



**HAL**  
open science

## On the use of hydrological models and satellite data to study the water budget of river basins affected by human activities: examples from the Garonne basin of France

Eric Martin, Simon Gascoin, Y. Grusson, C. Murgue, Mélanie Bardeau, F. Anctil, Sylvain Ferrant, Romain Lardy, P. Le Moigne, D. Leenhardt, et al.

### ► To cite this version:

Eric Martin, Simon Gascoin, Y. Grusson, C. Murgue, Mélanie Bardeau, et al.. On the use of hydrological models and satellite data to study the water budget of river basins affected by human activities: examples from the Garonne basin of France. *Surveys in Geophysics*, 2016, 37 (2), pp.223-247. 10.1007/s10712-016-9366-2 . hal-01529147

**HAL Id: hal-01529147**

**<https://hal.science/hal-01529147>**

Submitted on 30 May 2017

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## **On the use of hydrological models and satellite data to study the water budget of river basins affected by human activities: examples from the Garonne basin of France**

Eric Martin, Simon Gascoin, Youen Grusson, Clément Murgue, Mélanie Bardeau, François Anctil, Sylvain Ferrant, Romain Lardy, Patrick Le Moigne, Delphine Leenhardt, Vincent Rivalland, José-Miguel Sánchez Pérez, Sabine Sauvage, Olivier Therond

Eric Martin

CNRM-GAME (Météo-France, CNRS), 42 avenue Coriolis, 31057 Toulouse, France  
IRSTEA, UR RECOVER, 3275 route de Cézanne, 13182 Aix-en-Provence Cedex 5  
e-mail: [Eric.Martin@irstea.fr](mailto:Eric.Martin@irstea.fr)

Patrick Le Moigne

CNRM-GAME (Météo-France, CNRS), 42 avenue Coriolis, 31057 Toulouse, France

Simon Gascoin, Sylvain Ferrant Vincent Rivalland

Centre d'Études Spatiales de la Biosphère (CESBIO), UPS/CNRS/IRD/CNES, 18 avenue E. Belin bpi 2801, 31401 Toulouse, France

Youen Grusson

University of Toulouse; INPT, UPS; Laboratoire Ecologie Fonctionnelle et Environnement (EcoLab), Avenue de l'Agrobiopole, 31326 Castanet Tolosan Cedex, France

Youen Grusson, François Anctil

Chaire de recherche EDS en prévisions et actions hydrologiques, Department of Civil and Water Engineering, Université Laval, Québec, G1V 0A6, Canada

Sabine Sauvage, José-Miguel Sánchez Pérez

University of Toulouse; INPT, UPS; Laboratoire Ecologie Fonctionnelle et Environnement (EcoLab), Avenue de l'Agrobiopole, 31326 Castanet Tolosan Cedex, France  
CNRS, EcoLab, 31326 Castanet Tolosan Cedex, France

Clément Murgue, Romain Lardy, Delphine Leenhardt, Olivier Therond

INRA, UMR AGIR, BP52627, 31326 Castanet Tolosan, France

INP Toulouse, UMR AGIR, BP52627, 31326 Castanet Tolosan, France

Clément Murgue

CACG, BP 449 - 65004 Tarbes, France

Romain Lardy

ARVALIS - Institut du végétal 3 rue Joseph et Marie Hackin 75016 Paris, France

Mélanie Bardeau

BRGM, 3 Rue Marie Curie, 31520 Ramonville-Saint-Agne, France



## Abstract:

Natural and anthropogenic forcing factors and their changes significantly impact water resources in many river basins around the world. Information on such changes can be derived from fine scale in-situ and satellite observations, used in combination with hydrological models. The latter need to account for hydrological changes caused by human activities to correctly estimate the actual water resource. In this study, we consider the catchment area of the Garonne river (in France) to investigate the capabilities of space-based observations and up-to date hydrological modelling in estimating water resources of a river basin modified by human activities and a changing climate. Using the ISBA-MODCOU and SWAT hydrological models, we find that the water resources of the Garonne Basin display a negative climate trend since 1960. The snow component of the two models is validated using the MODIS (Moderate Resolution Imaging Spectroradiometer) snow cover extent climatology. Crop sowing dates based on remote sensing studies are also considered in the validation procedure. Use of this data set improves the simulated evapotranspiration and river discharge amounts when compared to conventional data. Finally, we investigate the benefit of using the MAELIA multi-agent model that accounts for a realistic agricultural and management scenario. Among other results, we find that changes in crop systems have significant impacts on water uptake for agriculture. This work constitutes a basis for the construction of a future modelling framework of the sociological and hydrological system of the Garonne river region.

**Keywords:** modeling; hydrology; agriculture; anthropogenic changes ; sociological and hydrological system; remote sensing

## 1 Introduction

Human-induced land use changes are now widespread over the planet. The primary objectives of land use are to satisfy immediate human needs (Foley et al. 2005). Agriculture and urbanization are important drivers of these changes. The hydrological cycle has been transformed in many places to provide freshwater for irrigation, domestic uses, and industry (Vörösmarty et al. 2000). The number of dams along rivers and associated reservoirs has rapidly increased over recent decades (Lehner et al. 2011). Groundwater resources are being extensively used in regions with large aquifers and frequent water stresses (Wada et al. 2010). As a consequence, water fluxes, including evapotranspiration, are modified in many regions of the world (Asokan and Destouni 2014). Depending on the region and the hydrological variable considered, the signal can be dominated by climatic variability and trends or human activities (Vörösmarty et al. 2000; Moss et al. 2010). In south India, for instance, irrigation relies totally on groundwater extraction. The imbalance between recharge and extraction leads to local groundwater depletion, and hence water scarcity episodes that depend on local settings, e.g., small surface reservoir capacity maintained by farmers to catch monsoon runoff, aquifer capacity to store this recharge, and irrigated area extent that condition the water demand (Perrin et al. 2012).

These water scarcity episodes are expected to increase due to dry climatic extremes projected for the Garonne region in the future (Ferrant et al. 2014b). In the Upper Mississippi basin, climate change is the dominant driver of runoff changes over the 20<sup>th</sup> century, while land use changes (e.g., in forested areas, grasslands and croplands) can influence the river runoff locally (Frans et al. 2013). The impact of irrigation on local climate varies according to climatic zones and the degree of anthropization (Lobell et al. 2009; Destouni et al. 2012). For example, Grouillet et al. (2015) found that, by 2050, in two Mediterranean catchments (Herauld in France and Ebro in Spain) anthropogenic impacts on water demand will dominate the impacts due to climate change.

Explicitly taking into account direct human forcing in hydrological modeling is now a recognized need in order to correctly simulate hydrological evolution of highly anthropized basins. Some models already attempt to do this as is the case, for example, of the global-scale WaterGAP model (Alcamo et al. 2003). This consists of the WaterGAP Global Hydrology

Model (Döll et al. 2003) and five water use models for irrigation, livestock, household, manufacturing and cooling of thermal power plants. This type of model is highly relevant for simulating large scale hydrological patterns, e.g., groundwater depletion (Döll et al. 2014). This type of approach is also implemented at the scale of individual catchments smaller than the typical catchments simulated by WaterGAP (Grouillet et al. 2015). The main limitations for small scale applications are the level of details needed to reproduce human processes and the availability of databases.

Nowadays there is a growing interest to better account for the co-evolutionary dynamics of coupled water-human systems. Sivapalan et al. (2012) introduced the concept of socio-hydrology, a new science coupling people and water resources, to highlight the need to study the coupled human-water system using an interdisciplinary approach. Preliminary attempts in this direction have been able to explain the multiples changes that occurred over the Murrumbidgee River basin in Australia during the 20<sup>th</sup> century (Kandasamy et al. 2014). In this example, the underlying modeling framework (van Emerik et al. 2014) is composed of five subsystems (hydrology, population, irrigation, ecology and environmental awareness) that non-linearly interact and have two external drivers - climate and socio-economic. The model results highlight the competition between human productive and environmental restorative forces that lead to a so-called pendulum swing between agricultural development and environmental health. Due to oversimplifications, the model cannot describe the precise evolution of the system, but contains enough key elements to describe it. Another approach to describe a socio-hydrology system is to use agent-based models able to handle multiple interactions between numerous agents (Gaudou et al. 2014; Therond et al. 2014). The main advantage of this new approach is a greater flexibility in simulating individual processes and their interactions. However, it is quite complex and sensitive to small variations in the parameterization of the interaction rules between agents.

Accounting for both climatic and anthropogenic changes remains a challenge for hydrological models. While in-situ and space-based hydrological measurements are able to provide information on human-induced changes, a large number of hydrological models do not simulate all the components of these changes, and only account for the corresponding processes indirectly.

Satellite observations are able to document fine scale processes with a high spatio-temporal resolution. For example, FORMOSAT-2, launched in 2004, is able to observe vegetation

development at a high spatial resolution (~10m) with a frequent revisit time (few days). This allows the detection of biophysical variables like the leaf area index (LAI) for selected areas (Courault et al. 2010, Claverie et al. 2012). The Sentinel-2 mission provides similar observations at the global scale. The Surface Water and Ocean Topography (SWOT) mission (whose launch is planned for 2020) is a swath-mapping radar interferometer designed to measure temporal changes of surface water elevation (lakes, reservoirs and river channels with a quasi-global coverage between 78° S and 78° N (Durand et al. 2014; Biancamaria et al. 2015, see also <https://swot.jpl.nasa.gov>). Concerning rivers, the basic SWOT measurements will consist of river water surface elevation, slope and width at a very fine scale. It is anticipated that rivers wider than 100m and lake or reservoir areas larger than 250x250m will be observed with good accuracy. The SWOT revisit time depends on longitude: it is about 4 days at mid-latitudes. In anthropized basins, river gauges networks are usually relatively dense, but SWOT may be used to estimate flows between gauges or measure the water volumes of man-made reservoirs. Such data are usually not easily available, unless in situ networks depend on public bodies.

On the modelling side, several human processes need to be taken into account. Large alpine dams modify water regimes; other dams may be used to sustain low flows. In general, only a small number of large reservoirs are involved and the associated processes may be taken into account relatively easily, if data are available. Irrigation is a critical process. Models should be able to account for the balance between crop water demand and resource availability (from groundwater, reservoirs and rivers, Döll et al. 2012, Perrin et al. 2012, Ferrant et al. 2014b). For instance, two major opposing effects of irrigation on aquifer dynamics may be identified: groundwater depletion in regions with primarily groundwater-fed irrigation, and groundwater accumulation in regions dominated by return flows from irrigation fed by surface-water (Goderniaux et al. 2009; Holman et al. 2009; Scibeck et al. 2006; Jyrkama et al. 2007; Döll et al. 2009; Gurdak et al. 2010; Kovalevski et al. 2007; Green et al. 2007). The main difficulty is to account for water management practices that depend on the basin, as well as local and national governance (Mazzega et al. 2014). The simulation of human processes requires integrated modelling tools, able to simulate spatio-temporal interactions (including feedbacks) within and between socio-ecological systems, at relevant scale, and accounting for water management and associated agricultural practices (Therond et al. 2014). Another important parameter is land use change, that can lead to threshold effects (e.g., change from agriculture

to forest, Donohu et al. 2007; Qiu et al. 2011; Murgue et al. 2015) or more diffuse variations (e.g., crop rotation, Parajuli et al. 2013).

The objective of this paper is to discuss some challenges in estimating the water budget of a highly anthropized basin subject to climate change. We take advantage of recent studies dedicated to the Garonne Basin (a river basin that is highly modified by human activities, in France, with complex irrigation systems and frequent water management problems) to discuss how the combination of modelling and space-based observations can be used to improve the water budget estimate. Section 2 describes the Garonne basin and its current hydrological behavior. Section 3 shows how fine scale satellite observations of snow cover and vegetation can be used to validate and calibrate the hydrological models. Section 4 presents an example of the use of a multi-agent platform developed for the Garonne Basin to assess realistic crop rotation scenarios.

## **2 The water balance at the scale of the entire Garonne basin**

### **2.1 Climate and physical properties**

The Garonne river basin (56,000 km<sup>2</sup> in total - 50,000 km<sup>2</sup> at the Tonneins station - see Figure 1) is located in southwestern France. It drains water from the northern slopes of the Pyrenees Mountains (along the French border with Spain) and the southern slopes of the Massif Central. The mean annual discharge based on 103 years of in situ data at the Tonneins gauging station is estimated to be 600 m<sup>3</sup> s<sup>-1</sup>. The main tributaries of the Garonne river are the Ariège (flowing from the Pyrénées), and the Tarn and Lot (flowing from the Massif Central). The broad range of altitudes and slopes within the Garonne watershed leads to a diversity of hydrological behaviors that can be associated with three geographic zones: the Pyrenees to the south, the Massif Central to the north east, and the plain between them (Probst 1983). The Pyrenean portion of the watershed (i.e. elevated mountains – with some peaks exceeding 3,000 m - above a large plain where the topography does not exceed a few hundred meters) largely influences the hydrological regime. The watershed altitudes range from 150 m to 3,145 m, with 44 % of the watershed below 500 m and 20 % above 1,500 m.

The basin climate is influenced by oceanic conditions in its western part. It is characterized by heavy rainfall events during winter and relatively warm weather during summer. There is an important precipitation gradient from west to east, ranging from approximately 1200 mm



year<sup>-1</sup> in the Atlantic coastal region to about 600 mm year<sup>-1</sup> 300 km to the east in the plain area. The upper Garonne and the Ariège river regimes are marked by spring snowmelt in the Pyrenees (Caballero et al. 2007), while summer flows are very low due to relatively dry conditions then.

From a geological point of view, the basin was marked by several marine invasions during the Jurassic and Cretaceous eras that led to the formation of limestone aquifers (some being heavily karstified) toward the north and the east. Some of these aquifers are exploited. More recently, the erosion of the Pyrenees, Massif Central and the Montagne Noire has led to the accumulation of a high amount of molasse substratum in the center of the basin. The hydrographic network, marked by the recent succession of glaciation and deglaciation, is composed of alluvial terraces. If the river is not deeply incised, the alluvial aquifer feeds the river during most of the time, while water is transferred to the aquifer during flooding periods. If the river is deeply incised, the aquifer only feeds the river; these aquifers are also exploited. According to the FAO soil classification on the European Soils Data Base map (ESDB 2006), the soil composition is dominated by different types of cambisols (65 % of the catchment).

The Garonne river flows to the Atlantic Ocean through the Gironde estuary, one of the most important in Western Europe. Due to this geographical arrangement, the hydrological influence of tides can be measured relatively far upstream. For this reason, the model domain is limited to the catchment area at the Tonneins gauge station, where there is no tidal effect.

## **2.2 Anthropization, environmental change due to human actions**

Land use analyses from the Corine Land Cover (CLC2000) reveal that the plain is dominated by crops and pastures (Figure 2). Agricultural activities cover 49 % of the watershed, while the hillsides of the Pyrenees (35 % of the watershed) are covered with forests. For altitudes above 2,500 m, the vegetation is composed of alpine grassland and shrub covers. The influence of human activities is high in the basin (irrigated agriculture). The irrigated surface area became five times larger between the 1970's and the 1990's, and has now stabilized at 160,000 ha (Sauquet et al. 2009). About 60% of the irrigated surface is devoted to maize, the second main irrigated crops being sunflower and wheat. Water uptake for irrigation represents

about 70% of the total during low flow period. Uptake comes primarily from surface waters (more than 80%), reservoirs (8%) and groundwater (9%). In some areas, e.g., the plain near the confluence of the Tarn and the Garonne, groundwater uptake can reach 23%.

At the basin scale, Sauquet et al. (2009) estimated that the total water uptake for agriculture, industry and drinking water amounted to 7% of the discharge. Agricultural usage is dominant, especially during the summer months. Compared to other river basins in France, the Garonne basin has the largest deficit between supply and demand. Hence regulation and management plans are implemented at the basin (or sub-basin) and departmental (administrative district) levels (Mazzega et al. 2014). At the basin level, the Master Scheme for Water Planning and Management (Mazzega et al. 2014) defines the general orientation for the management of water resources and water demands. It fixes (for 41 river gauges located in the Garonne catchment) two regulation rules: the “objective low-water flow” corresponding to the minimum flow that ensures a good functioning of the aquatic environment (and should be respected 8 years out of 10), and the “crisis flow”, corresponding to the level under which the drinking water supply and the survival of aquatic species are in danger.

Low Water Management Plans define medium term strategies and public policies to manage the imbalance between supply and demand. At the administrative level, departmental state services enforce water use restriction rules when they are required. Drought commissions are established when a crisis is foreseen in order to evaluate the most relevant strategy. The input data to the commission can be observations (flow, water level in reservoirs or in aquifers) or model results. In order to evaluate how much water can be withdrawn from the aquifers, hydrodynamic models of alluvial aquifers of the upper Garonne, Tarn and lower Aveyron were developed in 2009 by the French Geological Survey (BRGM) (Bardeau and Bourdaa 2010); these have been in continuous use since this date.

### **2.3 Hydrological regime of the Garonne Basin: trends and variability**

The mean annual air surface temperature over the basin increased by 1.1°C from 1901 to 2000, while over this time span the precipitation decreased (with a negative trend that is barely significant, however) (Moisselin et al. 2002). Discharge trends are clearly negative, especially since the mid 1990's. Figure 3 presents the observed rainfall and snowfall based on meteorological data analyzed by the Safran system (Vidal et al. 2010), the observed discharge

and the estimated pseudo-natural discharge. The pseudo-natural discharges estimated by Sauquet (2009) over the period 1995-2005 have been extended back to 1990 (the epoch when the irrigated surface area stabilized).

Evaporation is evaluated using two hydrological models. The first model is the ISBA-Modcou model developed at Meteo-France (SIM, Habets et al. 2008; Decharme et al. 2013). It has two components: the land surface model ISBA (Interaction Soil-Biosphere-Atmosphere) and the distributed hydrological model MODCOU (MODélisation COUplée). The mesh size is 8km over the basin for the land surface model, and varies between 0.25 and 2 km for the hydrological model. The land surface model transfers runoff from the surface and to the bottom of the hydrological model. Aquifers are only taken into account implicitly through conceptual transfer reservoirs (Artinyan et al. 2012).

The second model considered in this study is the SWAT model (Soil and Water Assessment Tool, Arnold et al. 1993), a comprehensive, physically-based, semi-distributed and watershed-scale hydrological model that allows the simulation of a large number of hydrology-related physical processes (Douglas-Mankin et al. 2010; Gassman et al. 2007). In SWAT, the basin is discretized into sub-watersheds, which thereafter are divided into hydrological response units (HRUs), based on homogeneous soil, land use and slope. The HRUs are then used to compute a water balance, considering four reservoirs: snowpack, soil, shallow aquifer, and deep aquifer. Hydrological processes connecting those reservoirs include infiltration, runoff, evapotranspiration, lateral flow and percolation. Computation is performed at the HRU level, aggregated at the sub-basin level, and routed through reaches toward the catchment outlet. SWAT was applied to the upper part of the Garonne basin by Grusson et al. (2015). It must be noted that originally the two models had different objectives. SIM aims to simulate the coupled energy and mass balance of continental surfaces, while SWAT is a hydro-agro-environmental model, able to simulate the impact of climate, land use, and agricultural practices on hydrology. We use both as they offer different kinds of information, and thus are complementary.

The results for both models presented in this paper include the whole Garonne river watershed up to Tonneins. The SWAT model has been calibrated at monthly time steps over the 2000-2010 period using 21 stations spread over the watershed. SIM was not specifically calibrated for this study; the performance is the same as in Habets et al. (2008).

Figure 3 shows the main components of the water balance at the outlet (Tonneins) between 1960 and 2013, including analyses, observations and model outputs. The total precipitation and snowfall come from the Safran reanalysis (Vidal et al. 2010). The small differences between the two models are due to the spatial interpolation of the original 8 km Safran grid used by SIM that have been re-interpolated at the sub-watershed scale for SWAT (150 sub-watersheds and 3156 HRUs from the minimum surface of 0.0174 km<sup>2</sup> and maximum 316 km<sup>2</sup>). The mean total precipitation over the period is 966 mm, but there is a marked negative trend since the middle of the 1990's. The linear trend over the common period of the two models (1960-2011) is small but significant (- 0.38 mm year<sup>-1</sup> for SIM, - 0.36 mm year<sup>-1</sup> for SWAT, 99% confidence using a Monte Carlo non-parametric test). During the same period, the evapotranspiration calculated by the two models presents a significant positive trend of +1.55 mm year<sup>-1</sup> for SIM and +0.76 mm year<sup>-1</sup> for SWAT. Concerning the discharge, the linear trend is - 3.82 mm year<sup>-1</sup> for SIM, - 3.25 mm year<sup>-1</sup> for SWAT and only - 2.30 mm year<sup>-1</sup> from the observations.

However, it must be noted that the largest differences appear during the first half of the period, which make an important impact on the computed trends. The reasons for these differences are many, but it is difficult to determine the main factor: uncertainties in meteorological forcing, changes in land use, anthropization, or model calibration, etc. It must be noted that anthropogenic forcing factors were not explicitly accounted for in the two models but were only indirectly considered in the calibration procedure. Land use and vegetation characteristics are based on the ECOCLIMAP database (Faroux et al., 2013). SWAT is calibrated for the period 2000-2010 using the observed discharge, so that it indirectly accounts for anthropization. In addition to agricultural changes in the plain area, rapid land cover changes are occurring in the mountainous areas of the Garonne catchment due to the abandonment of agro-pastoral areas, i.e. due to reforestation. These human-induced land cover changes also impact some key hydrological processes such as storm runoff and snow melt in the Garonne river headwaters (Szczypta et al. 2015). Further work on observation and model errors are needed to explain the larger differences at the beginning of the period.

Figure 3 shows that the observed or modelled discharge trends at the annual discharge are mainly linked to climate variability and change, and not to anthropization. The trends are due to the natural variability (from annual to multi-decadal scales (Boé and Habets, 2014)) and the human-induced climate change.

### 3 Interest of fine scale data to validate or constrain models

At the scale of the entire Garonne basin, uncertainties in the meteorological forcing and observation errors cause uncertainties in the discharge trend estimates which are larger than the averaged effects of anthropization. This is not the case for smaller sub-basins or at the seasonal scale, as irrigation is most prevalent during the summer months, and hydroelectric power production is dominant in winter, due to the high proportion of electrically heated houses in France. Discharge variability is also underestimated by the models because both land use and vegetation cycles are assumed to be constant over the whole period. In addition to discharge data, there is a need for additional data to either validate or constrain the models. Satellite data are especially adapted, provided that they have a high enough resolution. In the remaining part of this Section, we provide two examples that demonstrate the added value of fine scale satellite data for hydrological modelling.

#### 3.1 Snow cover

The Ariège basin at Foix is one of the major mountainous sub-basins of the Garonne basin. Its area is 1340 km<sup>2</sup> and its mean annual discharge is around 40 m<sup>3</sup> s<sup>-1</sup>. As it contains a complex network of dams used for hydropower, the observed discharge is not representative of natural processes (in particular snow melt). Recently, Gascoin et al. (2015) built a snow cover dataset based on the space-based MODIS products, MOD10A1 and MYD10A1 (Hall et al., 2007), for the Pyrenees. This dataset provides snow cover extent at a daily time step over the region since 2000, with 500 m resolution. The MODIS data set was validated against in situ and Landsat data. This dataset complemented the in situ snow cover and discharge observations that are available for the basin. In addition, Heindrickx and Sauquet (2013) produced a series of pseudo-natural discharge values for the Ariege River at Foix, based on dam operations.

The snow cover dataset was used to validate the snow cover extent simulated by SIM. The snow model of SIM is the multilayer model ISBA-ES (Boone and Etchevers, 2001). The snow cover fraction is a function of snow water equivalent. SIM is a distributed model using an 8 km grid; two versions of the model were considered. The first is the standard version

(ISBA) whereas the second is a version taking into account up to four elevation bands in mountainous grid cells, characterized by a high sub-grid variability of orography (ISBA-M). Figure 4 shows the comparison between snow observations and the two model versions for two contrasting winters (2008/2009 and 2009/2010). Over the whole period (from 2000 to 2013), the correlation for daily data is very high (0.96), but the model has a small negative bias (0.05), which is especially visible during, or immediately after, snowfalls (e.g., in November 2008). A possible explanation for these temporary biases may be the very simple relation between snow cover equivalent and the snow fraction implemented in the model. Indeed, in a study of an alpine catchment (the Durance), Magand et al. (2014) highlighted the fact that the snow cover extent varies faster during winter than during the ablation season because melting occurs at preferential locations. In our case, underestimation mainly occurs from December to March. The difference between the simulations with and without elevation bands is usually low, except at the end of the season, when the snow cover fractions simulated using elevation bands are higher.

The snow water equivalent produced by ISBA was also compared to the snow water equivalent simulated by the SWAT model applied to the Garonne basin (Grusson et al. 2015). In this version, the snow module of SWAT used 10 elevation bands over each snow dominated sub-watershed, where each band covers one-tenth of total sub-watershed elevation. The agreement between the two models is high (Figure 5), even if the SWAT model tends to overestimate the snow cover in spring and summer (as also shown by Grusson et al. 2015, using in situ measurements), the mean bias being less than 13 mm snow water equivalent (SWE).

Grusson et al. (2015) highlighted the positive impact of elevation bands in SWAT on the river discharge simulation. Even if the snow cover extents simulated by ISBA and ISBA-M are very close, the impact on the river discharge is substantial: the monthly efficiency improved from 0.48 to 0.68 when compared to the operational measurements at Foix, and from 0.63 to 0.85 when compared to the naturalized discharge proposed by Heindrickx and Sauquet (2013).

Logically, it is necessary to pay great attention to the spring season in the evaluation of the snow cover extent. In our case, the large differences between the simulations appeared during

this period. The use of space-based snow cover extent may be a good alternative for the validation of snow cover simulations in the absence of natural river discharge estimates.

### **3.2 Crop sowing date**

The water balance of crop areas is highly influenced by the precise timing of operations such as sowing and harvesting, as well as irrigation for some crops. Hydrology and crop models have been coupled to take into account the influences of both hydrological settings and of agricultural practices on the water and nutrient cycles at the agricultural catchment scale. Most of these applications require spatially distributed models, where information on soil-crop location within the slopes as well as on hydrological settings (i.e. topography, groundwater storage, reservoir location or irrigation pumping) are included to provide spatially explicit information on water uses (Ferrant et al. 2014a; Perrin et al. 2012) and nutrient transfer and transformation within the catchment (Beaujouan et al. 20012; Ferrant et al. 2011).

Uncertainties raised by these modelling approaches at the watershed level are mainly related to the lack of agronomical observations in all soil-climatic situations encountered within the catchment and to the lack of spatial a priori knowledge on physical processes, such as soil organic matter transformations, saturated area extent and dynamics after rainfall events which influence both runoff and crop growth. Senthilkumar et al. (2015) highlighted the link between sowing, harvesting dates and water scarcity. Hutchings et al. (2012) demonstrated the importance of the timing of field operations for complex dynamic carbon and nitrogen models. However, the timing of operations is often derived from rough regional estimates, or from farmers' enquiries further extrapolated to cover the whole catchment. The use of high resolution remotely sensed data is a promising way to improve our knowledge of some operations, in particular for winter crops.

Ferrant et al. (2014a) have explored the potential of satellite remote sensing to gain information on the crop sowing date in the cultivated hydrological catchment of Auradé (320 ha) in the Garonne basin. They used a series of 105 leaf area index (LAI) maps derived from high resolution Formosat-2 images acquired from 2006 to 2010 to calibrate the sowing date of sunflower and winter wheat crops at the crop field level in the agro-hydrological model TNT2 (Beaujouan et al. 2002). This model shares the same modeling objectives as the SWAT model

(a comparison between both models is reported in Ferrant et al., 2011). An optimization process of the sowing date was done by matching the early variations of simulated LAI with the LAI derived from Formosat-2 images at crop-field scale. The results showed a large impact on in-stream nitrogen fluxes, but a limited impact on the mean annual discharge.

However, at shorter time-scales, the impact was larger. The optimization process based on the sowing date significantly improved the temporal growth dynamic simulated for the winter wheat whereas that for sunflower was not much impacted. A delay of a few weeks in the sowing date of winter wheat (from October to November) postponed the emergence date by a few months (by 3 months in the case of the year 2010), while the emergence date of sunflower directly followed the sowing dates in spring (indeed in this season the cumulative daily temperature threshold was reached in a few days). The winter wheat growth and biomass was then highly impacted by the optimization process, which led to a modification of the nitrogen and water cycles between a priori and optimized situations.

We provide here the analysis of the water budget at a monthly time step. In Figure 6, we represent the differences between both simulations in % for the discharge and the simulated actual evapotranspiration (AET). It appears that the crop growth optimization highly impacts the monthly AET, from - 17% to + 8%. The differences are bigger in 2010 for which the use of satellite LAI leads to earlier sowing dates and wheat emergence dates for most of the fields. An increase of AET fluxes associated to this earlier development is simulated from March to June, followed by a relative decrease at the end of the growth period. This decrease is explained by a drop of soil water content due to an earlier root water uptake during spring. Monthly discharges are decreasing with the increase of AET at the end of winter and spring, and remain lower than a priori simulations because of drier soils.

This type of approach can be implemented at the scale of the Garonne, either with the SWAT or SIM models, when the Sentinel-2 data will be available. The optimization process requires running the model not more than six times. Depending on how fast a model run is, the process at the crop field level can be considered not to consume too much computer time. The satellite derived information can be used at the crop field level or at the finer spatial scale needed by the models, the hydrologic response unit (HRU) for SWAT. This is defined mainly by the land use spatial resolution, which can be either at the crop field level or at the computation square grid for SIM (8x8 km). The need for spatial aggregation of the satellite information



depends also on the agricultural context. In this example, sunflower and winter wheat crop succession implies that both crops are spatially mixed in the studied area and should not be aggregated at the sub-basin scale. Indeed, it is crucial to differentiate between winter and spring crops as the winter crops induce larger uncertainties in the simulations. The added value of the Formosat-2 high resolution (which will be provided with Sentinel-2) is that it can explicitly provide spatial information on the inter-crop field heterogeneity, to study its impact on the global water cycle.

## **4 Explicit modelling of human activities at the scale of the basin using a multi-agent simulation platform**

### **4.1 MAELIA: a multi-agent platform of social-ecological systems**

Water resource management problems arise from interactions within socio-hydrology systems, a particular type of human-nature systems. Classically these systems are conceptualized as being composed of four main core sub-systems (McGinnis et al. 2014): (a) resource systems (e.g., hydrological systems), (b) resource units (e.g., water volume and flow), (c) governance systems (e.g., which regulate uses and manage water resources), and (d) users (e.g., individuals and groups who use water). Anderies et al. (2004) highlighted the role of their infrastructure (e.g., dams, water distribution networks) in the functioning of these systems.

Therond et al. (2014) developed the Multi-Agent for Environmental Norms Impact Assessment (MAELIA) platform to perform an integrated assessment of the impacts of endogenous and exogenous changes on the functioning of socio-hydrology systems. MAELIA focuses on water deficit issues and was applied in two rivers sub-basins of the Garonne basin: the Aveyron basin (a sub-basin of the Tarn basin) and the upstream part of the Garonne basin itself (upstream of the confluence with the Ariège). Originally, it allows simulating the key interactions between and within the four core sub-systems. Thanks to its multi-agent architecture, it represents the decision making process of water users (including irrigators), dam managers and state services regarding water use restrictions. In this platform, hydrology is modelled through the use of formalisms of the Soil and Water Assessment Tool (SWAT) model (Arnold et al. 1993), which is fully coupled with human processes such as irrigation. Spatial delineation of farms' islets (a set of contiguous fields) and the annual crop pattern of

each farm of the investigated river basin are provided by the French Land Parcel Identification System (LPIS) dataset (Inan et al. 2010). The analysis of different annual LPIS values allowed the reconstitution of the crop rotations of the different fields of the different farms' islets (Murgue et al. 2014, 2015). According to local databases, expert knowledge and geographic information system (GIS) treatments, each irrigated islet was connected with one or several water resources (river, small dam, or groundwater). Climate data used with MAELIA came from the Safran analysis system on an 8 x 8 km grid (see Section 3.3).

Table 1 synthesizes the main processes represented and the nature of the models used in MAELIA. All these intertwined processes interact at different spatial levels and at daily time steps in the platform, including feedbacks. For example, the crop water requirement at field level determines the farmer's decision and thus irrigation water withdrawals in the different resources. This decision impacts river flows that determine other decisions for water releases and/or withdrawal restrictions. In return, the resulting hydrology determines the water available for irrigation and so the farmers' capacity to irrigate and therefore the crop growth. Modelling methods for these key processes are briefly described below.

#### 4.1.1 Agricultural processes

MAELIA simulates the spatio-temporal dynamics of crop management operations and their impacts on crop growth. The crop model AqYield (Constantin et al. 2015) simulates plant growth, soil water dynamics, and crop yield in each field. It is a simple empirical model that proved its robustness under the pedoclimatic (soil temperature and moisture) conditions and the crop irrigation strategies of the Garonne basin (Constantin et al. 2015; Murgue et al. 2014). AqYield allows the simulation of 17 crops/cultivars, including 12 species that cover 100% of the irrigated areas of the Garonne basin: sunflower, wheat, barley, peas, rapeseed, sorghum, soya, temporary and permanent meadows, apple, plum, and maize. Maize being locally the most intensively irrigated specie, it is considered under 8 crops/cultivars: 1 for seed, 1 for forage and 6 for grain production ranging in 6 earliness categories: very late (VL), late (L), semi late (SL), semi-early (SE), early (E), very early (VE). AqYield provides soil and plant indicators to the farmer agents and hydrological information (drainage and runoff) to the MAELIA hydrological module.

The use of MAELIA in a river basin requires the description of crop management strategies (CMS) by production situation type (e.g., a combination of pedoclimatic conditions and farm type). A CMS must be defined for each crop of each crop rotation affecting each field. A CMS is coded as a set of decision rules (DRs) using the typical syntax: “IF INDICATOR OPERATOR THRESHOLD AND INDICATOR OPERATOR [...] THEN ACTION (ELSE ACTION)”. Such a set of DRs should be seen as a pre-established strategy that defines the conditions to trigger various sequences of technical operations depending on soil, plant, climate, water resources conditions at field level or socio-economic conditions at farm level (e.g., workforce availability). There are about 30 individual rules per CMS (for up to 8 technical operations; Murgue et al. 2014). At the farm level, farmer agents manage the concurrence between technical operations considering pre-defined priorities. At the field level, farmer agents decide to withdraw water from a given resource, according to a priority rule between the various possible resources and accounting for how full they are.

#### 4.1.2 Hydrological processes

The hydrological module in MAELIA uses the formalisms of the SWAT model to simulate hydrological fluxes at the sub-watershed level (25 km<sup>2</sup> in average). In MAELIA the SWAT algorithms were implemented for both (a) the “land phase” of the hydrologic cycle that controls the water loads to the main channel of each sub-watersheds (snowmelt, runoff, infiltration, redistribution in soil profile, evapotranspiration for non-crop plants, lateral subsurface flow and percolation into shallow and deep aquifers) and (b) the “routing phase” of the hydrologic cycle that controls the water flows to the outlet of the watershed through the channel network (water routing through the channel, transfers to and from the shallow aquifer, evaporation).

#### 4.1.3 Water management

Regarding water management, decision-making processes of dam manager and state services, respectively for water releases and withdrawal restrictions, are also coded as a set of IF-THEN decision rules. These decision rules must be parameterized locally by eliciting dam managers’ and state services’ current practices. In MAELIA each dam manager agent seeks to optimize releases according to objectives of sustaining targeted river flows and specific constraints of its dam(s): (a) reserved flow (minimum water flow at the exit of the dam),

maximum flow due to dam and river characteristics, (b) period of release (e.g., for tourism), (c) transfer time between the dam and the targeted monitoring points, and (d) emptying curve of the reservoir (statistical curve used to help present releases without compromising late season ones). When it is not possible or sufficient to sustain water flow through water releases (no dams in the sub-watershed, no more available water in the dam) the state services might issue Drought Decrees that prohibit the withdrawal of water in some areas and for some days. Three levels of withdrawal restrictions can be launched: 1 or 2 days a week (level 1), 3 or 4 days a week (level 2), or 7 days a week (i.e. permanent prohibition, level 3). Each Drought Decree concerns one or several pre-defined “drought zones”. For level 1 or 2 these drought zones are divided in sectors (sub areas) so that each day of the week a different sector is successively concerned with the prohibition. Additionally, the decision to apply this restriction is constrained by principles regarding the progressiveness of regulations (i.e. withdrawal restrictions must be progressive) and down- and up-stream solidarity (up-stream area of a given drought zone must be in a restriction level that is greater or equal). Restriction decisions are taken once every week. The modeling of dams and regulation management is detailed in Mayor et al. (2012).

#### 4.1.4 Other socio-economic processes

Regarding other socio-economic processes, such as domestic and industrial water demands and non-agricultural land cover evolutions, MAELIA uses statistical and econometric formalisms either tailored (e.g., industrial demand) or existing (e.g., Reynault and Leenhardt, 2008, for an econometric model of domestic demand according to the water price, principal residence rate, household income, summer maximum temperature, and population density).

#### 4.1.5 Calibration of the model

When applying MAELIA to a river basin the calibration of the MAELIA platform is performed module by module, combining quantitative and qualitative approaches. Many parameters can influence the model outputs, with a high level of interactions. In order to get an overview of the model behavior and to screen influential parameters, multiple sensitivity analyses are performed, while considering some sub-sets of processes or not. These step-by-step sensitivity analyses enabled the different influences and interactions to be disentangled,

and are a preliminary step to the calibration process. The calibration process is multi-objective (e.g., reproducing water flows and anthropogenic dynamics). It uses a multi-point approximation method (Lardy et al. 2014). The principle of this method is to replace the original optimization problem by a succession of simpler and time-independent problems. This approximation is achieved thanks to meta-models for a limited part of the parameter space.

## **4.2 Evaluation and impact of changes in the spatial allocation of cropping systems in the Aveyron sub-basin**

### 4.2.1 Studied area and methodology

Through a participatory design methodology, Murgue et al. (2015) identified with stakeholders from the Aveyron sub-basin different types of changes in the socio-hydrology system that may limit the recurrent water deficits experienced. These deficits correspond to the annual water quantities necessary to maintain river flows above the regulatory minimum thresholds, i.e. the minimum flow that ensures the proper functioning of aquatic environment locally (for details see Mazzega et al. 2014). The methodology was implemented on an 800 km<sup>2</sup> irrigated landscape located in the lower reaches of the Aveyron sub-basin. The mean annual volume withdrawn for irrigation is around 18 hm<sup>3</sup>. Feedstock cereals and maize cropping dominate the area, with numerous patches of fruit and high-income seed-production fields. The utilized agricultural area is 40,000 ha. There are about 1150 farms, of which 43% are irrigated.

During the design process, agricultural land stakeholders as well as water management and environment authorities were asked to specify and quantify as precisely as possible the nature of the changes (e.g., crop rotation, crop management practices) and their location (e.g., in which soil, farm type, or pedoclimatic area), including farm level acceptability thresholds (e.g., which area in a farm can support changes). The geographical information system included in MAELIA acted as a hub during the design process, providing information to ease the elicitation of participants' visions and enabling the formalization of the proposals into spatially explicit alternatives.

Information on the current spatial distribution of cropping systems and the designed alternatives were used as inputs to the MAELIA platform. It was run on a 10 years climatic series (2001-2010) to assess effects of alternative spatial allocations of cropping systems on daily river flows and water management (e.g., dam releases of water).

#### 4.2.2 Evaluation of the MAELIA instance

As suggested by Bergez et al. (2010) regarding evaluation of integrated modeling tools, we articulated quantitative and qualitative approaches for the evaluation of the MAELIA usage in the Aveyron sub-basin. For this, we organized workshops with local agricultural and water management experts and presented them with outputs of simulations using the current cropping system spatial distribution, and dams and restriction management strategies as input. During these workshops the analyses of the simulations were focused on key outputs that were representative of the socio-hydrology system behavior; e.g., annual irrigation withdrawals, dynamics of crop management operations (per CMS pedoclimatic conditions), and simulated stream flow for the main rivers. We provided local experts with the quantitative data when available, mainly the regional Water Agency data on annual withdrawal levels (based on farmer annual declarations), daily measurements of the river flows at river basin outlet, daily dam water releases, etc.

Outcomes of the quantitative and qualitative assessments showed that our use of the MAELIA platform allowed the current intra- and inter-annual withdrawal dynamics from the field to the sub-basin scale to be reproduced (for details see Murgue et al. 2014). Local experts compared simulation outputs with the data from the regional Water Agency and concluded that the simulations were very satisfactory (Figure 7). They also validated the simulated dynamics of crop management operations (e.g., sowing dates, first and last irrigation dates). We also observed that MAELIA reproduced with a good accuracy the observed flow dynamic during the low-flow season (results not shown here). However, even if simulated dam water releases and restriction days were considered as being quite consistent in their patterns, they did not match with the observed daily data. The detailed analysis of these results with local experts showed that, actually, the decision process of releasing dam water and setting withdrawal restrictions does not follow the rules determined by the local authorities. The actual process is the outcome of a social negotiation where “the negotiation ingredients may include the

development of conflicts among the stakeholders, breaches of discussions, the game of political influences, issue linking, electoral considerations and the preservation of the social peace, etc.” (Mazzega et al. 2014). Even if the outcomes of such a negotiation process cannot be simulated with a modeling platform like MAELIA, this method can be used to assess ex ante (based on forecasts) theoretical impacts of changes in agricultural activities or water resources management under the *ceteres paribus* (all other things being equal) hypothesis (Mazzega et al., 2014)

#### 4.2.3 Impact assessment of crop rotation changes

Here, we present the assessment of one key co-designed alternative aiming at reducing the overall irrigation demand and so reduce the global water deficit of the Aveyron sub-basin. It corresponds to the replacement of irrigated maize mono-cropping by a maize-wheat rotation. The wheat crops are irrigated if necessary since they are cropped on fields where irrigation is possible. When designing this alternative, farmers specified that for economic reasons the maize-wheat rotation should be only implemented on 40% of farms’ maize mono-cropping area (i.e. in a particular year, the wheat crop would replace maize on only 20% of the maize mono-cropping area). This alternative resulted in changing maize rotation practices in 100 ha on about 3,000 ha of maize mono-cropping. As a test, we also assessed the potential impact on river flow of this type of alternative if they were implemented on 100% of the farms’ maize monocropping area. These two different simulations are called AltRot40% and AltRot100%, respectively.

Table 2 summarizes the impact on the reduction of annual withdrawals in the study area and the potential reduction of the estimated deficit during the two driest summers in the 10-year studied period. AltRot40% allows for an average 4.2% reduction of annual withdrawals from the watershed. For the years 2003 and 2009 (the two driest summers in the ten years climatic series), the change triggers a reduction of about 0.8 and 1.0 hm<sup>3</sup>, respectively 11% and 14% of the estimated water deficit of the basin. AltRot100% has a more significant impact, allowing a reduction of the withdrawals by about a half of the estimated deficit in the driest years.

The analysis of simulated discharges showed that AltRot40% and AltRot100% have different effects depending on the sub-watershed. In watershed, where river flows are driven by dam

releases (e.g., the Aveyron river), these alternatives have a low impact on the river flow itself. They allow the saving of water in dams at the beginning of the irrigation season, and therefore to secure the possibility of replenishing the flows with water releases at the end of the season. In catchments where water releases from the dam have no (significant) impacts, the simulations showed that the implementation of these alternatives variously raises and lowers the discharge, through the cropping season, and has a tendency to reduce the river discharge at the end of the season (Figure 8). For the Aveyron river, AltRot100% significantly raises the flow level during the low flow season. For the Lère sub-watershed, the impact can be either positive or negative; however, it is always negative towards the end of the season (October and November).

This occurrence is explained by the fact that replacing maize by wheat, while it reduces irrigation withdrawals, also induces less drainage and runoff from the fields to the surrounding rivers. Indeed, as wheat evapotranspiration is higher than that for maize in spring, the soil moisture level is lower: the spring rainfall almost entirely goes into the soil under wheat and evapotranspirates during May and June. Conversely, in a maize field, with the later development of the crop, the soil is kept moist and the rainfall is drained to the aquifers or runs off to the adjacent rivers. As the growing season progresses, the soil moisture under wheat is lower due to evapotranspiration. As a consequence, the summer rain has to replace the water in the soil before the adjacent rivers are fed. In contrast, as maize is intensively irrigated during low flow season the soil is kept moist, and the summer rain is drained or runs off to adjacent water bodies.

In conclusion, neither AltRot40% nor AltRot100% can meet the expectations of local water managers to suppress the annual water deficits but, of course, AltRot100% has a stronger impact than AltRot40%. However, as this alternative is far beyond that designed by local stakeholders, its acceptability by farmers seems to be difficult. The MAELIA simulations showed that in situations where water is not available from reservoirs to replenish the river flow and irrigation water is abstracted directly from the rivers, these alternatives may have negative effects all through the season, especially at the end of the growing season. Even if the evaluation of the MAELIA simulations gave satisfactory results, these scenarios are subject to model errors. The figures provided by MAELIA must be used with caution; they must be further confirmed by sensitivity studies to individual processes or by the use of different models.



## 5 Conclusions

The Garonne river area has been subjected to significant climate change over the past fifty years. Both ISBA-MODCOU and SWAT hydrological models highlight trends toward less water resources being available from year to year. This negative trend of the Garonne river flow is mainly due to the increasing simulated evapotranspiration.

There are now more high resolution space-based data providing useful information on both natural and anthropogenic processes. Two examples have been considered in this paper. In the case of snow, MODIS data were successfully used to validate the snow cover extent of the Ariège at Foix, a mountainous sub-catchment. However, some difficulties may arise when converting the snow cover extent to snow water equivalent, as the relation between these two quantities may be complex. The results over the Garonne basin derived from the ISBA-MODCOU model, which is able to simulate both the snow cover extent and discharge, are in good agreement with both the MODIS and the natural discharge of the Ariège river at Foix. The explicit treatment of elevation bands significantly improved the score of the discharge in ISBA-MODCOU and SWAT (Grusson et al. 2015), while the differences are small concerning the snow cover extent. The MODIS snow cover extent validation may then be extended to the whole mountain range, in order to complement existing in situ snow cover measurements and discharge data.

Concerning the vegetation growth, the use of realistic sowing dates modified the actual evapotranspiration and discharge, with a contrasted impact depending on the year. This pilot study was limited to a small watershed in the Garonne river basin because (a) the agro-hydrological model used requires calibration of water cycle using discharge and runs at the spatial resolution of the high-resolution satellite images (8 meters), and (b) these satellite data with a short revisit time were only available within a narrow swath (Formosat-2). However, a simplified crop growth modelling approach based on satellite images (Duchemin et al. 2008) can be adapted to larger study areas, and the upcoming Sentinel satellite missions will provide similar imagery at the global scale from 2016. In particular, the Sentinel-2 multispectral imagery (Drusch et al. 2012) will enable LAI maps to be generated at 20 m resolution every five days for all land areas. Such a high spatial resolution is necessary in areas such as the Garonne river basin because the cultivated fields are often smaller than 10 ha. With current

mid-resolution sensors such as MODIS (500 m), there is a risk of mixing the signal from winter and summer crops which are often cultivated in adjacent fields. Shorter revisit times (e.g., in comparison with the 16 days for the Landsat mission) are also needed to capture the crop growth and the date of the harvest. We expect that these remote sensing data will enable land surface models to be better constrained so that the hydrological modelling at the catchment scale may be improved. Concerning the impact of human activities, the multi-agent simulation platform MAELIA is able to simulate the impact of realistic agricultural scenarios discussed with local stakeholders on the river flows and water management (i.e. dam releases). The scenario tested in this paper showed that substantial hydrological impacts may only be caused by very significant changes of the crops being grown.

The aim of the work described here is to build a coherent framework representing the socio-hydrology system at the scale of the Garonne catchment. The work must be completed to cover the whole basin, accounting for additional human processes, such as large reservoir management for hydropower and agriculture, and develop the validation using additional data. First, there is a need to develop methods to aggregate the information from the field to relevant hydrological components (sub-basins, irrigated areas, local aquifers, administrative areas, etc.). Secondly, present and future high resolution satellite information should be used to calibrate, constrain or validate the modeling. In addition to information on sowing dates, data from Sentinel-2 will provide information on vegetation development and proxies for the soil water holding capacity. The SWOT mission (to be launched in 2020, Biancamaria et al. 2015) is designed to observe the surface water elevation in rivers wider than 100 m and water bodies (lakes, reservoirs, ponds, continuous wetlands) with an area greater than 250 m x 250 m. In the Garonne catchment, it will provide information on the main rivers and on the actual water storage in the largest reservoirs. It is hoped that the construction of this modelling framework of the Garonne socio-hydrology system will provide valuable information for (i) the operational management of the low water flow period, (ii) the evaluation of scenarios for the development of agriculture, and (iii) the adaptation to climate change.

### **Acknowledgments**

This work was carried out within the framework of the project REGARD funded by the STAE foundation (Toulouse, France). Discharge observations were provided by the French Hydro database (Ministère de l'Écologie, du Développement durable et de l'Énergie,

<http://www.eaufrance.fr>), which gathers data from many observers. The authors thank Eric Sauquet and Frédérick Hendrickx for fruitful discussions on the Garonne river and for making available the natural river flows at Foix, and the Editor in Chief for suggesting linguistic changes. This paper arises from the International Space Science Institute (ISSI) workshop “Remote sensing and water resources”, held at ISSI, Bern, Switzerland, from 6 to 10 October 2014.

## References

- Alcamo J, Döll P, Henrichs T, Kaspar F, Lehner B, Rosh T, Siebert S (2003) Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrological Sciences Journal* 48 :317-337
- Anderies J. M., Janssen MA, Ostrom E (2004) A framework to analyze the robustness of social-ecological systems from an institutional perspective. *Ecology and Society* 9 :1-18
- Arnold JG, Allen PM, Bernhardt G (1993) A comprehensive surface-groundwater flow model. *Journal of Hydrology* 142 :47-69
- Artinyan E, Habets F, Noilhan J, Ledoux E, Dimitrov D, Martin E, Le Moigne P (2008) Modelling the water budget and the riverflows of the Maritsa basin in Bulgaria. *Hydrology and Earth System Sciences* 12 :21-37
- Asokan S, Destouni G (2014) Irrigation Effects on Hydro-Climatic Change: Basin-Wise Water Balance-Constrained Quantification and Cross-Regional Comparison. *Surveys in Geophysics* 35:879-895
- Bardeau M., Bouardaa S. (2010) Gestion des systèmes aquifères alluviaux dans le bassin Adour-Garonne - Modélisation de la nappe alluviale de la Garonne en Haute-Garonne – Année 3. BRGM/RP-58063-FR. Rapport final.  
[http://sigesmpy.brgm.fr/IMG/pdf/mod31\\_annee3\\_final\\_rp-58063-fr.pdf](http://sigesmpy.brgm.fr/IMG/pdf/mod31_annee3_final_rp-58063-fr.pdf) Accessed 27 January 2016
- Beaujouan V, Durand P, Ruiz L, Arousseau P, Cotteret G (2002) A hydrological model dedicated to topography-based simulation of nitrogen transfer and transformation: rationale and application to the geomorphology - denitrification relationship. *Hydrological Processes* 16 :493-507
- Biancamaria S, Lettenmaier DP, Pavelsky TM (2015) The SWOT mission and capabilities for land hydrology. *Surveys in Geophysics* (submitted)
- Boone A, Etchevers P (2001) An intercomparison of three snow schemes of varying complexity coupled to the same land surface model: Local-scale evaluation at an Alpine site. *J. Hydrometeorol.* 2:374-394
- Caballero Y, Voirin-Morel S, Habets F, Noilhan J, LeMoigne P, Lehenaff A, Boone A (2007) Hydrological sensitivity of the Adour-Garonne river basin to climate change. *Water Resour. Res.* 43 doi:10.1029/2005WR004192
- Constantin J, Willaume M, Murgue C, Lacroix B, Therond O (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* 206:55-68
- Courault D, Hadria R, Ruget F, Oliosio A, Duchemin B, Hagolle O, Dedieu G (2010) Combined use of FORMOSAT-2 images with a crop model for biomass and water monitoring of permanent grassland in Mediterranean region. *Hydrology and Earth System Sciences* 14:1731-1744

- Decharme B, Martin E, Faroux S (2013) Reconciling soil thermal and hydrological lower boundary conditions in land surface models. *Journal of Geophysical Research: Atmospheres* 118:7819-7834
- Destouni G, Jaramillo F, Prieto C (2013) Hydroclimatic shifts driven by human water use for food and energy production. *Nature Clim. Change* 3:213-217
- Döll P, Hoffmann-Dobrev H, Portmann F, Siebert S, Eicker A, Rodell M, Strassberg G, Scanlon B (2012) Impact of water withdrawals from groundwater and surface water on continental water storage variations. *Journal of Geodynamics* 59-60:143-156
- Döll P, Kaspar F, Lehner B (2003) A global hydrological model for deriving water availability indicators: model tuning and validation. *Journal of Hydrology* 270:105-134
- Döll P (2009) Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. *Environ. Res. Lett.* doi:10.1088/1748-9326/4/3/035006
- Döll P, Müller Schmied H, Schuh C, Portmann FT, Eicker A (2014) Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites. *Water Resources Research* 50:5698-5720
- Donohue RJ, Roderick ML, McVicar TR (2007) On the importance of including vegetation dynamics in Budyko's hydrological model. *Hydrology and Earth System Sciences* 11:983-995
- Douglas-Mankin KR, Srinivasan R, Arnold JG (2010) Soil and Water Assessment Tool (SWAT) model: Current developments and applications. *Trans. Asabe* 53:1423-1431
- Drusch M, Bello U D, Carlier S, Colin O, Fernandez V, Gascon F, Hoersch B, Isola C, Laberinti P, Martimort P, Meygret A, Spoto F, Sy O, Marchese F, Bargellini P (2012) Sentinel-2: ESA's Optical High-Resolution Mission for GMES Operational Services. *Remote Sensing of Environment* 120:25-36
- Duchemin B, Maisongrande P, Boulet G, Benhadj I (2008) A simple algorithm for yield estimates; Evaluation for semi-arid irrigated winter wheat monitored with green leaf area index. *Environmental Modelling & Software* 23:876-892
- Durand M, Neal J, Rodriguez E, Andreadis KM, Smith LC, Yoon Y (2014) Estimating reach-averaged discharge for the River Severn from measurements of river water surface elevation and slope. *Journal of Hydrology* 511:92-104
- ESDB (2006) european soil data base v2.0, 1kmx1km "dominant value and dominant STU" Rasters.  
[http://eussoils.jrc.ec.europa.eu/ESDB\\_Archive/ESDB\\_data\\_1k\\_raster\\_intro/ESDB\\_1k\\_raster\\_data\\_intro.html](http://eussoils.jrc.ec.europa.eu/ESDB_Archive/ESDB_data_1k_raster_intro/ESDB_1k_raster_data_intro.html) Accessed 20 April 2015
- Faroux S, Kaptué Tchuenté A T, Roujean J-L, Masson V, Martin E, Le Moigne P (2013) ECOCLIMAP-II/Europe: a twofold database of ecosystems and surface parameters at 1 km resolution based on satellite information for use in land surface, meteorological and climate models. *Geosci. Model Dev.* 6:563-582.

- Ferrant S, Oehler F, Durand P, Ruiz L, Salmon-Monviola J, Justes E, Dugast P, Probst A, Probst J-L, Sanchez-Perez J-M (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* 406:1-15
- Ferrant S, Gascoin S, Veloso A, Salmon-Monviola J, Claverie M, Rivalland V, Dedieu G, Demarez V, Ceschia E, Probst J-L, Durand P, Bustillo V (2014a) Agro-hydrology and multi-temporal high-resolution remote sensing: toward an explicit spatial processes calibration. *Hydrology and Earth System Sciences* 18:5219-5237
- Ferrant S, Caballero Y, Dewandel B, Perrin J, Dazin F, Aulong S, Ahmed S, Maréchal, JC (2014b) "Projected impacts of climate change on farmers' extraction of groundwater from crystalline aquifers in South India", *Scientific Reports*, doi:10.1038/srep03697.
- Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK (2005) Global Consequences of Land Use. *Science* 309:570-574
- Frans C, Istanbuluoglu E, Mishra V, Munoz-Arriola F, Lettenmaier DP (2013) Are climatic or land cover changes the dominant cause of runoff trends in the Upper Mississippi River Basin? *Geophysical Research Letters* 40:1104-1110
- Gascoin S, Hagolle O, Huc M, Jarlan L, Dejoux J-F, Szczypta C, Marti R, Sánchez R (2015) A snow cover climatology for the Pyrenees from MODIS snow products. *Hydrology and Earth System Sciences* 19:2337-2351
- Gassman PW, Reyes MR, Green CH, Arnold JG (2007) The soil and water assessment tool: Historical development, applications, and future research directions. *Trans. Asabe*, 50:1211-1250
- Gaudou B, Sibertin-Blanc C, Therond O, Amblard F, Auda Y, Arcangeli J-P, Balestrat M, Charron-Moirez M-H, Gondet E, Hong Y, Lardy R, Louail T, Mayor E, Panzoli D, Sauvage S, Sánchez-Pérez J-M, Taillandier P, Van Bai N, Vavasseur M, Mazzega, P (2014) The MAELIA Multi-Agent Platform for Integrated Analysis of Interactions Between Agricultural Land-Use and Low-Water Management Strategies. In: Alam S J, Parunak HVD (ed) *Multi-Agent-Based Simulation XI*. Springer, Berlin, Heidelberg, pp 85-100.
- Goderniaux P, Brouyère S, Fowler HJ, Blenkinsop S, Therrien R, Orban P, Dassargue A (2009) Large-scale surface-subsurface hydrological model to assess climate change impacts on groundwater reserves. *J. Hydrol.* 373:122–138
- Green TR, Bates BC, Charles SP, Fleming PM (2007) Physically based simulation of potential effects of carbon dioxide-altered climates on groundwater recharge. *Vadose Zone J.* 6 :597–609
- Grouillet B, Fabre J, Ruelland D, Dezetter A (2015) Historical reconstruction and 2050 projections of water demand under anthropogenic and climate changes in two contrasted Mediterranean catchments. *Journal of Hydrology* 522:684-696

- Grusson Y, Xiaoling S, Gascoin S, Sauvage S, Raghavan, S, Anctil F, Sánchez Pérez JM (2015) Exploring snow and streamflow dynamics in an alpine watershed using the semi-distributed hydrological model SWAT. *Journal of Hydrology* 531:574-588
- Gurdak JJ, Roe CD (2010) Review: recharge rates and chemistry beneath playas of the High Plains aquifer, USA. *Hydrogeol. J.* 18:1747–1772
- Habets F, Boone A, Champeaux JL, Etchevers P, Franchistéguy L, Leblois E, Ledoux E, Le Moigne P, Martin E, Morel S, Noilhan J, Seguí- PQ, Rousset-Regimbeau F, Viennot P (2008) The SAFRAN-ISBA-MODCOU hydrometeorological model applied over France. *Journal of Geophysical Research* 113 doi:10.1029/2007JD008548
- Hall D, Riggs G (2007) Accuracy assessment of the MODIS snow products. *Hydrological Processes* 21:1534-1547
- Hendrickx F, Sauquet E (2013) Impact of warming climate on water management for the Ariège River basin (France). *Hydrological Sciences Journal* 58:976-993
- Holman IP, Tascone D, Hess TM (2009) A comparison of stochastic and deterministic downscaling methods for modelling potential groundwater recharge under climate change in East Anglia, UK: implication for groundwater resource management. *Hydrogeol. J.* 17:1629–1641
- Hutchings NJ, Reinds GJ, Leip A, Wattenbach M, Bienkowski JF, Dalgaard T, Dragosits U, Drouet JL, Durand P, Maury O, de Vries W (2012) A model for simulating the timelines of field operations at a European scale for use in complex dynamic models. *Biogeosciences* 9:4487-4496
- Inan HI, Sagris V, Devos W, Milenov P, van Oosterom P, Zevenbergen J (2010) Data model for the collaboration between land administration systems and agricultural land parcel identification systems. *Journal of Environmental Management* 91:2440–2454
- Jyrkama MI, Sykes JF (2007) The impact of climate change on spatially varying groundwater recharge in the Grand River watershed (Ontario). *J. Hydrol.* 338:237–250
- Kandasamy J, Sountharajah D, Sivabalan P, Chanan A, Vigneswaran S, Sivapalan M (2014) Socio-hydrologic drivers of the pendulum swing between agricultural development and environmental health: a case study from Murrumbidgee River basin, Australia. *Hydrology and Earth System Sciences* 18:1027-1041
- Kovalevskii VS (2007) Effect of climate changes on groundwater. *Water resour.* 34:140–152
- Lardy R, Mazzega P, Sibertin-Blanc C, Aud, Y, Sánchez Pérez JM, Sauvage S, Therond O. (2012) Calibration of simulation platforms including highly interweaved processes: the MAELIA multi-agent platform. In: Ames DP, Quinn N, Rizzoli A (ed) 7th Int. Congress on Env. Modelling and Software (iEMSs). pp 1-8
- Lehner B, Liermann CR, Revenga C, Vörösmarty C, Fekete B, Crouzet P, Döll P, Endejan M, Frenken K, Magome J, Nilsson C, Robertson JC, Rödel R, Sindorf N, Wisser D (2011) High-

resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment* 9:494-502

Lobell D, Bala G, Mirin A, Phillips T, Maxwell R, Rotman D (2009) Regional Differences in the Influence of Irrigation on Climate. *J. Climate* 22:2248-2255

McGinnis MD, Ostrom E (2014) Social-ecological system framework: initial changes and continuing challenges. *Ecology and Society*. doi:10.5751/ES-06387-190230

Magand C, Ducharne A, Le Moine N, Gascoïn S (2013) Introducing Hysteresis in Snow Depletion Curves to Improve the Water Budget of a Land Surface Model in an Alpine Catchment. *J. Hydrometeor* 15:631-649

Mayor E, Mazzega P, Panzoli D, Sibertin-Blanc C, Therond O., Vavasseur M. (2012) Formal representation of Water Withdrawal Policies for Integrated Assessment. In: Gilbert T, Kirkilionis M, Nicolis G. *Proceedings of the European Conference on Complex Systems 2012*, pp1-15

Mazzega P, Therond O, Debril T, March H, Sibertin-Blanc C, Lardy R, Sant'ana D (2014) Critical multi-level governance issues of integrated modelling: An example of low-water management in the Adour-Garonne basin (France) . *Journal of Hydrology* 519, Part C:2515-2526

Mishra AK, Singh VP (2010) A review of drought concepts. *Journal of Hydrology* 391:202-216

Moisselin JM, Schneider M, Canellas C, Mestre O (2002) Les changements climatiques en France au 20ème siècle. Etude des longues séries homogénéisées de données de température et de précipitations. *La Météorologie* 38:45-56

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP, Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. *Nature* 463:747-756

Murgue C, Lardy R, Vavasseur M, Leenhardt D, Therond O (2014) Fine spatio-temporal simulation of crop and farming systems effects on irrigation withdrawal dynamics within a river basin. In: Ames DP, Quinn N, Rizzoli A (ed) *7th Int. Congress on Env. Modelling and Software, iEMSs*. pp 1784-1791

Murgue C, Therond O, Leenhardt D (2015) Toward integrated water and agricultural land management: Participatory design of agricultural landscapes. *Land Use Policy* 45:52-63

Nash J, Sutcliffe J (1970) River flow forecasting through conceptual models part I – A discussion of principles. *Journal of Hydrology* 10:282-290

Parajuli P, Jayakody P, Sassenrath G, Ouyang Y, Pote J (2013) Assessing the impacts of crop-rotation and tillage on crop yields and sediment yield using a modeling approach . *Agricultural Water Management* 119:32-42



- Perrin J, Ferrant S, Massuel S, Dewandel B, Maréchal J, Aulong S, Ahmed S (2012) Assessing water availability in a semi-arid watershed of southern India using a semi-distributed model. *Journal of Hydrology* 460-461:143-155
- Probst JL (1983) *Hydrologie du bassin de la Garonne : Modèles de Mélange, Bilan de l'Erosion, Exportation des Nitrates et des Phosphates*. PhD Thesis, Univ. Toulouse.
- Qiu GY, Yin J, Tian F, Geng S (2011) Effects of the "Conversion of Cropland to Forest and Grassland Program" on the Water Budget of the Jinghe River Catchment in China. *Journal of environmental quality* 40:1745-1755
- Reynaud A, Leenhardt D (2008) MoGIRE : a model for integrated water management. In: Sánchez-Marrè M, Béjar J, Comas J, Rizzoli AE, Guariso G (ed) *Proceedings of the 2008 International Congress on Environmental Modelling and Software*. iEMSs. pp 576-583
- Sauquet E, Dupeyrat A, Hendrickx F, Perrin C, Samie R, Vidal J-P (2009) IMAGINE 2030, climate and water management: uncertainties on water resources for the Garonne river basin in 2030? <http://cemadoc.irstea.fr/oa/PUB00028876-imagine-2030-climat-amenagements-garonne-queelles-i.html> Accessed 20 April 2015
- Scibeck J, Allen DM (2006) Modeled impacts of predicted climate change on recharge and groundwater levels. *Water Resour.* doi:10.1029/2005WR004742
- Sivapalan M, Savenije HHG, Blöschl G (2012) Socio-hydrology: A new science of people and water. *Hydrological Processes* 26:1270-1276
- Szczypta C, Gascoin S, Houet T, Hagolle O, Dejoux JF, Vigneau C, Fanise P. (2015) Impact of climate and land cover changes on snow cover in a small Pyrenean catchment. *Journal of Hydrology* 521:84-99
- Taillandier P, Therond O, Gaudou B (2013) A new BDI agent architecture based on the belief theory. Application to the modeling of cropping plan decision-making. In: Seppelt R, Voinov AA, Lange S, Bankamp D (ed) *Managing Resources of a Limited Planet*, Proceedings of the sixth biennial meeting of the International Environmental Modelling and Software Society. iEMSs. pp. 2463-2470
- Therond O, Sibertin-Blanc C, Lardy R, Gaudou B, ballestrat M, Hong Y, Louail T, Mayor E, Nguyen VB, Taillandier V, Vavasseur M, Mazzega, P (2014) Integrated modelling of social-ecological systems: The MAELIA high-resolution multi-agent platform to deal with water scarcity problems. In: Ames DP, Quinn NWT, Rizzoli AE (ed) *7th Int Congress on Env. Modelling and Software*. iEMSs. pp 1833-1840
- van Emmerik THM, Li Z, Sivapalan M, Pande S, Kandasamy J, Savenije HHG, Chanan A, Vigneswaran S (2014) Socio-hydrologic modeling to understand and mediate the competition for water between agriculture development and environmental health: Murrumbidgee River basin, Australia. *Hydrology and Earth System Sciences* 18:4239-4259
- Vidal J-P, Martin E, Franchistéguy L, Baillon M, Soubeyroux J-M (2010) A 50-year high-resolution atmospheric reanalysis over France with the Safran system. *International Journal of Climatology* 30:1627-1644

Vörösmarty CJ, Green P, Salisbury J, Lammers RB (2000) Global Water Resources: Vulnerability from Climate Change and Population Growth. *Science* 289:284-288

Wada Y, van Beek LPH, van Kempen CM, Reckman JWTM, Vasak S, Bierkens MFP (2010) Global depletion of groundwater resources. *Geophysical Research Letters* 37  
doi:10.1029/2010GL044571

Table 1. Key processes of socio-hydrology systems represented in the MAELIA multi-agent platform. Note that “Reference watershed” in the Table corresponds to the Finest watershed used by French administration to manage water. HRU stands for “hydrological response unit” (with homogenous soil, slope and land cover)

Processes	Nature of the model	Spatial and temporal resolutions
<i>Ecological:</i>		
- Hydrology (surface and groundwater)	Land and routing phases of SWAT (Arnold et al. 1993)	Reference watershed /Day
- Crop growth	AqYield: empirical generic crop model (Constantin et al. 2015)	Field/Day
- Other plant growth	Simplified version of SWAT formalisms	HRU <sup>4</sup> /Day
<i>Socio-economic:</i>		
- Land cover change	Statistical and probabilistic model based on the analysis of the Corine Land Cover database ( <a href="http://sd1878-2.sivit.org/">http://sd1878-2.sivit.org/</a> )	HRU/Year
- Demography	Statistic model based on French national data	District/Year
- Domestic consumption	Econometric model (Reynaud and Leenhardt 2008)	Withdrawal and reject points/Day
- Industrial consumption	Statistical model	Withdrawal and reject points/Day
<i>Decision-making:</i>		
- Crop allocation (cropping plan)	Multi-criteria decision based on Dempster-Shafer belief theory integrated into a Belief-Desire-Intention architecture (Taillandier et al. 2012)	Farm/Year
- Crop management	Nested decision rules (IF THEN ELSE)	Field/Day
- Dam management	Nested decision rules (IF THEN ELSE)	Dam and supplied river section/Day
- Water use restriction	Nested decision rules (IF THEN ELSE)	Restriction zone/Day

Table 2. Impact of the alternate scenarios AltRot40% (replacement of irrigated maize mono-cropping by a maize-wheat rotation over 40% of the present maize fields) and AltRot100% (same as Alt40%, but over 100% of the irrigated maize mono-cropping) on the water withdrawn and the water deficit, expressed in %

	Water withdrawn	Water deficit	Water deficit
	2000-2010	2003	2009
AltRot40%	-4.2%	-11%	-14%
AltRot100%	-10.5%	-27%	-39%

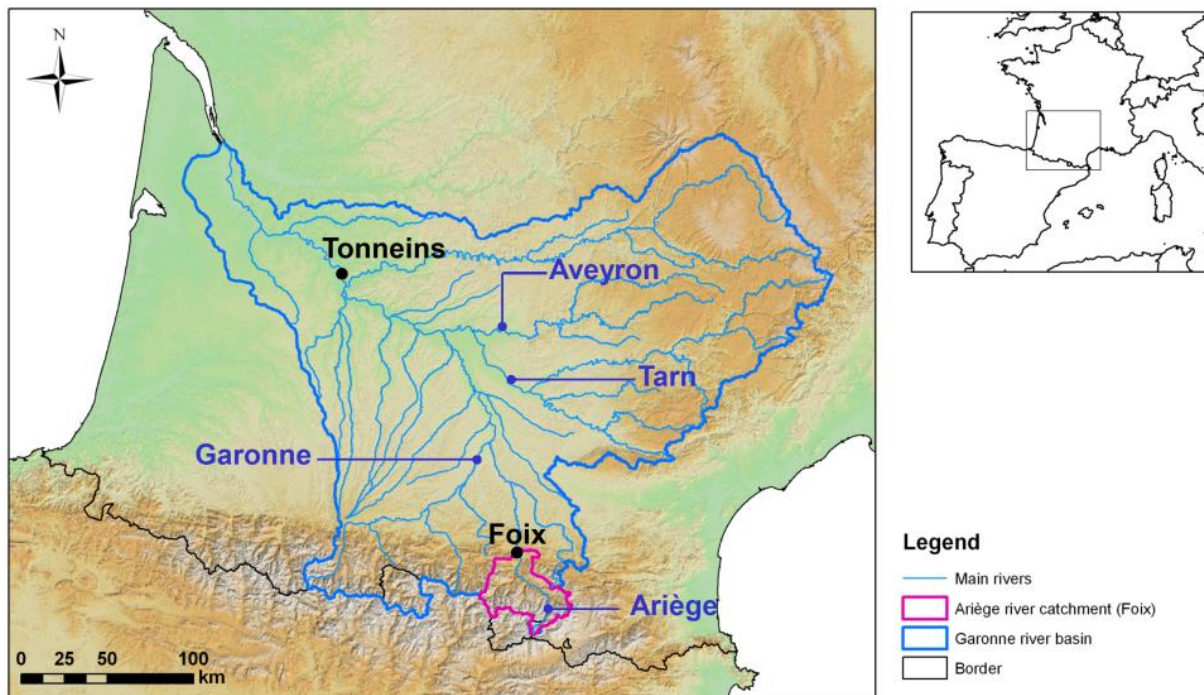


Figure 1: Map of the Garonne river basin, showing the main rivers and discharge stations mentioned in the paper.

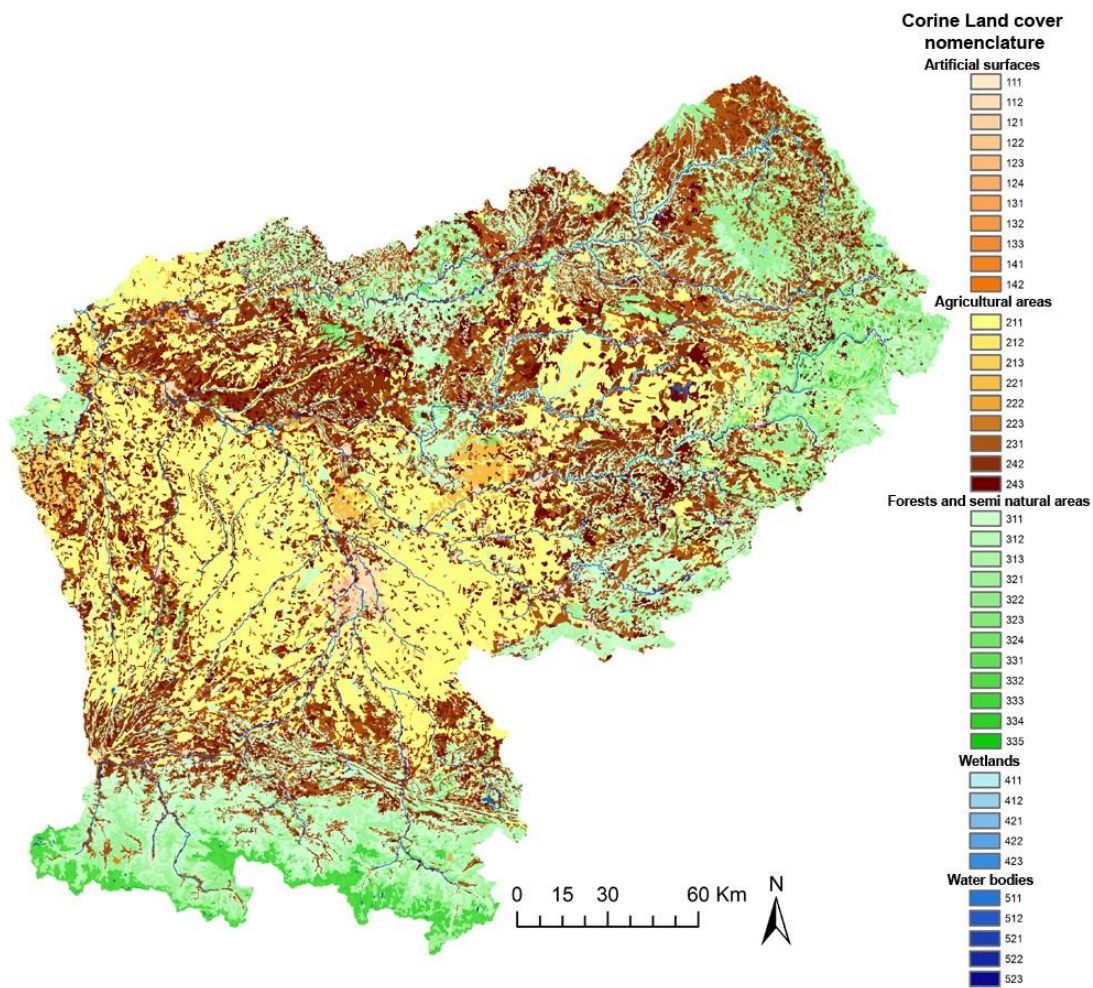


Figure 2: Map of the land use of the Garonne river basin. Sub-classification with numbers corresponds to the Corine-land cover classification

<http://www.eea.europa.eu/publications/COR0-landcover> .

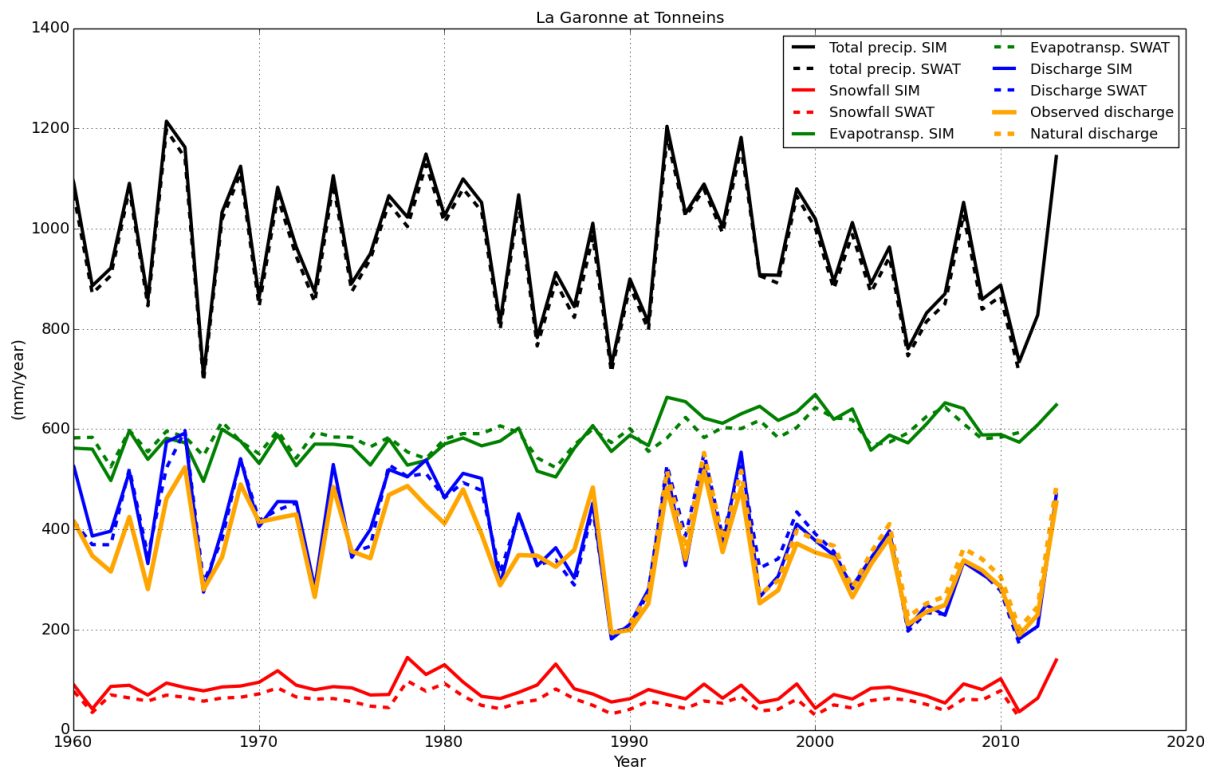


Figure 3: Variation of the main components of the water balance over the period 1960-2013 for the Garonne at Tonneins, as estimated by the Safran analysis system (precipitation) and the ISBA-MODCOU and SWAT models (evapotranspiration, discharge, snowfall)

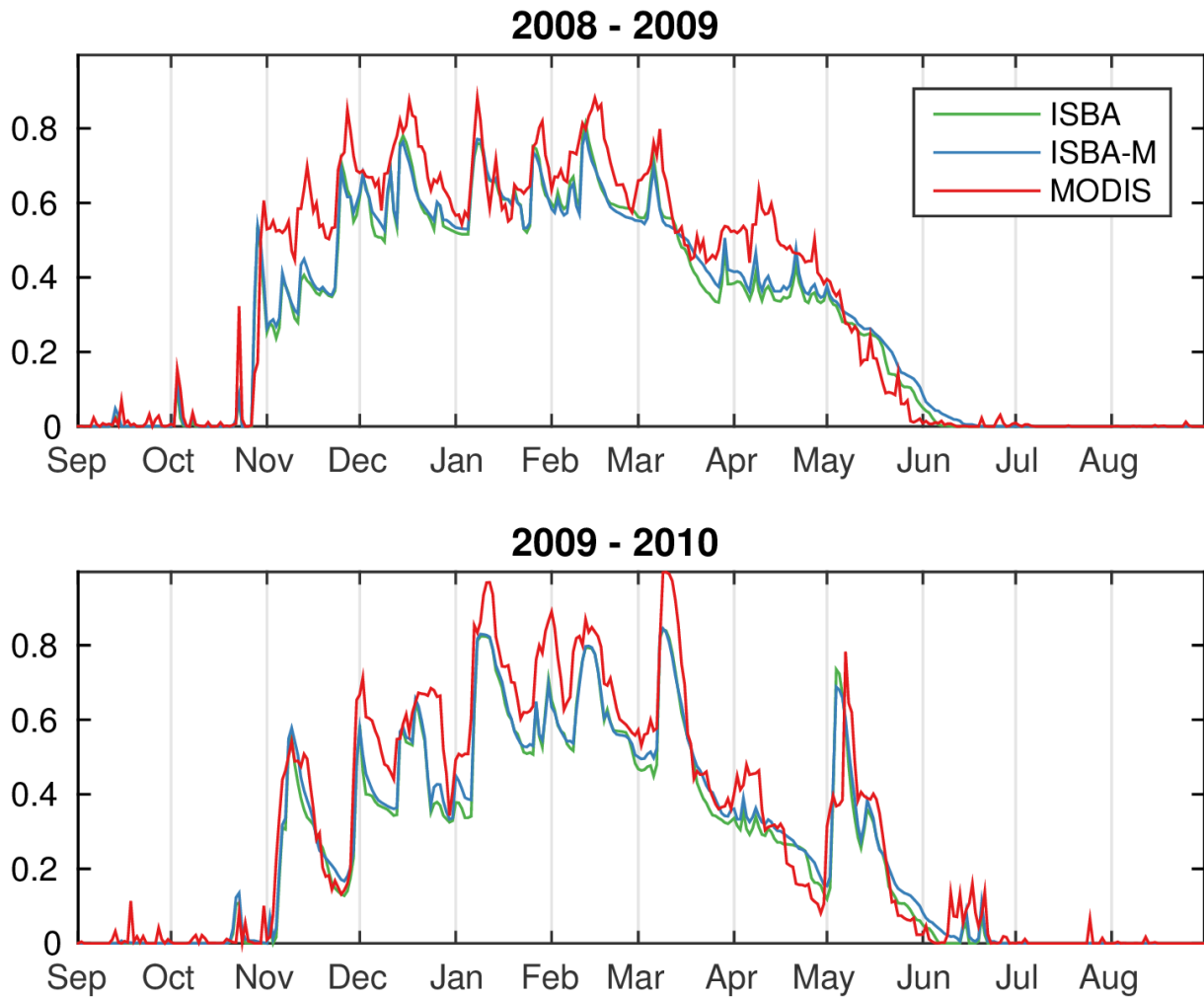


Figure 4: Fractional snow cover extent for the Ariège catchment at Foix : comparison of the snow cover extent simulated by the standard version of ISBA (ISBA) and the version accounting for elevation bands in mountain regions (ISBA-M) with the MODIS-derived climatology for two winters.



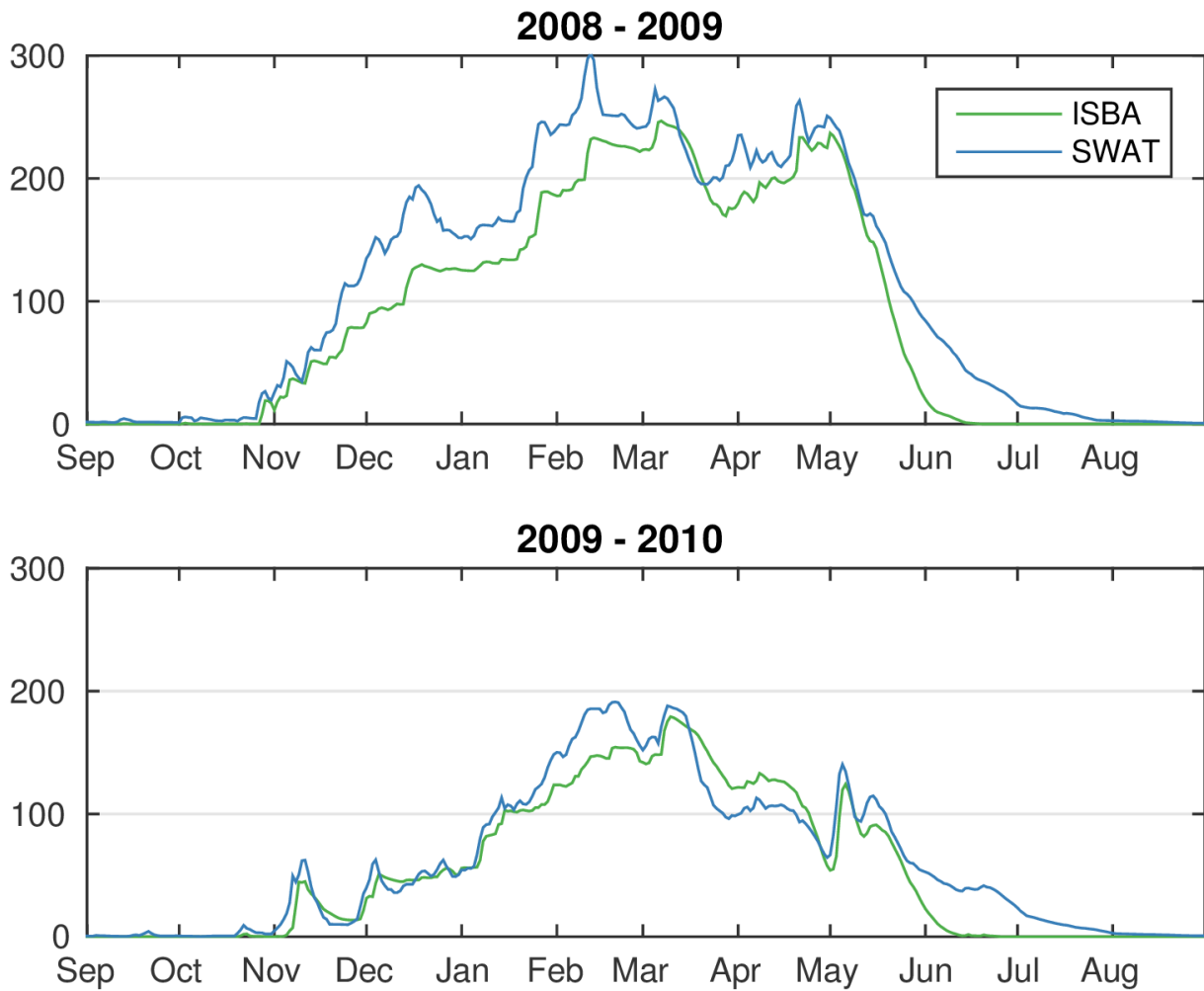


Figure 5: Snow water equivalent for the Ariège catchment at Foix: comparison of the snow water equivalent (mm) simulated by ISBA and SWAT over two years.

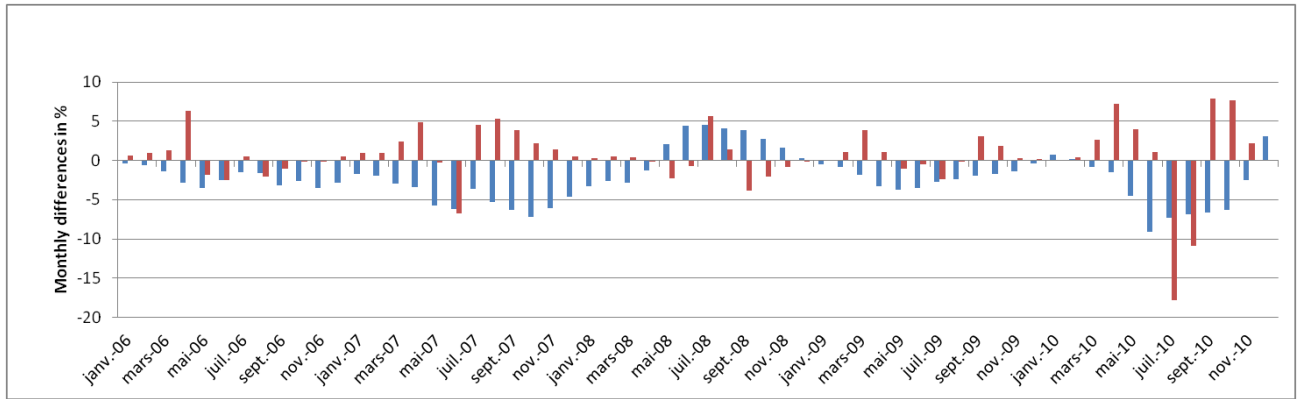


Figure 6: Monthly discharge (blue) and evapotranspiration (red) simulated by the TNT2 model: differences between “optimized sowing date” and “a priori sowing dates”

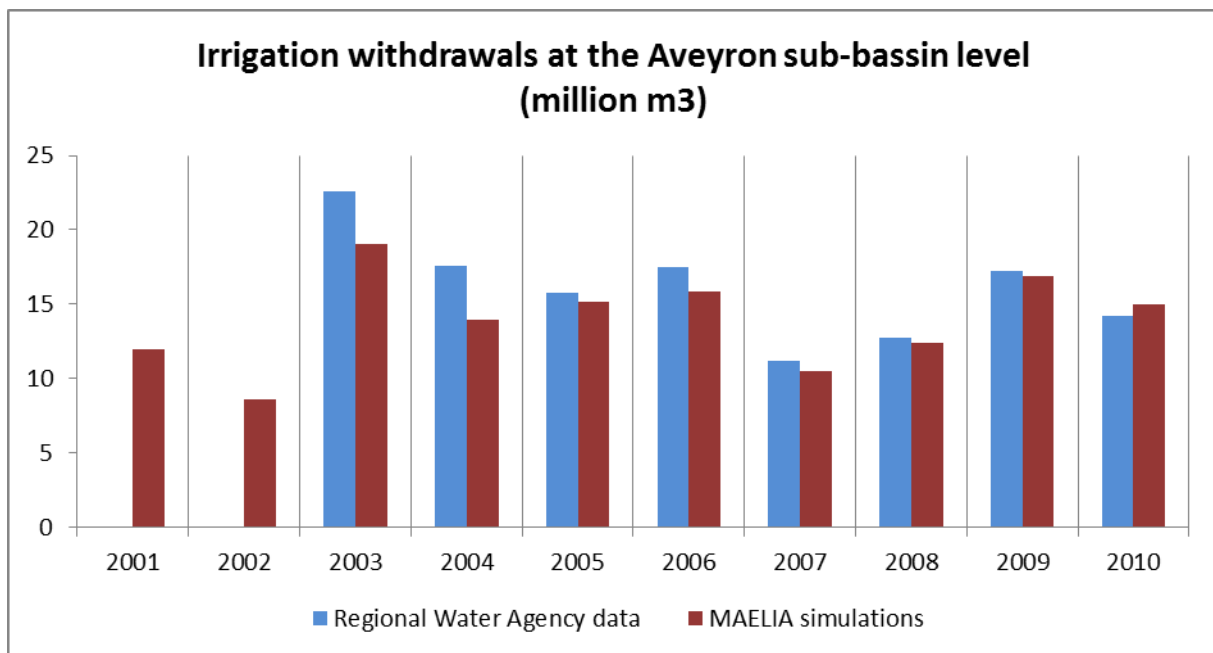
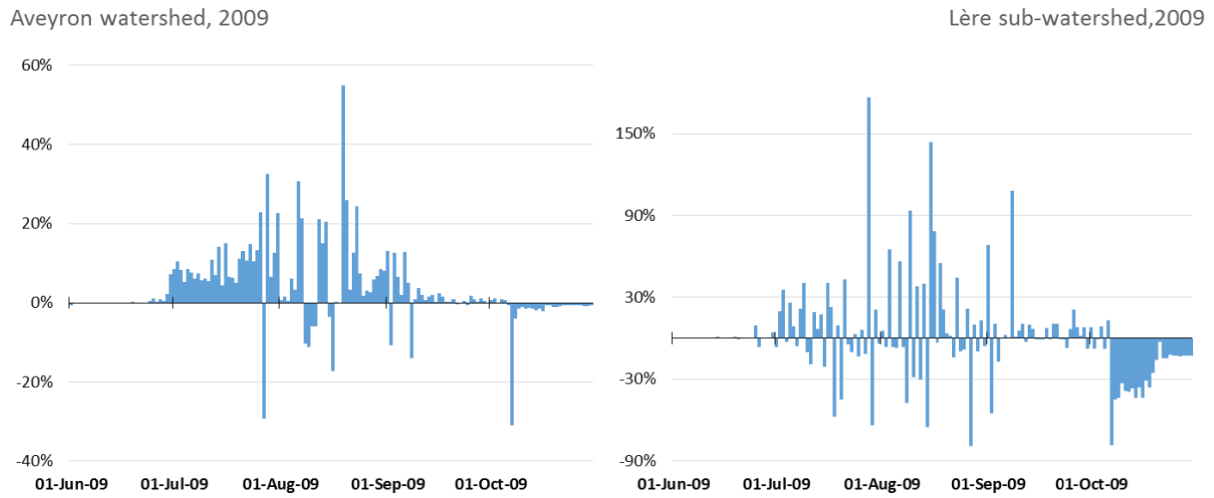


Figure 7: Annual withdrawal volumes (in million m<sup>3</sup>) estimated by the Regional Water Agency through aggregation of annual irrigator declarations (2003-2010, blue) and estimated with the MAELIA modelling platform through simulation of irrigation management strategies at the field level (2001-2010, red). For the MAELIA simulations, in 2003, 2004 and 2005, the crop patterns of farms in the sub-basin were estimated while for the other years observed data from the French Land Parcel Identification System were used. This may explain the underestimation of water withdrawals by MAELIA for 2003 and 2004

Hydrological impact of AltRot<sub>100%</sub>: difference in simulated flows  
 $Y = [\text{AltRot} - \text{CurSit}] / \text{CurSit}$



% of days simulated over/under the flow level in Current Situation [May - September, 2000-2010]		
watershed	Over	Under
Aveyron	10.6%	1.9%
Lère	18.1%	10.7%

Figure 8: Difference (in %) of the simulated outflows between AltRot100% and the current situation [  $(\text{AltRot} - \text{CurSit})/\text{CurSit}$  ] for the Aveyron river (strongly supported by water releases from dams) and the Lère river (with only a few water releases from dams)