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Benchmarking hydrological models for low-flow simulation and forecasting on French catchments

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Abstract

Low-flow simulation and forecasting remains a difficult issue for hydrological modellers, and intercomparisons are needed to assess existing low-flow prediction models and to develop more efficient operational tools. This study presents the results of a collaborative experiment conducted to compare low-flow simulation and forecasting models on 21 unregulated catchments in France. Five hydrological models with different characteristics and conceptualizations were applied following a common evaluation framework and assessed using a common set of criteria. Two simple benchmarks were used to set minimum levels of acceptability for model performance in simulation and forecasting modes. Results showed that, in simulation as well as in forecasting modes, all hydrological models performed almost systematically better than the benchmarks. Although no single model outperformed all the others in all circumstances, a few models appeared more satisfactory than the others on average. In simulation mode, all attempts to relate model efficiency to catchment characteristics remained inconclusive. In forecasting mode, we defined maximum useful forecasting lead times beyond which the model does not contribute useful information compared to the benchmark. This maximum useful lead time logically varies between catchments, but also depends on the model used. Preliminary attempts to implement simple multi-model approaches showed that additional efficiency gains can be expected from such approaches.

1 Introduction

1.1 Why anticipate low flows?

In many countries, rivers are the primary supply of water. In France, where this study was carried out, 81 % of the 33 km³ of total water withdrawals in 2009 came from rivers (CGDD, 2012). Municipal water supply, irrigation, navigation, hydropower and nuclear power plant cooling are highly dependent on surface water resources and can

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be strongly affected by water shortages in rivers (Bousquet et al., 2003). Increasing efforts to maintain minimum environmental flows in rivers make the issue even more acute (García de Jalón, 2003; Saunders and Lewis, 2003).

Early anticipation of low-flow periods is needed to improve water management and take more timely measures to mitigate the socio-economic and ecological impacts of water shortages (Chiew and McMahon, 2002; Hamlet et al., 2002; Karamouz and Araghinejad, 2008). Extreme droughts, which occurred in western Europe in 1921 (Duband et al., 2004), 1949 (Duband, 2010), 1976 (Gazelle, 1979) and more recently in 2003 (Moreau, 2004), underline the need for anticipation systems. In addition, the current trend and/or perspective of more severe summer low flows in the context of climate change further highlights the need for appropriate management tools for low flows (Svensson et al., 2005; Manoha et al., 2008; Feyen and Dankers, 2009). Operational tools to forecast river low flows are still quite limited in many basins and much less developed than those dedicated to flood forecasting.

In spite of early attempts to develop models (Riggs, 1953; Popov, 1964; Singh and Stall, 1971), low-flow forecasting has received only limited attention in the literature compared to flood forecasting. Although quite similar in essence, the two exercises have marked differences, essentially due to the different dynamics of floods and low flows. Indeed, low flows are long-lasting phenomena with slow dynamics, contrary to floods. Besides, expectations are different in terms of forecast lead times, which are longer in the case of low flows, typically ranging from a few days to a few weeks. Note that we will not investigate here seasonal forecasting with typical forecast horizons of several months (Singla et al., 2012) and the possible role played by teleconnections (Mosley, 2000; Chiew and McMahon, 2002; Rutten et al., 2008; Céron et al., 2010).

1.2 Hydrological models for low-flow forecasting

Hydrological models are essential tools for low-flow forecasting. The first models to be used for low-flow forecasting included linear ARMA-type models and recession curves

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(Yates and Snyder, 1975; Girard, 1977; Rivera-Ramirez et al., 2002; Stravs and Brilly, 2007). Campolo et al. (1999) also proposed a neural network modelling approach.

However, these methods generally make the assumption of no-rainfall future conditions, which is the most pessimistic case, but often a not entirely realistic one when lead times of a few weeks are considered. To make more informed forecasts and extend to longer lead times, it is necessary to account for future meteorological conditions. Due to the uncertainty in these future conditions (mainly in terms of temperature and precipitation), the typical methodology used to issue low-flow forecasts is to feed a hydrological model with an ensemble of meteorological scenarios describing the range of likely future conditions, and to statistically analyse model outputs for the target time period (see e.g. Garçon et al., 1999; Perrin et al., 2001; Demirel et al., 2013b). Rainfall-runoff models are therefore relevant for low-flow forecasting.

1.3 Experience in low-flow forecasting in France

In France, the first initiatives to develop models for operational low-flow forecasting date back to the 1960s and 1970s, with the use of simple methods based on the statistical analysis of flow characteristics and recession curves (Bernier, 1964; Larras, 1972; Oberlin and Michel, 1978). This coincided with the increase in hydroelectricity production capacities in mountainous regions and the development of a dense network of nuclear power plants in lowland areas, which needed reliable cooling water. In this perspective, investigations on low flows were made to develop strategies for the management of artificial reservoirs for low-flow augmentation (Lefèvre, 1974; Miquel and Roche, 1985). These authors applied linear models based on upstream information on the Loire and Seine basins. Avalos Lingan (1976) and Guilbot et al. (1976) compared several simple linear or recession-curve methods on the Oise basin (a tributary of the Seine) and also mentioned the possible use of conceptual rainfall-runoff models to overcome the limitations of the simple regression-based methods.

Among the first attempts to use conceptual models for river low-flow forecasting, CT-GREF (1977) developed a simple storage-type model on the Durance basin to improve

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irrigation water management in low-flow conditions. This model accounted for snow influence on this basin. The French Geological Survey (BRGM) first worked on aquifer level forecasts (Thiéry, 1982, 1988b). Subsequently, Thiéry (1988a) reported the application of a conceptual model to forecast low flows on four catchments with various characteristics in France. These studies yielded the hydrological model GARDENIA, which is now used in operational conditions (Thiéry, 2013). Moreover, EDF, the French national electricity company, was also active in the development of operational tools and they implemented a forecasting system based on a hydrological model (MOR-DOR) in the 1990s to better manage the reservoirs in the Durance River basin (Garçon, 1996; Garçon et al., 1999). This system was later extended to other river basins in the mountainous regions where EDF manages reservoirs, including the Loire River basin (Mathevet et al., 2010). Using similar methods, Perrin et al. (2001), Staub (2008) and Pushpalatha (2013) evaluated the performance of the GR4J model (or modified version of this model, see Pushpalatha et al., 2011) for low-flow forecasting on a large set of French catchments. Lang et al. (2006a, 2006b) also developed a platform for low-flow analysis and forecasting based on a conceptual hydrological model and implemented it on north-eastern France (Meuse, Moselle and Rhine basins). Last, Soubeyrou et al. (2010) discussed the implementation of tools developed by Météo-France for long-term forecasting, especially using the Safran–Isba–Modcou modelling suite running throughout France in operational conditions.

1.4 Limits of existing tools

Low-flow forecasting with hydrological models is actually a difficult task since processes conditioning low flows may depend on the region, season or lead time. For example, Demirel et al. (2013a) investigated the role of five indicators (precipitation, potential evapotranspiration, groundwater storage, snow storage and lake storage) on the Rhine basin low flows and found that their relative magnitude varies with the forecast lead time. Singla et al. (2012) also showed that the predictability of flows in the spring season strongly depends on snow cover in the mountainous regions. The relation between

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surface water and groundwater in low-flow conditions was also investigated by many authors, showing the need to account for this in low-flow forecasting models (Tajjar, 1993; Pointet et al., 2003; Rassam, 2011). Clearly, the applicability of hydrological models for low-flow forecasting depends on the way these various processes are accounted for in the model. For example, the work of Staudinger et al. (2011) illustrates the sensitivity of summer low-flow simulation to the formulation of the model structure. A number of techniques can be used in conjunction with a hydrological model to improve its forecasting efficiency and decrease modelling uncertainty. Assimilation of observed data (e.g. observed streamflow or soil moisture) available at the time the forecast is issued may be one option. Using post-processing techniques to correct the bias or the spread of model outputs may also prove useful (see e.g. the discussion by Demirel et al., 2013b).

Our literature review showed that there are very few studies comparing the performance of existing hydrological models so that is difficult to know their respective strengths and weaknesses in a low-flow forecasting perspective. A noteworthy exception is the study by Demirel et al. (2013b), who compared the HBV and GR4J models and found that the former provides better forecasts than the latter. These authors also indicate that parameter estimation is a major source of uncertainty for medium-range (10 days ahead) low-flow forecasts.

1.5 Scope of the paper

Given this lack of common evaluation of low-flow forecasting models and the need to provide end-users with advanced forecasting tools, the French national agency for water and aquatic environments (ONEMA), and the Ministry for Ecology (MEDDE) jointly decided in 2010 to launch a comparative study for evaluating existing operational (or pre-operational) low-flow forecasting models on basins within a variety of French hydroclimatic contexts. The project, called PREMHYCE, was designed as an open experiment: each participant was invited to follow a single testing protocol to run his own model on a common database set up for the project. Since the experience of the

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modeller may play a role in the quality of the model's implementation, this placed the models in the best conditions for obtaining optimal results. The test set intentionally included a wide variety of conditions to draw more general conclusions (Andréassian et al., 2009; Gupta et al., 2013). Although the project was restricted to the French context and limited to French participants for practical reasons, the results are likely to be of wider interest for the community of researchers and managers working on these issues. The project mainly intended to identify the respective advantages of the models on the selected catchments for low-flow simulation and forecasting objectives. Here, following the definitions given by Beven and Young (2013), simulation is understood as *the quantitative reproduction of the catchment behaviour, given defined inputs but without reference to any observed outputs*, whereas forecasting is *the quantitative reproduction of the catchment behaviour ahead of time, but given observations of the inputs, state variables (where applicable), and outputs up to the present time (the forecasting starting point)*.

The aim of this paper is to present the main outcomes of the PREMHYCE project. In the next section, we present the catchments and data used for this study, the tested models and an overview of the testing protocol, including evaluation criteria. Section 3 details the main results obtained on the catchment set in simulation and forecasting modes and analyses the differences between models. Section 4 opens the discussion on three questions, namely: (1) within a set of models, is a better low-flow simulation model also a better forecasting model? (2) Which maximum lead time can be expected in low-flow forecasting? (3) Can models be efficiently combined in a multi-model approach? The last section provides a discussion of the main lessons and perspectives of this work.

2 Material and methods

The approach followed in the PREMHYCE project was largely inspired by modelling experiments carried out in the past few years, in which participants had been invited to

run their models on a common data set. WMO (1975, 1986, 1992) was among the first to organize such experiments to evaluate model running for simulation, snowmelt or flood forecasting purposes. More recently, the DMIP experiments (Smith et al., 2004, 2012) carried out by the NOAA in the USA to evaluate distributed simulation models provide excellent examples of testing protocols. However, to our knowledge, none of these experiments were designed to evaluate models for a low-flow forecasting objective. Therefore, we built our own common testing protocol to evaluate the relative efficiency of several models currently used in France in operational or pre-operational conditions.

2.1 Catchment set and data

2.1.1 Selection of catchments

A set of 21 catchments spread over continental France was built to serve as the test bed. The catchments were selected based on several criteria. We intended to have (1) a wide diversity of physical and climate conditions representative of the diversity of conditions found in France; (2) sufficiently long time series from gauging stations that include a variety of low-flow events, with data deemed to be good quality by the operational hydrometric services and with human influences considered negligible in low-flow conditions; (3) a sufficient number of stations to reach general conclusions, but not too many to keep tests feasible for all participants.

The catchment set is well distributed over France (see Fig. 1), with hydrological regimes ranging from oceanic to Mediterranean. Table 1 lists the set of 21 catchments, showing catchment sizes ranging from 379 to 4316 km², median elevations ranging from 70 to 1020 m and streamflow data covering periods ranging from 36 to 97 yr.

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2.1.2 Data

Daily streamflow records were retrieved from the French HYDRO database (www.hydro.eaufrance.fr). Daily precipitation, temperature and potential evapotranspiration (PE) data originate from the gridded (8 km × 8 km) SAFRAN climate reanalysis developed by Météo-France (Vidal et al., 2010). PE was computed using the Penman-Monteith formula (Penman, 1948; Monteith, 1965). The climatic series are continuously available on the 1959–2010 period over France. To treat all catchments as uniformly as possible in the tests, the common 1974–2009 period was selected for model testing. This period includes severe low-flow conditions (e.g. in summers 1976, 1989, 2003 and 2005).

Table 2 displays the ranges of climate characteristics of the catchment set. Climate conditions in France are quite variable in terms of mean annual precipitation, PE and streamflow. Variations in rainfall, PE and streamflow can also be significant between years, as shown by interannual variability, especially for streamflow. On average, 36 % of rainfall becomes runoff for the catchment set, but this yield can vary between 21 and 76 %.

2.1.3 Characteristics of low flows

In France, low flows mostly occur in summer and at the beginning of autumn (except in snow-influenced conditions). However, the duration and intensity of low flows as well as the beginning and ending dates of low-flow periods vary substantially between years and catchments.

For the operational purposes, low-flow periods are often defined using a streamflow threshold, under which specific management measures must be taken to face water shortages. In this study, it was difficult to choose operational low-flow thresholds, because they do not represent the same level of severity in all catchments since managers did not use the same methods to define these thresholds in all catchments. So we considered low flows as periods when observed streamflow falls below the threshold

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defined by the 80th percentiles of the flow duration curve, noted Q_{80} , i.e. the flow exceeded 80% of the time. This was chosen as a compromise between focusing on specific low-flow periods and having a sufficient number of low-flow situations to obtain robust and significant model evaluations.

5 Table 2 illustrates the range of low-flow thresholds and low-flow conditions on the catchment set, using two descriptors, namely the base-flow index (BFI) and the Q_{90}/Q_{50} ratio (where Q_{90} and Q_{50} are the 90th and 50th percentiles of the flow duration curve, respectively). BFI represents the part of base flow in the total flow volume (Lvovitch, 1972). Low BFI values indicate a catchment with a flashy flow regime and limited
10 groundwater contribution, while high values are an indication of large storage capacity and groundwater-fed rivers (Gustard and Demuth, 2009). The catchment set examined provides a wide range of BFI values, ranging from 11.7 to 93.5%. The Q_{90}/Q_{50} ratio represents the difference between low flows and medium flows, thus indicating the severity of low flows. It shows a similar variability, with values between 7 and 67% and
15 half of the catchments set between 18 and 38%.

2.2 Models

Table 3 shows the five models used in this study. Four of them (GARD, GR6J, MORD and PRES) are lumped storage-type models, with various conceptualizations of the rainfall-runoff transformation. The fifth model (SIM) is distributed and more physically-oriented. These models have all already been applied in various conditions in France.
20 SIM is implemented throughout France, and the other models were tested in various basins or regions for different purposes (e.g. low-flow or flood simulation and forecasting). The simulation of low flows in these models is governed by different stores and functions. In forecasting mode, the models use assimilation schemes and/or statistical correction procedures (see Table 3).
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The models include different numbers of free parameters (Table 3). Each participant was free to choose the optimization method best suited to parameter estimation. Note that SIM was the only model where no calibration against observed flow data at

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the catchment outlet was performed. The spatially distributed parameters used in this model were estimated regionally. This should be kept in mind when interpreting the results. Moreover, this version of SIM includes a detailed simulation of the aquifers only on a few parts of France (Seine and Rhône catchments). This may impact the efficiency of the model outside these zones. Moreover, the larger computing requirements of SIM only allowed a limited number of tests (see Sect. 2.3.3).

The models were fed with the same meteorological inputs derived from SAFRAN. For the lumped models, the SAFRAN variables were first aggregated at the catchment scale by simple averaging.

2.3 Testing protocol and evaluation methodology

A common testing and evaluation framework was set up to make the results comparable. It was jointly elaborated by all project participants in the first phase of the project, so that most of the models' requirements and constraints could be accounted for.

2.3.1 Testing scheme

Model evaluation was based on a classical split-sample test approach (Klemeš, 1986). Streamflow records were divided into two approximately equal sub-periods. Each period was alternately used for calibration and validation, i.e. calibration on period 1 (noted C1) with validation on period 2 (V2), and then calibration on period 2 (C2) with validation on period 1 (V1). Thus the models could be evaluated in validation on all available data. The 1974–1991 and 1992–2009 periods based on calendar years were chosen for periods 1 and 2, respectively. A 3 yr warm-up period was used at the beginning of each test period (1971–1973 and 1989–1991 for periods 1 and 2, respectively) to initialize the internal states of the models.

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2.3.2 Differences between forecast and simulation tests

As underlined above, the simulation and forecasting exercises differ, which has clear implications in the way models were tested here.

In simulation mode, models are expected to simulate streamflow at time step t , knowing observed meteorological inputs until this time step. Observed streamflow values remain unknown at all time steps. The simulation mode shows the models' ability to reproduce the catchments' hydrological behaviour without uncertainties due to unknown future conditions (input scenarios) and without the information contributed by external data (typically observed flows) that could be assimilated to adjust the model.

In forecasting mode, models are expected to forecast streamflow from time steps $t + 1$ to $t + L$ (with L the lead time), knowing both observed meteorological inputs and streamflow until time step t and making assumptions (i.e. choosing scenarios) for the future meteorological inputs from $t + 1$ to $t + L$. Streamflow data can be used within an assimilation scheme and/or a statistical correction procedure. Models were actually tested in hindcasting mode, i.e. retrospectively running the models at each time step of the available test periods and making forecasts as if they were used in real time.

2.3.3 Choice of scenarios in forecasting mode

An ensemble of scenarios of future meteorological inputs must be chosen for the forecasting mode. Usually, real-time ensemble forecasts from meteorological models are used to forecast streamflow. Here, since no long-term archive of actual forecasts was available over the test period, the meteorological archive was used as possible scenarios for P , PE and T . The following procedure was applied. For a given catchment, let us consider that N years of meteorological inputs are available. One wishes to make a forecast on a calendar day t of a year Y within the test period, i.e. to forecast flows between calendar days $t + 1$ and $t + L$. The observed meteorological data available between days $t + 1$ and $t + L$ in the years $1, \dots, Y - 1, Y + 1, \dots, N$ (i.e. $N - 1$ scenarios) were used as input scenarios to the model, considering that they are likely meteorological

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conditions for this period of the year. Here, 51 yr (1959–2009) of daily climate data from the SAFRAN reanalysis were available, thus 50 scenarios (for rainfall, temperature and PE) could be used each time. We assumed that this number of scenarios was sufficient for a good representation of the variability of possible future climate conditions. Obviously, such scenarios are likely to be less accurate than actual ensemble forecasts from meteorological models, at least for short to medium lead times. The observed meteorological inputs of year Y were used as a control forecast, to estimate forecasting efficiency in the idealized case of perfect foreknowledge of future meteorological conditions.

Following this procedure, models were run to issue an ensemble of 50 streamflow forecasts for each day t , over a time window of 90 days (from $t + 1$ to $t + 90$). Due to computing time constraints, SIM only provided forecasts every 5 days, from $d + 1$ to $d + 30$ (and $d + 90$ for each first day of the month), over a period limited to 1 May to 26 October (the low-flow period) and on the second validation period only (1992–2009).

2.3.4 Benchmarks and evaluation criteria

Although models provided streamflow simulations or forecasts at a daily time step, we chose to evaluate models on the streamflow averaged over a 3 day sliding window. This aimed at smoothing the low-flow series and avoiding putting too much emphasis on isolated streamflow variations (Henny, 2010). Note that this target variable is quite commonly used in France for regulation purposes.

Since the use of benchmarks is important to evaluate the relative advantages of model predictions (Seibert, 2001; Perrin et al., 2006), results in simulation mode were compared to the daily average streamflow curve (noted DAQ). This benchmark was advocated by Martinec and Rango (1989). In forecasting mode, the probabilistic forecasts were compared to a benchmark describing the streamflow natural variability (noted NVQ). NVQ is defined for a given calendar day d of year Y as the distribution of available streamflows in the other years for this day.

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We used two sets of evaluation criteria for model evaluation in simulation (see list in Table 4) and forecasting (see Table 5) modes. They were chosen to assess various modelling skills expected in low-flow conditions for different objectives, after discussions with stakeholders. The detailed mathematical formulation of the criteria is given in the Appendix.

In forecasting mode, the models were expected to produce forecasts over a future time window of 90 days. Therefore, model forecasting performance could be investigated for all lead times between 1 and 90 days. To simplify the presentation of results, we choose to focus on two specific lead times: a short one (7 days) and a longer one (30 days). This choice was made in agreement with stakeholders since those are the typical horizons useful for water managers. The longer lead time was limited to 30 days given the computation constraints of the SIM model.

In some cases, the mathematical form of the criteria was changed to have all of them vary within the interval $[-\infty; 1]$ (1 being the optimum value) to ease interpretation.

Note that the forecasting results presented hereafter were limited in order to adapt to the availability of streamflow forecasts from SIM.

2.3.5 Presentation of results

Since the project produced a very large number of results, it is not possible to detail them all here. Instead, we chose to present summary evaluations using tables and graphical representations. Radial plots, as exemplified in Fig. 2, were used to present mean model performance on the set of 21 catchments for all selected criteria. Visually, the larger the polygon linking the performance values, the better the model. On these graphs, criteria focusing on similar aspects were grouped together. We also used performance maps to investigate the possible regional trend in results. These maps were drawn for three criteria only (C2MiQ, CSI and Vdef in simulation; RMSEut, BSutvig and Vdef in forecasting). They were found to be complementary, thus providing an overall picture of model performance in low-flow conditions.

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Last, two catchments were selected to illustrate the results using hydrographs: the Meuse River at St-Mihiel (B2220010) and the Orge River at Morsang-sur-Orge (H4252010). These two catchments are quite different in terms of mean annual precipitation (937 and 656 mm, respectively) and mean runoff yield (41 and 21 %) and in terms of low-flow conditions described by BFI values (25.5 and 65.7 %) and the Q_{90}/Q_{50} ratio (0.21 and 0.57).

3 Results

3.1 Simulation mode

Figure 3 summarizes the mean performance obtained by the five models tested in validation on the 21 catchments and the two test periods. Quite similar results can be observed for four lumped models on average. The performance of the SIM model was lower for a few criteria (C2MiQ, C2MQ, POD, FAR and CSI). However, no model seemed able to outperform all the other models for all criteria.

Performance on some criteria can vary substantially between catchments. Figure 4 presents the maps of mean performance on the two validation periods for three criteria (C2MiQ, Vdef and CSI). A few catchments (e.g. the Meuse at St-Mihiel) are properly simulated by more or less all models: however, performance can be much more variable between models on other catchments: e.g. the PRES model performs well on the Gapeau at Hyères for the C2MiQ and Vdef criteria, while the performance of the other models is significantly lower. The relative advantages of one model may also depend on the criteria selected. For the Gapeau at Hyères, PRES performs better than GARD in terms of C2MiQ, while the reverse is true for Vdef. Although it achieves lower performance than the other models on average, SIM can prove better on some catchments, e.g. the Orge at Morsang-sur-Orge for the C2MiQ criterion. Interestingly, most models tend to underestimate the volume deficit ($V_{def} < 1$), i.e. they tend to overestimate low flows below the Q_{80} threshold. GR6J is the only model which tends to underestimate

low flows. The models clearly outperform the benchmark (DAQ) for all criteria. Note that the DAQ model is by definition perfect for the DatSt and DatEn criteria (see the Appendix), so comparison with the other models on these criteria is pointless.

For an overall evaluation of the models, we ranked them by decreasing performance for each of the 11 criteria and computed their mean ranks for the nine criteria directly related to low flows (i.e. not considering C2MQ and KGEQ). Table 6 presents the results based on the mean performance in validation on the 21 catchments. It can be observed that GARD and PRES perform best for four criteria, MORD for two, MORD for two and GR6J with one. PRES appears the most consistently ranked among the best models on average, followed by GARD, GR6J and MORD, which are quite similar, and then SIM. DAQ performs poorly for most criteria. Interestingly, PRES performs a bit less well than the three other conceptual models on the two criteria focusing on high flows (C2MQ and KGEQ): the way PRES was implemented within this study makes it more low-flow-oriented than the other models.

These results indicate that differences are quite limited between the lumped conceptual models for low-flow simulations. A more detailed analysis (not shown here) indicated that performance can vary considerably between validation periods. Overall, obtaining satisfactory streamflow simulation seems to depend more on catchment characteristics than on the model itself. We analysed the relation between model performance and low-flow indices (BFI or Q_{90}/Q_{50} ratio) or catchment characteristic (drainage density here), but it did not show significant trends, as illustrated in Fig. 5.

3.2 Forecasting mode

Figures 6 and 7 present the radial plots of all criteria for each model, for 7 day and 30 day lead times, respectively. The performance of the benchmark model, NVQ, was also included. Here, the differences between models seem more significant than in simulation mode for a few criteria (e.g. containing ratio, sharpness, Vdef or low-flow duration), especially for the 7 day lead time. However, it is still difficult to identify a single best model. We can only confirm that SIM performs a bit less well, even if the

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differences with the other models appear to be more limited for the 30 day lead time. One of the expected results is the loss of performance with increasing lead time for all models and all catchments. This loss is significant for all criteria, except for the containing ratio, which is better: members of the ensemble forecast are more dispersed.

5 Containing ratio and sharpness are two complementary scores that should be evaluated together: a model should first be as reliable as possible and then provide as narrow a forecast interval as possible (excessively spaced forecasts do not contribute information). Performance even becomes close to the benchmark performance NVQ, but still remains better.

10 As in simulation mode, model performance based on several criteria strongly varies among the catchments. Figures 8 and 9 show the performance maps on validation period 2 for RMSEut (normalized by mean flow under the threshold), BSutvig and Vdef, and for each model on the 21 catchments, for forecasting 7 day (Fig. 8) and 30 day (Fig. 9) lead times, respectively. We reach the same conclusions as in simulation mode: even if for some catchments the models satisfactorily forecast low flows (e.g. the Andelle at Vascoeuil and the Oise at Sempigny in RMSEut, whatever the forecast lead time), performance is quite variable in other catchments (e.g. the Petite Creuse at Fresselines in RMSEut is properly modelled by GARD but less satisfactorily by the other models). Performance also depends on the criteria considered: for the Orge at
20 Morsang-sur-Orge, model performance is quite good in RMSEut for the two forecasting lead times but decreases significantly in BSutvig or Vdef, compared to the other catchments.

25 The fact that models remain better than the benchmark model indicates that they contribute information, even for a long forecasting lead time. An analysis on the two validation periods has shown that performance can vary greatly between periods. Overall, it appears that a satisfactory streamflow forecast depends more on the catchments and their specificities than on the model, as already noted in the case of simulation results. The analyses to link model performance to low-flow indices (BFI or Q_{90}/Q_{50} ratio) did not show significant trends, as had already be shown in simulation mode in Fig. 5.

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Table 7 presents the rank of the models on each criterion for the two selected lead times, based on the mean performance on the 21 catchments for validation period 2, and the mean rank on all criteria. For the short lead time (7 days), GARD and GR6J perform best on four criteria and MORD and PRES on one. GR6J is the most consistently ranked among the best models on average, followed by GARD. Then come PRES and MORD which are quite similar, and SIM. The benchmark remains the poorest model, which shows that all models contribute information compared to this reference. The ranking is a bit different for the longer lead time (30 days). It changes for some criteria, which modifies the mean ranks: GARD appears to be the most highly ranked model, followed by GR6J, PRES and MORD, which are similar. SIM does not seem to contribute information on average compared to the benchmark for this lead time.

3.3 Illustration of two case studies

Here, we present the results in simulation and forecasting modes for two catchments: the Meuse River at St-Mihiel, where the models perform well, and the Orge River at Morsang-sur-Orge, where they perform less satisfactorily.

Figure 10 shows the observed and simulated hydrographs in the logarithmic scale for two years where severe low-flow events occurred: 1976 and 1996. For the Meuse at St-Mihiel, GARD, GR6J, MORD and PRES simulated the low flows well, even if they overestimate streamflows from October to December in 1976 and in August in 1996. SIM does not adequately reproduce the low-flow dynamic with quite erratic streamflow simulations. For the Orge River at Morsang-sur-Orge, the models tend to substantially overestimate low flows for the two years, except SIM, which accurately simulates the low-flow event in 1996. Interestingly, this catchment benefits from a detailed simulation of the aquifer within SIM while most others do not.

Figures 11 and 12 present the observed and forecasted hydrographs in the logarithmic scale for the Meuse River at St-Mihiel in 2003 and the Orge River at Morsang-sur-Orge in 1996 (the most severe low-flow events for validation period 2). Forecast ensembles over the next 15 days are represented for a forecast produced every 20

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days, together with the control run in red (i.e. streamflow forecast obtained with a posteriori observed P , PE and T as the future scenario). For the Meuse River, GARD and GR6J tend to be less dispersed than the other models. The control run shows that SIM is overly reactive to precipitation, while PRES tends to underestimate streamflow.

Therefore, the ensemble forecasted by PRES surrounds the observation well, while MORD and SIM tend to overestimate streamflow when lead time increases. In these cases of severe low flows, the added value of models compared to the benchmark is clear: given its definition, the benchmark consistently overestimates severe low flows, whereas models issue forecast ensembles that are better centred on observation and less dispersed.

For the Orge River, the low-flow event is poorly forecasted by all models, with a general tendency to overestimation. This is confirmed by the control run, especially for GARD, GR6J and MORD. SIM and PRES surround the observation better and forecast low flows better despite a few missed forecasts for PRES (July and August). In this case and for other low-flow events for the Orge River, the added value of hydrological models compared to the benchmark is limited.

4 Discussion

This intercomparison experiment shows that hydrological models can provide useful information for low-flow simulation and forecasting. Here, we wished to further discuss three main issues raised in the introduction, relative to (1) the relation between simulation and forecasting performance, (2) the lead times achievable on the test catchments for low-flow forecasting and (3) whether models can collaborate to enhance overall performance. In each case, a few additional tests/analyses are presented. Here our intention is solely to provide complementary insights on these results to open clear perspectives based on this work, rather than propose new methodologies.

4.1 Within a set of models, is a better low-flow simulation model also a better forecasting model?

Section 3 showed the results of the comparison between hydrological models in simulation and forecasting modes. The mean model ranks show several differences between simulation (Table 6) and forecasting (Table 7) modes. This is further illustrated in Fig. 13, which presents the mean rank of each model in forecasting (for the 7 day lead time) for the models ranked in 1st, 2nd, 5th position in simulation for the 21 catchments. The hierarchy of the models between simulation and forecasting differs: the best model in simulation (mean rank in simulation equal to (1) is also the best model in forecasting for only nine catchments. Overall for all the ranks, the hierarchy between models is the same in only 33 % of cases. Therefore, a better model in simulation does not systematically mean a better model in forecasting, which strengthens the need for an evaluation relative to specific modeling objectives. These differences in performance in simulation and forecasting can be explained by the specific tools used in forecasting, which assimilate streamflow and/or correct model outputs (see Table 3). However, given the variety of assimilation and correction methods applied in this study, it is difficult to conclude on the relative advantages of each of them and more systematic tests would be needed.

4.2 Which maximum useful lead time can be expected in low-flow forecasting?

The results obtained in forecasting mode were presented for two specific lead times (7 and 30 days). As expected, model performance decreased when lead time increased, which means that the added value of the information provided by the models compared to the benchmark decreases. Therefore, there should be a maximum lead time beyond which the model cannot provide useful information compared to the benchmark. This lead time will be called “useful forecasting lead time” (noted UFL) hereafter, as proposed by Staub (2008). For each catchment and each model, the UFL can be determined by comparing the performance of the model tested and the benchmark (NVQ) when lead time increases. Here UFL was arbitrarily chosen as the lead time

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beyond which model performance is not at least 20 % better than benchmark performance. We considered that beyond this limit, the operational added value would be too little. Obviously, UFL depends on the criteria chosen and benchmark. The variability of UFL values when considering a given criteria will be an indication of model capacity to represent the corresponding low-flow characteristics, and the more demanding the benchmark, the shorter the UFL.

Figure 14 presents maps of mean UFL values obtained using three efficiency criteria (RMSEut, CSI and Vdef) for the 21 catchments. The symbol indicates the model which provides the best UFL. Note that SIM was not considered here because it was run to issue 90 day forecasts on too few time steps to allow robust conclusions. The results logically depend on the catchments. For some of them, it is not possible to usefully anticipate low flows beyond 1 week, while others seem to have longer inertia and hydrological memory, with forecasts still dependent on initial conditions after several weeks. However, we could not link UFL to low-flow characteristics (BFI or Q_{90}/Q_{50} ratio). It was also noted that UFL estimates vary between models and/or test periods (see Fig. 8). For example, for the Briance River at Condat-sur-Vienne, the best mean UFL is provided by PRES and reaches 60 days for validation period 2 vs. 21 days for period 1 provided by MORD. The variability in model efficiency may partly explain these results.

The UFL estimation is very useful operationally when adapted to specific criteria/objectives defined by the water manager. The level of improvement over the benchmark, here set to 20 %, could be raised if one wishes to reach a higher level of reliability or could even replace an absolute criterion under specific circumstances.

4.3 Could models be efficiently combined in a multi-model approach?

Since it was not possible to identify a single model which would outperform the others for all catchments, validation periods or evaluation criteria, we attempted to investigate the possible complementarity between models via model output combinations in simulation and forecasting modes. Many multi-model approaches exist to combine the

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outputs of several models (see e.g. Abrahart and See, 2002; Palmer et al., 2004; Velazquez et al., 2011). Here we chose to focus on three simple methods:

1. Average multi-model forecast (noted AMM): this is the simplest method and consists in averaging the outputs of the five hydrological models at each time step. In ensemble forecasting mode, each multi-model member corresponds to the mean of the forecasts issued by the models using the same scenario. This multi-model approach is applicable in simulation and forecasting modes.
2. Fixed-weight average multi-model forecast (noted FMM): this consists in averaging model outputs using weights based on model performance. The model weight W_m given to each model is:

$$W_m = \frac{\text{Crit}_m}{\sum_{m=1}^M \text{Crit}_m} \quad (1)$$

where m is the hydrological model, M the number of hydrological models, Crit the value of the criterion on the calibration period. Better performing models obtain higher weights. In ensemble forecasting mode, each member of the multi-model corresponds to the weighted mean of the forecasts issued by the five models using the same scenario. This multi-model approach is applicable in simulation and forecasting modes.

3. Variable-weight average forecast (noted VMM): the third method tested is inspired from Loumagne et al. (1995) and is applicable in forecasting mode only. It is equivalent to the previous method, but here weights are time-dependent and are based

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on the mean of model errors on the last p time steps. This error is calculated using the control run. For each time step, the weight given to a model is:

$$W_{m,d} = \frac{\sum_{s=d-p}^d \sqrt{(Qfor_{m,s} - Qobs_s)^2}}{\sum_{m=1}^M \sum_{s=d-p}^d \sqrt{(Qfor_{m,s} - Qobs_s)^2}} \quad (2)$$

where m is the hydrological model, M the number of hydrological models, d the day when the forecast is issued, $Qfor_{m,s}$ the streamflow forecasted by model m at date $s - 1$ for s , $Qobs_s$ the observed streamflow at date s , p the length of the time window over which previous forecasting errors are considered. This approach could not be applied to the SIM model given limited availability of streamflow forecasts.

Figure 15 presents the maps of the best ranked models in simulation (mean of the models' ranks by criteria for each catchment) for each evaluation period. The comparison between AMM and FMM (not detailed here) showed very similar results for each catchment and test period and we kept only the FMM approach in the rest of the analysis, since it is slightly better. The multi-model presented in Fig. 16 is FMM, weighted using the POD criteria. It provides better results than individual models on 13 and 12 catchments out of 21 for validation periods 1 and 2, respectively. For a few catchments, the multi-model performs best on one validation period but not on the other. Moreover, since a model that performs best on the calibration period compared to the other models does not systematically perform best on the validation period, the weight given to this model in the FMM approach may not be optimal. The performance of the multi-model seems not to be impacted by this robustness effect. The multi-model does not drastically change performance compared to the single best models: if all models perform poorly, the multi-model does not produce satisfactory results either,

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which is not surprising. Interestingly however, the multi-model seems more robust than the individual models in the sense that it limits severe model failures, since it allows compensations between poor and good models.

In forecasting mode, SIM was excluded from the three combination methods since it was not possible to use it in the VMM option. For VMM, the mean error to weight the model was calculated over the six last time steps, which appeared to be a good compromise between performance and length of this backtracking period. Here, as in simulation, the results (not detailed here) are similar between the three options, but VMM is slightly better. Therefore, we kept only the VMM model in the rest of the analysis. Figure 16 presents the maps of the best ranked model in forecasting for a 7 day lead time (mean of the ranks of models by criteria for each catchment) for each evaluation period. The multi-model provides the best results only on six and five catchments out of 21 for validation periods 1 and 2, respectively. GARD and GR6J are also often the best models. The limited efficiency of the multi-model may be due to the overly crude combination approach: even if it proved useful in a flood forecasting context in the study reported by Loumagne et al. (1995), other approaches accounting better for the slow dynamics of low flows may be more efficient and should be further investigated.

5 Conclusion and perspectives

In this paper, we presented a comparison between five hydrological models for low-flow simulation and forecasting on 21 French catchments representing a variety of physical and hydro-climatic characteristics. A general evaluation of models was made using several criteria which represent different qualities expected of models. Moreover, the use of benchmarks contributed comparative information on the actual operational utility of these models.

In simulation mode, the comparison showed that calibrated models perform better (GARD, MORD, GR6J and PRES). SIM, the only uncalibrated model included in the comparison, nonetheless performs as well as the other models on a few catchments. It

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was difficult to define a clear hierarchy between these calibrated models, since the results vary according to the selected criteria, the catchment considered or even the test period. Tests to relate performance to catchment characteristics proved unsuccessful. The relative gain compared to the benchmark (daily average streamflow) is very high and showed the usefulness of hydrological simulation for low flows.

In forecasting mode, we reached the same conclusions, with better results for calibrated models. Here, establishing a hierarchy between the models is also difficult, since performance varies according to the criteria, catchment, validation period and lead time. The results are quite good for short lead times, especially compared to the benchmark. As can be expected, this gain decreases as lead time increases. Although models perform differently from one period to another, overall they tend to present the same ability to forecast low flows on a catchment. The rainfall scenarios (historical archive) used here to test models were quite crude and it is likely that using the ensemble forecast from meteorological models would improve results, at least for short lead times, but this would require further investigation.

In forecasting, we presented a simple approach to determine the maximum lead time beyond which models do not add significant information compared to the benchmark. This maximum lead time was variable because models behaved differently with increasing lead time and the results differed according to the criteria and the validation period.

Combining the single models into a multi-model was successful even with simple combination methods, but the performance of the multi-model strongly depends on the performance of individual models: where all the models present difficulties in simulating or forecasting low flows, a model combination cannot compensate for model errors. The main advantage in building a multi-model lies in its robustness: where only one model presents difficulties on a catchment, a multi-model corrects this weakness.

As far as perspectives are concerned, we would like to mention (i) that tests were made on two other catchments in a very different climatic context on Reunion Island (Indian Ocean). They were not detailed here for the sake of brevity but yielded

similar conclusions. (ii) This study used catchments where human influence was considered negligible, but the use of catchments where anthropogenic pressure on water resources is significant constitutes the second part of the PREMHYCE project, and the results will be reported in due course.

5 Appendix A

A1 Formulation of the numerical criteria selected for simulation evaluation

KGE

10 This criterion was proposed by Gupta et al. (2009) as a modification of the Nash–Sutcliffe (1970) efficiency index:

$$KGE = 1 - \sqrt{(r - 1)^2 + (\alpha - 1)^2 + (\beta - 1)^2} \quad (A1)$$

with r the correlation coefficient between observed and simulated flows, α the ratio of simulated and observed flow standard deviations and β the model bias.

C2MQ

15 C2MQ is a bounded version of the Nash–Sutcliffe efficiency index calculated on stream-flow Q (NSE_Q), as proposed by Mathevet et al. (2006)

$$C2MQ = \frac{NSE_Q}{2 - NSE_Q}. \quad (A2)$$

C2MiQ

20 This is similar to the previous criterion, but NSE is calculated on inverse flows to more strongly emphasize low flows, as proposed by Pushpalatha et al. (2012).

RMSEut

RMSEut is the root mean square error for flows under the low-flow threshold, normalized by the mean observed flow.

$$\text{RMSEut} = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n (Q_{\text{sim}_i} - Q_{\text{obs}_i})^2}}{\frac{1}{n} \sum_{i=1}^n Q_{\text{obs}_i}} \quad (\text{A3})$$

5 where Q_{obs_i} is the observed streamflow for day i , Q_{sim_i} the simulated streamflow for day i , and n the number of time steps on the validation period where Q_{obs_i} is less than the Q_{80} threshold.

Vdef

Vdef is the ratio of simulated and observed flow deficits under the low-flow threshold:

$$10 \text{ Vdef} = \frac{\sum_{i=1}^n \max(0; Q_{\text{threshold}} - Q_{\text{sim}_i})}{\sum_{i=1}^n \max(0; Q_{\text{threshold}} - Q_{\text{obs}_i})} \quad (\text{A4})$$

LFD

This is the ratio of simulated and observed low-flow durations:

$$\text{LFD} = \frac{\text{Duration}_{\text{sim}}}{\text{Duration}_{\text{obs}}} \quad (\text{A5})$$

15 where $\text{Duration}_{\text{sim}}$ is the number of days where the Q_{sim_i} is less than the Q_{80} threshold on the validation period and $\text{Duration}_{\text{obs}}$ is the number of days where the Q_{obs_i} is less than the Q_{80} threshold on the validation period.

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DatSt and DatEn

This is a comparison of observed and simulated dates when low flows start (St) or end (En).

$$\text{Dat} = \text{Date}_{\text{sim}} - \text{Date}_{\text{obs}} \quad (\text{A6})$$

5 where Date_{obs} is the Julian day of daily average streamflow when 10 % (resp. 90 %) of the observed volume deficit is exceeded for DatSt (resp. DatEn). The threshold for the observed volume deficit calculation is the observed Q_{80} calculated of the daily average streamflow. Date_{sim} is the Julian day of the daily average streamflow where 10 % (resp. 90 %) of the simulated volume deficit is exceeded for DatSt (resp. DatEn). The
10 threshold for the simulated volume deficit calculation is the simulated Q_{80} calculated of the daily average streamflow.

False alarm ratio (FAR), probability of detection (POD) and critical success index (CSI)

15 These are criteria based on the contingency table for low flows considering the Q_{80} threshold (Schäfer, 1990):

$$\text{FAR} = \frac{b}{a + b} \quad (\text{A7})$$

$$\text{POD} = \frac{a}{a + c} \quad (\text{A8})$$

$$\text{CSI} = \frac{a}{a + b + c} \quad (\text{A9})$$

20 where a is the number of hits, b the number of false alarms, c the number of correct misses and d the number of correct rejects.

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A2 Numerical criteria for forecasting evaluation

RMSEut, Vdef, LFD

These criteria have the same definition as in the simulation but are calculated using the mean of the ensemble forecasts for the horizon considered.

5 Sharpness

This criterion measures the width of the ensemble forecast (Franz and Hogue, 2011):

$$\text{Sharp} = \frac{1}{n} \sum_{i=1}^n Q_{90_i} - Q_{10_i} \quad (\text{A10})$$

10 where n is the number of time steps on the validation period where the Q_{obs_i} is less than the Q_{80} threshold, and Q_{90} (resp. Q_{10}) the 90 % (resp. 10 %) percentile of the distribution of forecasts for day i .

Reliability

The containing ratio measures how often the observation lies within the ensemble forecast (Franz and Hogue, 2011):

$$\text{Cont_ratio} = \frac{n}{N} \quad (\text{A11})$$

15 where n is the number of observed streamflows in the 80 % forecasted confidence interval when the Q_{obs_i} is less than the Q_{80} threshold, and N the number of time steps where the Q_{obs_i} is less than the Q_{80} threshold.

FAR, POD and CSI

20 The same definition as in the simulation is used. Here an event is forecasted if more than 50 % of members are below the low-flow threshold.

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BS

The Brier Score (BS) (Brier, 1950) compared the observed and forecast probabilities relative to a threshold:

$$BS = \frac{1}{n} \sum_{i=1}^n (y_i - o_i)^2 \quad (A12)$$

5 where o_i is the observation probability, y_i the forecast probability. An event is observed/forecasted if the observed/forecasted streamflow is less than the vigilance threshold (Q_{80} for BSutvig) or the crisis threshold (Q_{95} threshold). n is the number of time steps where Q_{obs_i} is less than the Q_{50} threshold (BSutvig) or the Q_{80} threshold (BSutcri).

10 DRPS

The Discrete Ranked Probability Score (DRPS) (Toth et al., 2003):

$$DRPS = \frac{1}{N_{threshold}} \sum_{k=1}^{N_{threshold}} (BS_k) \quad (A13)$$

where $N_{threshold}$ is the number of thresholds chosen (ten percentiles here, $k = Q_{80}, Q_{82}, Q_{84}, \dots, Q_{96}, Q_{98}$).

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Table 1. Summary of the 21 selected catchments' characteristics.

No.	HYDRO Code	River at Station	Area (km ²)	Median elevation (m)	Starting date for flow series	Ending date for flow series	Flow availability (years)
1	A1080330	Ill at Didenheim	657	390	1 Nov 1973	2 Mar 2010	36
2	B2220010	Meuse at Saint-Mihiel	2542	350	1 Jul 1968	3 Jan 2010	42
3	H2342020	Serein at Chablis	1121	309	1 Aug 1954	3 Mar 2010	56
4	H4252010	Orge at Morsang-sur-Orge	927	133	1 Oct 1967	7 Mar 2010	43
5	H7401010	Oise at Sempigny	4316	137	1 Jan 1955	2 Mar 2010	55
6	H8212010	Andelle at Vascoeuil	379	159	1 Jan 1973	27 Feb 2010	36
7	I5221010	Vire at Saint-Lô	868	159	1 Jan 1971	3 Feb 2010	39
8	J7483010	Seiche at Bruz	811	70	1 Dec 1967	11 Mar 2010	42
9	K1321810	Arroux at Etang-sur-Arroux	1798	431	1 Nov 1971	27 Mar 2010	39
10	K6402520	Sauldres at Salbris	1200	220	1 Jan 1971	28 Mar 2010	39
11	L0563010	Briance at Condat-sur-Vienne	597	386	1 Jan 1966	28 Mar 2010	44
12	L4411710	Petite Creuse at Fresselines	850	393	1 Jan 1958	28 Mar 2010	52
13	M0243010	Orne Saosnoise at Montbizot	510	103	1 Dec 1967	4 Mar 2010	43
14	M7112410	Sèvre Nantaise at Tiffauges	817	170	1 Nov 1967	4 Mar 2010	43
15	O0592510	Salat at Roquefort-sur-Garonne	1570	986	1 Jan 1913	22 Mar 2010	97
16	O3121010	Tarn at Montbrun	588	1020	1 Jan 1961	31 Dec 2009	38
17	Q5501010	Gave de Pau at Berenx	2575	916	1 Jul 1923	28 Mar 2010	87
18	S2242510	Eyre at Salle	1650	78	1 Jan 1967	19 Mar 2010	43
19	U4644010	Azergues at Lozanne	798	517	1 Jan 1965	28 Mar 2010	43
20	V4264010	Drôme at Saillans	936	936	1 Jan 1910	28 Mar 2010	46
21	Y4624010	Gapeau at Hyères	517	316	1 Feb 1961	1 Mar 2010	49

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Table 2. Percentiles of the distribution of certain climate and hydrological catchment characteristics of the 21 selected catchments. Interannual variability values correspond to coefficients of variation calculated on the 1974–2009 period. Q_{50} , Q_{80} and Q_{90} are respectively the 50th, 80th and 90th exceedance percentiles of the flow duration curve.

	Min	25 %	Median	75 %	Max
Mean annual precipitation P_A (mm)	656	842	931	1039	1400
Interannual variability of P_A	0.13	0.15	0.17	0.17	0.26
Mean annual potential evapotranspiration PE_A (mm)	606	683	698	717	1031
Interannual variability of PE_A	0.05	0.06	0.08	0.09	0.11
Mean annual streamflow Q_A (mm yr ⁻¹)	135	255	325	437	1033
Interannual variability of Q_A	0.23	0.28	0.33	0.38	0.62
Catchment yield Q_A/P_A (%)	21	31	37	41	76
Base-flow index (BFI) (%)	11.7	35	45.3	51.1	93.5
Q_{90}^*/Q_{50}^* (%)	7	18	28	38	67
Q_{80}^* (mm day ⁻¹)	0.03	0.13	0.19	0.31	1.21

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Table 3. Overview of the characteristics of the five models tested.

Short name used here	GARD	GR6J	MORD	PRES	SIM
Full name	GARDENIA	GR6J	MORDOR	PRESAGES	SIM
Reference on model structure	Thiéry (2013)	Pushpalatha (2011, 2013)	Garçon (1999); Andreassian et al. (2006)	Lang et al. (2006a, b)	
Type	Conceptual	Conceptual	Conceptual	Conceptual	Physically-based
Spatial distribution	Semi-distributed	Lumped	Lumped	Lumped	Distributed
Number of free-parameters	4 to 9 (+2 to 4 for snowmelt)	6 (+2: snow routine)	11 (+4: snow routine)	7 (+3: snow routine)	0
Calibration method	Automatic calibration on observed streamflow and groundwater levels	Automatic calibration: local research method (step by step)	Automatic calibration: Shuffled Complex Evolution Method and Pareto Front Exploitation	Automatic calibration: simplex method with multistart	No calibration
Calibration criteria	User selected: Nash, Nash(Log(flow)) Nash(sqrt(flow)) + weighting on bias	(KGEQ + KGEIQ)/2	(KGEQ + KGEIQ)/2	Nash–Sutcliffe with $Q^{0.2}$ with $Q^{0.2}$	
Post-correction method (simulation)	Not used	Not used	Not used	Empirical method (Berthier, 2005)	Quantile/quantile post-treatment
Assimilation method (forecast)	When a flow discrepancy appears, the model tanks are updated proportionally to their variance	Correction based on error at first time step before forecast, with decreasing effect when lead time increases	Correction based on errors at previous time steps before forecast, with decreasing effect when lead time increases. No update of model stores.	Update of gravitary routing store	No assimilation method but a quantile/quantile post-treatment
Structure overview: production	Actual evapotranspiration is computed using a non-linear soil capacity. GW exchange is a proportion of the GW flow	A rainfall interception by PE, a non-linear SMA store, an intercatchment GW exchange function	A rainfall excess/soil moisture accounting store; an evaporating reservoir; an intermediate store and a deep store	A soil store, rainfall interception by PE	
Structure overview: transfer	A non lineau tank distributes the effective rainfall into runoff and GW recharge. The aquifer is represented by a linear tank.	Two unit hydrograph, two parallel nonlinear routing stores	Direct, indirect and baseflow components are routed using a unit hydrograph (Weibull law) one for interflow	Two unit hydrographs, two linear routing stores: one for streamflow recession,	
References on simulation applications in France	800 to 1000 rivers simulated in France		Garavaglia (2011); Paquet et al. (2013)	Lang et al. (2006a, b)	
References on low-flow forecasting applications in France		Pushpalatha (2011, 2013)	Mathevet et al. (2010)	Lang et al. (2006a, b)	

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Table 4. List of efficiency criteria used for model evaluation in simulation mode.

Name	Description
Quadratic criteria	
KGEQ	Kling–Gupta Efficiency
C2MQ	Nash–Sutcliffe Efficiency bounded in] – 1; 1]
Low-flow quadratic criteria	
C2MiQ	Nash–Sutcliffe Efficiency calculated with $1/Q$ and bounded in] – 1; 1]
RMSEut	Root mean square error calculated when observed streamflow is less than Q_{80} threshold
Volume based criteria	
Vdef	Ratio of observed and simulated cumulative annual volume deficits
Temporal criteria	
LFD	Ratio of observed and simulated cumulative low-flow duration
DatSt	Relative difference between observed and simulated start of annual low-flow period
DatEn	Relative difference between observed and simulated end of annual low-flow period
Threshold criteria	
POD	Probability of detection, based on contingency table
FAR	False alarm rate, based on contingency table
CSI	Critical success index, based on contingency table

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Table 5. List of efficiency criteria used for model evaluation in forecasting mode.

Name	Description
Low-flow quadratic criteria	
RMSEut	Root mean square error calculated when observed streamflow is less than Q_{80} threshold
Volume based criteria	
Vdef	Ratio of observed and simulated cumulative annual volume deficits
Temporal criteria	
LFD	Ratio of observed and simulated cumulative low-flow duration
Sharpness/reliability	
Sharpness	Mean width of interval defined by 10 % and 90 % percentiles of forecast distribution when observed streamflow is less than Q_{80} threshold
Reliability	Percentage of observation in the 80 % forecasted confidence interval when observed streamflow is less than Q_{80} threshold (80 % of observed streamflow should be included in the interval)
Threshold criteria	
POD	Probability of detection, based on contingency table
FAR	False alarm rate, based on contingency table
CSI	Critical success index, based on contingency table
BSutvig, BSutcri	Brier Score with vigilance threshold (Q_{80}) or crisis threshold (Q_{95})
DRPS	Discrete Ranked Probability Score

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Table 6. Models ranked based on mean performance in validation on the 21 catchments. The mean rank is calculated with the nine low-flow criteria (i.e. not considering C2MQ and KGEQ). Italic values indicate the best model.

Criterion	Model's rank					
	GARD	GR6J	MORD	PRES	SIM	DAQ
C2MQ	<i>1</i>	2	3	4	5	6
KGEQ	3	2	<i>1</i>	5	4	6
C2MiQ	<i>1</i>	3	4	2	5	6
RMSEut	<i>1</i>	3	4	2	5	6
FAR	<i>1</i>	4	3	2	6	5
CSI	4	2	3	<i>1</i>	5	6
POD	4	<i>1</i>	3	2	5	6
Vdef	5	3	2	<i>1</i>	4	6
LFD	5	4	<i>1</i>	3	2	6
Date Start	2	3	4	<i>1</i>	5	NA
Date End	2	3	4	<i>1</i>	5	NA
Mean rank	2.8	2.9	3.1	<i>1.7</i>	4.7	5.9

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Table 7. Models ranked based on mean performance on the 21 catchments for validation period 2 and for the two forecasting lead times selected.

Criterion	Model's rank											
	7 day lead time						30 day lead time					
	GARD	GR6J	MORD	PRES	SIM	NVQ	GARD	GR6J	MORD	PRES	SIM	NVQ
RMSEut	1	2	3	4	5	6	1	5	2	4	3	6
DRPS	3	1	4	2	5	6	3	1	4	2	6	5
POD	3	2	1	4	6	5	3	2	1	4	6	5
FAR	3	2	4	1	5	6	2	3	4	1	5	6
CSI	2	1	3	4	5	6	3	2	1	4	6	5
BSutvig	3	1	4	2	5	6	3	2	4	1	5	6
BSutcri	2	1	4	3	6	5	1	2	5	3	6	4
Cont_ratio	6	5	4	2	3	1	6	4	5	2	3	1
Sharp	1	2	3	4	5	6	1	3	2	5	4	6
Vdef	1	2	4	3	5	6	1	3	4	2	5	6
LFD	1	2	3	4	5	6	1	3	2	4	6	5
Mean rank	2.4	1.9	3.4	3.0	5.0	5.4	2.3	2.7	3.1	2.9	5.0	5.0

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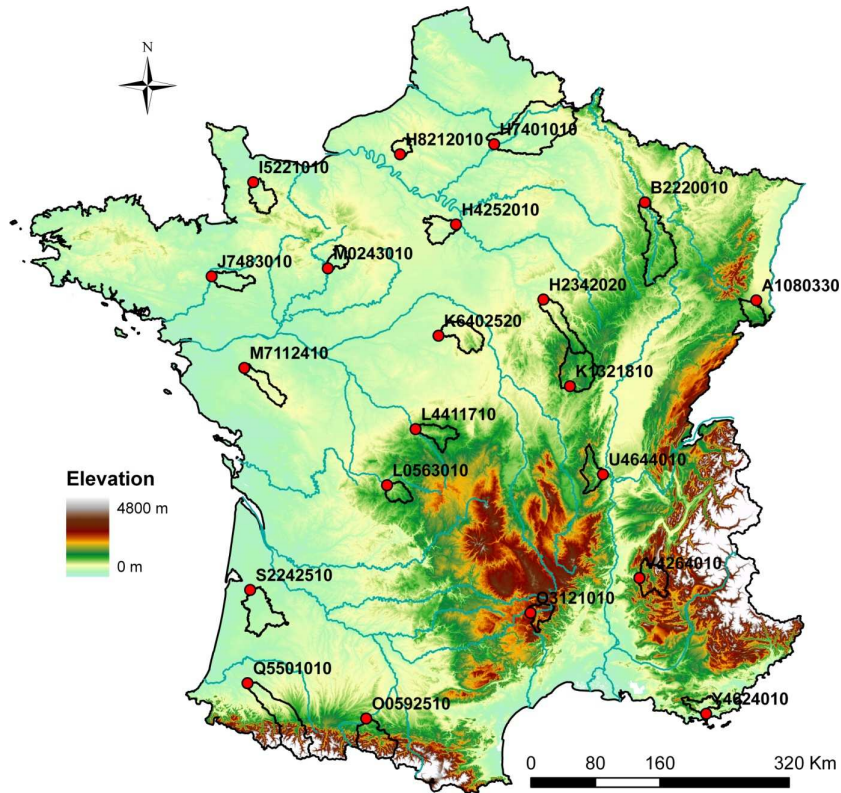


Fig. 1. Location of the 21 selected catchments in France.

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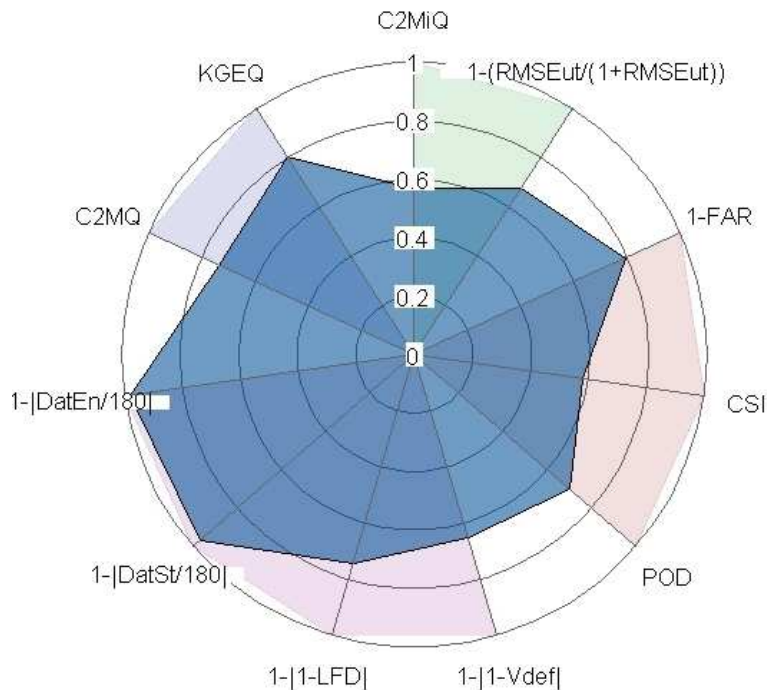


Fig. 2. Example of radial plot showing mean model results on the set of 21 catchments for the selected evaluation criteria. The larger the blue surface, the better the model. Background colours link criteria focusing on similar aspects.

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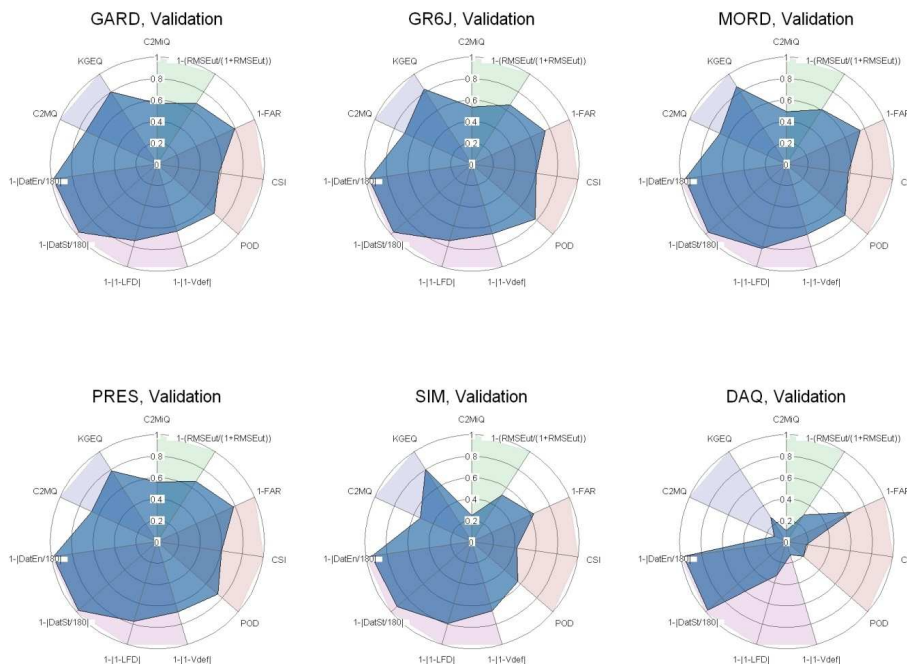


Fig. 3. Radial plot showing the mean results for the selected criteria in validation for the 21 catchments and the two periods. Results of the five models tested and the benchmark (DAQ) are shown.

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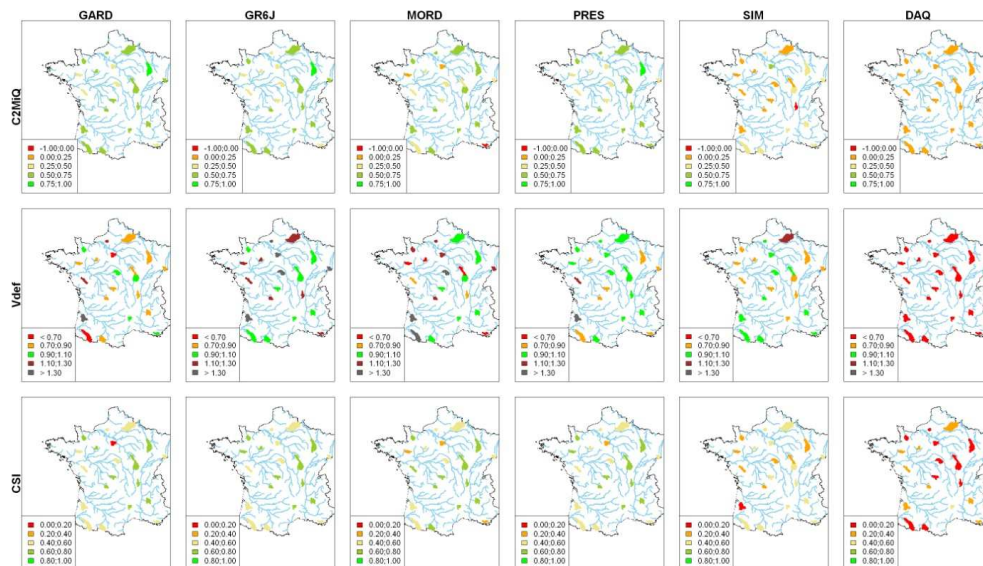


Fig. 4. Maps of mean performance on the two validation periods in C2MiQ, Vdef and CSI for the five models tested and the benchmark (DAQ) on the 21 catchments.

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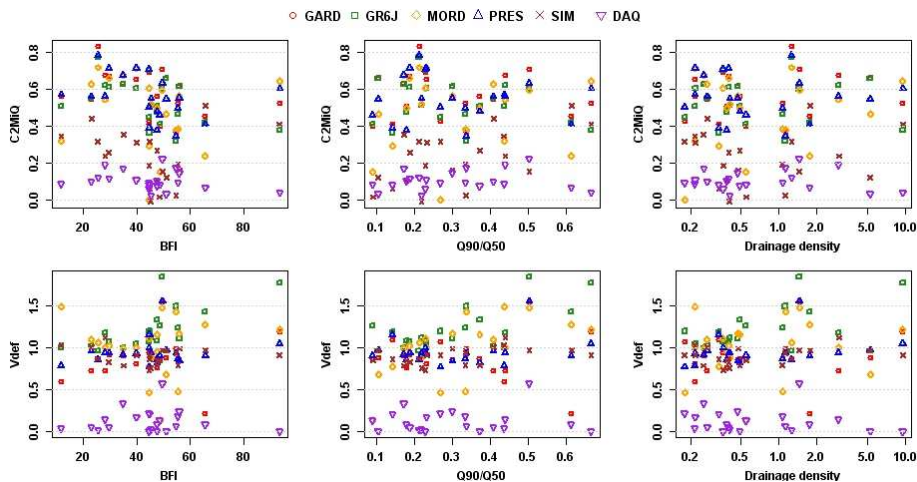


Fig. 5. Relation between mean performance on the two validation periods in terms of C2MiQ (a) and Vdef (b), and catchment characteristics (left: Base-Flow Index, centre: Q_{90}/Q_{50} ratio; right: drainage density) for the 21 catchments and the models tested.

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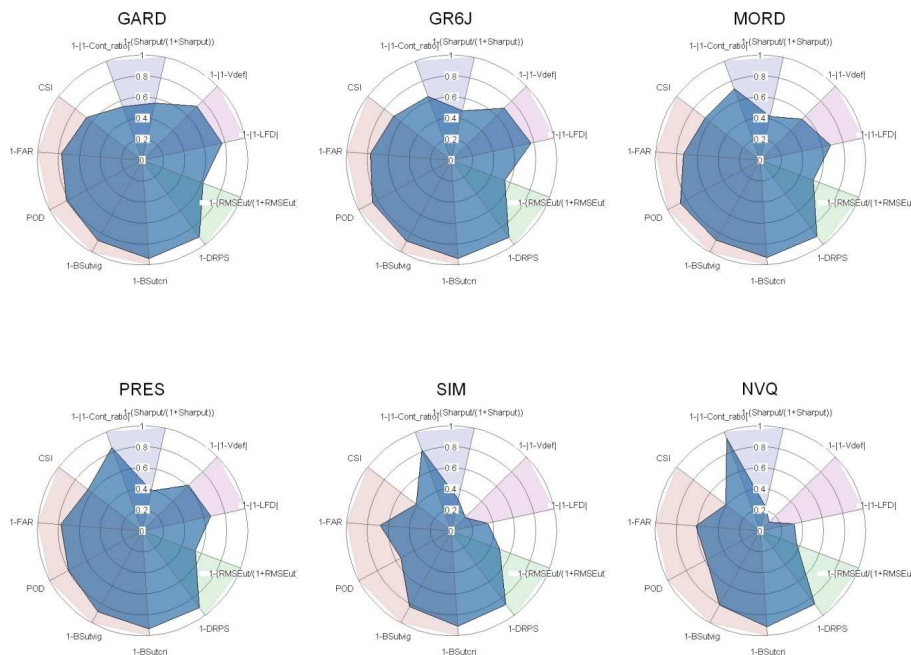


Fig. 6. Radial plot of the results of the mean selected criteria in validation for the 21 catchments in validation period 2, for a $d + 7$ forecasting lead time.

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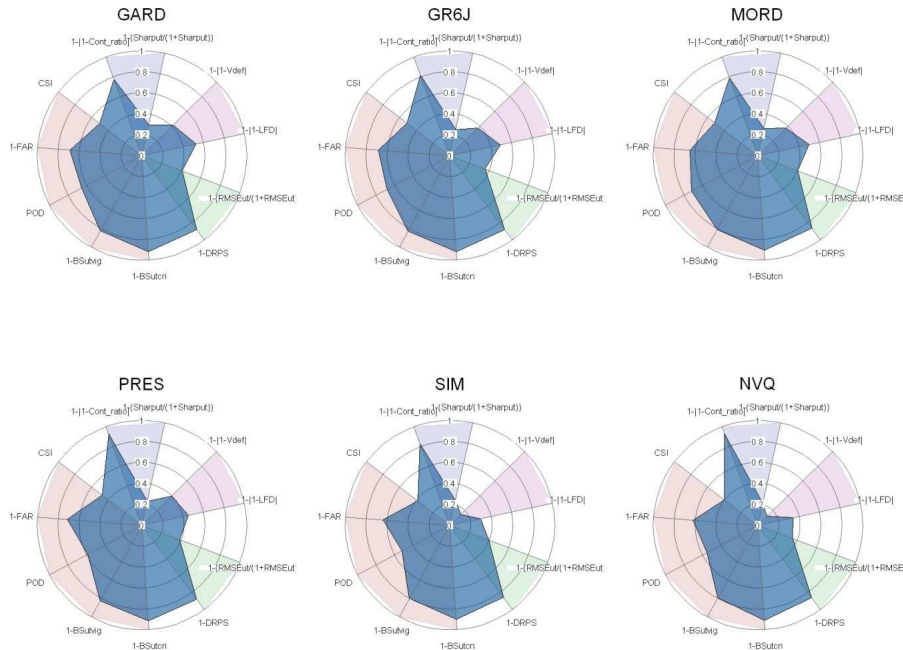


Fig. 7. Radial plot of the results of the mean selected criteria in validation for the 21 catchments in validation period 2, for a $d + 30$ forecasting lead time.

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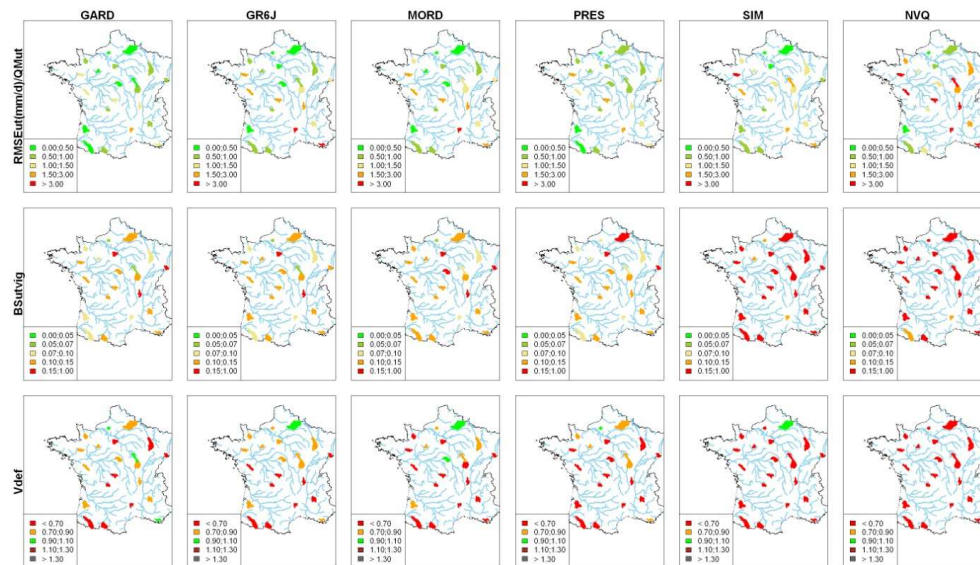


Fig. 8. Performance on validation period 2 in RMSE_{ut}, BS_{utvig} and V_{def} for each model on the 21 catchments for a 7 day forecasting lead time.

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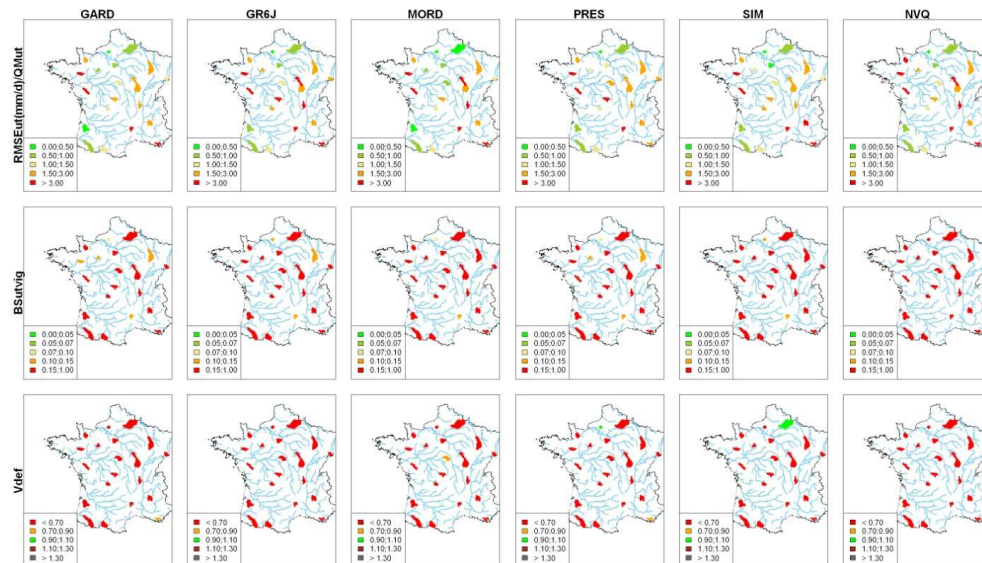


Fig. 9. Performance on validation period 2 in RMSEut, BSutvig and Vdef for each model on the 21 catchments for a 30 day forecasting lead time.

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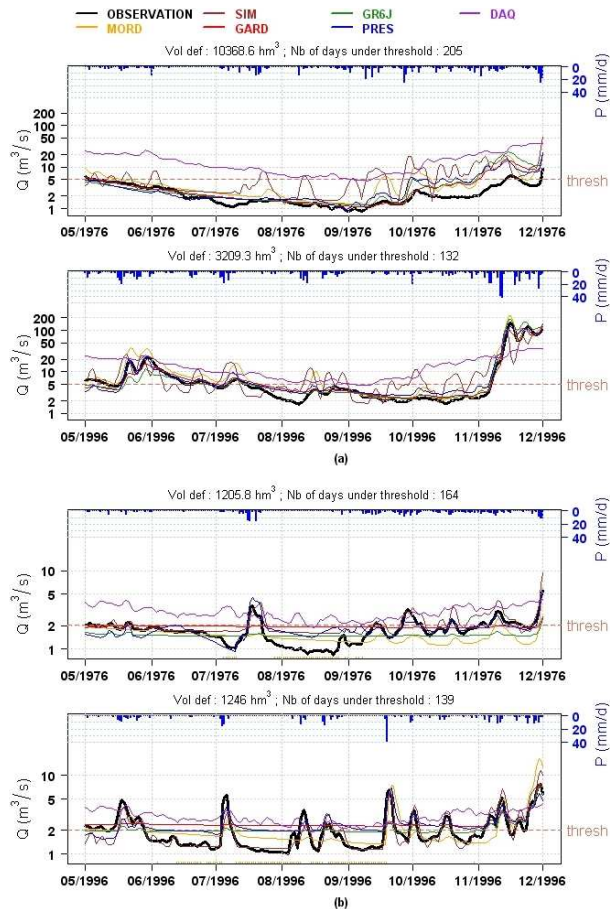


Fig. 10. Observed and simulated hydrographs for **(a)** the Meuse River at St-Mihiel and **(b)** the Orge River at Morsang-sur-Orge for 1976 (top graph) and 1996 (bottom graph). The secondary axis shows rainfall.

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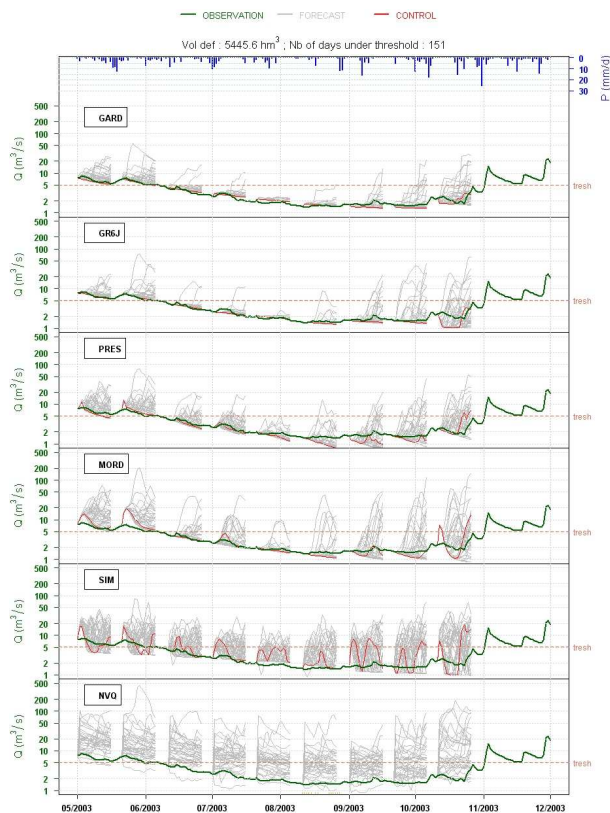


Fig. 11. Examples of forecasts issued by the five models tested and the benchmark every 20 days for the next 15 days for the Meuse River at St-Mihiel for 2003.

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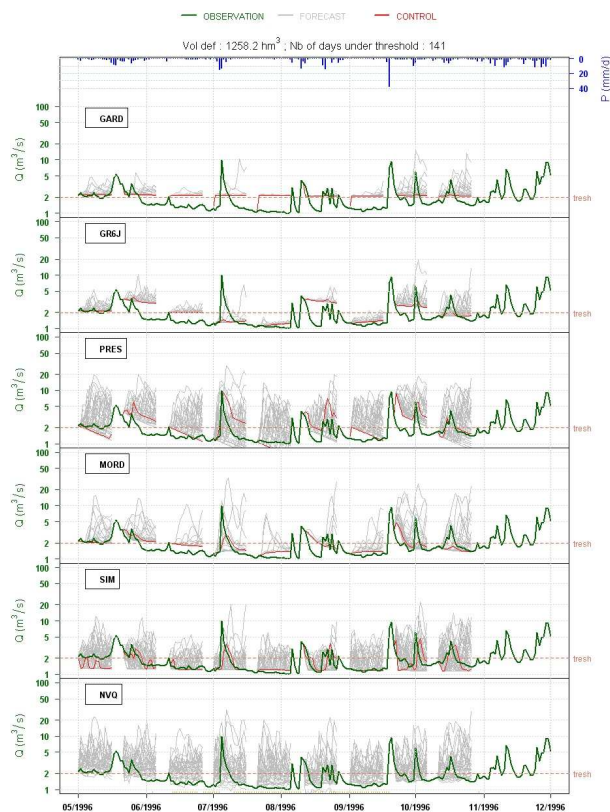


Fig. 12. Examples of forecasts issued by the five tested models and the benchmark every 20 days for the next 15 days for the Orge River at Morsang-sur-Orge for 1996.

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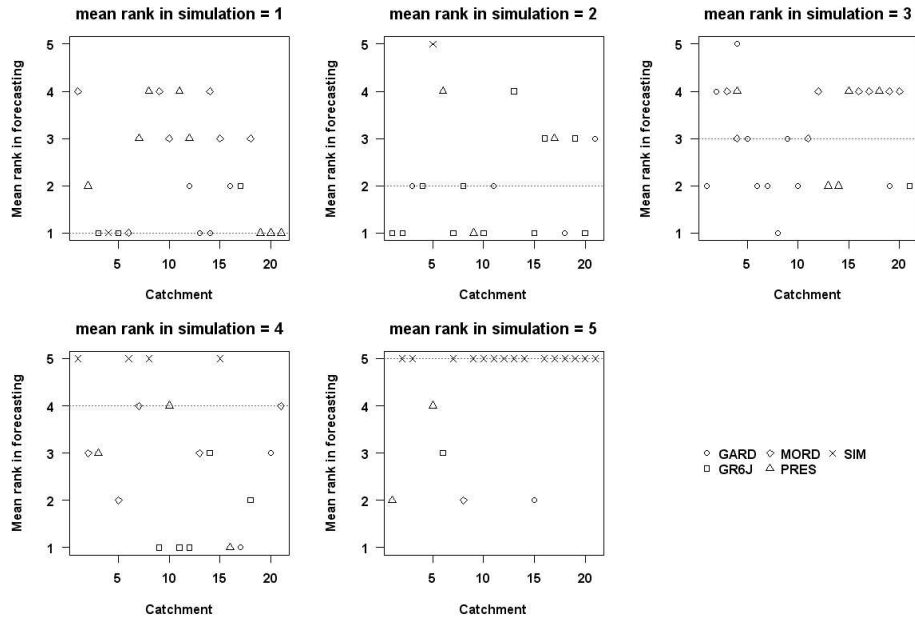


Fig. 13. Mean rank in forecasting at the 7 day lead time for the 21 catchments for the models ranked 1st, 2nd, . . . , 5th in simulation.

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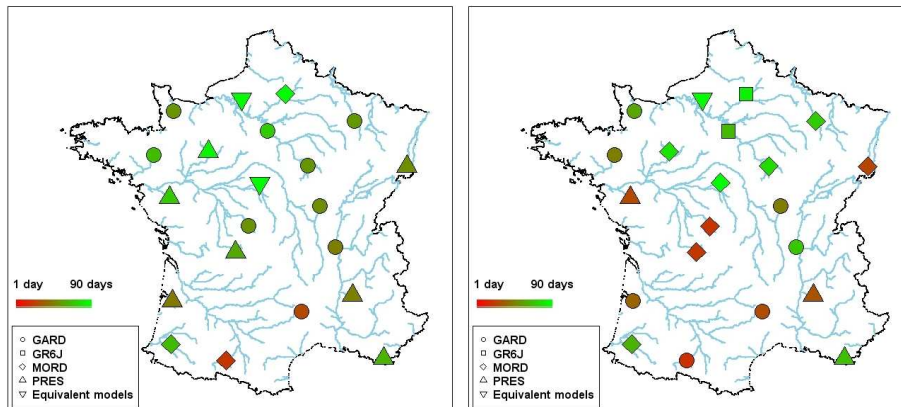


Fig. 14. Map of useful forecasting lead time (UFL) for the 21 catchments, for validation periods 1 (left) and 2 (right). Symbols indicate the model which provides the best UFL and the colour scale indicates the value of this UFL.

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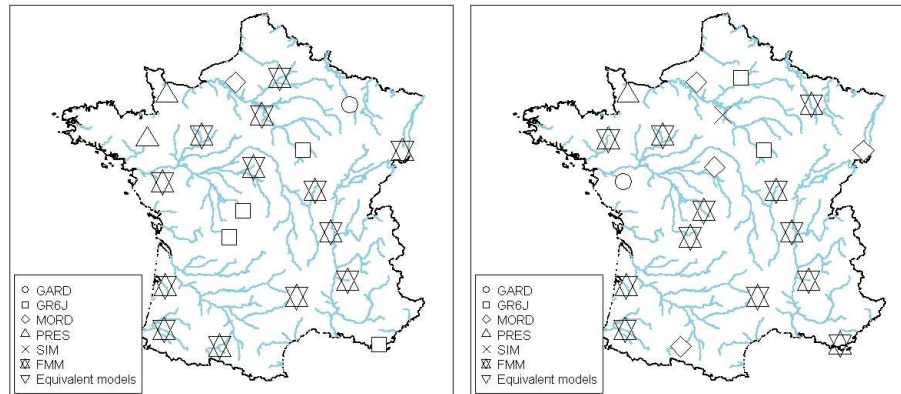


Fig. 15. Maps of the model ranked best in simulation for the mean of all criteria and for validation periods 1 (left) and 2 (right), including the multi-model (fixed-weight average approach, FMM).

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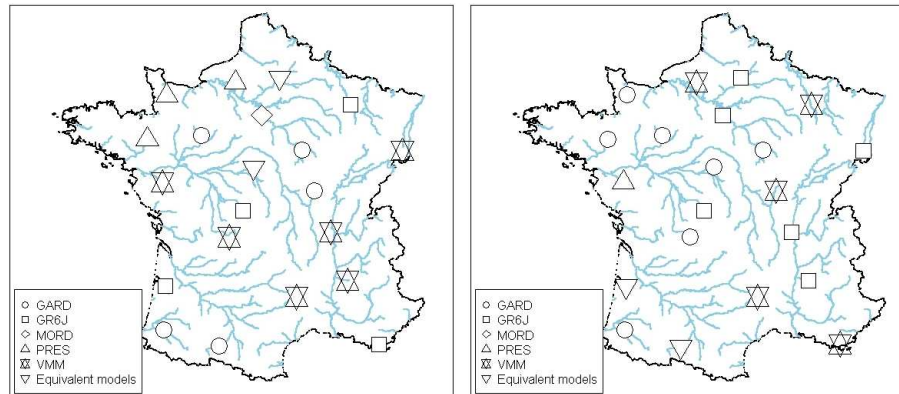


Fig. 16. Maps of the model best ranked in forecasting for the mean of all criteria and for validation periods 1 (left) and 2 (right), for a $d + 7$ forecasting lead time.

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