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Highlights:

- We present an agro-hydrological catchment model considering small reservoirs
- Catchment elements (reservoir, plot, stream reach, etc.) are explicitly represented
- The model satisfactorily simulates hydrological and agricultural variables and fluxes
- Local and cumulative impacts of small reservoirs are simulated
- One of the goals of the model is to gain insight into the causes of the impacts

Abstract: Small-reservoir development is a challenging issue in agricultural catchments facing water scarcity. An integrated, new and original agro-hydrological model considering small reservoirs, MHYDAS-Small-Reservoirs, is presented. The model explicitly represents relevant spatial scales (plot, small-reservoir, stream reach, groundwater, and catchment scales) and the agronomic and hydrological links between these scales at which agriculture-hydrology interactions occur. After numerical verification, the model is evaluated by applying it to a 19-km² catchment. The model satisfactorily simulates the annual stream runoff (within 6%) and daily stream runoff (Nash efficiency=0.47) but tends to overestimate the crop yield (+21%). Simulations, one under actual basin

conditions and one under virtual conditions, were carried out. This highlighted the potential of the model to predict the local and cumulative impacts of small reservoirs. Hence, MHYDAS-Small-Reservoirs is a promising model for land use planning and water management of agricultural catchments containing small reservoirs.

Keywords: small reservoirs, crop, plot, farmer decisions, agricultural water management

Introduction

The frequency of droughts has been increasing worldwide in many arid and semi-arid regions (East Asia, Africa, Australia, and the Mediterranean basin) and temperate regions, such as Western Europe (Spinoni et al., 2013). Drought occurrences may increase in the future due to climate change (Sheffield and Wood, 2008) and anthropogenic pressures on water resources (Vörösmarty et al., 2000). Droughts induce severe consequences notably on hydrology and agriculture (Van Loon, 2015, Malakoff and Sugden, 2020). In agricultural catchments, small reservoirs are considered by water managers and farmers as a potential way to adapt agricultural practices to drought occurrences (e.g., Rodrigues et al., 2012; Malveira et al., 2012; Albergel et al., 2005; Essegbey et al., 2012). Previous global studies have shown the often-overlooked potential of small water storage to increase water and food security. Small water storage or a soft-path approach would avoid the construction of large, capital intensive, and environmentally damaging water infrastructure. Previous studies estimated that irrigation with small reservoirs can globally feed an additional 800 million people under current climate conditions (Rosa et al., 2020a) and an additional 300 million people under a 3°C warmer climate (Rosa et al., 2020b). Most of these studies are global and cannot account for many local site-specific variables.

Small reservoirs are reservoirs whose storage capacity does not exceed 10^6 m^3 (Habets et al., 2018). By intercepting and storing surface, subsurface and stream runoff during high-flow periods, they constitute an alternative water resource for crop irrigation purposes during drought periods. As a consequence, the number of small reservoirs has multiplied in recent decades in many regions worldwide, and their spatial density may exceed 5 small reservoirs per km² (Habets et al., 2018). However, the increase in small reservoirs may impose antagonistic impacts. As a positive effect, small reservoirs represent an alternative resource required to maintain crop yields (Biemans et al., 2011; Wisser et al., 2010). As a negative effect, each small reservoir may have a local hydrological effect on its nearby environment, such as by modifying the groundwater-surface exchanges or reducing the stream flow. The reservoirs taken as a whole (the reservoir network) may also induce a cumulative effect. Hydrological modifications, especially local modifications, may induce ecological, biogeochemical and geomorphological disturbances in catchments and the ecosystems they support (Habets et al., 2018).

Small reservoirs in an agricultural catchment enhance the interactions between hydrology and agriculture, particularly through crop water needs and farmers' decisions on crop management and water withdrawals for irrigation (Figure 1). The elucidation and prediction of the hydrological and agricultural impacts of small reservoirs require the articulation of the different spatial scales involved in these interactions:

i. the agricultural plot, where farmers decide cropping practices, where crop growth occurs and where water is partitioned between evaporation, transpiration, runoff and infiltration

ii. the small reservoir, which, on the one hand, is related to its upstream hydrological drained area and downstream catchment area and, on the other hand, to each irrigated plot

iii. the catchment, which integrates hydrological effects, especially those on stream runoff and groundwater.

These different scales are linked by hydrological processes (surface runoff, stream runoff, groundwater recharge, etc.) and crop and agricultural water management operations (water withdrawal operations from reservoirs and irrigation applications).

Numerical modelling is a widely adopted approach to better understand and predict small-reservoir impacts. Most of the models dedicated to this aim are based on hydrological catchment models. Among these hydrological models, few explicitly consider the plot scale at which management operations are conducted. The spatial representation of reservoirs can be explicit (Deitch et al., 2013; Nathan et al., 2005), statistical (e.g., Çetin et al., 2009; Güntner et al., 2004; Nathan et al., 2005; Zhang et al., 2012) or global (e.g., Habets et al., 2014; Perrin et al., 2012; Tarboton and Schulze, 1991). The explicit spatial representation has the advantage of simulating both local and cumulative hydrological impacts of the reservoir networks (Deitch et al., 2013; Nathan et al., 2005). Regarding the representation of crop growth, very few models couple crop and hydrological models (e.g., Neitsch et al., 2011; Therond et al., 2014). Most models simply represent crop growth through functional parameters (e.g., leaf area and crop development coefficient) or forcing variables (transpiration fluxes), while other models neglect this aspect. The interaction between crop growth and hydrological processes is thus not considered. Water withdrawal from reservoirs and the irrigation amount applied to crops can be modelled depending on both crop water requirements and water availability (Murgue et al., 2014; Neitsch et al., 2011). However, certain models consider constant irrigation amounts over given periods (e.g., Hughes and Mantel, 2010), while others do not consider crop irrigation (e.g., Rousseau et al., 2013). With the exception of very few catchment models (e.g., Therond et al., 2014), farmer decisions on crop and agricultural water management are not represented in catchment models dedicated to agricultural catchments containing small reservoirs. Finally, to our knowledge, very few, if any, of these models simultaneously consider the various spatial scales (plot, reservoir, and catchment), the water dynamics in small reservoirs in relation to water withdrawals and the agronomic and hydrological links between these scales at which agriculture-hydrology interactions occur.

We developed a new distributed agro-hydrological model named MHYDAS-Small-Reservoirs. This model is designed for agricultural catchments containing small reservoirs dedicated to irrigation. It simulates the interactions between the hydrological behaviour of the catchment, crop growth and farmer decisions related to the management of crops and reservoirs. MHYDAS-Small-Reservoirs is based on the coupling of three already proven models: i) the catchment-scale distributed MHYDAS hydrological model (Moussa et al., 2002), ii) the plot-scale crop model AqYield (Constantin et al., 2015) that includes yield calculation and iii) a plot and reservoir-scale farmer's decision model (Murgue et al. 2014), without any name, that represents the farmer decisions related to crop and water reservoir management. The latter two have already been used in a water management model, Maelia, (Therond et al., 2014), which has been applied to water resource catchments of 1000-10,000 km^2 with reservoirs dedicated to irrigation (e.g., Aveyron catchment in France, Allain et al., 2018). The spatial representation used for MHYDAS-Small-Reservoirs combines landscape objects (e.g., plot, reservoir) at the catchment scale and is based on that of MHYDAS, fully described in Lagacherie et al (2010). This representation proves to be particularly effective for simulating surface hydrology (e.g., Hallema et al.,), erosion (e.g., Gumière et al., 2011) or pesticide transfer (e.g., Bouvet et al., 2010) in small to medium agricultural catchments. The main novelty of this model is thus the explicit representation of the relevant spatial scales (plot, reservoir, and catchment) and the links between these scales involved in hydrology-agriculture interactions. MHYDAS-Small-Reservoirs is intended to be used in catchments of 10-100 km^2 to understand and estimate the local and cumulative effects of small reservoirs on the hydrology of catchments, especially stream runoff, and on crop production.

The objective of this paper is fourfold. First, it describes the principles of MHYDAS-Small-Reservoirs in terms of catchment spatial segmentation and the modelling of hydrological processes, crop growth and farmer management practices of crops and reservoirs. Second, it demonstrates the numerical and computing consistency of the model. Third, it demonstrates the capacity of the model to represent the hydrological and agricultural functioning of an agricultural catchment containing small reservoirs, via an application to a real case study (the Gélon catchment, France). Fourth, it investigates the feasibility of model application in the examination of the hydrological and agricultural impacts of catchment situations in terms of the density of reservoirs dedicated to irrigation.

1. Model description

1.1 Spatial segmentation

The catchment is segmented in spatially homogeneous units according to the principles adopted for MHYDAS model representation (Moussa et al., 2002) and fully described and discussed in Lagacherie et al. (2010), as shown in Figure 1.

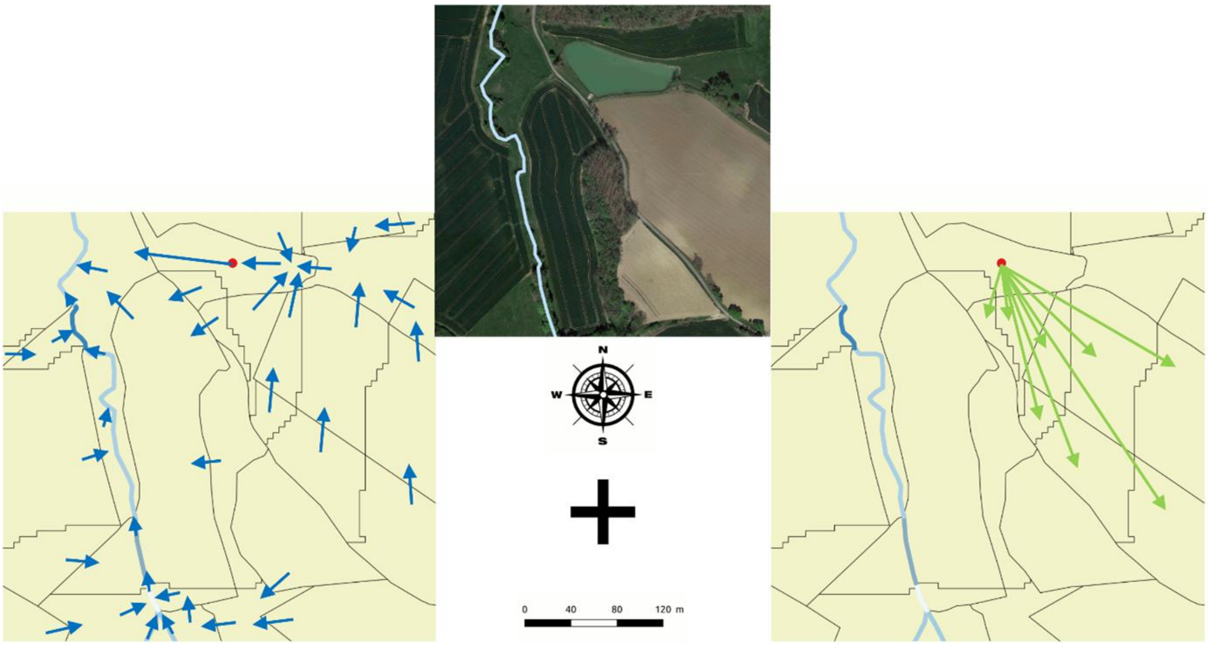

Figure 1: Spatial segmentation of the MHYDAS-Small-Reservoirs model. Top: satellite view of a catchment area including one non-connected reservoir used for irrigation, agricultural plots and hydrographic network (blue line). Bottom: spatial segmentation in MHYDAS-Small-Reservoirs of this catchment area. The polygons delimited by the black lines are entire or partial plots called surface units (SUs). The blue lines represent the reach segment units (RSs). The red dot indicates a non-connected reservoir unit (RE). The water transfer between plots is indicated by arrows. Water transfer is the result of hydrological processes (the hydrological links are marked in blue in the left map) or water withdrawal to irrigate crops (the agronomical links are marked in green in the right map).

Four spatial unit types, corresponding to the physical elements of a catchment, are explicitly represented in MHYDAS-Small-Reservoirs (Figure 1):

- The surface unit (SU) represents a homogeneous spatial entity in terms of its properties (soil and land use) corresponding to one sub-part of a real plot with a uniform water flow direction. Therefore, depending on the topography, a real agricultural or non-agricultural plot may be represented in the model as a unique SU or several SUs. The SU boundaries are determined by overlapping three geographical layers: the plot map, the flow direction map derived from the topography and the soil map (Lagacherie et al., 2010). An agricultural SU is dedicated to crop cultivation and can be irrigated. Non-agricultural SUs are plots with non-cultivated vegetation, such as forests, moors or natural pastures, or non-vegetated plots (e.g., urban areas, bare rock areas, and sand areas).
- The water reservoir unit (RE) represents a reservoir that can eventually be used for irrigation. The RE directly connected upstream to a certain reach of the hydrographic network is hereafter called a connected RE. This type of RE is filled by surface runoff from upstream SUs, stream runoff from upstream RSs, and direct rainfall. In some countries, a minimum flow prescribed by environmental regulations has to be released downstream. The RE not connected upstream to a reach is hereafter called a non-connected RE. Unlike a connected RE, a non-connected RE is not filled by stream runoff from upstream RSs, and a minimum flow has not been prescribed to be released downstream.
- The groundwater unit (GU) represents a hillslope shallow aquifer characterised by a subsurface saturated flow following the structure of the hydrological catchment. Each GU is therefore derived from the topography considered to identify the flow direction. Each GU discharges in a single specific reach segment (RS).
- The reach segment unit (RS) represents a section of the hydrographic network between water sources, confluence points, and connected RE or SU boundaries. RSs are connected to comprise the hydrographic network. An RS can be used for irrigation purposes.

These four spatial unit types differ in their shape and geometrical properties (Table 1). SUs and GUs are polygons whose boundaries are fixed based on the topography and anthropogenic discontinuities (plots, vegetation cover, etc.). RSs are linear elements, while REs are represented by points.

Table 1: Main geometrical properties of the spatial unit types in MHYDAS-Small-Reservoirs. The flow distance between any two units corresponds to the distance between the centroids of these two units.

	Surface Unit (SU)	**Reservoir Unit (RE)**	**Reach Segment Unit (RS)**	**Groundwater Unit (GU)**
Geometrical properties	Flow distance (m) Position (x,y,z) Slope (m/m) Area (m²)	Position (x,y,z) Volume capacity (m^3) Maximum water surface (m²) Volume-to-surface ratio (m^3/m^2)	Position (x,y,z) Slope (m/m) Length (m) Width (m) Height (m)	Position (x,y,z) Area (m^2)

These units are linked by two types of relations:

- Hydrological links correspond to the water flows caused by a hydrological process, such as surface runoff, stream runoff, drainage, and groundwater discharge. To establish a hydrological link between SUs, REs and RSs, it is assumed that surface water (surface and stream runoff) flows along the steepest slope to a downstream spatial unit (RE, RS or SU). Every GU is linked to its upstream SUs and downstream RS.
- Agronomic links correspond to the water transfer from a water resource (RE or RS) to an irrigated SU. A water resource can be linked to one or several SUs.

In the three following sections, the hydrological, crop growth and crop and agricultural withdrawal management models are described. The equations are shown for the new model developed specifically for the MHYDAS-Small-Reservoir model.

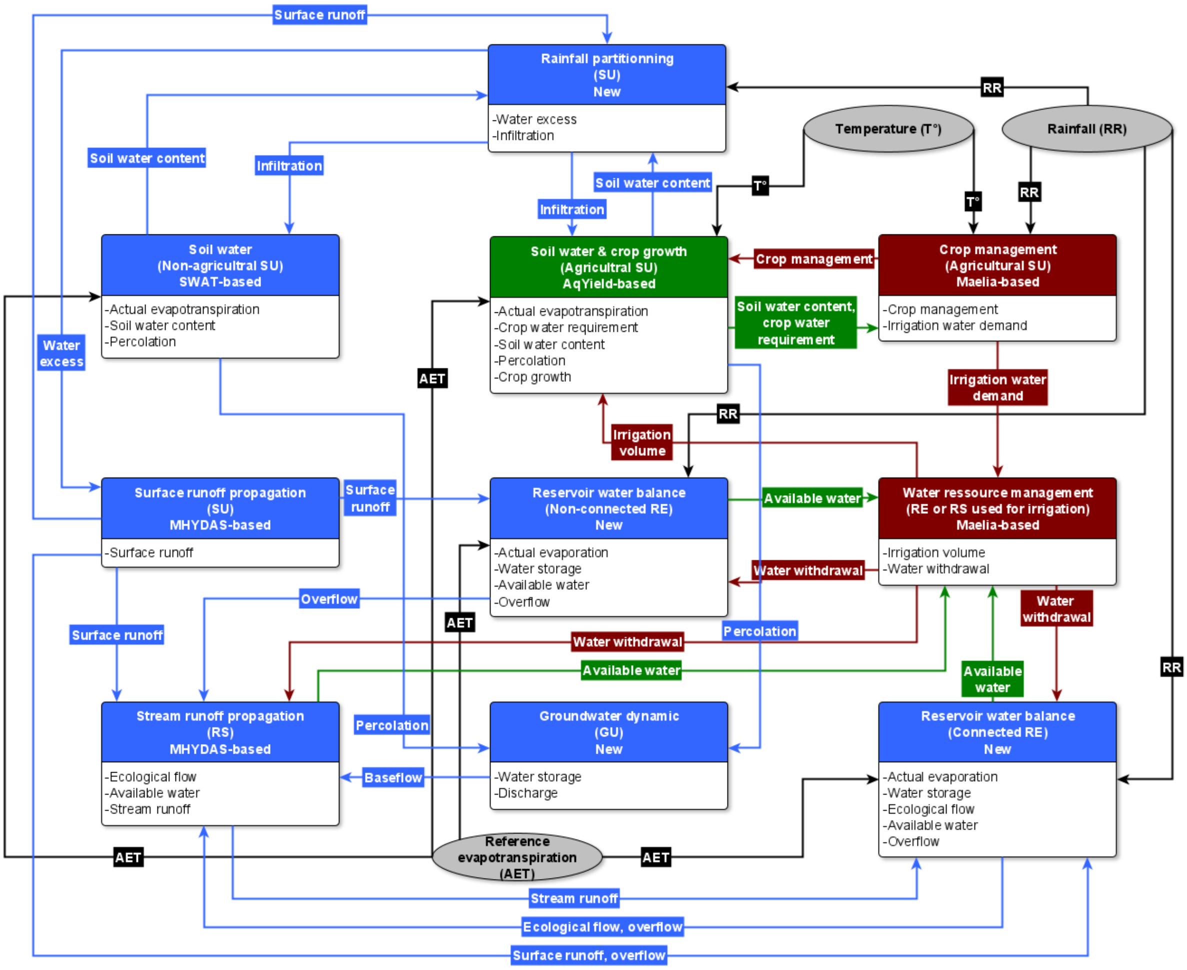

Figure 2: Diagram of the different components of the MHYDAS-Small-Reservoirs model (coloured boxes), simulated flows (black, green, blue or red lines) and state variables (grey circles). The black, blue, green and red arrows correspond to the exchanged variables between the model's components coloured according to their type of climate forcing variables, hydrological variables, agronomic variables and crop and water management variables, respectively. For each model, the simulated flows are listed in the corresponding box. The grey circles represent the input variables. The colour of the boxes indicates the type of model's component according to whether it is hydrological (blue), agronomic (green), or crop and water management (red)

1.2 Hydrological processes

The fluxes and state variables associated with the following hydrological processes are calculated for each spatial unit corresponding to one of the physical elements (SU, RS, RE, or GU) and at each time step. The time step can range from 1 s to 1 d for all simulated hydrological processes, except for the percolation and evapotranspiration of agricultural SUs, which are simulated at a daily time step.

1.2.1 Water excess, infiltration, percolation and soil water content

The water excess is the fraction of the water inputs (i.e., rainfall, irrigation or upstream runoff) that does not infiltrate and runs off along the soil surface. Infiltration is the water input fraction infiltrating into the soil. The water input distribution between infiltration and water excess is simulated by considering the soil infiltration capacity concept. The maximum infiltration rate is equal to the infiltration capacity. The soil infiltration capacity varies over time depending on the temporal variations in the soil water content. A power law is adopted to relate the soil infiltration capacity and soil water content:

$$f_p(t_i) = (I_{max} - K_s) * \left(\frac{SW_s - SW(t_i)}{SW_s - SW_r}\right)^{\lambda} + K_s$$

Equation 1

where f_p is the soil infiltration capacity (m/s), t_i is the current time index, K_s is the mean saturated hydraulic conductivity (m/s) over the full soil depth, I_{max} is the maximum soil infiltration capacity (m/s), SW_s and SW_r are the soil water storage capacities (m) considering the total soil porosity and the water-filled soil porosity at the residual water content, respectively, SW is the available water storage (m) and λ is a shape parameter (-).

In the soil, the percolation, evaporation and transpiration are considered the main drivers of the soil water dynamics. The soil water dynamics modelling differs between agricultural and non-agricultural SUs. In agricultural SUs, the soil is divided in three homogeneous layers, following the AqYield model formalisms (Constantin et al. 2015). The effect of tillage on soil is simulated by decreasing the water storage capacity of the top soil layer every day after the tillage. The soil water balance is calculated at a daily time step by simulating the soil water content, crop transpiration, soil evaporation and percolation. In non-agricultural SUs, Soil and Water Assessment Tool (SWAT) model formalisms are adopted, with the principle that percolation in soil occurs as soon as the soil water content exceeds the retention capacity (Neitsch et al., 2011). The soil is divided into several layers for which the water content is calculated by considering evapotranspiration, infiltration and percolation. These SWAT formalisms are adapted for use at the sub-daily time scale, as they are not very sensitive to time scale changes (Brighenti et al., 2019; Maharjan et al., 2013). Regardless of the type of the SU (agricultural and non-agricultural), the water flows downward from one layer once the soil water content in the layer reaches the soil water capacity. The simulated percolation flux along the soil base of any SU, whether agricultural or non-agricultural, contributes to the simulated recharge of the GU connected to the SU.

1.2.2 Surface and stream runoff

Surface and stream runoff are simulated with the diffusive wave equation solved by the Hayami kernel method assuming a unidirectional flow to represent runoff routing as described by Moussa and Bocquillon (1996). Surface runoff corresponds to the downslope propagation of the water excess. Surface runoff flows downstream from an SU to another SU, an RS or an RE, depending on the spatial segmentation. Stream runoff is simulated at every time step in every RS considering the upstream flow from any connected SUs, RSs, REs and GUs to the given RS. The simulated stream runoff from an RS or RE flows into either a downstream RS or downstream RE. Every ~~RS~~ connected RE or RS used for irrigation is characterised by a user-defined parameter called minimum flow used, denoted Q_{min} ($m^3.s^{-1}$), to model the withdrawals (see section 1.4.2 Management of the withdrawal from water resources). The minimum flow is a floor threshold introduced to represent the minimum flow imposed by water regulation laws to maintain the ecological quality of the stream. Any water withdrawal can be performed in the stream only if the stream runoff does not fall below this floor threshold.

1.2.3 Evapotranspiration

In regard to the agricultural SUs, the actual evapotranspiration (AET) is the sum of the actual crop transpiration and actual soil evaporation. The AET is calculated at a daily time step based on the soil surface water content, reference evapotranspiration (ET0), and soil clay content (Constantin et al., 2015; Therond and Villerd, 2020). The actual crop transpiration depends on the crop growth and soil water content (please refer to section 1.3, Crop growth). Regarding the non-agricultural SUs, the AET is calculated at each time step according to SWAT formalisms (Neitsch et al., 2011) based on ET0, soil characteristics (e.g., bulk density, wilting point, and thickness), soil water content and the fixed leaf area index depending on the given land use.

1.2.4 Groundwater recharge and stream baseflow

The groundwater unit (GU) recharge is the sum of the percolation fluxes from all the upstream SUs connected to the GU. The groundwater discharge from a GU to its connected reach stream (RS) is calculated with a power-law storage-discharge function (Kirchner, 2009) as follows:

$$Qb_{GU}(t_i) = A_{GU} * \left(Qref_{GU} * \left(\frac{S_{GU}(t_{i-1}) - Sref_{GU}}{a}\right)^{B}\right)$$

Equation 2

where Qb_{GU} is the GU discharge ($m^3.s^{-1}$); t_i and t_{i-1} are the current and previous time index, respectively; $Qref_{GU}$ is the reference specific discharge of GU ($m.s^{-1}$); A_{GU} is the surface area of GU (m^2); S_{GU} is the water storage in the GU by area unit (m); $Sref_{GU}$ is a reference water storage by area unit (m); and *a* (m) and *B* (-) are characteristic parameters of the GU.

The groundwater discharge from a GU to an RS represents the stream baseflow.

1.2.5 Water dynamics in reservoirs

The water volume dynamics in reservoirs are simulated at each time step based on a water balance. Inflows include i) the surface runoff from upstream SUs, ii) the stream runoff from upstream RSs to a connected RE and iii) the direct rainfall volume. The latter is calculated as the product of the rainfall rate and the reservoir maximum water surface. The infiltration through the reservoir bed is not considered. Outflows may include i) minimum flow, ii) overflow, iii) evaporation volume and iv) water withdrawal for crop irrigation.

$$V_{RE}(t_i) = \left(Q_{REup}(t_i) - Q_{REout}(t_i)\right) * (t_i - t_{i-1}) + R(t_i) * A_{REmax} - E(t_i) * A_{RE}(t_i) - W(t_i) + V_{RE}(t_{i-1})$$

Equation 3

where V_{RE} is the water volume of the reservoir (m^3); t_i and t_{i-1} are the current and previous time indexes, respectively; Q_{REup} is the runoff from the upstream spatial units (m^3.s^{-1}); Q_{REout} is the discharge released by the reservoir (m^3.s^{-1}); E is the evaporation over the time step (m); R is the rainfall over the time step (m); A_{REmax} and A_{RE} are the maximum surface area and the water surface area of the reservoir, respectively (m^2); and W is the withdrawal volume (m^3). Following the conclusion of numerous studies about reservoir evaporation (Lowe et al., 2009; McJannet et al., 2013;), the evaporation is assumed to be proportional by a factor k to the reference evapotranspiration, ET0, such as E=k.ET0.

The released discharge is simulated differently between the non-connected and the connected reservoirs. A non-connected reservoir is generally not equipped with a discharge control system and releases water only when it is full. Consequently, the released discharge is modelled as the water volume, $V_{REexceed}$, exceeding the reservoir storage capacity, such as $Q_{REout}=V_{REexceed}/(t_i-t_{i-1})$. When the water volume is lower than the storage capacity, the released discharge is simulated as zero. Following water regulation rules in some countries, a connected reservoir has to be equipped with a control system to release a minimum flow, considered an ecological flow. When the upstream runoff to the reservoir exceeds the minimum flow, a discharge equivalent to the regulatory minimum flow has to be released. When the upstream runoff is lower than the minimum flow, the equivalent of all the upstream runoff has to be released. In accordance to these regulatory and management rules, the released discharge for a connected reservoir, Q_{REout}, is simulated as follows:

Equation (4)

1.3 Crop growth

The crop growth is calculated only in agricultural SUs at daily time steps based on the principles of the AqYield crop model (Constantin et al., 2015). Crop growth, both aerial and root, controls crop transpiration and crop yield.

The crop aerial development is simulated using a crop coefficient representing foliar growth. Crop coefficient dynamics are a function of crop transpiration, development stage (phenology), and various parameters specific to a given species. Globally, the crop coefficient increases until the flowering stage and then declines until the harvesting stage. Crop development stages, particularly the flowering and maturity stages, are simulated based on the concept of growing degree days, with threshold values of the growing degree days and parameters specific to each species and cultivar precocity class.

The actual crop transpiration is calculated with an empirical function of the maximum transpiration and soil water available to roots. The maximum transpiration depends on the crop coefficient and ET0 minus soil evaporation. The soil water available to roots varies as a function of root growth. Root growth depends on the cumulative daily effective temperature, a species root-growth coefficient and a reduction coefficient linked to the soil structure.

The crop yield is calculated at harvest as a function of the potential yield, locally defined for a species or cultivar precocity class, and the water satisfaction index defined as the ratio of the actual crop transpiration to the maximum crop transpiration during the cropping season.

1.4 Crop and agricultural withdrawal management

1.4.1 Crop management

The model simulates farmer management decisions at daily time steps and for every agricultural SU. The decisions are related to several practices (tillage, sowing, harvesting and irrigation), but only one practice, respecting a given priority order, is operated each day. Technical interventions are simulated over a given user-defined period of the year. Within this window period, the exact dates of technical operations and amounts of water applied to crops are determined according to decision rules based on crop growth and development characteristics, soil type and water content, and weather conditions. These rules, the priority order between practices, and the window period for each practice and crop may be adjusted to the context via a user-defined set of parameters. The thusly simulated technical operations modify the other model variables. Tillage operations affect the soil structure and thus the soil water content capacity. The sowing and harvesting dates determine the start and end, respectively, of crop cycles. Irrigation decisions trigger water withdrawal operations from REs or RSs and influence the SU soil water content and thus the crop growth and crop yield. The irrigation demand by the farmer depends on the crop water requirement according to its development stage but also accounts for equipment constraints through a minimum delay between two irrigations.

Complementary to the presentation of Murgue et al. (2014), Appendix A details the simulation rules applied to farmer management decisions.

1.4.2 Management of the withdrawal from water resources

Management of water withdrawal for irrigation purposes is modelled at a daily time step for each water resource dedicated to irrigation, with RS being first withdrawn, then RE. This approach prioritizes stream water as a resource used for irrigation.

The total irrigation water demand on a given resource (RE or RS) is determined as the sum of the daily farmer's irrigation demand for all irrigable agricultural SUs linked to that resource. If the available water in the resource is larger than the total irrigation water demand, the water demand is satisfied by the water withdrawal, and the irrigation volume provided to each SU is equal to its demand. Otherwise, the withdrawal volume corresponds to the available water volume in the resource, and the irrigation volume applied to each SU is proportionally reduced compared to the water demands.

$$W(t_i) = min(V_{WR}(t_{i-1}) - V_{WRmin}\ ;\ \sum_{j=1}^{n_{SU}} IrrDem_j(t_i))$$

Equation 5

where W is the water withdrawal from the resource (m^3); V_{WR} is the water volume in the resource (m^3); V_{WRmin} is the minimum water volume (m^3) of the resource below which any withdrawal is never performed; t_i and t_{i-1} are the current and previous time indexes, respectively; $IrrDem_j$ is the farmer's water demand for SU_j (m^3); and n_{SU} is the number of SU irrigated from the water resource. The minimum water volume of the resource, V_{WRmin}, corresponds to the minimum flow, Q_{min}, multiplied by the daily time step or to a volume threshold, V_{REmin}, when the water resource is a stream reach (RS) or a reservoir, respectively. The volume threshold, $V_{REmin,}$ is the water volume below which water pumping is technically difficult and usually not performed due to high concentrations of sediments in the water. Similarly, the available water volume of the resource, V_{WR}, corresponds to the reservoir water volume, V_{RE}, and to the stream runoff, Q_{RS}, multiplied by the daily time step when the resource is a reservoir and a stream reach, respectively.

1.5 Computer implementation

The MHYDAS-Small-Reservoirs model was developed within the OpenFLUID platform (Fabre et al., 2020; Fabre et al., 2010). This platform facilitates model building by sequentially coupling blocks of code, called simulators, with each simulator supporting one of the main model functions. The OpenFLUID platform achieves the coupling of models via the exchange of simulation variables varying both in space and time. The overall structure of the spatial domain is managed using a graph where the nodes are the spatial units (here, SUs, RSs, GUs, and REs) and the edges are these relations between the above spatial units (hydrological or agronomic links). MHYDAS-Small-Reservoirs consists of 16 simulators described in Appendix B and considers a total of 40 variables. All simulators were written in the C++ language, which allows unit-oriented data entry (Jordan, 1990).

1.6 Input and simulated variables, parameters and initial conditions

The input variables are weather variables, namely, rainfall, ET0 and air temperature (Figure 2). The input variables are spatially distributed. The simulated variables per spatial unit type are shown in Figure 2. The parameters adopted in the equations and relations implemented in the simulators are listed in Appendix C. They correspond to either empirical values or functional properties of the spatial units. They can be either global (i.e., a unique and common value for all the spatial unit types) or spatially distributed (i.e., each spatial unit has its own value). The initial model conditions include the soil water content in all agricultural and non-agricultural SUs, the water level in each GU, and the volume of water stored in each RE, connected or not.

2. Materials and methods

2.1 Study area

The Gélon catchment was chosen for the application of the model, for the hydrologic year 2014-2015, for which most of the data required for model implementation and evaluation was available, notably the agricultural plot map.

2.1.1 General characteristics

The Gélon is a 19.8-km² catchment belonging to the Arrats catchment, which is a 620 km² sub-catchment of the Garonne River located in southwestern France in the Gers department (Figure 3). The outlet is located at 43°51'38"N-0°48'07"E. It is a hilly catchment with the elevation ranging from 110 to 193 m above sea level. The soils are mainly composed of alluvial and molassic slope deposits (Party et al., 2016). The lithology is globally impermeable, without a deep aquifer, which leads to a high density of the hydrographic network (Cavaillé and BRGM, 1968). The total length of the Gélon stream is 8 km. The oceanic climate of the catchment induces a rainfall of 675 mm, an ET0 level of 905 mm and a temperature of 13.5°C on average over the period from 1989-2016.

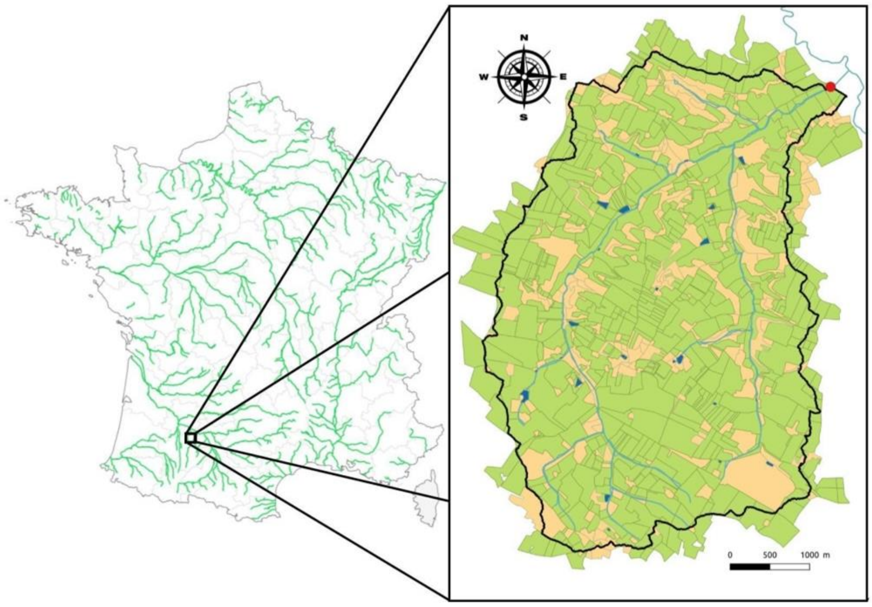

Figure 3: Location and map of the Gélon catchment. The agricultural and non-agricultural plots in the map are marked in green and yellow, respectively. The outlet is indicated by a red dot. The hydrographic network and small reservoirs are represented by blue lines and dark blue areas, respectively.

The Gélon catchment is mostly agricultural. The majority (75%) of the catchment area is devoted to agriculture, representing 585 cultivated plots (IGN, 2015). The remaining 25% (244 plots) comprises non-cultivated, urbanized or forested areas (MTES, 2012). The whole cultivated area is covered by annual field crops, and the main crops are straw cereals (mostly wheat, barley, triticale and oats) and sunflower (accounting for 41 % and 33 %, respectively, of the cultivated area in 2015). Maize, soybeans, peas, chickpeas, lentils, flax, market gardening (largely garlic, strawberry, butternut and onion), sorghum, rapeseed, and temporary and permanent grassland are also cultivated to a lesser extent in this region where organic farming is increasingly applied.

Most crops are rainfed (sunflower, permanent grassland and vineyard plots), some are systematically irrigated (mostly maize and soybeans), and others are irrigated only when weather conditions are particularly dry (straw cereals, temporary grassland, market gardening, rapeseed and orchards). Field surveys indicate that farmers generally irrigate their fields with an amount of 30 mm, except for rapeseed, which can be irrigated only once, at the sowing time, with half the amount (i.e., 15 mm). Irrigation occurs during the cropping season, namely, temporary grasslands are irrigated from April to mid-May, straw cereals from mid-May to mid-June, maize from mid-May to mid-September, market gardening from mid-May to mid-October, soybeans and orchards from June to September, and rapeseed in September.

The catchment contains 25 water reservoirs of varying capacities (100 to 30,000 m^3), 13 of which are used for irrigation, while the remaining 12 reservoirs, often smaller, have no current irrigation use following the change to non-irrigated crops or following the purchase of the land by private individuals who are not farmers. The 13 reservoirs are the only resource for irrigation water, i.e., in this catchment, no water is withdrawn from the river. There are no channel networks: the water is directly pumped from the reservoirs and distributed to the fields under pressure. Overall, 19 % of the agricultural area is irrigated, mainly by aspersion using 25-m travelling guns. The limited availability of irrigation equipment, the time required to install the equipment and the limited flow rate of the equipment result in a delay between two irrigations of 6 or 7 days depending on the crop.

2.1.2 Weather, pedological, agricultural and hydrological data

The weather variables were retrieved from the SAFRAN database of MeteoFrance (Durand et al., 1993), namely, the hourly rainfall and air temperature and daily ET0 calculated according to Penman's formula, at an 8 km x 8 km resolution. The map of the agricultural plots includes the land use at the field plot level and is available on a yearly basis from the French Land Parcel Identification System (IGN, 2015). Crop yield data are only available at the Gers department level (6,200 km^2) from data collected from agricultural cooperatives by public authorities (DRAAF Occitanie, 2020). No database provides information about the agricultural practices in the Gélon catchment, but specific surveys offer insights on the irrigation practices in the Gélon and Arrats catchments. The soil data were provided by the Référentiel Régional Pédologique, a French soil database (Party et al., 2016).

Stream discharge data at the Gélon outlet have only been available since 14/09/2018. We thus estimated the 2014-2015 discharge from the daily specific stream runoff data recorded at the closest station of the French station hydrometric network, assuming that both specific stream runoffs were equal. This assumption was carefully verified over the period 14/09/2018 to 13/09/2019 at a daily time step during which the discharge at both catchment outlets was monitored. The similarity was very high for 47% of stream runoff (i.e., between 0.086 and 1.0 mm/d) encountered in the Gélon catchment, with an r^2 value of 0.68 considering linear regression, an NSE_Q value of 0.53 and an NSE_{sqrt} value of 0.71 (Figure 4). The similarity was low for extreme stream runoff, lower than 0.086 mm/d (an r^2 value of 0.02) or higher than 1.0 mm/d (an r^2 value of 0.11).

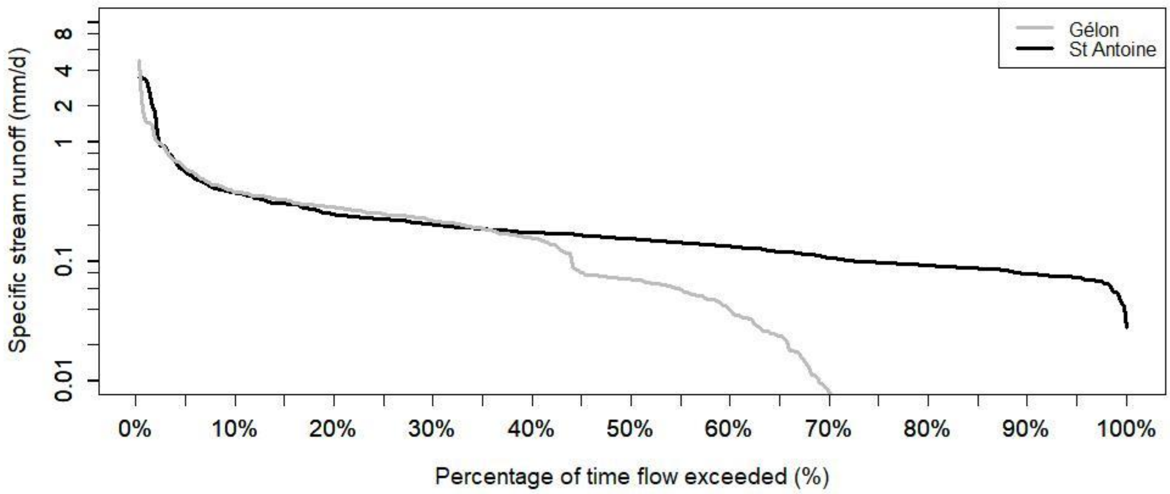

Figure 4: Flow duration curves for the Gélon and St Antoine stream runoff.

2.2 Model implementation

2.2.1 Spatial segmentation

Several geographic data sources (Table 2) were adopted to determine and characterise the geometrical properties of all spatial units of the Gélon catchment, resulting in 25 REs, 17 GUs, 365 RSs and 2402 SUs, 1666 of which are agricultural SUs.

Table 2: Sources of data considered for the segmentation of the Gélon catchment.

Data type	Data source	Spatial resolution
Topography	Digital elevation model (DEM) RGE ALTI 5 m (IGN, 2017)	5 m
Hydrographic network	BD Carthage (Agence de l'Eau et al., 2014)	10 m
Reservoir location and characteristics	Aerial view analysis (IGN, 2016) and in situ surveys	reservoir resolution
Map of the agricultural plots	Land Parcel Identification System (IGN, 2015)	plot resolution
Map of the non-agricultural plots	Land use inventory (MTES, 2012)	plot resolution

2.2.2 Parametrisation

As far as possible, the parameters corresponding to the functional properties (Appendix C) were determined from existing databases, measurements and in situ observations or retrieved from the literature.

Values of crop growth parameters were fixed based on previous studies. Indeed, these parameters were determined previously for several field crops in southwestern France and then validated for three rainfed and irrigated spring crops (sunflower, maize, and sorghum) (Constantin et al., 2015), for wheat on 14 experimental sites in France and for rotations on two sites in southwestern France (Tribouillois et al., 2018). We grouped crops into classes to limit the number of crop parameter sets, especially for minority crops. For example, the soybean class includes soybeans as the main crop but also peas, chickpeas, flax and lentils as minority crops. The soil texture and soil depth also used in the crop growth model are parameters derived from the French soil database (Référentiel Régional Pédologique, Party et al., 2016) by considering the dominant soil type in each SU. The soils of the agricultural SU show low variability (all clay-loam soils) and all belong to a single soil class. In addition, the three shape parameters of the SU infiltration capacity curve (Equation 1) not defined in the AqYield database, namely, I_{max}, K_s and □, were adjusted as detailed below. Two of the four parameters of the GU storage-discharge function were defined based on an analysis of Gélon outflow discharges during recession periods, while the other two, namely, parameters a and b of Equation 2, were fitted. A simple calibration of the outflow at the outlet of the Gélon was performed by considering 3 values for each of the 5 parameters to be fitted and by varying them one at a time. Thus, only 243 sets of parameters were then tested. The three values were chosen to explore a realistic range of variation by selecting the minimum and maximum values found in the literature and their arithmetic mean. The extreme values for the parameters of the SU infiltration curve were defined according to Mishra et al. (2003), Fernández-Pato et al. (2016), Party et al. (2016) and those for the GU storage-discharge function from Kirchner (2009).

2.2.3 Time step of the simulation

An hourly simulation time step was adopted for all the hydrological processes (blue boxes, Figure 2), except for those processes for which the formalism required a daily time step, as indicated in Section 1, namely, the water balance of agricultural plots as well as crop growth processes, and crop and agricultural water management operations (red and green boxes, Figure 2).

2.2.4 Climate input variables and initial conditions

Climate input variables, namely, rainfall, ET0 and air temperature were considered spatially uniform in the application of the model to the Gélon catchment. Due to the lack of data, all the initial conditions were set using a warm-up approach, consisting of a simulation over a period long enough to reach equilibrium (Kollet and Maxwell, 2008). In this study, we adopted the recursive simulation approach described by Ajami et al. (2014): the previous hydrological year from 2013-2014 was repeated 25 times with constant crop rotations. We verified that the equilibrium state was reached after these 25 year-long simulations by determining whether the annual simulated variations in water storage at a one-year interval were lower than 1% in 95% of the units of each type. This warm-up process was initiated considering a full saturation of the catchment, including a complete filling of the reservoirs to limit the spin-up time (Rahman et al., 2016).

2.3 Model verification

To verify the model, we considered virtual and real catchments and monitored i) each simulator, ii) the model determinism and iii) the conservation of water volumes. Furthermore, the computation time was also analysed.

2.3.1 Simulator testing

For each simulator, the agreement between the computer code and conceptual model was verified using simple test cases. The verifications were based on a comparison of the simulated and expected values of the variables, with the latter obtained from either algebraic equations or reference simulations. These tests also allowed us to evaluate the hydrological and agronomic links between all the units.

As an example, the combined testing of the irrigation decision and application simulators (Appendix C) allowed us to simultaneously verify the following:

- the identification of all the RE or RS dedicated to irrigation and the links between that water resource and the irrigable SUs,

- the consistency between the available water volume, water withdrawal volume, irrigation water demand and irrigation amount provided to crops, and
- the absence of withdrawal from a water resource not dedicated to irrigation.

2.3.2 Model determinism

Model determinism is guaranteed when identical simulations, repeated in the same computing environment with unchanged parameterizations, initial conditions and boundary conditions, result in exactly the same simulated values. A numerical test was performed on a sub-catchment of the Gélon catchment, modelled with 341 SUs, 112 RSs, 69 GUs and 13 REs, with one of the latter being dedicated to irrigation. The test was executed by repeating the same 5-year simulation 1,000 times, and we assessed whether the water volumes in the GUs, REs, and SUs and water fluxes in the SUs and RSs remained unchanged across the whole catchment.

2.3.3 Water volume conservation

Water volume conservation is an important criterion in hydrological model verification. We monitored the water volume conservation in MHYDAS-Small-Reservoirs at the daily resolution considering the whole catchment. In the case of perfect water volume conservation, the total volume of all simulated outflows from the catchment equals the total volume corresponding to the variation in the simulated water storage and all simulated inflows to the catchment. We monitored the water mass conservation level in the same real catchment as was adopted for model determinism assessment (section 2.3.2, Model determinism) at the daily time step, considering that the difference between the above two volumes should remain below 0.001% of the total inflow volume.

2.4 Model evaluation

Model evaluation determines the ability to simulate hydrological and agricultural functioning in a real case study. Basically, the evaluation relies on the comparison of simulated variables to available observed, or reference, data. As the primary intention in using MHYDAS-Small-Reservoirs is to quantify the cumulative effects of reservoirs on crop yields and on stream runoff at the catchment outlet, we chose these two variables to evaluate the model. The evaluation therefore followed two steps. The first step involved the evaluation of the model in the simulation of global variables corresponding to the annual fluxes across the entire catchment for which reference data were available for the case study. In the second step, the model ability to finely simulate the daily stream runoff was analysed using the Nash-Sutcliffe efficiency (1970) calculated as follows:

$$NSE_q = 1 - \frac{\sum_{i=1}^{n} (q_i^s - q_i^o)^2}{\sum_{i=1}^{n} (q_i^s - \bar{q}^o)^2}$$

where NSE_q is the Nash-Sutcliffe efficiency of the stream runoff, q^o_i is the reference stream runoff at the i^{th} time index, q^o is the mean reference stream runoff and q^s_i is the simulated stream runoff at the i^{th} time index. The closer the value is to 1, the higher the quality of the stream runoff simulation is. The efficiency considering the square root of the stream runoff, denoted as NSE_{sqrt}, was also calculated since it assigns a high weight to low values of the stream runoff when NSE_q is highly sensitive to high flows (Oudin et al., 2006; Pushpalatha et al., 2012).

When applying the model to the Gélon catchment, the efficiencies were calculated based on the daily stream runoff over the full hydrologic year of 2014/2015 starting on 1 September. The daily simulated stream runoff, q^s_i, was calculated as the sum of hourly simulated stream runoff for the i^{th} day. As we determined that the stream runoff data used as reference data were less reliable between June and October and for stream runoff below the threshold of 0.086 mm/d (cf section 2.1.2), we also calculated the efficiencies by considering those days when the stream runoff exceeded the above threshold, excluding the period from June to October.

2.5 Numerical explorations

The model was then applied to simulate, in the Gélon catchment, two situations that differed in terms of crop allocation and reservoir water management (Table 3). The objective was to analyse the capacity of the model to predict possible future conditions and assess the potential consequences of different policies in crop and agricultural water management strategies, as is commonly achieved in scenario exercises using models in water resource management (Leenhardt et al., 2012). The "Reference" situation represents the current state, as simulated for the 2014-15 hydrological year, which is compared to the second situation, named "All-RE". The All-RE situation was not designed to be realistic but for its illustrative potential. In this situation, we therefore assumed that all reservoirs of the catchment were used for irrigation purposes and that all agricultural SUs within a radius of 500 m around every RE were irrigated and cropped with maize, the most irrigated crop in the region. The All-RE situation thus differs from the Reference situation both in terms of number of reservoirs considered for irrigation and in terms of crops and cropping area.

Table 3: Reservoir and crop and irrigated area characteristics of the "Reference" and "All-RE" situations simulated with MHYDAS-Small-Reservoirs in the Gélon catchment

Situations	Reference	All-RE
Reservoirs	25 reservoirs, including 13 used for irrigation (164,300 m^3)	25 reservoirs (206,800 m^3) for irrigation purposes
Crop distribution	straw cereals (617 ha) sunflower (497 ha) maize (25 ha) soja (108 ha) other crops (142 ha) set aside (52 ha)	maize (1,067 ha) other crops (405 ha) set aside (21 ha)
Irrigated area	288 ha including: ● straw cereals (213 ha) ● soybeans (16 ha)	1,056 ha including: ● maize only

	• maize (14 ha) • rapeseed (7 ha) • sorghum (3 ha) • other crops (35 ha)	

3. Results

3.1 Model verification

3.1.1 Simulator testing, model determinism and water volume conservation

Testing of all the simulators was successful since the variables simulated with the model matched the expected values. The results are not presented but are available upon request. The model determinism was verified since the simulated variables in terms of the total water storage in the GUs, SUs and REs and water fluxes (surface runoff in the SUs and stream runoff in the RSs) were strictly identical for all 1,000 simulations. Water volume conservation in the simulations was also verified: at the annual scale, the error was lower than 0.0001 % of the inflow volume.

3.1.2 Computation time

The simulation was performed based on an Ubuntu Quad-Core microprocessor at 2.90 GHz, with 128 GB of RAM and a 32-bit CPU. The computation time reached 17 hours for a 26-year period in the Gélon catchment, with a display of the daily global variables in the whole domain and an additional display of all of the variables in each spatial unit (3 per RS and GU, 7 per RE and 30 per SU) for the last simulated year, which represents 4.7 Go.

3.2 Model evaluation

At the catchment level, the simulated stream runoff over the hydrological year of 2014/2015 is 102.8 mm (Table 4), which is only 6.4% higher than the reference stream runoff (96.6 mm). The efficiencies of NSE_q and NSE_{sqrtq} of the simulated daily stream runoff are 0.32 and 0.26, respectively. In regard to the days when the stream runoff exceeds 0.086 mm/d between November and May, when the reference stream data are considered reliable (please refer to section 2.4), the calculated NSE_q and NSE_{sqrtq} values are both 0.47. These values approaching 0.5 indicate that the model yields nearly satisfactory results not only for high flows, in terms of NSE_q (Moriasi et al., 2015), but also for low flows, in terms of NSE_{sqrtq} (Oudin et al., 2006). Over the period corresponding to these days, the simulated daily stream runoff matches the reference stream runoff well (Figure 5). During this period, the simulated cumulative stream runoff is 82.6 mm, which is 3.3% higher than the cumulative reference stream runoff (80.0 mm). According to Moriasi et al. (2015), an error of less than 5% is considered very good. On the basis of all the efficiencies and differences between the simulation and reference data, the model applied to the Gélon catchment yields acceptable or even good simulations of the hydrology.

Table 4: Catchment water balance terms simulated for the two situations of the Gélon catchment for the hydrologic year 2014/2015. The simulated AET, stream runoff at the outlet, irrigation and storage variation between the start and the end of the simulation period are expressed in mm. The rainfall and ET0, as input variables, are also indicated and expressed in mm. For irrigation, the value in brackets indicates the mean annual irrigation per irrigated plot area (mm).

Situations	**AET (ET0)**	**Rainfall**	**Stream runoff**	**Storage variation**	**Irrigation**
Reference	436.4 (960.7)	570.7	102.8	+31.5	4.2 ***(28.9)***
All-RE	473.9 (960.7)	570.7	97.0	-0.1	7.1 ***(13.3)***

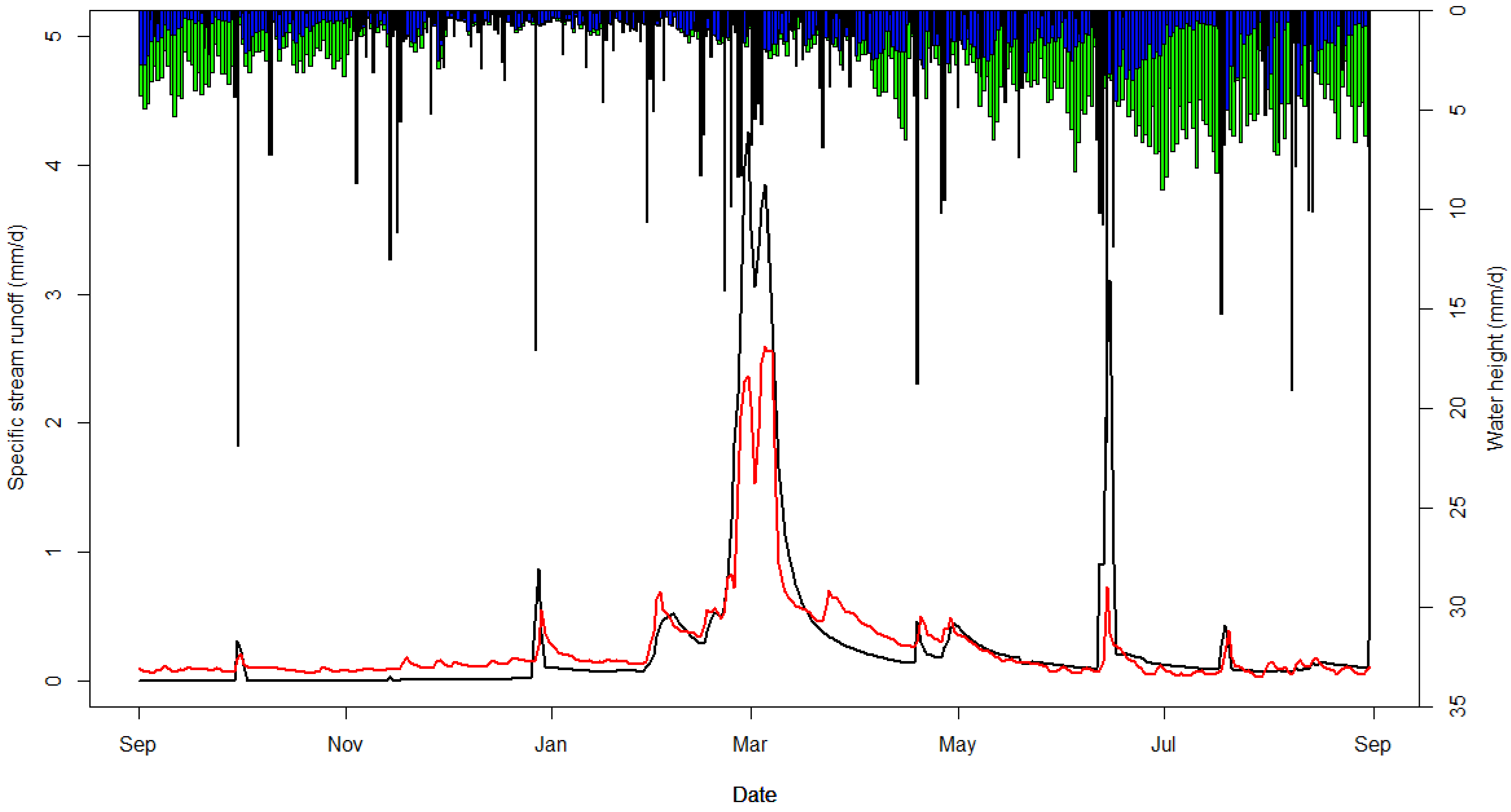
Specific stream runoff (mm/d)
Water height (mm/d)
Date
Sep
Nov
Jan
Mar
May
Jul
Sep
0
1
2
3
4
5
0
5
10
15
20
25
30
35

Figure 5: Simulated (black line) and reference (red line) daily specific stream runoff (mm/d) at the Gélon catchment outlet for the hydrologic year of 2014/2015. The daily rainfall (in black), ET0 (in green) and AET (in blue) are also represented (in mm/d) on the right inverted y-axis.

Table 5 summarizes the simulated and regionally observed crop yields. Considering all the crops, the area-weighted average of the relative root mean square errors across the Gélon catchment is 21.4%, which is quasi-acceptable according to Cabelguenne et al. (1990) and Constantin et al. (2015), who considered a difference of 20% between the observed and simulated yields acceptable. This performance results from the good performance of the model in the simulation of the sunflower and sorghum yields and the poor yield simulation performance for soybeans, rapeseed, maize and straw cereals.

Table 5: Simulated and regionally observed crop yields in the Gélon catchment, accounting for 86.1% of the crop area. The regionally observed crop yields correspond to data retrieved from the Gers department in 2015 (DRAAF Occitanie, 2020), considering the maize yield in proportion to the irrigated and non-irrigated maize areas in the Gélon catchment.

Species	Regionally observed yield ($T.ha^{-1}$)	Simulated yield ($T.ha^{-1}$)	Yield error (%)	Cultivated area (%)
Soybeans	3.50	2.21	-37%	7.28%
Sunflower	1.70	1.45	-15%	33.28%
Rapeseed	2.5	3.30	+32%	0.45%
Sorghum	5.5	5.84	+6%	2.12%
Maize	8.4	5.43	+35%	1.65%
Straw cereals	5.4	6.70	+24%	41.30%

3.3 Numerical experiment results

3.3.1 Global variables

The annual catchment water balance terms in the two situations are reported in Table 4. The simulated irrigation amounts rank as expected with the largest volume occurring in the All-RE situation, due to both the large irrigated area and abundant available water resources. The simulated stream runoff in the All-RE situation was 6% lower than in the Reference situation.

The crop yield varies both between crops within a situation and between the two situations (Table 6). In the All-RE situations, yields of non-irrigated crops (i.e., sunflower) are not very different from those in the Reference situation (<2%) since a rainfed crop in the reference situation remains non-irrigated in All-RE. Crops irrigated on only part of their area in the Reference situation are either replaced by irrigated maize or maintained as non-irrigated in the All-RE situation. As a result, when they do not disappear (as for rapeseed and sorghum), their yield decreases slightly if they were lightly irrigated (e.g., straw cereals) or considerably if they were intensively irrigated (e.g., soybeans). Regarding maize, the yield decrease observed in All-RE (-12% compared to the Reference) has another explanation. In All-RE, the number of reservoirs for irrigation increased, and all irrigated surfaces were converted into maize crop plots. The increase in the overall volume of water available for irrigation purposes did not compensate for the increase in the total water demand resulting from the increase in the area of irrigated maize, hence the decrease in yield.

Table 6: Variations in the crop yields in the Gélon catchment considering the two simulated situations. The values are given in T/ha but also in T at the catchment scale. Variations are also given in percent compared to the Reference situation.

	Soybeans	Sunflower	Rapeseed	Sorghum	Maize	Straw cereals
Reference	2.21 T/ha **240 T**	1.45 T/ha **720 T**	3.30 T/ha **22 T**	5.84 T/ha **185 T**	5.43 T/ha **134 T**	6.70 T/ha **4,131 T**
All-RE	1.99 T/ha (-10.0%) **119 T**	1.47 T/ha (+1.4%) **213 T**	-	-	4.78 T/ha (-12.0%) **5,100 T**	6.70 T/ha (0.0%) **1,048 T**

3.3.2 Spatially distributed variables

MHYDAS-Small-Reservoirs simulates a large number of spatially distributed variables related to the hydrological and agricultural responses of a catchment. We illustrate three of them, namely, i) stream runoff, ii) irrigation water demand and iii) reservoir filling rate evolution.

The stream runoff is simulated along the whole hydrographic network at the RS resolution. This allows us to assess and compare the inner-catchment variability, as shown in Figure 7, where the difference in the monthly stream runoff along the hydrographic network between the Reference and All-RE situations in December 2014 and July 2015 is plotted. These two months were chosen because they corresponded to high flow and low flow periods, respectively. In that respect, several results can be highlighted. The first result is that the relative variation in the monthly stream runoff between the situations at the catchment outlet differs from one month to another and that the variation in the annual stream runoff also differs. For example, although the simulated annual runoff in the All-RE situation was lower by -6% compared to the Reference situation, the difference of monthly stream runoff between both situations was -3% in July and -14% in December. The second notable result is that the variation in the stream runoff at the outlet may mask the high variability in stream runoff along the hydrographic network. The simulated stream runoff variation was negative in most of the stream reaches (Figure 7), indicating a lower stream runoff in the All-RE situation than in the Reference situation over the two months analysed. This result was expected due to i) the higher crop water requirement of maize compared to the straw cereals, which is the main irrigated crop in the Reference situation, and ii) the larger water withdrawals in the reservoirs in order to irrigate maize. This leads to emptier reservoirs at the beginning of the rainy period and thus to an increase of water interception of runoff and stream runoff by the reservoirs and to a decrease of the stream runoff in the catchment. However, in July, in the western branch of the hydrographic network, delimited by A and B in Figure 7, the stream runoff was higher (+9%) than that in the Reference situation. This counterintuitive result is explained by an increase of the baseflow in the All-RE situation, which is 8% higher in July for certain GUs in the southwest of the catchment. This increase in the baseflow is first related to the irrigation. Indeed, the absence of irrigation under the Reference situation in the northwest of the catchment (Figure 7) leads to a lower soil water content than that in the All-RE situation, where the soils are cropped with highly irrigated maize. The rainfall in July and the subsequent infiltration allows the soil water content to exceed the soil field capacity faster, thus triggering larger soil percolation in the All-RE situation than in the Reference. However, this phenomenon is limited to a small part of the catchment. Indeed, in the rest of the catchment, the water amount available for irrigation in the reservoirs is smaller than the demand, and the mean soil water content in the All-RE situation remains lower than that in the Reference situation. Thus, at the catchment scale, the stream runoff is slightly modified by these changes and driven more by the increasing AET due to the maize crops.

The irrigation water demand also exhibits inner spatial and temporal variability, as shown in Figure 7, where the irrigation water demand is plotted for the Reference and All-RE situations and two months corresponding to the beginning (June) and the end (August) of the irrigation period. These two months illustrate well how the water demand depends on crop requirements and water resource availability in reservoirs, which usually decreases with time during the irrigation period . The water demand is quite uniform in the catchment for the All-RE situation because all irrigated fields are cropped with the same crop, maize. The difference in water demand between June and August relies mainly on this situation in crop water requirements. In June, the maize was planted a few weeks earlier, and the crop water requirement, and thus the water demand for irrigation, is low. In August, the crop requirement is large due to the crop development and the high ET0 (Figure 5). As the reservoirs are empty at this time (Figure 8), the water demand remains high most of the time. In the reference situation, water demand is slightly more variable than for the All-RE situation because there are different irrigated crops, such as straw cereals, soybean and maize. The crop development in time and the irrigation period are different from one crop to another one. As straw cereals are harvested in July, all fields with this crop are simulated with a zero water demand in August for the reference situation (fields with black dots in the left map of Figure 7). As in the All-RE situation, the temporal variation in water demand for maize fields between June and August also results from the water availability in the reservoirs. For instance, the simulated water demand for the field in maize indicated by a red circle in Figure 7 varies from zero in June to more than 60 mm in August. The water volume in the reservoir connected to this field (grey line in Figure 8) is not large enough in August to meet the crop requirement, leading to a permanent high water demand.

The reservoir filling rate, which is the ratio between the volume of water stored and the RE capacity, also reveals a high spatial and temporal variability (Figure 8). This finding is explained by the spatial distribution of the crops, the different water requirements and cycles of the different crops, and the locations and properties of the reservoirs. Whether a reservoir is used for irrigation or not is the first variation factor of the filling rate between reservoirs: either connected or non-connected, REs remain almost full throughout the year as long as they are not applied for irrigation purposes (the blue and red curves in Figure 8b). The type of irrigated crop is the second factor, namely, in the Reference situation, where the various crops are irrigated, the reservoir levels decrease first in June to irrigate the straw cereal, market gardening and soybean crops and again from July to September when the maize and soybean crops are irrigated (the orange, green, grey and black lines in Figure 8b), while in the All-RE situation with all irrigated plots cropped with maize, the decrease in June is not observed (all the coloured lines in Figure 8c). The type of reservoir, connected or non-connected, is another factor explaining the differences in filling rate. When the irrigation water demand is high, as that during maize irrigation in the All-RE situation, the connected reservoirs (the red and orange lines in Figure 8b and 8c) are more likely to become filled because they benefit from both surface and stream runoff from the upstream reach, while the non-connected reservoirs, only receiving surface runoff, are less likely to become filled (the blue and green lines in Figure 8b and 8c). The last factor is the location of the reservoir, as illustrated by the difference between two non-connected reservoirs reserved for irrigation (the black and grey lines, respectively, in Figure 8). In one case (the black line), the drained area is not large enough to fill the reservoir during the surface runoff period, and the reservoir remains almost empty throughout the year regardless of the situation. In the second case (the grey line), the drained area is large enough to support a high filling rate, as indicated by the filling rate approaching the reservoir capacity during the rainfall events in late June.

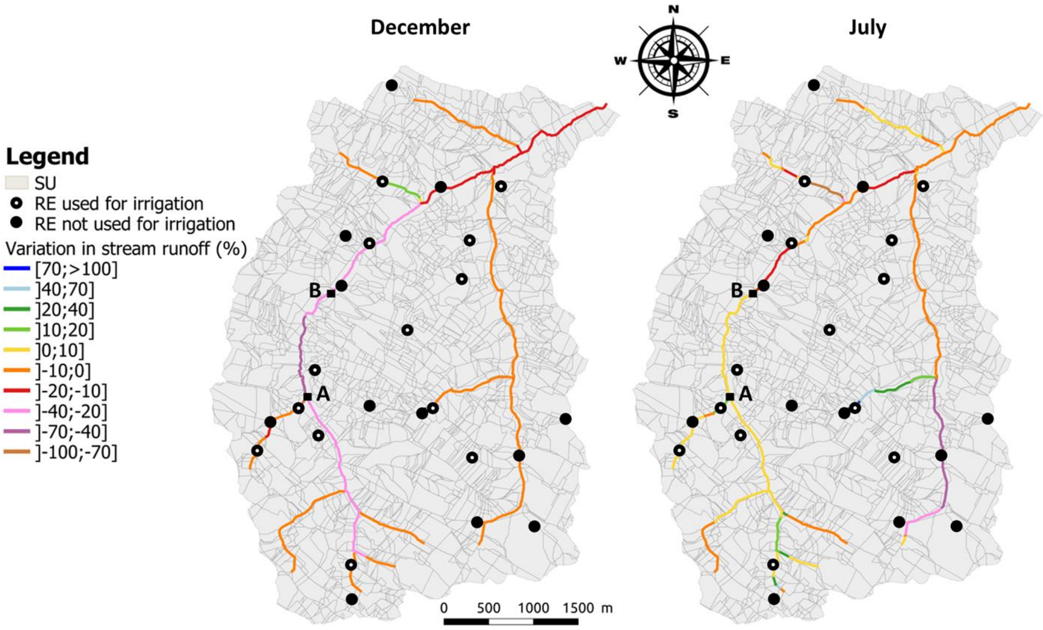

Figure 6: Stream runoff differences simulated along the hydrographic network in two months (December 2014 and July 2015) for the All-RE situation. The differences are calculated between the mean monthly simulated stream runoffs in each of the situations and the Reference situation. The depicted water reservoir units (REs) dedicated to irrigation or not are those in the Reference situation. Black squares A and B delimit the western branch of the hydrographic network.

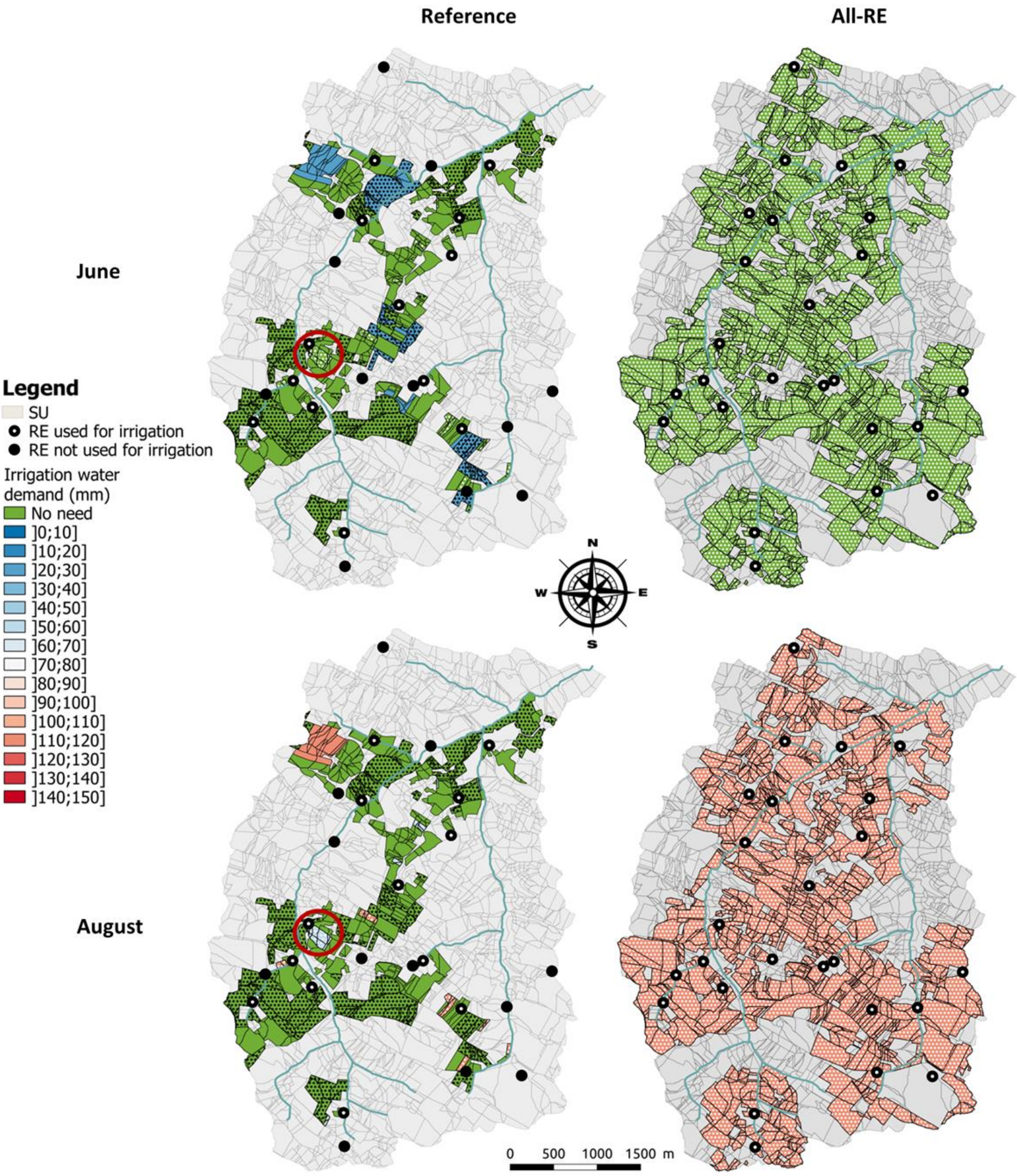

Figure 7**:** Monthly cumulative irrigation water demand simulated in June 2015 and August 2015 in the Reference and All-RE situations. The non-irrigated SUs are indicated in grey. The irrigable agricultural SUs without a water demand are marked in green. The various colours from dark blue to red indicate a low to high irrigation water demand. The blue lines are the RSs, the black crosses and the black points are the Res, with a white dot for those dedicated to irrigation. The maize crops are indicated with white dots and cereals by black dots.

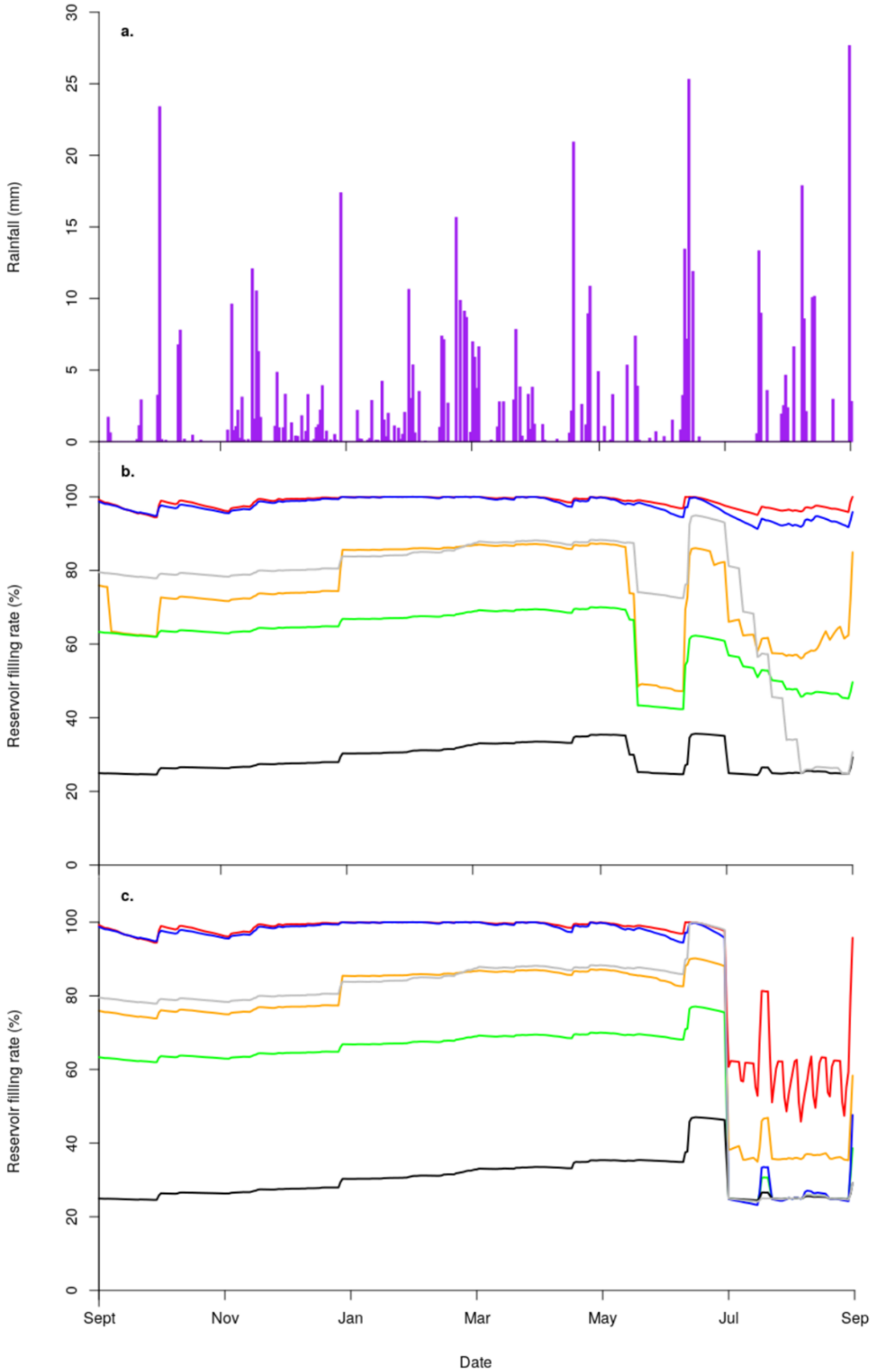

Figure 8: Daily rainfall (a) and variations in water storage in the reservoirs relative to their volume capacities in the Reference (b) and All-RE (c) situations. The coloured lines indicate the different RE configurations and groupings defined in the Reference situation, which were maintained in the All-RE situation. The mean reservoir filling rates are represented for the connected REs reserved for irrigation (6 REs, orange line), the connected REs not dedicated to irrigation (4 REs, red line), the non-connected REs dedicated to irrigation (7 REs, green line) and the non-connected REs not dedicated to irrigation (8 REs, blue line). In addition, the specific reservoir filling rate for two non-connected REs dedicated to irrigation (in black and grey, respectively) is also plotted.

4. Discussion

The first application of the MHYDAS-Small-Reservoirs model to the Gelon catchment gave promising results (Figure 5; Tables 4 and 5). The main processes underlying the hydrological and agricultural functioning of the catchment seem to be well modelled. However, considering the application of the model to other catchments and other agropedoclimatic contexts requires questioning (i) the availability of the data needed for its application to other real case studies and (ii) the improvements to the model in terms of the processes represented. The two points are discussed hereafter.

The first point of discussion concerns the data needed to use the MHYDAS-Small-Reservoirs model, either to define forcing variables to obtain the spatial representation of the flow domain to parameterise it on the study area or to evaluate it. Most of the necessary data (e.g., topography, hydrographic network, soil characteristics, nature of crops, and meteorological variables) may be extracted or derived from generic databases, often available throughout Europe. Moreover, as this model is built on already proven models and on widely used equations, some parameters can be fixed from the literature. For example, this is the case for the plant growing coefficients or for the k factor for converting reference evapotranspiration to reservoir evaporation. This makes it easy to envision the use of the model in catchment areas other than the one we studied.

However, there is no generic database for all model inputs or for all variables used for its evaluation. In such cases and when available, those data may be derived from local databases, specific surveys or local expertise. This is particularly the case for data on reservoirs: there is currently no database at the European or even the French level that allows a complete and high-quality description of small water reservoirs. The availability and estimation of the small reservoirs properties and the water use from the reservoirs have remained a real challenge regardless of the approaches used in catchment hydrological modelling with reservoirs (Hughes and Mantel, 2010, Lowe et al. 2005). This has motivated the development of remote sensing methods to estimate position and capacity of small reservoirs over large areas (Ogilvie et al., 2016). In France, the collective water management structures recently set up in deficit areas ("Organismes Uniques de Gestion Collective de l'Eau") are beginning to create a type of database gathering characteristics and water uses of small reservoirs. Databases describing agricultural practices are also incomplete, either in terms of geographical location or in terms of content, as explained in Leenhardt et al. (2010, 2020). Therefore, this requires the implementation of specific acquisition methods, for example, as presented for cropping systems by Murgue et al. (2016) and Rizzo et al. (2019). It is clear that the lack of generic databases for some of the necessary variables to use or evaluate the model makes using the model more difficult. However, this constraint is not specific to MHYDAS-Small-Reservoirs and has been encountered by other modelling approaches dealing with the cumulative effect of small reservoirs.

The quality of the data used also guarantees the predictive quality of the model and the reliability of the model assessment. The use of indirect acquisition methods necessarily introduces inaccuracies, either because of the quality of the expertise (Rizzo et al., 2019) or because of the method itself. For example, in our case study, we did not manage to meet all the owners of the reservoirs (absences or refusals) so that the data for some reservoirs correspond to hypotheses based on our observations or on the expertise of neighbours. However, the existence of generic databases does not exclude the need to examine the quality of the data included in them. For example, in the present study, although we had databases providing stream flow, meteorological data and crop yield values, we were only able to access stream flow data at a nearby station located within the same basin but outside the Gélon catchment, while meteorological data and crop yield values, respectively, were at a resolution that was too low to obtain internal spatial variability on an 8 km² grid and averaged over the entire Gers department,. These spatial discrepancies necessarily affect the quality of the data. More intensive field work, for example, by monitoring flows at the Gélon outlet or by obtaining yield values from agricultural cooperatives or traders who collect crops in this sector, would have enabled a better evaluation of the model's performance.

The second point of discussion is about the way to improve the modelling of processes in MHYDAS-Small-Reservoirs, in particular processes directly affecting the reservoir. Regarding this point, the modular design of the MHYDAS-Small-Reservoirs model under the OpenFLUID platform easily allows adding or improving simulators. In the current version of the model, some processes are neglected. This is the case for infiltration of water from the reservoirs to the underlying groundwater or conversely for the discharge of groundwater directly to the reservoirs. Neglecting these processes appeared to be acceptable in the Gélon catchment given the characteristics of the reservoirs and their connection to the groundwater. However, depending on the pedological and lithological contexts and the properties of the reservoirs, in particular the hydrodynamic properties of the reservoir bed, exchanges between the reservoir and the groundwater can be dominant processes in the hydrological dynamics of the reservoir (Bouteffeha et al., 2015). Modelling the exchanges would therefore improve the model in its ability to simulate a diversity of contexts. The modelling could be done simply by considering the differences in water levels between the reservoir and groundwater. This type of relationship is reported to well predict the dynamics of exchanges in various contexts (Sharda et al., 2006).

Another improvement of the model is in the modelling of the water management rules of the reservoirs. Indeed, the cumulative hydrological effect of reservoir networks cannot be explained solely by the geometric characteristics of the network (density in terms of number of reservoirs, volume or surface area). The management rules of the reservoirs, which sometimes differ from one reservoir to another, appear to be an important factor in this effect (Habets et al., 2018; Hughes and Mantel, 2010). In the present case study, the sharing of available water in a reservoir is modelled by a fairly standard approach by considering that the water withdrawn is distributed to the irrigated field proportionally to the water demand, but other priority rules could be considered. Priority could be given, for example, to crops providing high financial incomes. We could also consider defining rules based on short-term weather predictions. For actual water management rules being modelled within a specific simulator, the modular design of the MHYDAS-Small-Reservoirs model will be a clear asset to allow various water management modalities.

5. Conclusions

The MHYDAS-Small-Reservoirs model has been developed to understand and predict the local and cumulative hydrologic and agricultural effects of a reservoir network in an agricultural catchment. Hydrological models are already available to assess the cumulative impact of reservoir networks. Compared to these models, the originality of MHYDAS-Small-Reservoirs lies in two of its features. The first is that it integrates processes related to the three major components of the catchment's agro-hydrological functioning: hydrology, crop growth, and water management decisions. The second feature is that it explicitly represents the main elements of the agricultural catchment - the plot, the reach, the reservoir, and the water table - and the hydrological and agricultural relationships between these elements. In addition, the model distinguishes between reservoirs according to their connection to the hydrographic networks. In doing so, it allows the simulation of both local effects in the immediate environment of each reservoir and cumulative effects on overall yields (Table 6) and flows (Figure 6).

Numerical verification of the model was successful. The first application of the model to a 19-km² catchment gave promising results in terms of stream runoff and crop yield simulations. However, the evaluation and validation of the model are incomplete. The model could be improved in two directions. The first concerns its validation, with an analysis of the model performance to simulate the variables for which it was intended, such as stream runoff, crop yields and water withdrawals and availability in small reservoirs. Model validation could also gain from its application to catchments where comprehensive, reliable and distributed data sets, such as water tables, stream runoff and crop yield data, are available based on in situ measurements and observations. The second direction would be to perform a sensitivity analysis. In particular, a sensitivity analysis of the reservoir characteristics and of the parameters associated with water dynamics modelling in small reservoirs could be helpful when parameterizing the model in future applications. Thus, the MHYDAS-Small-Reservoirs model could potentially be adopted by land use planners and water managers to assist them in their decisions regarding new small-reservoir projects in catchments or management of the water stored in reservoirs.

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Software and data availability

MHYDAS-Small-Reservoirs runs with the OpenFLUID platform. OpenFLUID is a software environment for modelling and simulation of complex landscape systems. The documentation and versions of OpenFLUID platform can be found on the OpenFLUID site at www.openfluid-project.org. A dedicated GitHub workspace is also available at https://github.com/OpenFLUID/openfluid. The GitHub workspace dedicated to MHYDAS-Small-Reservoir is available at https://github.com/UMR-LISAH/MHYDAS-Small-Reservoirs.

References

Agence de l'Eau, French Ministry of the Environment, SANDRE, and IGN. 2014. 'BD CarTHAgE'. Base de Données sur la CARtographie THématique des AGences de l'Eau et du ministère chargé de l'environnement. http://services.sandre.eaufrance.fr/telechargement/geo/ETH/BDCarthage/FXX/2014/.

Ajami, Hoori, Matthew F. McCabe, Jason P. Evans, and Simon Stisen. 2014. 'Assessing the Impact of Model Spin-up on Surface Water-Groundwater Interactions Using an Integrated Hydrologic Model'. *Water Resources Research* 50 (3): 2636–56. https://doi.org/10.1002/2013WR014258.

Algayer, Baptiste, Philippe Lagacherie, and Jean Lemaire. 2020. 'Adapting the Available Water Capacity Indicator to Forest Soils: An Example from the Haut-Languedoc (France)'. *Geoderma* 357 (January): 113962. https://doi.org/10.1016/j.geoderma.2019.113962.

Allain, S., Obiang Ndong, G., Lardy, R., Leenhardt D., 2018. Integrated assessment of four strategies for solving water imbalance in an agricultural landscape. Agron. Sustain. Dev. 38: 60. https://doi.org/10.1007/s13593-018-0529-z

Beven, Keith, and Andrew Binley. 1992. 'The Future of Distributed Models: Model Calibration and Uncertainty Prediction'. *Hydrological Processes* 6 (3): 279–98. https://doi.org/10.1002/hyp.3360060305.

Biemans, Hester, Ingjerd Haddeland, Pavel Kabat, Fulco Ludwig, Ronald W. A. Hutjes, Jens Heinke, Werner von Bloh, and Dieter Gerten. 2011. 'Impact of Reservoirs on River Discharge and Irrigation Water Supply during the 20th Century'. *Water Resources Research* 47 (3). https://doi.org/10.1029/2009WR008929.

Bouvet, Lionel, Xavier Louchart, Martin Barès, Sylvain Lalauze, Roger Moussa, and Marc Voltz. 2010. 'Modélisation intégrée des agro-hydrosystèmes avec MHYDAS: Exemple Des Transferts de Pesticides En Milieu Viticole Méditerranéen'. In *Proceedings of the 40th Colloquium of the GFP*. Banyuls-sur-Mer, France: Cooper, J.F. et al, 2010.

Brighenti, Tássia Mattos, Nadia Bernardi Bonumá, Raghavan Srinivasan, and Pedro Luiz Borges Chaffe. 2019. 'Simulating Sub-Daily Hydrological Process with SWAT: A Review'. *Hydrological Sciences Journal* 64 (12): 1415–23. https://doi.org/10.1080/02626667.2019.1642477.

Cabelguenne, Maurice, Charles Allan Jones, Jean-Robert Marty, Paul T. Dyke, and Jimmy R. Williams. 1990. 'Calibration and Validation of EPIC for Crop Rotations in Southern France'. *Agricultural Systems* 33 (2): 153–71. https://doi.org/10.1016/0308-521X(90)90078-5.

Cavaillé, Albert, and BRGM. 1968. 'Note on the geological map of Beaumont-de-Lomagne (Notice de la carte géologique de Beaumont-de-Lomagne)'. Detailed geological map of France N°955. France: BRGM. http://ficheinfoterre.brgm.fr/Notices/0955N.pdf.

Çetin, Lydia T., Andrew C. Freebairn, Phillip W. Jordan, and Bianca J. Huider. 2009. 'A Model for Assessing the Impacts of Farm Dams on Surface Waters in the WaterCAST Catchment Modelling Framework'. In *18th World IMACSMODSIM Congress*, 3478–84. Cairns, Australia. http://mssanz.org.au/modsim09.

Chiarelli, Davide Danilo, Corrado Passera, Lorenzo Rosa, Kyle Frankel Davis, Paolo D'Odorico, and Maria Cristina Rulli. 2020. 'The Green and Blue Crop Water Requirement WATNEEDS Model and Its Global Gridded Outputs'. *Scientific Data* 7 (1): 273. https://doi.org/10.1038/s41597-020-00612-0.

Chow, Ven T. 1959. *Open-Channel Hydraulics*. First edition. New York: McGraw-Hill.

Constantin, Julie, Magali Willaume, Clément Murgue, Bernard Lacroix, and Olivier Therond. 2015. 'The Soil-Crop Models STICS and AqYield Predict Yield and Soil Water Content for Irrigated

Crops Equally Well with Limited Data'. *Agricultural and Forest Meteorology* 206 (June): 55–68. https://doi.org/10.1016/j.agrformet.2015.02.011.

Deitch, Matthew J., Adina M. Merenlender, and Shane Feirer. 2013. 'Cumulative Effects of Small Reservoirs on Streamflow in Northern Coastal California Catchments'. *Water Resources Management* 27 (November): 5101–18. https://doi.org/10.1007/s11269-013-0455-4.

DRAAF Occitanie. 2020. 'French Annual Agricultural Statistics - Areas, yields and production from 2000 to 2019 by department of Occitanie for cereals, oilseeds and protein crops (Statistique Agricole Annuelle (SAA) - Surfaces, rendements et production de 2000 à 2019 par département d'Occitanie des céréales, oléagineux, protéagineux)'. Edited by French Ministry of Agriculture. Statistical data of the SRISET Occitanie. http://draaf.occitanie.agriculture.gouv.fr/Cereales-oleagineux.

Durand, Yves, Eric Brun, Laurent Merindol, Gilbert Guyomarc'h, Bernard Lesaffre, and Eric Martin. 1993. 'A Meteorological Estimation of Relevant Parameters for Snow Models'. *Annals of Glaciology* 18: 65–71. https://doi.org/10.1017/S0260305500011277.

Fabre, Jean-Christophe, Armel Thöni, and David Crevoisier. 2020. 'OpenFLUID'. Documentation. OpenFLUID: Modelling Fluxes in Landscapes. September 2020. https://www.openfluid-project.org/. (accessed 9.9.20).

Fabre, Jean-Christophe, Xavier Louchart, François Colin, Cécile Dagès, Roger Moussa, Michael Rabotin, Damien Raclot, Philippe Lagacherie, and Marc Voltz. 2010. 'OpenFLUID : A Software Environment for Modelling Fluxes in Landscapes'. In *International Conference on Integrative Landscape Modelling*, 1–13. Montpellier: Quae ; INRA ; CIRAD. http://www.documentation.ird.fr/hor/fdi:010051568.

Faivre, Robert, Claude Bruchou, Jean Couteau, Nicolas Dumoulin, Thierry Faure, Bertrand Ioss, Sigrid Lehuta, Stéphanie Mahévas, David Makowsky, Hervé Monod, Benjamin Poussin, Eric Ramat, Hervé Richard, Lauriane Rouan, Jean-Christophe Soulié, and Juhui Wang. 2013.

Sensitivity analysis and model exploration: application to natural and environmental sciences (Analyse de sensibilité et exploration de modèles: application aux sciences de la nature et de l'environnement). Editions Quae. http://site.ebrary.com/lib/uqat/Doc?id=10825807.

Fernández-Pato, Javier, Daniel Caviedes-Voullième, and Pilar García-Navarro. 2016. 'Rainfall/Runoff Simulation with 2D Full Shallow Water Equations: Sensitivity Analysis and Calibration of Infiltration Parameters'. *Journal of Hydrology* 536 (May): 496–513. https://doi.org/10.1016/j.jhydrol.2016.03.021.

Ferrant, Sylvain, François Oehler, Patrick Durand, Laurent Ruiz, Jordy Salmon-Monviola, Eric Justes, Philippe Dugast, Anne Probst, Jean-Luc Probst, and José-Miguel Sanchez-Perez. 2011. 'Understanding Nitrogen Transfer Dynamics in a Small Agricultural Catchment: Comparison of a Distributed (TNT2) and a Semi Distributed (SWAT) Modeling Approaches'. *Journal of Hydrology* 406 (1–2): 1–15. https://doi.org/10.1016/j.jhydrol.2011.05.026.

Gaudou, Benoit, Christophe Sibertin-Blanc, Olivier Therond, Frédéric Amblard, Yves Auda, Jean-Paul Arcangeli, Maud Balestrat, Charron, Marie-Hélène, Gondet, Etienne, Hong, Yi, Lardy, Romain, Louail, Thomas, Mayor, Eunate, Panzoli, David, Sauvage, Sabine, Sánchez Pérez, José, Taillandier, Patrick, Nguyen, Van, Vavasseur, Maroussia and Mazzega, Pierre. 2016. 'The MAELIA Multi-Agent Platform for Integrated Assessment of Low-Water Management Issues'. *MABS 2013-14th International Workshop on Multi-Agent-Based Simulation*, May.

Grayson, Rodger B., Ian D. Moore, and Thomas A. McMahon. 1992. 'Physically Based Hydrologic Modeling: 2. Is the Concept Realistic?' *Water Resources Research* 28 (10): 2659–66. https://doi.org/10.1029/92WR01259.

Gumiere, Silvio Jose, Damien Raclot, Bruno Cheviron, Gregory Davy, Xavier Louchart, Jean-Christophe Fabre, Roger Moussa, and Yves Le Bissonnais. 2011. 'MHYDAS-Erosion: A Distributed Single-Storm Water Erosion Model for Agricultural Catchments'. *Hydrological Processes* 25 (11): 1717–28. https://doi.org/10.1002/hyp.7931.

Güntner, Andreas, Maarten S. Krol, José Carlos De Araújo, and Axel Bronstert. 2004. 'Simple Water Balance Modelling of Surface Reservoir Systems in a Large Data-Scarce Semiarid Region'. *Hydrological Sciences Journal* 49 (5): 901-18. https://doi.org/10.1623/hysj.49.5.901.55139.

Habets, Florence, Jérôme Molénat, Nadia Carluer, Olivier Douez, and Delphine Leenhardt. 2018. 'The Cumulative Impacts of Small Reservoirs on Hydrology: A Review'. *Science of The Total Environment* 643 (December): 850–67. https://doi.org/10.1016/j.scitotenv.2018.06.188.

Habets, Florence, Elodie Philippe, Eric Martin, Cervantes Hernández David, and Frédéric Leseur. 2014. 'Small Farm Dams: Impact on River Flows and Sustainability in a Context of Climate Change'. *Hydrology and Earth System Sciences* 18 (10): 4207–22. https://doi.org/10.5194/hess-18-4207-2014.

Hallema, Dennis W., Roger Moussa, Patrick Andrieux, and Marc Voltz. 2013. 'Parameterization and Multi-Criteria Calibration of a Distributed Storm Flow Model Applied to a Mediterranean Agricultural Catchment'. *Hydrological Processes* 27 (10): 1379–98. https://doi.org/10.1002/hyp.9268.

Herman, Jonathan D., Joshua B. Kollat, Patrick M. Reed, and Thorsten Wagener. 2013. 'Technical Note: Method of Morris Effectively Reduces the Computational Demands of Global Sensitivity Analysis for Distributed Watershed Models'. *Hydrology and Earth System Sciences Discussions* 10 (4): 4275–99. https://doi.org/10.5194/hessd-10-4275-2013.

Hermida, Lucía, Laura López, Andrés Merino, Claude Berthet, Eduardo García-Ortega, José Luis Sánchez, and Jean Dessens. 2015. 'Hailfall in Southwest France: Relationship with Precipitation, Trends and Wavelet Analysis'. *Atmospheric Research* 156: 174–88. https://doi.org/10.1016/j.atmosres.2015.01.005.

Hoogeveen, Jippe, Jean-Marc Faurès, Livia Peiser, Jacob Burke, and Nick van de Giesen. 2015. 'GlobWat – a Global Water Balance Model to Assess Water Use in Irrigated Agriculture'.

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Hydrology and Earth System Sciences 19 (9): 3829–44. https://doi.org/10.5194/hess-19-3829-2015.

Hughes, Denis A., and Sukhamani K. Mantel. 2010. 'Estimating the Uncertainty in Simulating the Impacts of Small Farm Dams on Streamflow Regimes in South Africa'. *Hydrological Sciences Journal* 55 (4): 578–92. https://doi.org/10.1080/02626667.2010.484903.

IGN. 2017. 'DEM RGE ALTI 5m'. Database. France. https://www.data.gouv.fr/fr/datasets/registre-parcellaire-graphique-rpg-contours-des-parcelles-et-ilots-culturaux-et-leur-groupe-de-cultures-majoritaire/#_.

IGN. 2016. 'Digital aerial photography (Prises de vues aériennes dématérialisée)'. Photographs. France. https://www.data.gouv.fr/fr/datasets/prises-de-vue-aeriennes-dematerialisees-de-lign/.

IGN. 2015. 'Land Parcel Identification System (Registre Parcellaire Graphique, RPG)'. Database. France. https://www.data.gouv.fr/fr/datasets/registre-parcellaire-graphique-rpg-contours-des-parcelles-et-ilots-culturaux-et-leur-groupe-de-cultures-majoritaire/#_.

Jordan, David. 1990. 'Implementation Benefits of C++ Language Mechanisms'. *Communications of the ACM* 33 (9): 61–64. https://doi.org/10.1145/83880.84460.

Kirchner, James W. 2009. 'Catchments as Simple Dynamical Systems: Catchment Characterization, Rainfall-Runoff Modeling, and Doing Hydrology Backward'. *Water Resources Research* 45 (2). https://doi.org/10.1029/2008WR006912.

Kollet, Stefan J., and Reed M. Maxwell. 2008. 'Capturing the Influence of Groundwater Dynamics on Land Surface Processes Using an Integrated, Distributed Watershed Model'. *Water Resources Research* 44 (2). https://doi.org/10.1029/2007WR006004.

Lee, Yooyoung, James J. Filliben, Ross J. Micheals, and P. Jonathon Phillips. 2013. 'Sensitivity Analysis for Biometric Systems: A Methodology Based on Orthogonal Experiment Designs'.

Computer Vision and Image Understanding 117 (5): 532–50. https://doi.org/10.1016/j.cviu.2013.01.003.

Leenhardt, Delphine, Olivier Therond, Marie-Odile Cordier, Chantal Gascuel-Odoux, Arnaud Reynaud, Patrick Durand, Jacques-Eric Bergez, Lucie Clavel, Véronique Masson, and Pierre Moreau. 2012. ‘A Generic Framework for Scenario Exercises Using Models Applied to Water-Resource Management’. *Environmental Modelling & Software* 37 (November): 125–33. https://doi.org/10.1016/j.envsoft.2012.03.010.

Leenhardt D., Angevin F., Biarnes A., Colbach N., Mignolet C., 2010. Describing and locating cropping systems on a regional scale. A review. Agronomy for Sustainable Development 30 : 131–138, DOI: 10.1051/agro/2009002. http://dx.doi.org/10.1051/agro/2009002

Leenhardt D., Therond O., Mignolet C., 2020. Chapitre 9. Décrire les systèmes de culture pour la gestion intégrée des ressources en eau. In : Leenhardt D., Voltz M., Barreteau O. (Eds). L'eau en milieu agricole. Outils et méthodes pour une gestion intégrée et territoriale. Collection Synthèses, Éditions Quæ, 2020, ISBN 978-2-7592-3123-2. p.141-152

LEMA. 2006. *French Law on Water and Aquatic Environment (Loi sur l’Eau et les Milieux Aquatiques, LEMA)*. *Environmental Code*. Vol. 214–18, Law n°2006-1772. https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000000649171.

Lewis, David C., and Robert H. Burgy. 1964. ‘The Relationship between Oak Tree Roots and Groundwater in Fractured Rock as Determined by Tritium Tracing’. *Journal of Geophysical Research* 69 (12): 2579–88. https://doi.org/10.1029/JZ069i012p02579.

Lowe, L., Nathan, R., and Morden, R. (2005). “Assessing the impact of farm dams on streamflows, Part II: Regional characterisation.” Aust. J. Water Resour., 9(1), 13–26

Lowe, L.D., J.A. Webb, R.J. Nathan, T. Etchells, and H.M. Malano (2009), Evaporation from water supply reservoirs: An assessment of uncertainty, J. Hydrol., 376(1-2), 261–274, doi:10.1016/j.jhydrol.2009.07.037.

Malakoff David, Andrew Sugden, 2020, Dry times, Science,Vol. 368, Issue 6488, pp. 254-255, DOI: 10.1126/science.abc0396

Maharjan, Ganga Ram, Youn Shik Park, Nam Won Kim, Dong Seok Shin, Jae Wan Choi, Geun Woo Hyun, Ji-Hong Jeon, Yong Sik Ok, and Kyoung Jae Lim. 2013. 'Evaluation of SWAT Sub-Daily Runoff Estimation at Small Agricultural Watershed in Korea'. *Frontiers of Environmental Science & Engineering* 7 (1): 109–19. https://doi.org/10.1007/s11783-012-0418-7.

McJannet, D. L., F. J. Cook, and S. Burn (2013), Comparison of techniques for estimating evaporation from an irrigation water storage, Water Resour. Res., 49, 1415–1428, doi:10.1002/wrcr.20125

Mishra, Surendra Kumar, Jaivir V. Tyagi, and Vijay P. Singh. 2003. 'Comparison of Infiltration Models'. *Hydrological Processes* 17 (13): 2629–52. https://doi.org/10.1002/hyp.1257.

Moreno, Gerardo, José J. Obrador, Elena Cubera, and Christian Dupraz. 2005. 'Fine Root Distribution in Dehesas of Central-Western Spain'. *Plant and Soil* 277 (1–2): 153–62. https://doi.org/10.1007/s11104-005-6805-0.

Moriasi, Daniel N., Margaret W. Gitau, Naresh Pai, and Prasad Daggupati. 2015. 'Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria'. *Transactions of the ASABE* 58 (6): 1763–85. https://doi.org/10.13031/trans.58.10715.

Moussa, Roger, Nanée Chahinian, and Claude Bocquillon. 2007. 'Distributed Hydrological Modelling of a Mediterranean Mountainous Catchment – Model Construction and Multi-Site Validation'. *Journal of Hydrology* 337 (1–2): 35–51. https://doi.org/10.1016/j.jhydrol.2007.01.028.

Moussa, Roger, Marc Voltz, and Patrick Andrieux. 2002. 'Effects of the Spatial Organization of Agricultural Management on the Hydrological Behaviour of a Farmed Catchment during Flood Events'. *Hydrological Processes* 16 (2): 393–412. https://doi.org/10.1002/hyp.333.

MTES. 2012. 'CORINE Land Cover'. Database. France. https://www.data.gouv.fr/fr/datasets/corine-land-cover-occupation-des-sols-en-france/.

Murgue, Clément, Romain Lardy, Maroussia Vavasseur, Delphine Leenhardt, and Olivier Therond. 2014. 'Fine Spatio-Temporal Simulation of Cropping and Farming Systems Effects on Irrigation Withdrawal Dynamics within a River Basin'. In *International Environmental Modelling and Software Society (IEMSs): Agro-Ecosystem Modeling for Spatial Solutions to Watershed Conundrums,* 4:1817–24. San Diego, CA, USA. https://hal.inrae.fr/hal-02741968/document.

Murgue C., Therond O., Leenhardt D., 2016. Hybridizing local and generic information to model cropping system spatial distribution in an agricultural landscape. Land Use Policy, 54, 339-354. http://dx.doi.org/10.1016/j.landusepol.2016.02.020

Nash, James E., and John V. Sutcliffe. 1970. 'River Flow Forecasting through Conceptual Models Part I — A Discussion of Principles'. *Journal of Hydrology* 10 (3): 282–90. https://doi.org/10.1016/0022-1694(70)90255-6.

Nathan, Rory, Phillip Jordan, and Robert Morden. 2005. 'Assessing the Impact of Farm Dams on Streamflows, Part I: Development of Simulation Tools'. *Australasian Journal of Water Resources* 9 (1): 1–12. https://doi.org/10.1080/13241583.2005.11465259.

Neitsch, Susan L., Jeff G. Arnold, James R. Kiriny, and Jimmy R. Williams. 2011. *Soil & Water Assessment Tool - Theorical Documentation*. Version 2009. Texas Water Resources Institute Technical Report 406. Texas, USA: Texas A&M University System.

Ogilvie, A., Belaud, G., Massuel, S., Mulligan, M., Le Goulven, P., Calvez, R., 2016. Assessing Floods and Droughts in Ungauged Small Reservoirs with Long-Term Landsat Imagery. Geosciences 6, 42. https://doi.org/10.3390/geosciences6040042

Oudin, Ludovic, Vazken Andréassian, Thibault Mathevet, Charles Perrin, and Claude Michel. 2006. ‘Dynamic Averaging of Rainfall-Runoff Model Simulations from Complementary Model Parameterizations’. *Water Resources Research* 42 (7). https://doi.org/10.1029/2005WR004636.

Party, Jean-Paul, Nicolas Muller, Quentin Vauthier, Laurent Rigou, Benoît Toutain, Sébastien Lehmann, Bertrand Laroche, and Maritxu Guiresse. 2016. ‘Regional Pedological Databank of Midi-Pyrénées : Gers Department (Référentiel Régional Pédologique de Midi-Pyrénées : Département du Gers)’. CNRS/EcoLab. https://doi.org/10.6096/70324.

Perrin, Jérôme, Sylvain Ferrant, Sylvain Massuel, Benoit Dewandel, Jean-Christophe Maréchal, Stéphanie Aulong, and Shakeel Ahmed. 2012. ‘Assessing Water Availability in a Semi-Arid Watershed of Southern India Using a Semi-Distributed Model’. *Journal of Hydrology* 460–461 (August): 143–55. https://doi.org/10.1016/j.jhydrol.2012.07.002.

Potter, Kenneth W. 2006. ‘Small-Scale, Spatially Distributed Water Management Practices: Implications for Research in the Hydrologic Sciences’. *Water Resources Research* 42 (3). https://doi.org/10.1029/2005WR004295.

Puissant, Anne, Arnaud Sellé, Nicolas Baghdadi, Vincent Thierion, Arnaud Le Bris, and Jean-Louis Roujean. 2019. ‘The “Urban” Component of the French Land Data and Services Centre (THEIA)’. In 2019, *Joint Urban Remote Sensing Event (JURSE)*, 1–4. Vannes, France: IEEE. https://ieeexplore.ieee.org/abstract/document/8808998.

Pushpalatha, Raji, Charles Perrin, Nicolas Le Moine, and Vazken Andréassian. 2012. ‘A Review of Efficiency Criteria Suitable for Evaluating Low-Flow Simulations’. *Journal of Hydrology* 420–421 (February): 171–82. https://doi.org/10.1016/j.jhydrol.2011.11.055.

Quintana-Seguí, Pere, Patrick Le Moigne, Yves Durand, Eric Martin, Florence Habets, Martine Baillon, Claire Canellas, Laurent Franchisteguy, and Sophie Morel. 2008. 'Analysis of Near-Surface Atmospheric Variables: Validation of the SAFRAN Analysis over France'. *Journal of Applied Meteorology and Climatology* 47 (1): 92–107. https://doi.org/10.1175/2007JAMC1636.1.

Rahman, Mohammad M., Minjiao Lu, and Khin H. Kyi. 2016. 'Seasonality of Hydrological Model Spin-up Time: A Case Study Using the Xinanjiang Model'. *Hydrology and Earth System Sciences Discussions*, July, 1–22. https://doi.org/10.5194/hess-2016-316.

Rizzo D., Therond O., Lardy R., Murgue C., Leenhardt D., 2019. A rapid, spatially explicit approach to describe cropping systems dynamics at the regional scale. Agricultural Systems, 173: 491-503, ISSN 0308-521X, https://doi.org/10.1016/j.agsy.2019.04.003

Rosa, Lorenzo, Davide Danilo Chiarelli, Matteo Sangiorgio, Areidy Aracely Beltran-Peña, Maria Cristina Rulli, Paolo D'Odorico, and Inez Fung. 2020a. 'Potential for Sustainable Irrigation Expansion in a 3 °C Warmer Climate'. *Proceedings of the National Academy of Sciences* 117 (47): 29526–34. https://doi.org/10.1073/pnas.2017796117.

Rosa, Lorenzo, Davide Danilo Chiarelli, Maria Cristina Rulli, Jampel Dell'Angelo, and Paolo D'Odorico. 2020b. 'Global Agricultural Economic Water Scarcity'. *Science Advances* 6 (18): 1–10. https://doi.org/10.1126/sciadv.aaz6031.

Rousseau, A.N., S. Savary, D.W. Hallema, S.J. Gumiere, E. Foulon. 2013. the effects of agricultural BMPs on sediments, nutrients and water quality of the Beaurivage River watershed (Quebec,Canada) Canadian Water Resources Journal, 38(2): 99-120. DOI:10.1080/07011784.2013.780792

Sheffield, Justin, and Eric F. Wood. 2008. 'Projected Changes in Drought Occurrence under Future Global Warming from Multi-Model, Multi-Scenario, IPCC AR4 Simulations'. *Climate Dynamics* 31 (1): 79–105. https://doi.org/10.1007/s00382-007-0340-z.

Skaggs, Richard W., Marlón A. Brevé, and James W. Gilliam. 1994. 'Hydrologic and Water Quality Impacts of Agricultural Drainage∗'. *Critical Reviews in Environmental Science and Technology* 24 (1): 1–32. https://doi.org/10.1080/10643389409388459.

Spinoni, Jonathan, Gustavo Naumann, Hugo Carrao, Paulo Barbosa, and Jürgen Vogt. 2014. 'World Drought Frequency, Duration, and Severity for 1951-2010'. *International Journal of Climatology* 34 (8): 2792–2804. https://doi.org/10.1002/joc.3875.

Stafford, John V., Bruce Ambler, Murray R. Lark, and John A. Catt. 1996. 'Mapping and Interpreting the Yield Variation in Cereal Crops'. *Computers and Electronics in Agriculture* 14 (2–3): 101–19. https://doi.org/10.1016/0168-1699(95)00042-9.

Tarboton, Kenneth C., and Roland E. Schulze. 1991. 'The ACRU Modelling System for Large Catchment Water Resources Management'. In *Hydrology for the Water Management of Large River Basins. International Symposium. General Assembly of the International Union of Geodesy and Geophysics (20)*, 219–32. IAHS-AISH Publication. United Kingdom: International Association of Hydrological Sciences, Wallingford. http://hydrologie.org/redbooks/a201/iahs_201_0219.pdf.

Therond, Olivier, Christophe Sibertin-Blanc, Romain Lardy, Benoît Gaudou, Maud Balestrat, Yi Hong, Thomas Louail, Van Bai Nguyen, David Panzoli, José-Miguel Sánchez-Pérez, Sabine Sauvage, Patrick Taillandier, Maroussia Vavasseur, Pierre Mazzega. 2014. 'Integrated Modelling of Social-Ecological Systems: The MAELIA High-Resolution Multi-Agent Platform to Deal with Water Scarcity Problems'. In *7. International Congress on Environmental Modelling and Software (IEMSs 2014)*, 2386 p. Proceedings of the 7th International Congress on Environmental Modelling and Software, June 15-19, San Diego, California, USA. San Diego, Californie, United States: International Environmental Modelling and Software Society (iEMSs). https://hal.inrae.fr/hal-02742949.

Therond, Olivier, and Jean Villerd. 2020. ‘Modelling of socio-Agro-Ecological system for Landscape Integrated Assessment’. Documentation. Documentation plateforme Maelia. January 2020. http://maelia-platform.inra.fr/accueil/contributeurs/. (accessed 5.6.20).

Vörösmarty, Charles J., Pamela Green, Joseph Salisbury, and Richard B. Lammers. 2000. ‘Global Water Resources: Vulnerability from Climate Change and Population Growth’. *Science* 289 (5477): 284–88. https://doi.org/10.1126/science.289.5477.284.

Wisser, Dominik, Steve Frolking, Ellen M. Douglas, Balazs M. Fekete, Andreas H. Schumann, and Charles J. Vörösmarty. 2010. ‘The Significance of Local Water Resources Captured in Small Reservoirs for Crop Production – A Global-Scale Analysis’. *Journal of Hydrology* 384 (3–4): 264–75. https://doi.org/10.1016/j.jhydrol.2009.07.032.

Zhang, Chi, Yong Peng, Jinggang Chu, Christine A. Shoemaker, and Aijing Zhang. 2012. ‘Integrated Hydrological Modelling of Small- and Medium-Sized Water Storages with Application to the Upper Fengman Reservoir Basin of China’. *Hydrology and Earth System Sciences* 16 (11): 4033–47. https://doi.org/10.5194/hess-16-4033-2012.

Appendix A: Simulation rules used for farmer management decisions

The farmer management decisions considered in the model include tillage, sowing, harvest and irrigation. The decision rules adopted to simulate these technical operations are described below. The variables employed as indicators are mentioned between brackets.

- A tillage day occurs during the tillage period (temporal window) according to the soil type, when the soil water content is favourable, i.e., this depends on the weather conditions (antecedent cumulative rainfall) and soil conditions (soil water content);
- A sowing day may occur on the first day of the simulation or after the harvesting period, which depends on the weather conditions (antecedent cumulative rainfall and minimal temperature), possible sowing period (temporal window) according to the crop type and precocity class and soil conditions (soil water content);
- A harvesting day is simulated either when the crop is mature (crop development stage) or before poor soil and weather conditions occur (antecedent cumulative rainfall and soil water content), which could result in soil damage;
- Depending on the development of the crop and the weather conditions (previous rainfall and rainfall forecasts), the water demand for irrigation may be zero or have a non-zero fixed value. This fixed value depends on the crop, the soil and the irrigation equipment. It is a model parameter (e.g., 30 mm for maize in the Gelon catchment application). The volume of water actually withdrawn and delivered to the cultivated field is conditioned by the availability of the water resource (see section 1.4.2). The farmer's water demand is calculated at a time step depending on the farmer's equipment constraints. The time step is a model parameter (e.g., 6 or 7 days in the Gelon catchment application depending on the field).

Appendix B: Description of the MHYDAS-Small-Reservoirs simulator

Number (Nb.), name, model component, spatial unit type and main simulated variables of every simulator constituting MHYDAS-Small-Reservoirs. The model component refers to the integrated model component, namely, hydrology (Hydrol.), crop growth (Crop) or crop and agricultural water management (Water Manag.).

Nb.	Name of the simulator	Model component	Unit type	Main simulated variables
1	water.atm-surf.evapotranspiration-su.files	Hydrol. and Crop	SU	Reference evapotranspiration
2	water.atm-surf.evaporation-re.files	Hydrol.	RE	Reference evaporation
3	water.atm-surf.rain-su.files	Hydrol.	SU	Rainfall
4	water.atm-surf.rain-re.files	Hydrol.	RE	Rainfall
5	energy.atm-surf.T.temperature	Crop	SU	Mean air temperature
6	energy.atm-surf.T.temperature-min	Crop	SU	Minimum air temperature
7	water.surf.ecological-flow-rs-re.mean-annual-discharge	Water Manag.	RE	Ecological flow
8	crop.surf.practices-su.decision-Murgue	Crop and Water Manag.	SU	Farmer management decisions (sowing day, tillage day, harvesting day, irrigation day, and irrigation water demand)
9	crop.surf.practices-su.application-Murgue	Crop and Water Manag.	SU	Application of Farmer management decisions (sowing day, tillage day, harvesting day, irrigation day, and irrigation water demand)
10	water.surf-sz.abstraction-priority-wp.decision-order	Water Manag.	WP*	Priority order for irrigation

11	water.surf.withdrawal-irrigation-wp.prorata-water-demand	Crop and Water Manag.	WP*	Available water for irrigation Total irrigation water demand Water withdrawal Irrigation
12	water-soil-crop.surf-uz.runoff-cropsoilwaterdynamics-transfer-su-storage-non-connected-re.Horton-Hayami-AqYield-water-balance	Crop and Hydrol.	SU	Infiltration Crop growth Evapotranspiration Percolation Surface runoff Soil water content Crop water requirement
			RE	Overflow Water storage Evaporation
13	water-soil.surf-uz.percolation-evapotranspiration-su.soil-swat	Hydrol.	SU	Evapotranspiration Percolation
14	water.surf-sz.storage-baseflow-gu.storage-discharge-function	Hydrol.	GU	Water storage Discharge and baseflow
15	water.surf.transfer-rs-storage-connected-re.hayami-water-balance	Hydrol.	RS	Stream runoff
			RE	Overflow Water storage Evaporation
16	water.surf.variable-surface-re.bathymetric-relation	Hydrol.	RE	Water surface area

* WP (withdrawal point) corresponds to a water resource (RS or RE) dedicated to irrigation

Appendix C: Main parameters of the MHYDAS-Small-Reservoirs model

List of the main MHYDAS-Small-Reservoirs model parameters given by spatial unit type. For each parameter, the spatial unit type, the model relying on it, a description of the parameter with values of the non-distributed parameters and the origin database are listed. Bold and italicised numbers indicate the number of the simulator, as referenced in Appendix B, that relies on that parameter.

Unit type	*Model component*	*Parameters*	*Data sources used in the Gélon application*
SU (agricultural)	Crop	Crop type ***(8, 12)***	Land Parcel Identification System of 2015 (IGN, 2015)
		Crop growth potential, root growth coefficient, evaporation coefficient and sum of the growing degree days at the maturity and flowering stages (the complete list of AqYield parameters can be found on the Maelia website http://maelia-platform.inra.fr/donnees/donnees-agricoles/liste-des-cultures/) ***(12)***'	Table of crop cultivar characteristics provided by breeders and AqYield calibration (Constantin et al., 2015)
SU (non-agricultural)	Hydrol.	Type of land use ***(12, 13)***	Land use inventory of 2012 (MTES, 2012)

		Grassland root depth: 0.80 m ***(13)***	Moreno et al. (2005)
		Forest root depth: the maximum soil depth ***(13)***	Lewis & Burgy (1964), Algayer et al. (2020)
SU	Crop and Water Manag.	(Agricultural SUs) Technical itinerary according to the type of crop, soil and irrigation equipment ***(8);*** irrigation equipment ***(8)***	Gaudou et al. (2016), Murgue et al. (2014), Therond and Villerd (2020), field surveys
SU	Hydrol.	Soil minimum infiltration capacity coefficient ***(12)***; Soil maximum infiltration capacity coefficient ***(12)***; and shape coefficient ***(12)***	Mishra et al. (2003), Fernández-Pato et al. (2016), sensitivity analysis
		Soil maximum infiltration capacity, bulk density, clay rate, potential maximal available water content, and thickness ***(12, 13)***	Regional Pedological Databank (Party et al., 2016)
RS and SU	Hydrol.	Manning ($m.s^{-1}$): 0.05 (SU); 0.10 (RS) ***(12, 15)***	Chow (1959)
		Celerity ($m^2.s^{-1}$): 0.045 (SU); 0.49 (RS) ***(12, 15);*** diffusivity ($m.s^{-1}$): 500	Moussa et al. (2002)

		(SU and RS) ***(12, 15);*** iteration number in Hayami kernel calculations: 100 ***(12, 15)***	
RE	Crop and Water Manag.	Irrigated plots ***(10)***	BD CACG-OUGC-DDT, completed by field surveys
RE	Hydrol. and Water Manag.	Evaporation coefficient (0.6) ***(2)***	Neitsch et al. (2011)
		Dead volume of the reservoir: 0.25 of the total capacity ***(11)***	Therond and Villerd (2020)
		Minimum flow: 10% of the interannual flow ***(7)***	LEMA (2006)
GU	Hydrol.	Reference flow ($m^2.s^{-1}$): $5.365*10^{-8}$ ***(14)***; divisor parameter (0.05) ***(14)***; exponential parameter (5.66) ***(14)***	Flow recession curve analysis