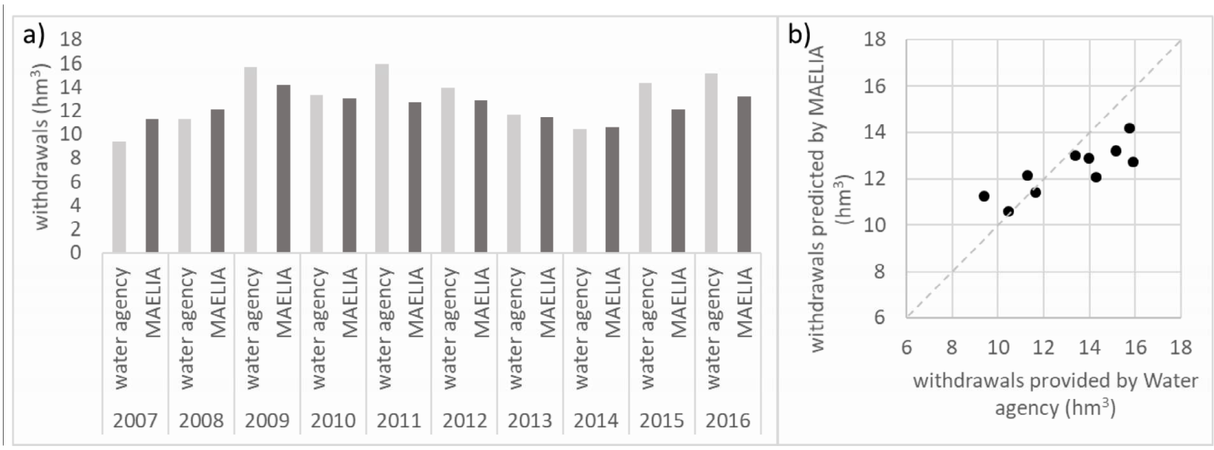

Figure 3. Annual withdrawal volumes observed by the water agency and predicted by the MAELIA model's benchmark scenario

During the study period, the mean monthly flow rate during the low-flow period was 7.4 m^3.s^{-1} for the Aveyron (range: 3.1–19.6 m^3.s^{-1}) and 0.7 m^3.s^{-1} for the Lère (range: 0.1–5.3 m^3.s^{-1}). The model's results showed that observed flow dynamics were well recreated (Figure 4), especially those during the low-flow period, months of great importance for water management. Indeed, the predicted values highly resembled the observed values, with a mean flow rate of 6.2 $m^3.s^{-1}$ for the Aveyron (range: 2.6–17.1 $m^3.s^{-1}$) and 0.4 $m^3.s^{-1}$ for the Lère (range: 0.0 to 1.8 $m^3.s^{-1}$). The calculated NSE for the monthly flow rate during the low-flow period for the entirety of the study period was 0.85 for the Aveyron and 0.75 for the Lère. This result confirms that the model could effectively represent these flow dynamics, even if high flow peaks appeared to be underestimated and were flatter in the simulations.

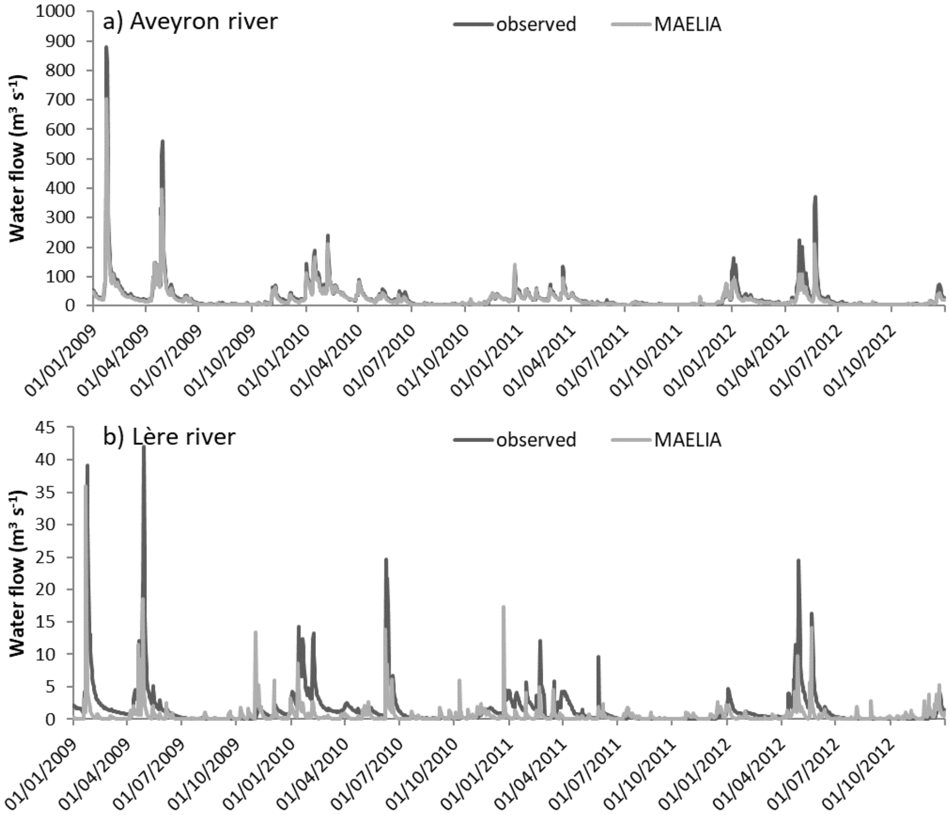

Figure 4. Example of observed and predicted daily flow rates (from 2009 to 2012) for the a) Aveyron River and b) Lère River. Please note that the scale for the y-axis is not the same for the two rivers because of their very different flow volumes.

3.2 *Effects of the scenarios on field water balance*

At the field scale, the irrigation efficiency scenario resulted in evapotranspiration levels similar to those in the benchmark scenario, which confirms that the customized irrigation strategy did not negatively impact maize development despite the reduced irrigation levels during the summer (Figure 5a). In the example field, irrigation levels dropped by 80 mm in 2008 and 2009, which corresponds to approximately two summer irrigation events.

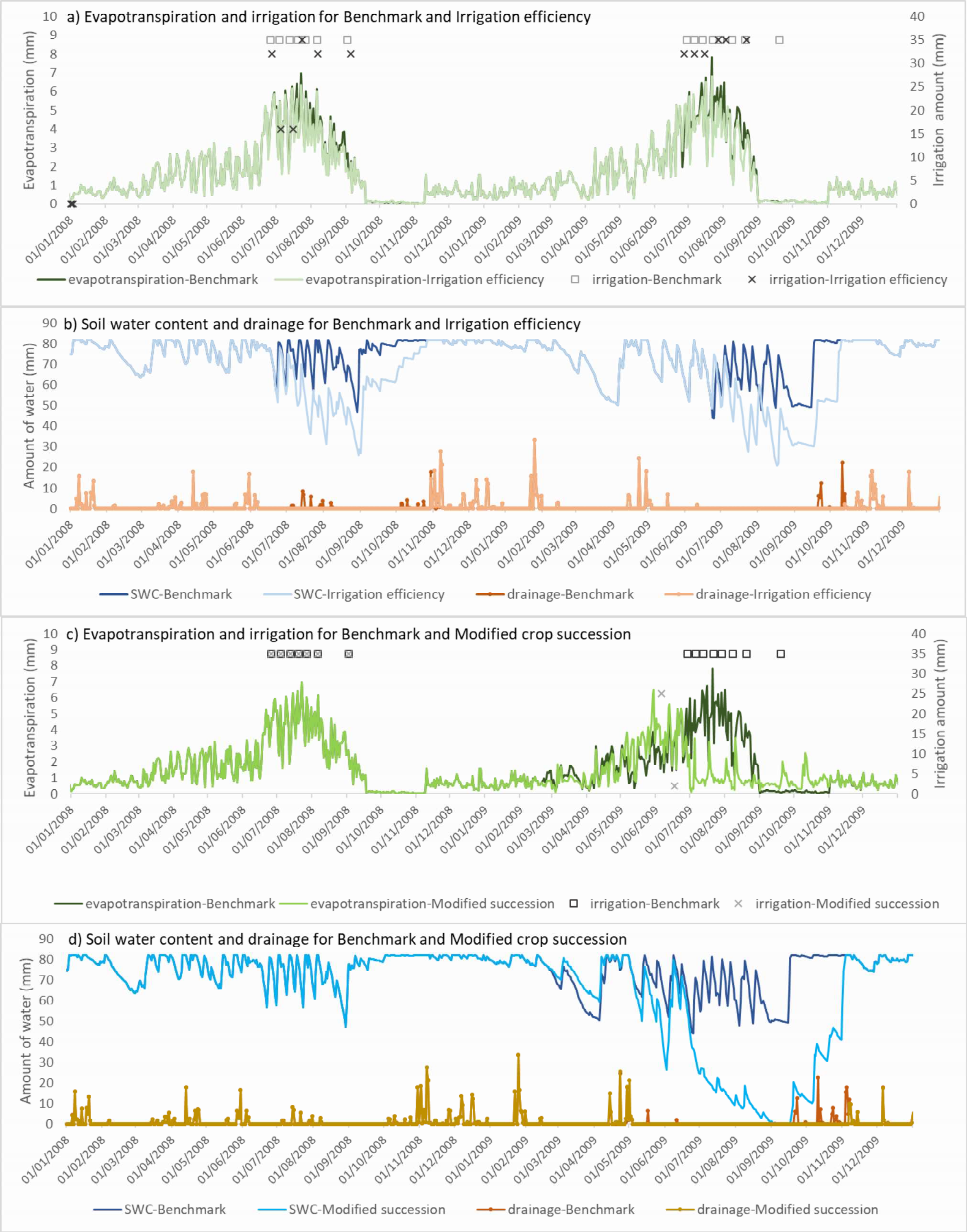

Figure 5. Daily evapotranspiration, irrigation, soil water content and drainage dynamics for an example field with maize grown in 2008 and 2009: a) and b) the benchmark scenario and the irrigation scenario; c) and d) the benchmark scenario and the modified scenario. "SWC" is soil water content.

However, during the low-flow period, soil moisture levels dropped by a mean of 15 mm because irrigation water was being efficiently taken by the maize (Figure 5b). This fact explains why drainage declined in the late summer and fall in the irrigation efficiency scenario (by 18 mm in 2008 and by 53 mm in 2009; Figure 5b). In the modified crop succession scenario, evapotranspiration dynamics were different due to differences between wheat and maize crops, as can be seen in 2009 (Figure 5c). The earlier growth of wheat results in earlier evapotranspiration and irrigation events (i.e., in May); however, because this period is wetter and cooler, overall levels are lower than in the summer (i.e., August). As a consequence of the wheat crop, spring rainfall almost entirely infiltrates the soil and departs via evapotranspiration in June. Conversely, maize growth and evapotranspiration peaks in July and August, resulting in a strong demand for irrigation water. In maize fields, the soil thus remains moist, and rainfall may enter aquifers or drain into nearby water bodies. In wheat fields in August and September, soil moisture levels are quite low due to the harvest and high evaporation pressure. Rainfall is needed to renew soil water content. As a result, drainage declined by 77 mm in fall 2009 (Figure 5d).

3.3 Effects of the scenarios on watershed water balance

3.3.1 Irrigation withdrawals

Over the study period, the mean withdrawal volumes were 12.4 hm^3 (range: 10.6–14.2 hm^3), 10.1 hm^3 (range: 7.8–12.1 hm^3), 10.5 hm^3 (range: 9.2–12.0 hm^3), and 8.9 hm^3 (range: 7.2–10.6 hm^3) for the benchmark, irrigation efficiency, modified crop succession, and combined scenarios, respectively (Figure 6a). Compared to the benchmark scenario, the irrigation efficiency and modified crop succession scenarios resulted in significantly lower withdrawal volumes, with an average reduction of 18% (annual range: 10–31%) and 15% (annual range: 13–27%), respectively. The combined scenario led to an even greater reduction: 28% (annual range: 22–32%). In absolute terms, there was a mean decrease of 2.2 hm^3 in the irrigation efficiency scenario, 1.9 hm^3 in the modified crop succession scenario, and 3.4 hm^3 in the combined scenario. The three alternative scenarios thus reduced the mean annual water deficit of the Aveyron watershed (7 hm^3) by an average of 32%, 27%, and 49%, respectively. For the two farms used to explore the maximum potential effects of these scenarios, withdrawal volumes decreased by an average of 42% for the irrigation efficiency scenario, 35% for the modified crop succession scenario, and 60% for the combined scenario, relative to the benchmark scenario; the level of reduction depending on the year (data not shown). As early as May, current practices resulted in overirrigation relative to crop needs, as reflected in the irrigation efficiency scenario, resulting in larger withdrawal volumes (Figure 6b). In the modified crop succession scenario, withdrawal volumes were slightly greater than they were in the irrigation efficiency scenario in the spring, showing that optimizing irrigation was more efficient than replacing half of the maize area by irrigated wheat at the watershed scale to reduce withdrawals in spring. By July, this pattern was reversed because wheat has lower water requirements than maize with need-based irrigation. Finally, in mid and late September, withdrawal volumes were reduced more in the irrigation efficiency scenario than in the modified crop succession scenario. The combined scenario allowed for a synergy in these reductions, particularly during the summer, starting in July.

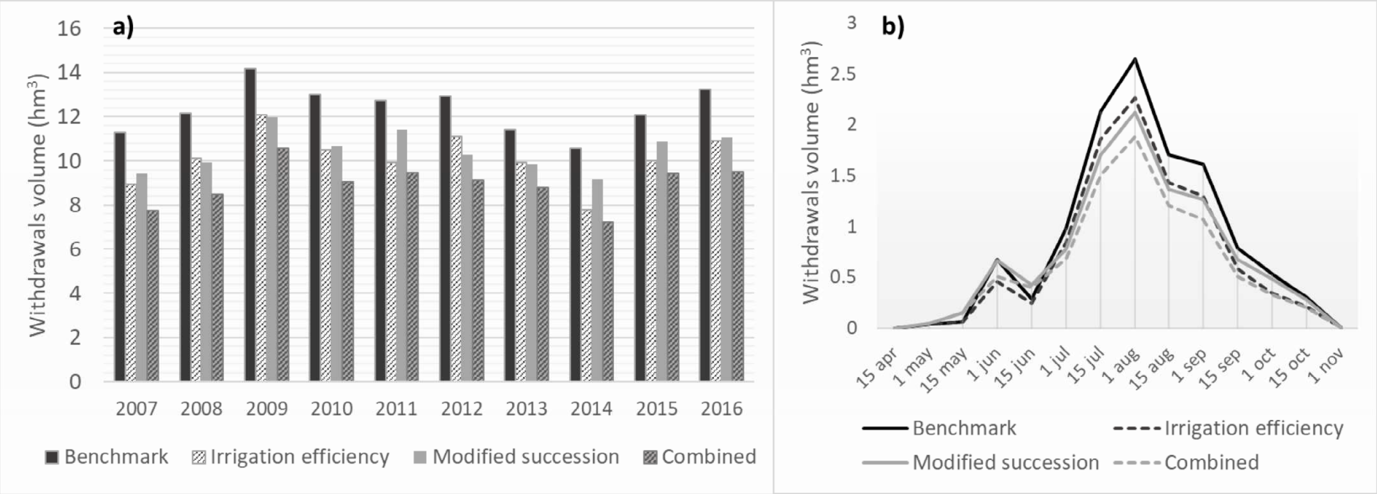

Figure 6. Irrigation withdrawal volumes in the four model scenarios for the study period from 2007 to 2016: a) withdrawal volumes on an annual basis and b) biweekly withdrawal volumes over the irrigation period averaged for the different years

3.3.2 *Drainage from agricultural fields*

Over the study period, mean annual drainage from the agricultural fields was 344 mm (range: 155–556 mm) in the benchmark scenario (Table 1). At the watershed scale, there were minimal differences in drainage among scenarios since only 7–16% of the agricultural surfaces were affected by the implementation of alternative practices. We found that annual drainage was reduced, on average, by 0.5% (-1.6 mm.yr^{-1}) in the irrigation efficiency scenario, by 0.2% (-0.7 mm.yr^{-1}) in the modified crop succession scenario, and by 0.6% (-1.7 mm.yr^{-1}) in the combined scenario. At the watershed scale, these figures translate into mean annual withdrawal reductions of 0.62 hm^3 in the irrigation efficiency scenario, 0.26 hm^3 in the modified crop succession scenario, and 0.69 hm^3 in the combined scenario. In the irrigation efficiency and combined scenarios, a constant level of reduction occurred every year that depended less on climatic conditions and more on optimizing maize irrigation. In contrast, there was more interannual variability in the modified crop succession scenario, given that there was an increase or no change in drainage in some years (2007, 2014), even if there was a decline overall across the 10-year study period (Table 1).

In the 20 target islets used to explore the maximum potential effects of the scenarios, the mean reduction in drainage was 27 mm.yr^{-1} (range: 22–35 mm.yr^{-1}) in the irrigation efficiency scenario, depending on the year (Table 1). Because irrigation was tailored to plant needs, no excess water ended up in the soil, limiting drainage below the soil surface. In the modified crop succession scenario, drainage dropped by 7 mm on average, although this amount varied dramatically among years. In 2007 and 2014, drainage actually climbed by 17 mm while, in other years, it was reduced as much as in the irrigation efficiency scenario (2010: -25 mm; Table 1). This pattern stems from the fact that wheat requires less irrigation and, therefore, less excess water ends up draining off. Interestingly, 2007 and 2014 had the driest low-flow periods, resulting in the wheat crops being irrigated earlier and at higher levels at the beginning of the summer. These conditions led to wetter soils, resulting in larger drainage events when significant amounts of precipitation subsequently fell. The combined scenario reduced drainage by an average of 22 mm.yr^{-1} (range: 0–43 mm.yr^{-1}), depending on the year. This effect was intermediate to those of the irrigation efficiency and modified crop succession scenarios.

Table 1. Mean annual drainage (in mm) for the benchmark scenario compared to the three alternative scenarios for the 20 target islets with extensive maize monocultures and for the entire watershed. The values shown for the alternative scenarios are the differences from the benchmark scenario.

Year		20 target islets				Watershed				
	Benchmark		Irrigation efficiency	Modified crop succession	Combined	Benchmark		Irrigation efficiency	Modified crop succession	Combined
2007	262	vs.	-25	12	-1	342	vs.	-1.7	0.6	-0.6
2008	308		-26	-5	-18	408		-1.7	-0.5	-1.8
2009	307		-26	-16	-31	350		-1.5	-1.1	-2.1
2010	295		-31	-26	-43	330		-1.8	-1.2	-2.5
2011	81		-22	-3	-19	155		-1.4	-0.6	-1.6
2012	212		-35	-22	-39	288		-1.6	-0.9	-1.9
2013	476		-24	-12	-25	556		-1.1	-1.0	-1.8
2014	295		-31	17	0	391		-2.0	0.0	-1.5
2015	200		-26	-9	-22	260		-1.5	-1.2	-2.3
2016	260		-26	-5	-21	357		-1.7	-0.7	-1.9
Mean	270		-27	-7	-22	344		-1.6	-0.7	-2.0

3.3.3 River flow rates

In the benchmark situation, the mean daily flow rate in the summer was 6.2 m^3.s^{-1} for the Aveyron and 0.29 m^3.s^{-1} for the Lère. The irrigation efficiency and modified crop succession scenarios had quite similar effects on river flow rates. Over the entire study period, they tended to increase flow rates slightly during the low-flow season. For the Aveyron, these mean increases amounted to 0.12 m^3.s^{-1} (+2.2%) and 0.13 (+2.4%) for the two scenarios, respectively (Figure 7). For the Lère River, the increase was 0.004 m^3.s^{-1} (+1.9%) for both scenarios. In the combined scenario, river flow rates increased even more: by 0.21 m^3.s^{-1} (+3.9%) for the Aveyron and by +0.008 m^3.s^{-1} (+3.9%) for the Lère.

For the entire study period, in the summer, the maximum percent increase in flow rate for both rivers could be as high as 9% for the irrigation efficiency and modified crop succession scenarios, depending on the month. For the combined scenario, the maximum percent increase was 10% for the Averyon and 12% for the Lère. Even if the irrigation efficiency and modified crop succession scenarios had similar average effects on summer flow rates, their flow rate distribution patterns differed across the summer months (Figure 6). In the modified crop succession scenario, the flow rate was lower toward the beginning of the irrigation period (May and June) because of increased withdrawals (Figure 6b) for wheat, which starts earlier than maize. The effect on flow rates was clearly stronger in July and August because there is less maize to be irrigated and therefore less water withdrawn from the rivers (Figure 6). In the irrigation efficiency scenario, flow rates appeared to be more constant during the summer, probably because irrigation levels were constantly adapted to meet the maize's needs, resulting in less drainage stemming from overirrigation and less water withdrawn from the rivers in comparison to the benchmark scenario. In the combined scenario, spring flow dynamics resembled those in the modified crop succession scenario, since more land was covered by wheat. However, flow rates experienced a greater boost in July, August, and September because significantly less water was withdrawn since less land was dedicated to maize and the remaining maize was irrigated in an optimized manner. Thus, combining the two approaches significantly increased flow rates more than either individual approach alone (Figure 7).

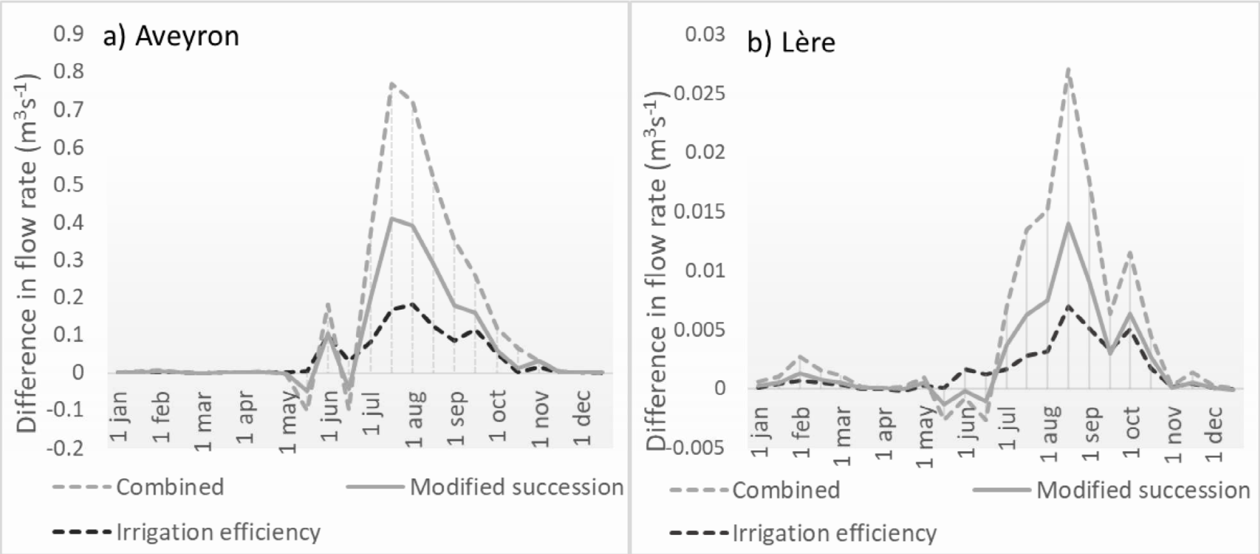

Figure 6. Differences in the biweekly flow rates between the benchmark scenario and each alternative scenario for the a) Aveyron River and b) Lère River.

3.3.4 *Low-flow target and water restrictions*

For almost every year of the study period, the three alternative scenarios slightly reduced the number of days with flow rates below the low-flow target (Table 2), the threshold that can trigger withdrawal restrictions. The irrigation efficiency and combined scenarios reduced this metric slightly more than did the modified crop succession scenario. For the Aveyron, the number of below-target days declined by 7%, 6%, and 11% for the irrigation efficiency, modified crop succession, and combined scenarios, respectively. For the Lère, the percent decrease was 5%, 2%, and 3% in the same respective order. The effect was more pronounced for the Aveyron than for the Lère, likely because the fields most affected by the scenarios are more commonly found in the former's basin.

Finally, in all three alternative scenarios, the volume of reservoir releases from various locations within the watershed (see Supplementary Materials B) dropped since demand for irrigation water was reduced overall and flow rates during the low-water period were improved. Taking the mean for the four main reservoirs over the entire study period, the percent reduction in release volume was 15% (range: 0–35%), 17% (range: 1–36%), and 22% (range: 0–45%) for the irrigation efficiency, modified crop succession, and combined scenarios, respectively (see Supplementary Materials B). There was marked variability in release volumes because of geographical and administrative differences among the reservoirs.

Table 2. Number of days between June 15 and September 15 with flow rates below the low-flow target for the benchmark scenario compared to the three alternative scenarios. The values shown for the alternative scenarios are the differences from the benchmark scenario.

Year		Aveyron				Lère				
	Benchmark		Irrigation efficiency	Modified crop succession	Combined	Benchmark		Irrigation efficiency	Modified crop succession	Combined
2007	1	vs.	-1	-1	-1	42	vs.	-3	0	-1
2008	20		-2	-1	-3	32		-2	-2	-2
2009	56		-3	-1	-5	67		-3	-2	-3
2010	56		0	-1	-1	52		-2	-2	-3
2011	69		-8	-2	-9	46		-1	-1	-1
2012	58		1	-4	-3	54		-1	-1	-3
2013	13		-3	-4	-4	36		-1	1	1
2014	1		0	0	0	16		0	1	-1
2015	46		-6	-4	-8	33		-1	1	1
2016	28		-3	-2	-4	54		-2	-2	-2
Overall	**348**		**-25**	**-20**	**-38**	**432**		**-16**	**-7**	**-14**

4 Discussion

4.1 *All three alternative scenarios improved watershed water management*

The three alternative scenarios that we modeled improved water management by reducing the overall water deficit in the watershed. The deficit decreased by around 30% in both the irrigation efficiency and the modified crop succession scenarios and by up to 50% in the combined scenario. There were also slight improvements to river flow rates, an key contributor to efforts to preserve aquatic biodiversity (Bunn and Arthington, 2002). It is striking that implementing just one change to farming practices (i.e., either irrigating maize as needed or shifting to wheat/maize successions) could help eliminate nearly one-third of the current water deficit. Combining the two changes reduced the water deficit by half and seems to be a better overall approach to optimizing water usage in the watershed. The effects are not necessarily additive since it is not possible to systematically apply both practices to a given field (e.g., in a wheat/maize succession, the wheat cannot be optimally irrigated).

The alternative scenarios reduced withdrawals, by 18%, 15%, and 28% for the irrigation efficiency, modified crop succession, and combined scenarios, respectively, and slightly boosted river flow rates during the low-flow period. Thus, our simulations showed that the reduced drainage levels attributable to the alternative management strategies did not have negative effects on flow rates. This reduction in drainage can be explained at the field level: the soil was drier in the late summer because the wheat fields were irrigated earlier in the season and the maize fields received optimized irrigation. It is interesting to note that the two individual scenarios yielded relatively similar results, even though there was a two-fold difference in the surface areas affected: 6,400 ha in the case of the irrigation efficiency scenario and 2,800 ha in the case of the modified crop succession scenario. Our findings indicate that irrigating grain and silage maize on an as-need basis with the help of a decision-support tool could help limit withdrawals and ensure higher river flow rates in the summer, while having very little impact on yield; in some cases, there may even be a slight improvement (see Supplementary Materials C). Indeed, new techniques are increasingly used by advisors to optimize the efficiency of allocated irrigation water, so as to give the highest crop production with the least water use. The use of a tensiometer probe to evaluate the level of soil water deficit combined with a decision support tool, such as MODERATO for example, improves irrigation schedules according to maize crop needs (Bergez et al., 2002). These results are consistent with those of García-Vila and Fereres (2012), which showed that using irrigation levels slightly below full irrigation requirements (i.e., -16%) allow yield to be maintained. However, it is important to note that this effect of improving irrigation efficiency is dependent on current irrigation efficiency in our case-study and on the capacity of MAELIA to simulate irrigation withdrawals. As we showed that MAELIA well reproduces levels and interannual variation of observed annual withdrawals, we can conclude that, in our case study, there is an over-irrigation and so increasing irrigation efficiency is a relevant option to reduce the water deficit in this watershed.

The results for the modified crop succession scenario demonstrated that replacing maize monocultures by a wheat/maize succession had a relatively large effect on irrigation withdrawal volumes even if a relatively small surface area was affected by this change.

The findings we obtained with the irrigation efficiency and modified crop succession scenarios are consistent with those of a study on a water-deficient watershed in China (Yan et al., 2015). The researchers evaluated a scenario in which regulated deficit irrigation was used to grow maize (a scenario resembling that in our study); this approach reduced maize water demands by about 20%. The researchers also implemented a scenario in which a specific crop succession was adopted to reduce amounts of maize (like in our modified crop succession scenario); the scenario’s wheat-maize-maize succession required 12% less water (water needs declined even further if maize was completely eliminated from the crop succession). The conclusion was that these scenarios can improve water management, eliminating up to two-thirds of the water deficit without hurting agricultural production (Yan et al., 2015).

Given the difficulty of implementing the proposed practices in all the fields where they could potentially be used, we expect that only an intermediate level of change could be achieved. One way to maximize the adoption of these strategies is to make them more appealing to farmers. For example, in watersheds where regulatory restrictions are frequently applied, there would be an impetus to plant crops with lower water needs in some fields if it ensured that farmers had access to water to properly irrigate more profitable crops (García-Vila and Fereres, 2012).

Despite these challenges, our multifarious results obtained at different scales can guide regional stakeholders and water resource managers who wish to develop integrated land management strategies adapted to local conditions.

4.2 *Farm-scale economic evaluations are needed*

An important future direction for this work is to evaluate the economic impacts of the three alternative scenarios. For the irrigation efficiency scenario, there were negligible impacts or even slight improvements to maize yields. Furthermore, water management decision-support tools are inexpensive, supporting the economical acceptability of this scenario (Allain et al., 2018). Several studies have found that irrigation optimization has little impact on yield and profitability. For example, Playán and Mateos (2006) concluded that properly implementing irrigation efficiency strategies can do more to boost economic performance than improvements to irrigation structures.

In contrast, replacing maize monocultures with a wheat/maize succession can decrease farm income by 9% (ibid.). To compensate for economic losses, it could be useful to deploy agroecological practices such as cover crops, which can provide a suite of ecosystem services with multiple agricultural and societal benefits (Duru et al., 2015; Wezel et al., 2014; Zhang et al., 2007). Economic losses could also be circumvented by introducing other crops, especially those with a high added value, into the crop successions. To subsidize the incorporation of more agroecological practices, farmers could receive remuneration for the ecosystem services their farms deliver to society (Redford and Adams, 2009).

It is also important to underscore that the three alternative scenarios led to an approximately 20% decrease in reservoir release volumes. The latter represent a significant cost for regional governments (Debril and Therond, 2012). Indeed, Thuriès and Pareloup are hydroelectric dams operated by the main French electricity company (EDF). Thus, any water released from the reservoirs to maintain river flow rates must be purchased by public authorities at a rate of €0.049/m^3 (i.e., cost in 2016). Consequently, the three alternative scenarios resulted in an overall reduction in reservoir release volumes of 2.4 to 3.6M m^3, depending on the specific scenario (see Supplementary Materials B), which amounts to €120,000–180,000 in savings.

4.3 *MAELIA modeling delivered satisfactory results*

MAELIA modeling has advantages, as well as certain limitations. For example, we observed that our simulations tended to slightly underestimate withdrawal volumes and flow rates, mainly outside the low-flow period. However, overall, the model was successful in recreating observed results, which supports its usefulness for comparing the performance of current and potential agricultural practices. Our evaluation of MAELIA modeling performance was carried out using a new dataset that runs through 2016. Our findings strengthen and support the results of earlier studies (Martin et al., 2016; Murgue et al., 2016).

A key advantage of MAELIA models is that they can be developed for different, contrasting French watersheds. With some adjustments, the type of model we employed can be adapted to represent most of the constraints found in watersheds, namely those related to soils, climatic conditions, water management strategies, cropping systems, and water use regulations. MAELIA is thus a very powerful tool that should be deployed to explore how this study's scenarios might play out in other regions of France.

4.4 *Broader implications for other watersheds, practices, and environmental issues*

Our findings are exclusively applicable to the downstream Aveyron watershed, which has specific climatic conditions (e.g., levels of precipitation and evapotranspiration), soil types, cropping systems (e.g., crop succession types and crop management practices), and hydrology. It would be interesting to see the results produced by our three alternative scenarios in other watersheds, to assess how general our conclusions are. Furthermore, our study watershed already experiences large water deficits, where particularly dry years can lead to numerous irrigation restrictions. Under climate change, such years are predicted to increase in frequency, and water management problems will become more pronounced (see the introduction). Consequently, we must identify solutions, such as these three alternative scenarios, in order to reduce withdrawals, an essential task if we are to preserve water resources and agricultural systems. Since the three alternative scenarios reduced water percolation, they could have a negative influence on deep water infiltration and groundwater recharge. However, aquifer water quality must also be considered. For example, if the water in the system has lower levels of nitrates and plant protection products, then it might be environmentally beneficial to trade off groundwater recharge quantity for water quality. Moreover, the positive impacts of these scenarios should be enhanced via complementary agroecological practices that provide environmental benefits, such as cover crops or legume-based crop diversification (Constantin et al., 2012; Gregorich et al., 2001; Poeplau and Don, 2015; Tonitto et al., 2006; Tribouillois et al., 2018a). The next step would be to incorporate nitrogen levels into the model, which could be accomplished via the AqYield-N module (Tribouillois et al., 2020), for example. This addition would allow us to analyze how the three alternative scenarios affect nitrate leaching and thus water quality in the watershed. Finally, incorporating carbon storage and greenhouse gas indicators would also make it possible to comprehensively assess the scenarios' environmental impacts.

5 Conclusion

In this study, we demonstrated the usefulness of a multiagent integrated modeling platform that can conduct simulations at fine levels of spatial and temporal resolution. We used this tool to explore how shifts in agricultural practices could affect agrohydrological conditions in the downstream Aveyron watershed, which often experiences large water deficits. By either optimizing maize irrigation efficiency or replacing maize monocultures with a wheat/maize crop succession, it was possible to reduce annual irrigation withdrawal volumes and eliminate around 30% of the watershed's current water deficit; up to 50% of the deficit could be eliminated by combining the strategies. Furthermore, in the combination scenario, there were additive effects: withdrawal volumes declined by 28%, and river flow rates increased by 4%. Given the concurrent challenges of water scarcity and climate change that we are facing at present, it behooves us to adopt solutions that combine several water management practices. If farms are to implement need-based irrigation, they must also equip themselves with a decision-support tool or with probes to estimate the maize's water stress in real time. Therefore, it is more a question of improving the current system's efficiency, which entails few changes in maize management and thus constrains farmers less. Replacing maize monocultures with wheat/maize successions would affect a smaller agricultural surface area, but it would require more profound changes in cropping systems, which may have economic impacts for farmers. However, this scenario represents a first step toward crop diversification and puts farmers on a more agroecological path. It might be possible to compensate farmers for any economic losses with payments for ecosystem services. Expanding on this line of thought, it would be interesting to explore the implementation of more ambitious agroecological practices, like the incorporation of cover crops and/or greater succession diversification, in addition to looking at the scenario's impacts on nitrate leaching, GHG emissions, and/or carbon storage.

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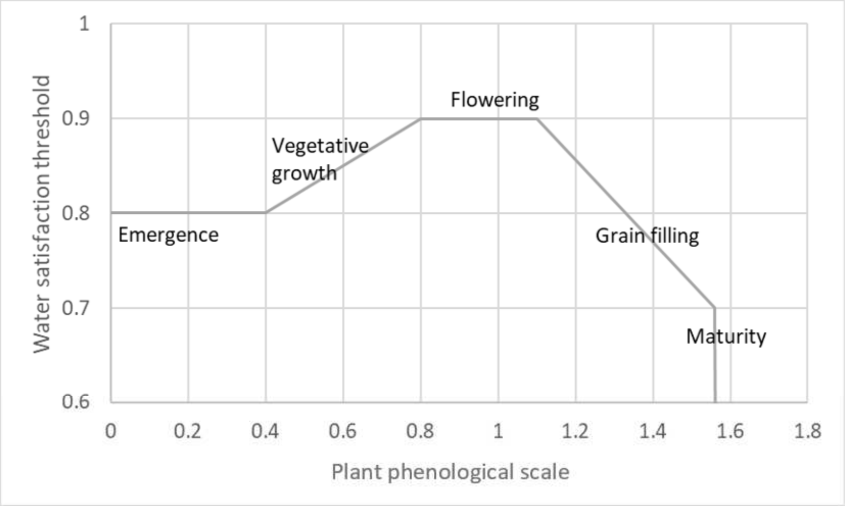
Supplementary Materials A



The water satisfaction threshold as a function of plant phenological stage

Supplementary Materials B

Reservoir release volumes (m^3) for the watershed's four dams in the benchmark scenario versus the three alternative scenarios (% difference); the abbreviations are as follows: BM = benchmark scenario, IE = irrigation efficiency scenario, MCS = modified crop succession scenario, and CB = combined scenario

	Pareloup				Thuriès				Saint-Géraud				Les Falquettes			
Year	BM	IE	MCS	CB	BM	IE	MCS	CB	BM	IE	MCS	CB	BM	IE	MCS	CB
2007	0	-	-	-	15,849	-100%	-100%	-100%	0	-	-	-	800,000	0%	0%	0%
2008	0	-	-	-	770,000	0%	0%	0%	2,688,748	-24%	-19%	-41%	698,484	1%	-3%	0%
2009	468,089	-100%	-100%	-100%	770,000	0%	0%	0%	7,500,000	-4%	-8%	-15%	800,000	0%	0%	0%
2010	1,893,538	-35%	-42%	-66%	770,000	0%	0%	0%	7,500,000	0%	0%	0%	788,948	-1%	0%	-1%
2011	3,500,000	0%	0%	0%	1,100,000	-21%	0%	-30%	8,313,731	-10%	-7%	-10%	800,000	0%	0%	0%
2012	3,241,460	-40%	-37%	-58%	770,000	0%	0%	0%	7,500,000	0%	0%	0%	800,000	0%	0%	0%
2013	0	-	-	-	770,000	0%	-2%	-9%	374,287	-44%	-77%	-100%	800,000	0%	0%	0%
2014	0	-	-	-	0	-	-	-	0	-	-	-	659,004	-5%	-3%	-3%
2015	0	-	-	-	770,000	0%	0%	0%	2,691,686	-19%	-27%	-37%	800,000	0%	0%	0%
2016	1,070,564	0%	0.2%	0.2%	770,000	0%	0%	0%	5,451,314	-3%	-9%	-11%	800,000	0%	0%	0%
Mean	1,017,365	-35%	-36%	-45%	650,585	-13%	-11%	-15%	4,201,977	-13%	-19%	-27%	7,746,436	0%	-1%	0%

Supplementary Materials C

Effects of the benchmark (BM) and irrigation efficiency (IE) scenarios on the yields of different maize varieties; the percent difference is for the IE scenario compared to the BM scenario; * = the area-weighted effect across varieties

	Very early maize	Early maize	Mid-early maize	Mid-late maize	Late maize	Very late maize	Mean
BM yield (t.ha^{-1})	6.1	4.8	5.6	8.5	10.9	10.7	7.8
IE yield (t.ha-1)	6.1	4.8	5.6	8.4	10.7	10.4	7.7
Difference (%)	-0.6%	-0.6%	-0.9%	1.4%	2.3%	2.5%	+0.7%
Area covered (ha)	49	168	288	1352	1035	323	***+1.5%**