Indecis
Sectorial Climate Services

Integrated approach for the **d**evelopment across **E**urope of user oriented **c**limate **i**ndicators for GFCS high-priority **s**ectors: Agriculture, disaster risk reduction, energy, health, water and tourism

Work Package 6

Deliverable 6.4

A French spatially distributed hydrological model as a demonstrator for a national groundwater management tool

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Introduction

The objective of this study is to highlight the potential of a large-scale hydrogeological model over France for providing indicators that could be useful for stakeholders and for studies of climate change impact. This study presents a demonstrator developed with the MARTHE hydrogeological modeling software and preliminary results obtained using different sources of hydro-meteorological inputs. This demonstrator rely on a previous methodology presented in Vergnes et al. (2012) specifically developed for taking into account groundwater in large-scale climate models. The grid-cell resolution of this previous study was approximately 10 km over France. Here we choose a finer resolution of 2 km in order to capture the spatial variability of the water table evolution with better confidence.

Methods

Parameterization of the model

This part takes over the parameterization of Vergnes et al. (2012) and presents only the main aspects of the methodology as well as the main changes.

The MARTHE hydrogeological modelling software

The Modélisation d'Aquifères avec un maillage Rectangulaire, Transport et HydrodynamiquE (Modelling Aquifers with Rectangular cells, Transport and Hydrodynamics) computer code is the hydrogeological modelling software programme from the French Geological Survey (BRGM) (Thiéry, 2015; Thiéry et al., 2018). MARTHE embeds single-layer to multilayer aquifers and hydrographic networks. It is designed for 2-dimensional or 3-dimensional modelling of flows and mass transfers in aquifer systems, including climatic, human influences and possible geochemical reactions. Groundwater flow is computed by a 3-dimensional finite volume approach to solve the hydrodynamic equation based on Darcy's law and mass conservation, using irregular rectangular grids, with the possibility of nested grids. River flows are simulated based on a kinematic wave approach that is fully coupled to groundwater flow. Groundwater–river exchanges are taken into account in both directions.

River Network

Building the river network and the river parameterization of the model requires the use of a Digital Elevation Model (DEM). Figure 1 shows the topography of the GMTED2010 DEM (Danielson and Gesch, 2011) at a 7.5 arcseconds (grid cell of around 250 m width) and converted to a 2 km resolution grid using a bilinear interpolation.

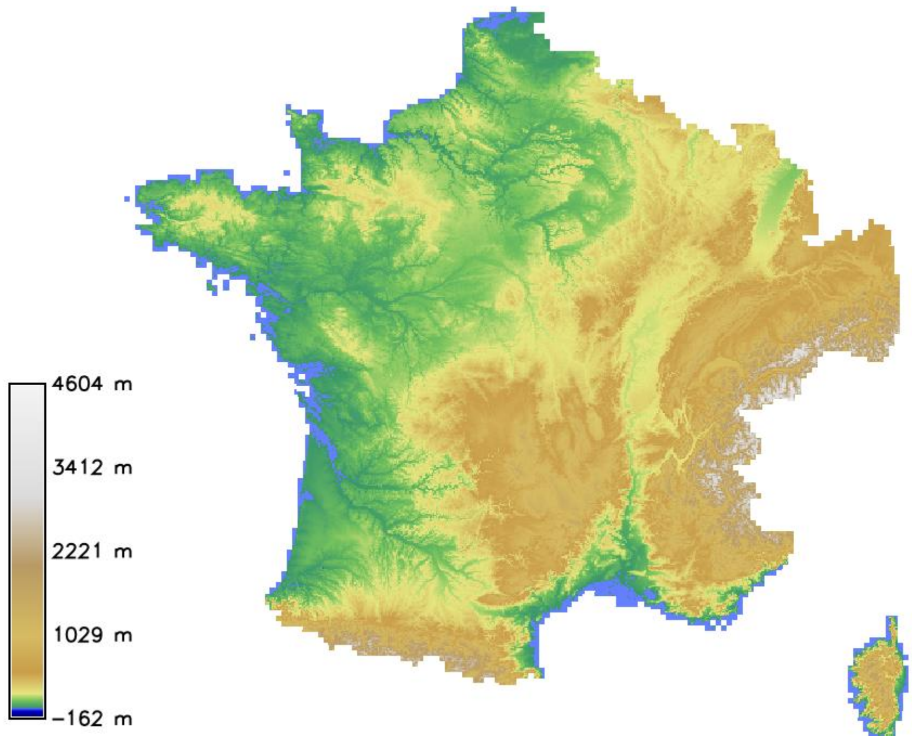

Figure 1: GMTED2010 Digital Elevation Model over France.

This DEM helps to compute drainage direction in each grid cell using GIS treatment. This drainage direction allows building the river basins and river tributaries to integrate in the model. Figure 2 shows the 960 tributaries defining the river network in the MARTHE demonstrator. River grid cells define each tributaries.

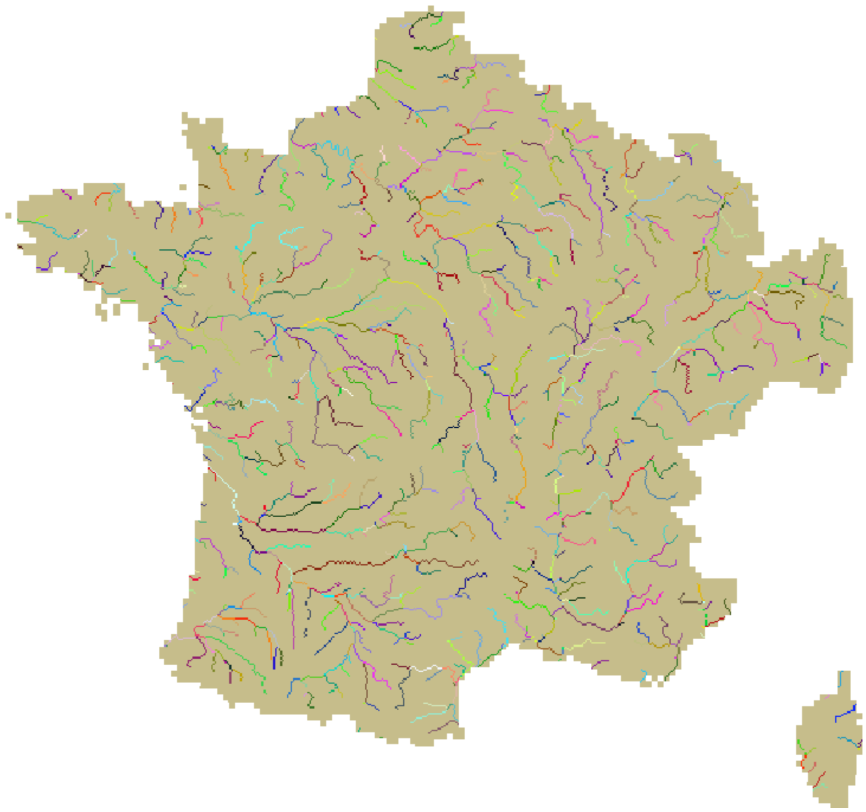

Figure 2 : River network of the model. 960 tributaries are represented.

Each of these river grid cells can potentially exchange water with the river (gaining or losing streams). The parameterization of groundwater-river flows is:

$$Q_{riv} = \begin{vmatrix} RC(H - H_{riv}) & \text{where} & H > Z_{bed} \\ RC(Z_{bed} - H_{riv}) & where & H < Z_{bed} \end{vmatrix} \tag{1}$$

With

$$RC = \frac{LW}{\tau} \tag{2}$$

where Z_{bed} (m) is the riverbed elevation, which is the elevation in the grid cell minus the river bankfull height h_c (m) and H_{riv} (m) is the river stage elevation, calculated as the sum of Z_{bed} (m) with the river water height h_s (m). W (m) and L (m) are the width and the length of the river respectively. Τ (s) represents the time transfer coefficient between river and groundwater. It varies arbitrarily from 30 days in major river streams to 5 days in the upstream grid cells through a linear relationship with the river stream order given by the river network in each grid cell of a given basin (Vergnes et al., 2012). H_{riv} is computed using the Manning's formula with roughness coefficient varying from 0.04 to 0.06 from the upstream to the downstream of the river network of a given basin. Figure 3 shows the scheme of river-groundwater exchanges in the model.

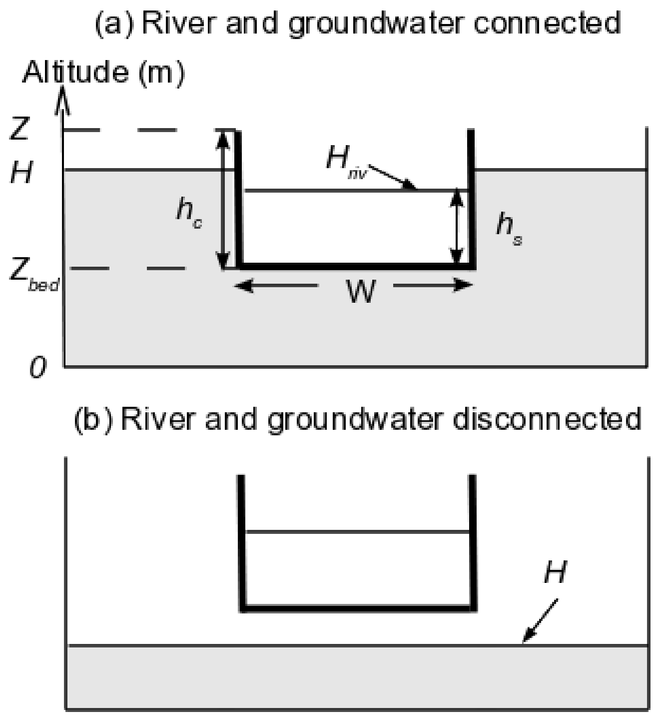

Figure 3 : Scheme of the river-groundwater exchanges for (a) river and groundwater connected and (b) river and groundwater disconnected (from (Vergnes and Decharme, 2012)).

Aquifers

The hydrodynamic characteristics of aquifers (i.e. transmissivity and porosity) and the delineation of the simulated aquifers are defined in Vergnes et al. (2012). The model only contains one superficial layer connected to the rivers and replenished by groundwater recharge.

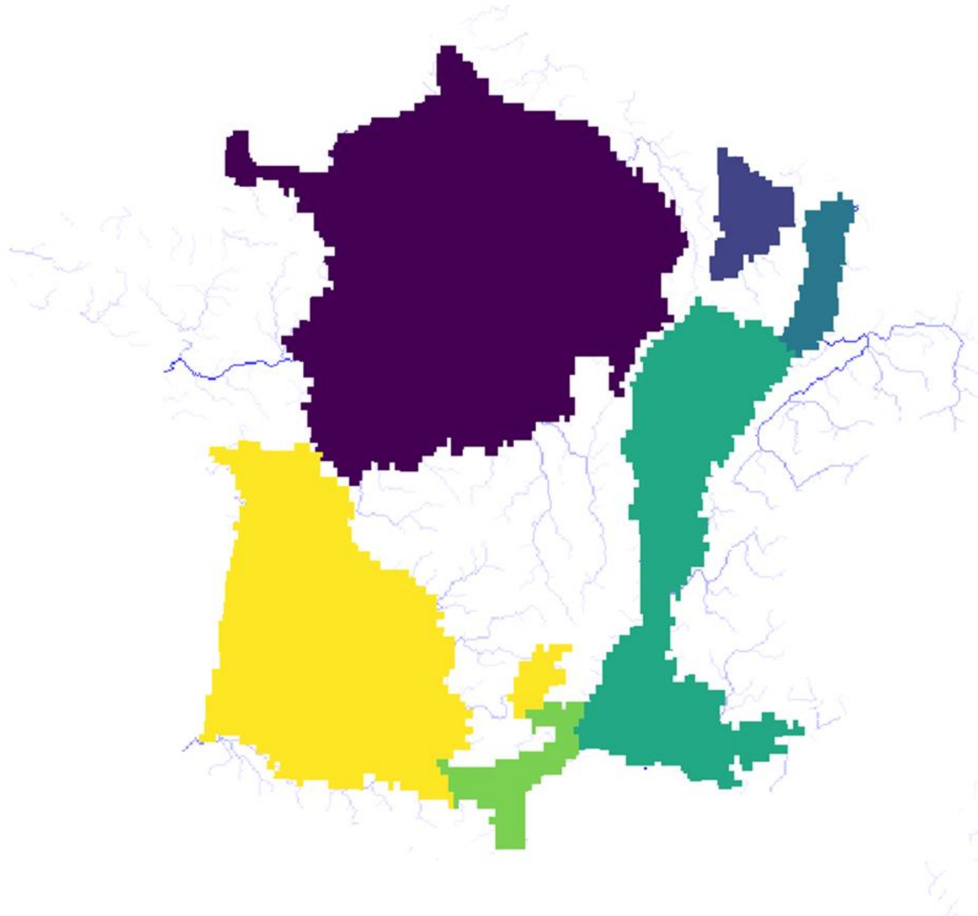

Figure 4 : The simulated aquifer over the whole domain.

Experimental design

The MARTHE computer code requires groundwater recharge and surface runoff as inputs for simulating hydrologic systems. This study compares three simulations using three different inputs over a 10-years period from 1 August 2000 to 31 July 2010. The corresponding simulations are:

- SURFEX/SAFRAN: This simulation uses groundwater recharge and surface runoff computed by the SURFEX land surface model (Le Moigne et al., 2020) with the SAFRAN meteorological inputs (Vidal et al., 2010).
- IDPR/SAFRAN: Groundwater recharge and surface runoff comes from the IDPR method using the SAFRAN meteorological inputs.
- IDPR/EOBS: Groundwater recharge and surface runoff comes from the IDPR method using the EOBS meteorological inputs.

SAFRAN

The SAFRAN meteorological analysis is a mesoscale atmospheric analysis system for surface variables (Vidal et al., 2010). It provides meteorological forcing data over France on an 8 by 8 km grid at the hourly time step using observed data and atmospheric simulations. Originally intended for mountainous areas, it was later extended to cover France. SAFRAN estimates eight variables: rainfall, snowfall, incoming solar and atmospheric radiation, cloudiness, air temperature and relative humidity 2m above ground, and wind speed at 10 m. SAFRAN uses all the observations available to estimate each atmospheric variable except for radiation.

SURFEX

SURFEX is a modelling platform aimed at simulating the water and energy fluxes at the interface between the surface and the atmosphere (Masson et al., 2013). It includes databases, interpolation schemes and several physical options that allow its use over different spatial and temporal scales. SURFEX gathers several physical schemes in a single platform, allowing for the simulation of the urban surfaces and the main components of the water cycle: sea and ocean, lake, vegetation, and soil. Land surface processes are taken into account using the Interaction between Soil, Biosphere, and Atmosphere (ISBA) land surface scheme (Noilhan and Planton, 1989). ISBA uses a short list of parameters depending on vegetation and soil types. The temporal evolution of the soil water and energy budget is computed using a multilayer soil scheme based on the explicit resolution of the one-dimension Fourier law as well as the mixed form of the Richards equation (Decharme et al., 2013).

EOBS

EOBS is an Europe-wide temperature and precipitation data set covering Europe and available at a 0.25° resolution grid (Cornes et al., 2018). This gridded dataset is based on the interpolation of station-derived meteorological observations available at the European scale.

IDPR

The Network Development and Persistence Index (IDPR) makes it possible to qualify indirectly the capacity of soils and the subsurface to allow infiltration or on the contrary, to cause rainfall to run off (Mardhel et al., 2020). Here it was used to partition the daily effective precipitation computed using one simple water balance method forced with the SAFRAN data on the one hand and EOBS data on the oher hand. Details about effective precipitation computation and groundwater recharge and runoff partition can be found on the D6.4 BRGM contribution n°1.

Preliminary evaluation of the demonstrator

Surface water budget comparison

Figure 5 show the yearly, monthly and daily accumulation of total runoff spatially averaged over the simulated domain for SURFEX/SAFRAN, IDPR/SAFRAN and IDPR/EOBS. The total runoff corresponds to the sum of the groundwater recharge and the surface runoff. On a yearly basis, the IDPR/EOBS provides lees total runoff than the two other inputs based on the SAFRAN meteorological data. The daily evolution shows smoother variations for SURFEX/SAFRAN than for the IDPR method. Figure 6 and Figure 7 show the same results for the groundwater recharge and the surface runoff respectively. The amount of groundwater recharge computed through the IDPR method is higher than SURFEX. It is the opposite for surface runoff.

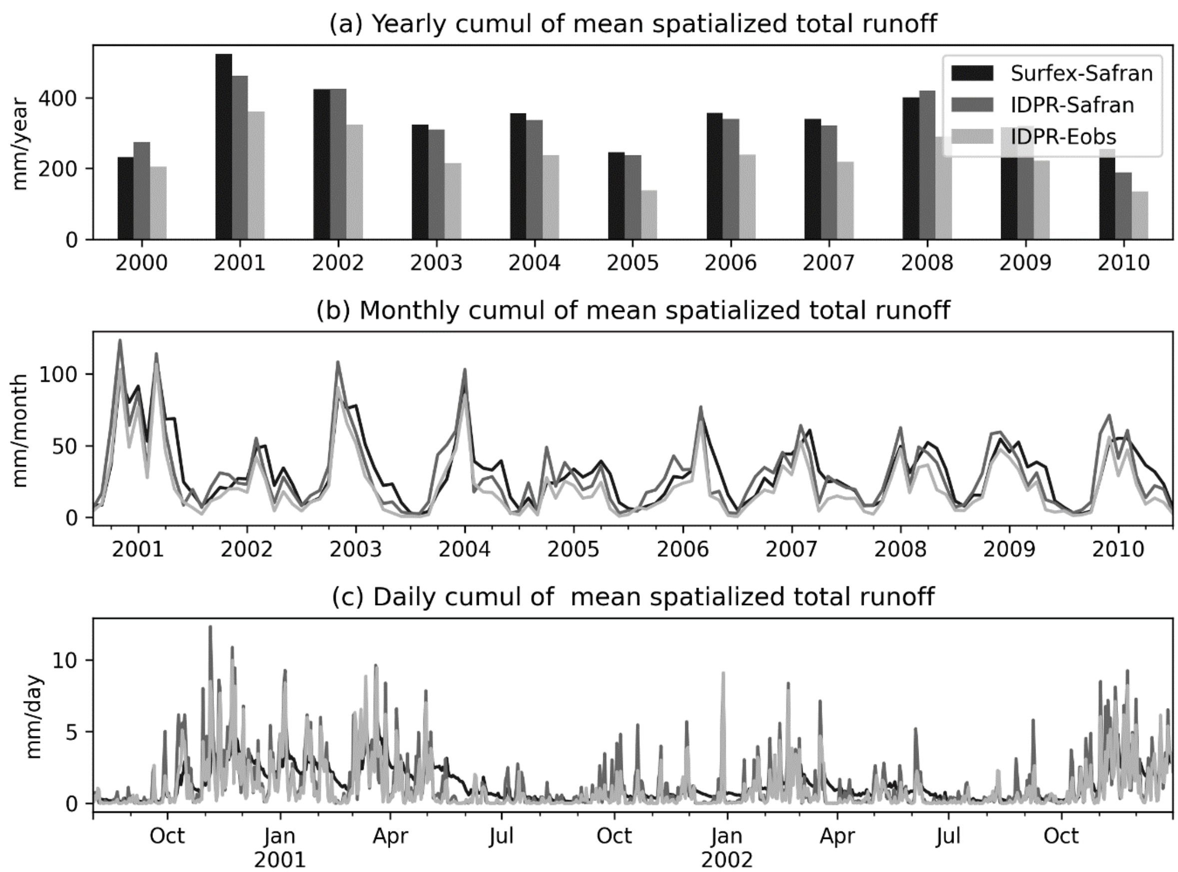

Figure 5 : (a) Yearly, (b) monthly and (c) daily cumul of mean spatialized total runoff

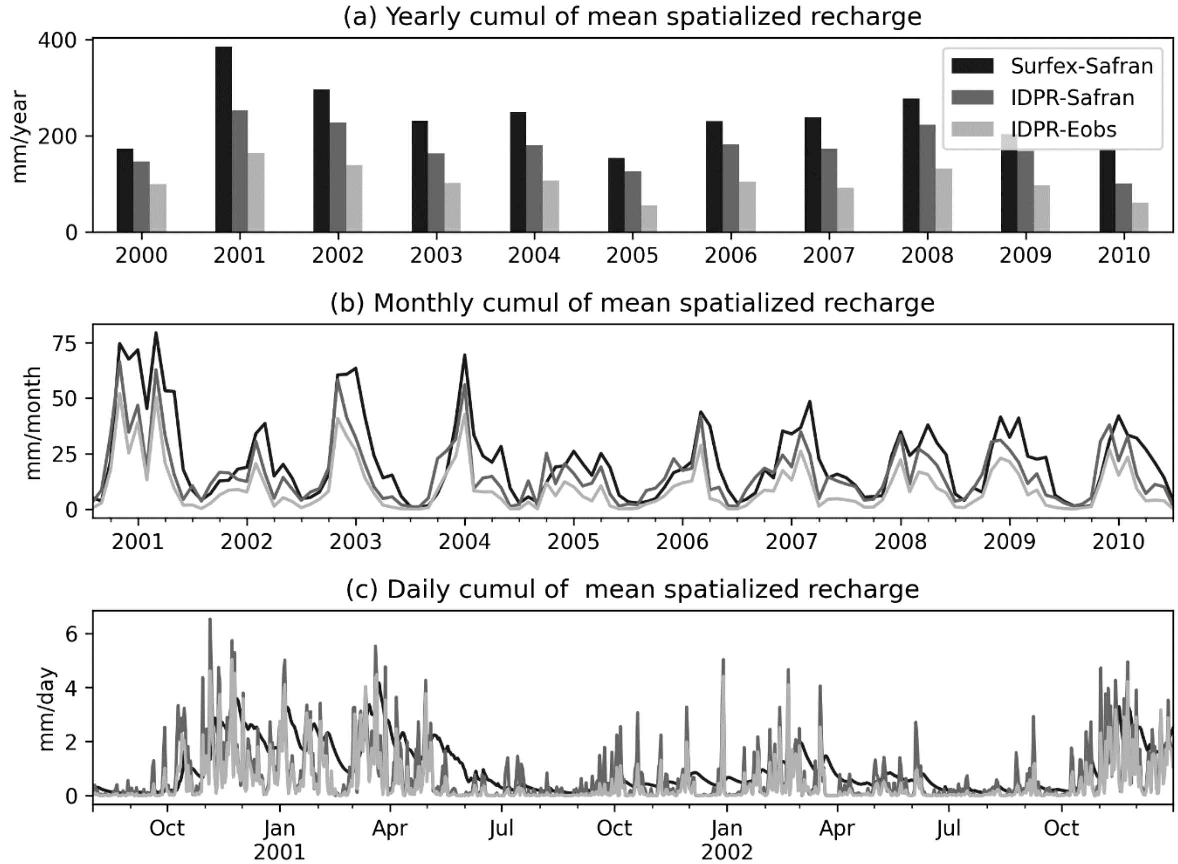

Figure 6 : (a) Yearly, (b) monthly and (c) daily cumul of mean spatialized groundwater recharge

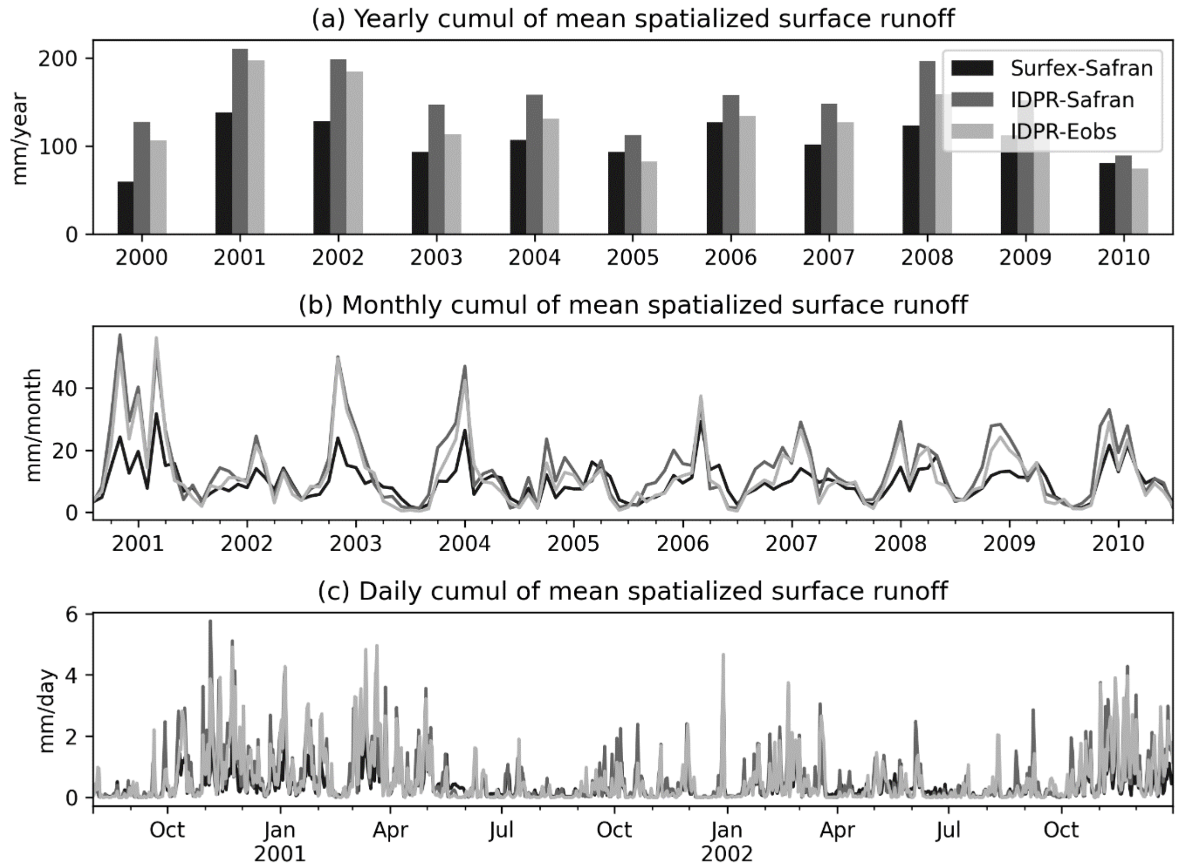

Figure 7: (a) Yearly, (b) monthly and (c) daily cumul of mean spatialized surface runoff

River discharges

Figure 8 shows the observed and simulated river discharges at the gauging stations located at the outlet of the Seine, the Loire, the Garonne and the Rhône Rivers. Table 1 presents the scores of Ratio and Nash-Sutcliff (Nash and Sutcliffe, 1970) coefficients for these four gauging stations. All the Nash coefficients presents Nash scores greater than 0.7 showing the relevance of the chosen parameterization. The ratio score corresponds to the ratio between the mean simulated discharge and the mean observed discharge. Ratios not equal to one mean underestimated or overestimated simulated river discharges. For example, SURFEX/SAFRAN overestimates the mean Seine river discharges. Lower ratio scores can be attributed to uncertainties in the estimation of the surface drainage of the basins. Errors due to uncertainties in the computation of the effective rainfall in SURFEX or with the IDPR can also be invoked.

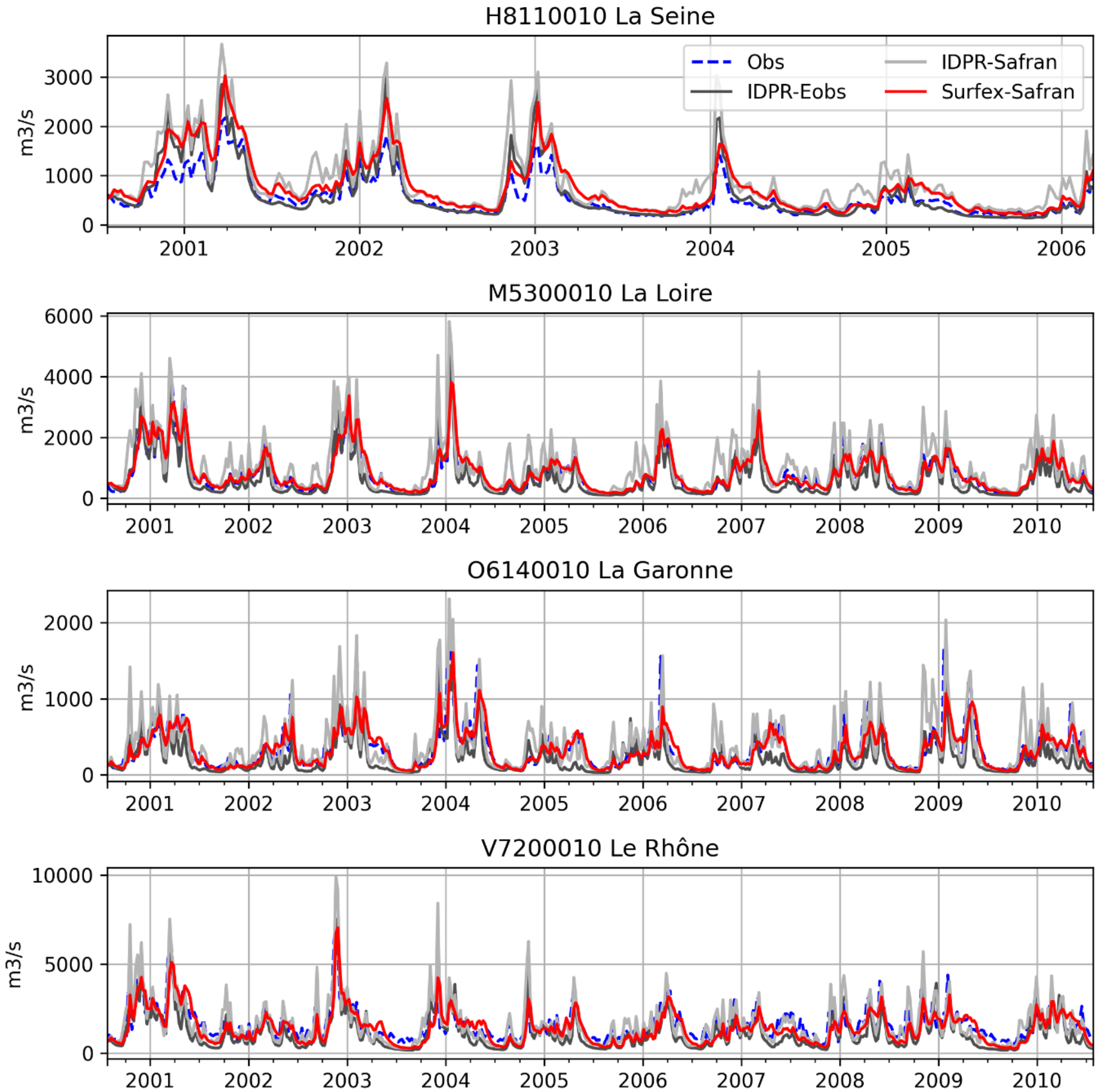

Figure 8 : Simulated river discharges at the outlet of the Seine, the Loire, the Garonne and the Rhône rivers.

Table 1 : Nash-Sutcliff and ratio scores for the four gauging stations of Figure 8 for the three simulations

Code station	**H8110010**		**M5300010**		**O6140010**		**V7200010**	
	Ratio	**Nash**	**Ratio**	**Nash**	**Ratio**	**Nash**	**Ratio**	**Nash**
IDPR-Eobs	1.04	0.92	0.75	0.97	0.56	0.92	0.68	0.88
IDPR-Safran	1.56	0.72	1.26	0.93	1.01	0.91	0.97	0.89
Surfex-Safran	1.28	0.89	0.98	0.99	0.82	0.96	0.84	0.93

Piezometric heads

About 81 piezometers from the ADES piezometer database (https://ades.eaufrance.fr/) were selected to compare observed to simulated water table levels as a preliminary evaluation of the model. Figure 9 show the spatial distribution of correlation scores for (a) the Surfex/Safran simulation and the differences between IDPR/EOBS and Surfex/Safran, and IDPR/SAFR and Surfex/Safran. This figure shows relative similar results between the three simulations. About 40% of the piezometers exhibits correlations greater than 0.7.

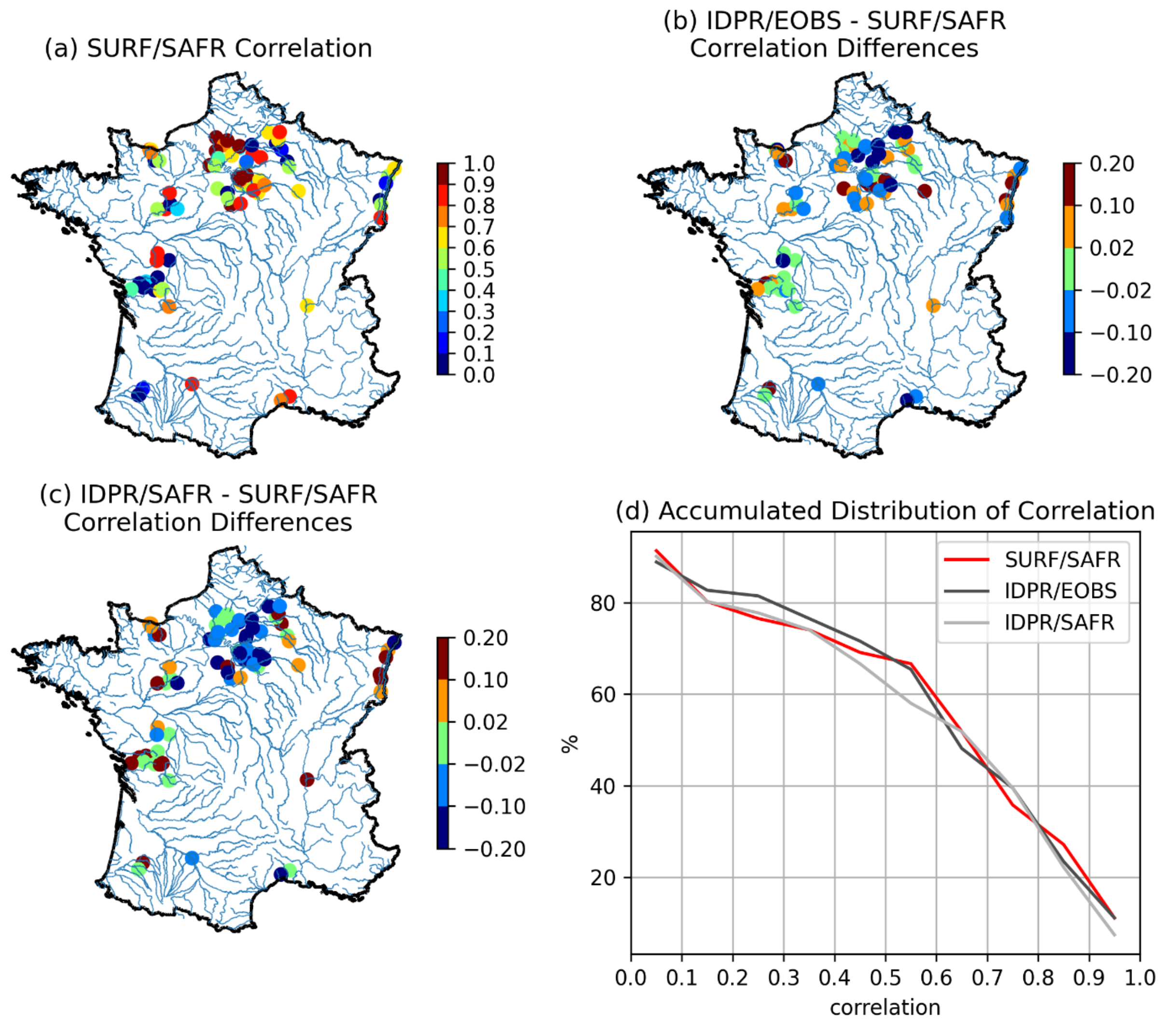

Figure 9 : Correlations of the 81 selected piezometers over France for (a) SURF/SAFR. The differences between (b) IDPR/EOBS and SURF/SAFR, and (c) IDPR/SAFR and SURF/SAFR are shown. (d) shows the accumulated distributions of correlations.

Figure 10 shows a selection of five piezometers comparing observations to the three simulations. Table 2 shows bias and correlation scores for these five piezometers.

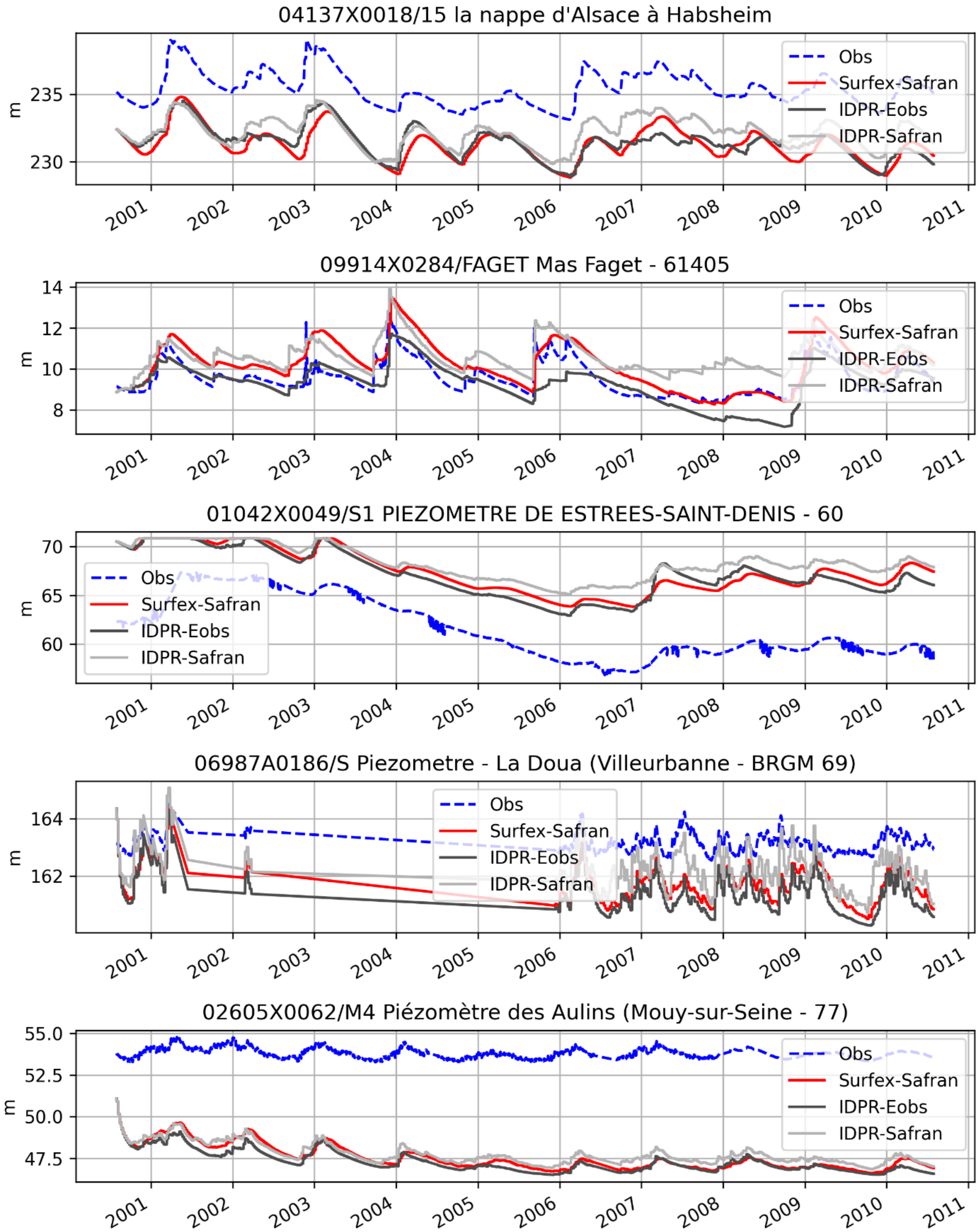

Figure 10 : Piezometric head variations for 5 piezometers located in the simulated domain.

Table 2 : Correlation and bias scores for the five piezometers of Figure 10 for the three simulations

	04137X0018		09914X0284		01042X0049		06987A0186		02605X0062	
	Cor.	**Bias**	**Cor.**	**Bias**	**Cor.**	**Bias**	**Cor.**	**Bias**	**Cor.**	**Bias**
Surfex-Safran	0.8	-4.14	0.86	0.65	0.9	5.86	0.61	-1.42	0.57	-6.27
IDPR-Eobs	0.77	-3.98	0.77	-0.24	0.85	5.53	0.63	-1.77	0.59	-6.51
IDPR-Safran	0.88	-3.24	0.87	0.99	0.83	6.78	0.77	-0.93	0.69	-6.04

At last, Figure 11 shows the annual mean of water table levels for the 10-years period of simulation over the whole aquifer domain simulated by the model.

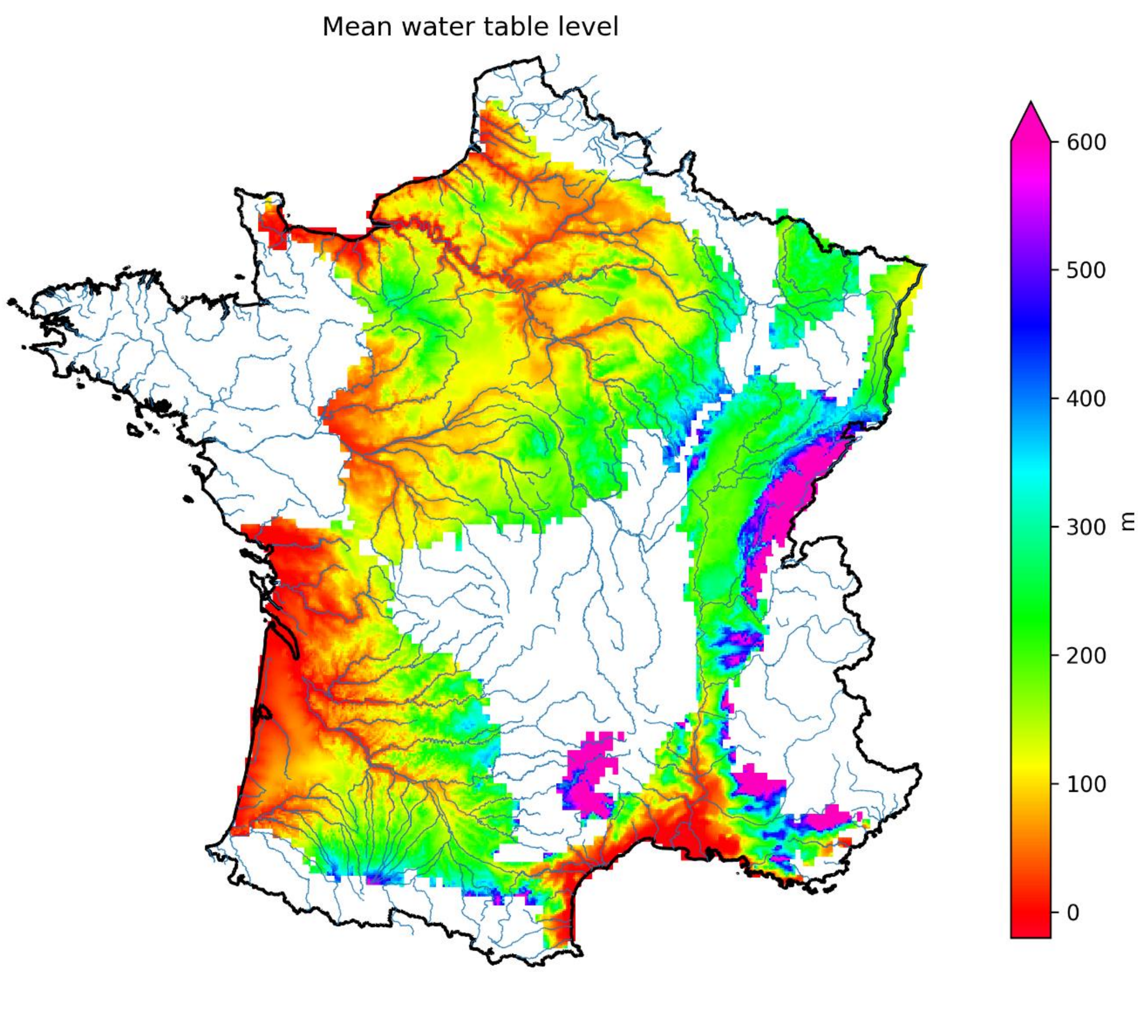

Figure 11 : Mean water table simulated over France for the 2000-2010 period.

Conclusions

A preliminary demonstrator for a national hydrogeological modelling using the MARTHE hydrogeological modelling software was built during this study. Such national tool would help to propose short to long-term forecasts of groundwater evolution for either operational groundwater management purpose or climate impact studies. This demonstrator is based on a methodology developed in Vergnes et al. (2012) using a single-layer aquifer with a 10-km resolution grid. The present study enhanced this approach by using a 2-km resolution grid. This resolution is closer to the resolution adapted for groundwater management with hydrogeological modelling (i.e. lesser or equal to 1 km). The demonstrator shows the feasibility of developing a hydrogeological model at the French national scale at a finer resolution using MARTHE. MARTHE is dedicated to the simulation of hydrologic systems and several regional models already exists in France. The results obtained with this simple demonstrator encouraged to go further in the development of this tool. Prioritizes are already identified, including the representation of all kind of aquifers (i.e. multilayer aquifer systems, bedrock aquifers, alluvial aquifers, or karstic systems), the improvement of the river networks (i.e. better delineations of watersheds and better estimation of river-groundwater exchanges parameters), and a better coupling of the superficial sol layer with the underlying groundwater.

Nevertheless, the present demonstrator is already able to provide first approximates of climate change impact on groundwater resources. Future works are planned to use climate change scenarios in this preliminary tool to demonstrate the viability of using it with climate model outputs.

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