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Small farm dams: impact on river flows and sustainability in a context of climate change

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Abstract

The repetition of droughts in France has led to a growing demand for irrigation water and consequently to an increase in requests for the construction of small farm dams. Although such dams are small, their accumulation in a basin affects the river flows. In order to gain more insight into their impact, a small farm dam model was built and connected to a hydrometeorological model. Several scenarios with different volume capacity, filling catchment size and filling period were tested for such dams. The results were analysed in a small basin in western France, where the pressure for building such dams is high, and then extended to the whole country. It was found that, due to the hydrometeorological conditions (mainly precipitation), the development of small farm dams in north-western France would lead to larger impacts on the riverflows and to less efficient filling of the small farm dams than in other regions of France. Moreover, such behaviour is projected to worsen in a context of climate change, despite the uncertainty on the evolution of precipitation.

1 Introduction

In recent decades, France has suffered several droughts (Vidal et al., 2010b), with large impacts on hydrology (Giuntoli et al., 2013) and on agriculture (Amigues et al., 2006; van der Velde et al., 2012). Moreover, droughts are projected to be both more frequent and more extreme in the context of climate change (Vidal et al., 2012). Irrigation is a solution to protect farmers from water shortages, the water being provided by rivers and/or groundwater where the hydrogeological conditions are suitable, or from reservoirs elsewhere. Irrigation dams have been used for a thousand years in the Mediterranean area (Albergel et al., 2004) and have proved to be efficient in providing irrigation water in semi-arid regions, with positive impact on the economic activity of the countries concerned (Khlifi et al., 2010). Although irrigation dams can be large, most of them are associated with reservoirs of small storage capacity located on farms, and thus usually not connected to the main rivers. We will use the term “small farm dams” to distinguish these dams from the larger man-made structures for flood control and/or water supply.

Small farm dams can be seen as a potential solution to the projected increase in droughts. For these reasons, there is growing pressure from French farmers' unions to allow their development, in the aim of protecting or extending production capacities (FNSEA, 2012). One argument is that small farm dams are expected to provide water when the crops need it, by storing water during the winter, which would also help to mitigate winter flood events. In France, such small farm dams are used extensively in the south west (http://www.eau-adour-garonne.fr/fr/etat-des-ressources-gestion-quantitative/barrages-et-reservoirs-du-bassin-adour-garonne.html), with a storage capacity above 800 million m^3 (Hébert et al., 2012). Such a dense concentration is quite unique in France. The economic impact of these dams was studied in detail by Hébert et al. (2012), but few studies in France have focused on their hydrological impact, with the notable exception of Galéa et al. (2005), who, by analysing the observed riverflows of some basins, found that these dams mostly impacted the winter floods. When the time series of the observed river flow is too short, the methodology used by Galéa et al. (2005) cannot be applied. In such cases, modelling can be used to estimate the impact of small farm dams. One issue for such modelling is the determination of the geolocalization and volumes stored in the numerous reservoirs. Several studies have focused on determining the number and extent of the small farm reservoirs by using satellite data (Bhagat and Sonawane, 2011; Casas et al., 2011; Rodrigues et al., 2012; Shao et al., 2012). A few authors have been able to perform detailed studies of the impact on hydrology, based on the simulation of a large number of small farm dams. Among them, Ramireddygari et al. (2000) in the USA, Hughes and Mantel (2010) in South Africa and Nathan and Lowe (2012) in Australia, found that the impact of such dams could reach 10 % of the annual discharge. Cudennec et al. (2004), using a simpler approach based on a unit hydrograph, performed a prospective study in north-western France and found an impact limited to the downstream basin.

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The regional environmental agency of Pays de la Loire (DREAL Pays de la Loire), responsible for authorizing the building of such small farm dams, has received an increasing number of requests over the past few years. The issue for the DREAL has therefore been to form an idea of the impact of such dams, so as to implement the policy that best fits the farmers water demand while preserving the hydrological environment. The main questions are: what is the maximum water volume that can be stored in the irrigation dams without having too great an impact on the flow? Is there a need to modify the regulations with regards to the functioning of these dams, especially the authorized filling period? and how can we be sure that the decisions taken at the present time will be economically and environmentally sustainable, especially in a context of climate change?

To perform the necessary study, a physically-based hydrometeorological model was used. A small farm dam module was built, with several hypotheses concerning the storage capacity and the filling capacity. This model is presented in the next section. The study first focused on the Layon basin (Fig. 1), one economically important basin of the Pays de la Loire that sometimes lacks water for the irrigation of maize. The impacts of the small farm dams on the river flows of the Layon basin are detailed below. Then, the method is generalized to the whole of France, which gives an idea of the impact of the hydrometeorological drivers. The last section considers the evolution of such anthropized basins in a context of climate change.

2 Material and methods

2.1 Hydrometeorological modelling

The method chosen was to use a hydrologically established model but without calibrating it. Calibration implies the use of observed river flows, but these flows are affected by anthropization, especially by the numerous points where water is drawn from rivers and aquifers. Unfortunately, such withdrawals are not sufficiently well-known to be correctly imposed, in spite of the great efforts made by water agencies to obtain these data. Thus, the hydrometeorological model SIM (Safran Isba Modcou) was used (Habets et al., 2008). In this model, the atmospheric forcing (precipitation, 2 m temperature and humidity, wind speed, incoming radiations) is provided by Safran (Durand et al., 1993; Quintana-Seguì et al., 2008) at an hourly time step and on an 8 km grid. Safran analyses are now available from 1958 (Vidal et al., 2010a). The water balance is computed using the Isba atmospheric surface scheme (Noilhan and Planton, 1989), for which the parameters are derived from a physiographic database (Masson et al., 2003). Isba is coupled to the Modcou hydrological model (Ledoux et al., 2007), for which hydrogeological parameters were calibrated in the Seine and Rhone aquifers. However, as the region of interest is not deeply affected by aquifers, the groundwater modelling is not used, and only the surface water routing is used. The river flow is simulated using the Rapid routing scheme (David et al., 2011a, b) for which the parameters were calibrated over the whole of France and, thus, not calibrated over a single basin. SIM was assessed over the whole of France (Habets et al., 2008), and one of the results is a better ability to reproduce the daily river flow of the largest basins. Quintana-Seguì et al. (2009) improved the results on the smallest basins by calibrating some soil parameters but, as mentioned above, it was decided not to use a calibrated simulation for this study. Section 3.1 presents an evaluation of the SIM results on the Layon basin.

2.2 The small farm dam model

For this study, a small farm dam model was developed and connected to SIM. This model is based on several hypotheses concerning the number and location of the dams, the area and depth of the reservoirs, and their functioning (Fig. 2):

- The reservoirs are small (less than 20 000 m^3) but several small farm dams can be located in the same sub-basin. Several studies have succeeded in inferring the number of dams and the area they cover using satellite data and GIS (Bhagat and Sonawane, 2011; Rodrigues et al., 2012; Shao et al., 2012). As our study is more a prospective than a retrospective study, the future location of the dams cannot be observed, and the choice was made to build simple hypotheses that could fit both the present day and the coming decades. In the Layon basin, the number of dams is limited to $3\,km^{-2}$ (SDAGE Loire Bretagne, 2009). But, since the water balance is computed on an 8 km grid by ISBA, if several dams are present in an 8 km grid space, they have to be considered as aggregated (Fig. 2). In a basin larger than $64\,km^2$, the distribution of the dams can be heterogeneous. A preliminary test was used to determine whether the results were sensitive to dam locations in a $1000\,km^2$ basin. It was found that, as long as the dams were small and sparsely distributed (i.e. not all located on the same tributary) the impact was reduced. This is consistent with the findings of Hughes and Mantel (2010). Therefore, for the sake of simplicity, the distribution of the dams was assumed to be homogeneous in space, i.e. there was one aggregated dam in each $8\,km \times 8\,km$ cell used to compute the water balance.

– To estimate the volume stored in the small farm reservoirs, another hypothesis was made. In the Pays de la Loire region, the spatial extent of the surface water area should not reach 5 % of the basin area (SDAGE Loire Bretagne, 2009), a figure far from being achieved in most basins of the region, even when all the natural lakes and large reservoirs are counted. As the regulation is expressed as a percentage of the basin area, we used the same formalism to express the small farm dam fraction D, i.e. the accumulated area of the small farm dam (A_{SFD}) in a basin as a percentage of the basin area (A_{basin} in m^2):

$$D = A_{SFD}/A_{basin} \times 100 \quad (1)$$

The small farm dam fraction can be estimated using the present day irrigation water volume in the Pays de la Loire region, by considering that all the irrigation water taken from the surface water comes from small farm dams. To do this, we used the pumping volume (V_P in m^3) provided by the basin water agency. We then needed to estimate an average water depth, d_w, of the small farm dams. An average value of $d_w = 3$ m was chosen, as it is below the 5 m for which an annual survey of the dam structure is required. Then, the small farm dam fraction can be expressed as:

$$D = V_P / d_w / A_{basin} \times 100. \tag{2}$$

Table 1 gives an estimate of this percentage for seven basins of the Pays de la Loire. From Table 1, reasonable extension of the use of small farm dams in the future could lead them to reach 0.5 to 1 % of the basin area.

– The reservoirs are expected to fill up naturally by capturing runoff on their topographic watersheds. This is compatible with the small irrigation dams located in the south west of France but not with all the existing small irrigation dams located in Pays de la Loire. Some of these are filled up by pumping from rivers. They are then able to collect water from a larger area than the small dam's catchment. In any case as the exact locations of the small dams are unknown, it is not possible to compute their catchments. Therefore, to try to encompass these two characteristics, several sizes of catchment that can contribute runoff to the dams are studied here. These dam catchment areas (A_{catch}) were considered to be proportional to the area of small farm dam's:

$$A_{catch} = R \times A_{SFD} \tag{3}$$

with R varying from 20 to 200. Since the dam's area is defined as a percentage of the basin, the area of the dam's catchment can also be expressed as a proportion of the basin area:

$$A_{catch} = R \times D \times A_{basin} = C \times A_{basin} \tag{4}$$

C varies from 10 to 100 % (see Sect. 3.2). In order to be compatible with filling by pumping, the inflow was limited to 1 m^3 s^{-1}.

– The filling period is regulated: farmers can fill the dams from November to March. However, the DREAL Pays de la Loire pays special attention to the occurrence of floods in the autumn because they have a strong positive impact on migratory fish and because they are morphogenic. Moreover, it appeared that most of the farmers used a shorter period to fill up their dams, with increased water intake from January to March. Therefore, two filling periods were tested in this study: a 5 month period from November to March and a 3 month period from January to March.

– A strong hypothesis is made on how the dams operate: all the water in the dams is expected to be used for irrigation purposes, i.e., the small farm dams are assumed to be emptied every year, and this water is taken to be spread on the fields (Fig. 2) where it is expected to evaporate with no return to the river.

– Evaporation from the small farm dams is neglected, and the impact of this hypothesis will be discussed in Sect. 6.

The small farm dam module was connected to SIM with a daily time step by collecting both the simulated surface runoff and infiltration (Fig. 2). When the dams are full or outside the filling period, the presence of dams does not affect the simulated hydrology. Hereafters the word “basin” is used for the river basin, while “catchment” is used for the dam’s catchment area.

3 Simulation of the Layon basin

The study first focused on the Pays de la Loire region. Although several rivers were studied, we concentrate, here, on the Layon basin (Fig. 1). There are several river gauges in the Layon, and we consider the largest one, Saint Lambert (930 km^2). The main irrigated crop is maize. The declared irrigation volume reached 3 000 000 m^3 in 1998 (SAGE, 2002a) and had almost doubled by 2010, the water being mostly stored in small farm dams or being directly pumped from the river or alluvial aquifer (SAGE, 2002a). Only a quarter of this volume was stored in dam reservoirs larger than 2000 m^3 (about 180 dams). In order to reduce the pumping in summer and its large effect on the hydrology, it is projected to increase the irrigation dam facilities in the basin (SAGE, 2002b). If all the irrigation water is expected to be provided by dams, then, according to our hypotheses, the area of the reservoirs associated with small farm dams within the Layon basin will be about 0.2 % of the basin (Table 1).

3.1 Assessment of the hydrometeorological model without small farm dams

As explained earlier, the SIM model was not calibrated to reproduce the observed river flow. The comparison with the observed river flow was made over the period 1970–2000. The mean observed discharge was 4.35 $m^3 s^{-1}$, which implies that the irrigation pressure represented at least 4 % of the discharge. The simulated river flows show a clear overestimation of the river flow from September to February (Fig. 3), the mean annual error on the discharge being 13 %, while the error from November to March reaches 23 %. There is slightly better agreement with the monthly low flows (VCN3: minimum 3 day river flow) and high flows (VCX3: maximum 3 day river flow), although the low flow tends to be underestimated. The daily efficiency (Nash and Sutcliffe, 1970) reaches 0.61, and the ones computed from November to March is only 0.56. Although it is clear that part of the error is linked to a poor estimation of the parameters describing the basin characteristics and to the physics of the model, between 25 and 50 % of the error can be linked to the water intake, depending on the period of reference for the water uptake. The consequences of such overestimation of the river flows during the filling period is that the simulated ability to fill up the small irrigation dams might be overestimated while the impact of the water withdrawals on the river flows might be underestimated.

3.2 Impacts of the small farm dams in the Layon basin

Several scenarios for the extent and configuration of the dams were used: two filling periods, two maximum storage capacities, and three areas of the contributing catchment were tested (Table 2). Only the smallest dams' catchment was expected to be incompatible with dams that were filled by pumping. The impacts were estimated using a 30 yr simulation, from 1970 to 2000.

3.2.1 Storage efficiency

Only the smallest dams' catchment showed poor ability to fill up in the Layon basin (Fig. 4), with dams full less than one year in ten while the full capacity was reached in at least seven out of ten years for the other scenarios. Therefore, the smallest dams' catchments are probably not economically efficient, and larger dams' catchments or pumping facilities should be preferred in the Layon basin. For the larger catchments, when the full capacity is not reached (three years out of ten), the storage is more efficient when the filling period lasts 5 months rather than 3 months. Similar results are obtained when the area of the dams represents 0.5 % and the catchment area is 50 % of the basin area or when the area of the dams is 1 % and the catchment area is 100 % of the basin, which was to be expected since the dam catchment areas are then similar (Table 2).

3.2.2 Impact on river flows

During the filling period, the dams are expected to capture all the water that flows on their topographic catchment as long as the inflow is below 1 $m^3 s^{-1}$ and as long as the dams are not full. Thus, Fig. 5 shows, quite logically, that the impact of the dams is greater in the first month of the filling period, except for the scenario with the smallest dams' catchment, which has already been shown not to be the most suitable. The impact on the first month is lower for the 3 month period than for the 5 month period because the river flows are higher in January than in November. The significance of the results was estimated using a bootstrap approach. The impacts were significant at a 95 % interval only for the first month for the scenario in which the catchment covered 100 % of the basin. The area of the dam catchment has a large impact on the intensity of monthly river flow reduction, with a maximum reduction of the flow varying from 56 to 38 % for a catchment areas reaching 100 % and 50 % of the basin, respectively, for a 5 month filling period, and is limited to between 29 to 25 % for a 3 month filling period. Similar results were found for the low and high river flows (VCN3 and VCX3), but with a larger impact on the low flows. Thus, compared to a 5 month period, a 3 month period has a reduced impact on the monthly river flow while being almost as efficient for filling the dams (Table 2).

The impact of the dams varies each year according to the hydrometeorological conditions. The frequency distribution of the impact on the annual discharge is presented in Fig. 6. The largest extent ($D = 1\,\%$) leads to a reduction of the annual discharge by up to 20 % in six out of ten years. Such strong impact might not be acceptable for the local hydrologic environment.

3.2.3 Focus on a dry year

As the irrigation dams are intended to supply water in a context of shortage, we focus here on one of the driest years. Figure 7 presents the impact on the monthly flow in 1991–1992. When the dam area is 0.5 % of the basin area the flow of the first month of the filling period is reduced by more than 90 % for a dam catchment as large as the basin and around 50 % for a dam catchment of half the basin, for the two filling periods. On an annual basis (Table 2), the best filling efficiency is achieved for a 5 month filling period and a 0.5 % dam area with a catchment covering the full basin (85.6 %). Halving the size of the catchment limits the storage efficiency to 60 %. The impact on the annual discharge is considerable, −40 % and −30 %, respectively, for the two-dam implementations discussed above. The 3 month filling period leads to a reduced impact on the monthly river flow, but also to weaker efficiency of dam filling during the driest years. From this study, it seems that a 0.5 % area, with catchments covering all or half the basin are the most stable scenarios, with rather good filling efficiency even during dry years.

4 Results over France

The extension of the results to the whole of France allows some comparisons to be made with areas where the irrigation dams are already well developed (south-west of France). Of course, an even distribution of the small farm dams is not realistic. Moreover, in some regions, pumping from regional aquifers might be preferred to small farm dams. But the use of a spatially homogeneous scenario gives better insight into the hydro-climatic constraints on small farm dam filling capacity and on their impact on river flow. In this section, only the scenarios with a 0.5 % area for the small farm dams are used, and the sensitivities to the dam's catchment and the filling periods are studied. Mean annual precipitation in France ranges from about 500 to about 2500 mm yr^{-1}, with high precipitation in the mountains, and low precipitation in most of the north-west and in the Mediterranean area (Fig. 8). Such contrasts will of course impact the efficiency with which the dams are filled and also their impact on river flow. Figure 8 shows that the Pays de la Loire region is associated with relatively low rainfall.

The mean filling efficiency shows large spatial variation when averaged over the 30 yr period and for the dry year of 1991–1992 (Figs. 9 and 10). In the south-west and Brittany, maximum capacity is reached for all catchment sizes and the 2 filling periods even for the driest year, confirming that the hydro-climatic conditions are favourable in these regions. The mountainous regions with large snowpack (Alps, Pyrennees) have a low filling ratio, which is linked to the fact that, during the filling period, the water is stored in the snowpack. Actually, numerous hydro-power dams exist in these mountainous regions, with a quite different filling periods. Other regions like the Seine basin and the Pays de la Loire region have a weak mean annual filling ratio (50 %) for the smallest catchment, and present a weaker filling ratio during the dry year 1991–1992 for all catchment sizes and filling periods. The 3 month filling period leads to similar mean filling ratios over France for the 2 larger catchment sizes, but is shown to be less efficient during drier years than the 5 month period (Fig. 10).

The impacts on the discharge averaged over the 30 yr period and for the dry year are presented in Fig. 11 for one medium scenario ($D = 0.5\,\%$, $C = 50\,\%$, 5 month filling period) only, as similar results were found for the others. The impact on river discharge is lower than 2 % in the Alps and Pyrenees areas, where the small farm dams were not able to fill up. More surprising, the mean annual impact is also lower than 2 % in south-western France even though the dams there have a high mean annual filling ratio. In contrast, mean annual impacts are larger than 5 % in most parts of the Seine basin, Pays de la Loire region, and along the river Garonne, and exceed 10 % in some parts of these regions. When we focus on the dry year, the Pays de la Loire region and Seine basin stand out as places where the impact is largest, above 15 %.

These results show that small farm dams have smallest impact on the discharge and best storage efficiency in the south-west of France, where they are numerous. This is linked to the high precipitation in this area, especially during the filling period. These results emphasize that, due to the variability of the hydroclimatic conditions, the management developed in the south-west would be less efficient and would have more impact in the river discharge of the Seine basin and Pays de la Loire regions.

5 Projection in a context of climate change

In order to form an idea of the sustainability of small farm dams in the context of climate change, three downscaled climate projections were used to estimate how the storage efficiency and the impact on the river flows could evolved. The downscaled projections had already been used over France (Boé et al., 2009; Chauveau et al., 2013; Habets et al., 2013), which allowed three contrasting projections to be selected. The three downscaled projections share the A1B emission scenario and a weather typing downscaling method (Boé et al., 2006; Pagé et al., 2008). Two time periods are used:

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1970–2000 for the present day, and 2045–2065 for the future. The precipitation projected by the three downscaled projections on the Layon basin and over the whole of France are presented in Fig. 12 and Table 3. ARPEGE gives the driest projection, with a decrease in precipitation that reaches 13.6 % on average and with significant evolution over most of France, while GFDL0 is the projection with smallest change (−3.7 %) and no significant change over France. In the Layon basin, the same observations can be made, ARPEGE is the driest projection while GFDL0 is the wettest one. In the following, the impact of climate change on the Layon basin with the small farm dams is presented first, and then the focus is extended to the whole of France.

5.1 Combined impacts of small farm dams and climate change on the Layon basin

Climate change alone is projected to have a strong impact on the river flow of the Layon basin, with rather large uncertainty: the annual discharge is projected to decrease by 7 to 34 % (Table 3). The presence of small farm dams both in the present day and in 2050 leads to a more pronounced decreased, from −8 to −36 %, and if the small farm dams are considered to be developed by 2050 but not to exist in present day, the decrease is more pronounced, from −16 % to −42 %. The impact of (i) climate change alone and (ii) both climate change and dams, on the monthly discharge compared to the present day without dams are presented in Fig. 13. Although the climate projections show considerable dispersion, the impact of climate change and small farm dams in the first month of the filling period is large, ranging from −40 % to −80 % in November for a 5 month filling period, and from −30 to −50 % in January for a 3 month filling period. Comparing the results in 2050 with and without small farm dams, it is found that the impact of the dams is significant at a 95 % level only in the first month for the ARPEGE projection, and is not significant for the others two projections.

The impact of the small farm dams is partly limited by a decrease of their ability to fill up for all projections except GFDL0 (Fig. 14). On average over the three projections, for a 5 month filling period, full storage is reached in six years out of ten in the present day, but only in four years out of ten in 2050, the small farm dams being projected to be less than 70 % full for two years out of ten in 2050. The impact of climate change is accentuated for a 3 month filling period, the small farm dams being projected to be full for three years out of ten in 2050, and to be less than 50 % full for two years out of ten in 2050.

5.2 Combined impacts of small irrigation dams and climate change in France

When the view is widened to the whole of France, it is found that, although the climate projections are rather different the regions that were found to be the most sensitive to drier years in the present day are the most impacted by climate change. A strong decrease (above 15 %) in storage is found in the Seine basin, the centre of the Garonne Valley, the south of the Loire basin, and the Pays de la Loire (Fig. 15). Regions with a large snow pack in the present day are projected to improve their storage capacity in 2050 due to a diminution of the snowpack (Alps and Pyrenees mountain ranges). However, as stated before, hydro-power dams are present nowadays in these mountainous regions, and they are not affected by the same regulation on the filling period. Therefore, the results obtained in these regions should not be considered. This is why, in Table 3, the results on the evolution of the filling capacity are given for the area below 1250 m high (93 % of France), as well as on the whole of France. The filling efficiency presents a more extensive and larger decrease when the filling period is reduced to 3 months (Table 3). For instance, the part of France where the filling efficiency decreases by up to 10 % is almost doubled when the filling period is reduced to 3 months instead of 5 (Fig. 15). The results are significant in the Garonne Valley for the MRI and ARPEGE projections, and also over part of the Seine basin for ARPEGE.

The impact of climate change alone on the annual discharge has a more contrasted spatial pattern (Fig. 16). Two of the three scenarios project an increase of the river flow in the south of France (although the increase is not significant at the 95 % level), while the third one projects a weak change of the flow in the Charente basin. On average over France, the river flows are projected to decrease by about 15 to 30 % (Table 3).

Figure 16 shows the impact of small farm dams in 2050 compared to the simulation in 2050 without small farm dams (results for a 5 month filling period are presented, but similar results were found for a 3 month period). It can be seen that, although the impact of climate change alone is rather different between the three projections, the impact of small farm dams in the context of climate change has the same spatial pattern as at present day, but with greater intensity. However, the evolutions are not significant at the 95 % level.

6 Discussion

By using a simple model of small farm dams and several hypotheses, this study was able to estimate the impact of extended small farm dams spread over the Pays de la Loire region, and to compare the results in this region with those for the rest of France, especially with the regions where such dams are already well developed. In the Pays de la Loire region, it was found that large capacity storage dams would have large impacts on the river discharge (above 15 %), and would need to collect water from the whole basin if they were to be completely filled. Smaller capacity storage dams would have a reduced impact on the annual discharge (above 7 %), but would still need to collect water from a large part of the basin to be able to be fill up efficiently. These results are consistent with the findings of Hughes and Mantel (2010) and Nathan and Lowe (2012). It was also shown that a 3 month filling period reduced the impact on the monthly discharge, (and of course on floods occurring in autumn), but led to more filling failure during drier years. Moreover, these failures are projected to increase in the context of climate change. The Pays de la Loire region was shown to be one of the regions of France where the impact of the small farm dams is the greatest and where the filling efficiency is the lowest.

However, this study was based on several hypotheses that influenced the results. First, the water balance was estimated by the hydrometeorological model SIM, which is, of course, not perfect. In fact, SIM was shown to overestimate the river flow of the

Layon basin, and this error cannot only be explained simply by the water pumping in the basin. An overestimation of the river flow would lead to an overestimation of the filling efficiency of the small farm dams, and to a reduced impact of the small farm dams on the river flow. Thus the impact of small farm dams on the river flow of the Layon river could possibly be stronger than computed in this study. The error between the observed discharge and the discharges simulated by SIM varies in space but with no clear spatial pattern (Habets et al., 2008). Therefore, the distinction between the strongly impacted regions (Pays de la Loire and Seine basin), and the less impacted regions (south-western France, Brittany), which is driven by the spatial distribution of the precipitation, is expected to be robust. This result is consistent with the analysis of Shao et al. (2012), who found that the dams were more widespread in regions with large precipitation in winter and moderate slopes.

Strong hypotheses were also made on the spatial extent of the small farm dams and their associated storage. As several spatial extent were tested, the estimated volume should be discussed. The volume of water stored in the dams was simply estimated using an assumed water depth of 3 m. However, previous studies have found a non-linear relationship between the volume capacity and the surface area of the form $V = \alpha A^{\beta}$ with V the volume and A the area (Hughes and Mantel, 2010; Shao et al., 2012, for instance). According to the relationship used in Shao et al. (2012), it appears that the 3 m depth is the lower boundary, and corresponds to really small farm dams. However, sensitivity to the volume was assessed indirectly by considering several values of the area of the dams as discussed above. A better relationship between volume and surface area of the dams might have led to different values being considered for their areas. In our study, the dam's area was only sensitive via its impact on the storage volume, because the evaporation from dams was neglected. Martínez-Granados et al. (2011) have quantified the evaporation in a semi-arid region of Spain, and they estimated that the evaporation loss could reach 8 % of the water stored. As most part of France has a more humid climate, it can be considered that the loss will be lower in France. Thus, it is expected that the evaporation loss would affect the estimated impact on the river

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flow by less than 10 %. Such evaporation loss would lead to larger water withdrawal and, thus to a larger impact on the river flow or to greater filling failure, with a larger impact for the 5 month filling period than for the 3 month filling period.

Another issue is that the water from dams is expected not to have any feedback on the river flow, i.e. it is assumed to evaporate on the fields. According to our scenarios, the water stored would represent a 15 $mm\,m^{-2}$ to 30 $mm\,m^{-2}$ of irrigation water which would be used in summer (3 months) over the entire basin. Although these are small quantities that can easily evaporate in summer, as only a part of the basin is irrigated, they can still impact the autumn runoff. However, the impact should be very limited at the beginning of the filling period, i.e. in November. Thus, the influence on the study is expected to be reduced.

7 Conclusions

The main objective of this study was to gain some understanding of the maximum storage capacity of small farm dams that would be sustainable in time and have limited impact on the Pays de la Loire region. A simple modelling approach was set up, and showed that the development of small farm dams should be more limited in the Pays de la Loire region, and also in the Seine basin, compared to other regions of France, because the hydroclimatic conditions are not favourable. The study gives some qualitative answers to the main questions of the regional environmental agency: the full storage capacity of the dams should be limited (perhaps around 15 000 $m^3\,km^{-2}$ but probably less than 30 000 $m^3\,km^{-2}$) in the Pays de la Loire region in order to ensure a good filling efficiency even in a dry year. A limitation of the filling period to 3 months would have a positive impact on the flow, but would decrease the efficiency of the dam filling and thus the ability of the dams to provide water in periods of shortage; and this ability is projected to decrease in a context of climate change.

The study found that the regions that are sensitive to filling failure and have a large impact on river flow nowadays (Pays de la Loire, Seine basin) are projected to have greater difficulties in the future in a context of climate change. This reinforces the sensible idea that adaptation to climate change begins with adaptation to present-day extremes.

Acknowledgements. This study was supported by the DREAL-Pays de la Loire. We would like to thank Stéphanie Poligot-Pitsch for her support, as well as Michel Déqué from CNRM-GAME and Christian Pagé and Laurent Terray from Cerfacs for providing the downscaled climate projections.

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Table 1. Estimation of the fraction of small farm dams based on known pumping pressure derived from surface water pumping in seven river basins of the Pays de la Loire region. The pumping pressure was provided by the Loire-Bretagne water agency. A uniform water depth of 3 m is assumed for the small farm dams.

River name	A_{basin} km^2	Number of pumping points (excluding groundwater pumping)	Pumping pressure million m^3	fraction of small farm dam (D) %
Sarthe upstream	2827	133	3.00	0.035
Huisne	1833	218	1.89	0.034
Loir	5419	1565	17.09	0.105
Authion	1453	1268	23.00	0.528
Oudon	1341	167	2.58	0.064
Layon	1040	500	5.80	0.186
Sevre Nantaise	2310	828	15.48	0.223

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Table 2. Small farm dam (SFD) properties used to study the impact on the Layon basin (930 km^2). The values refer to the whole Layon basin The driest year is 1991–1992. 5 m and 3 m stand for 3 month and 5 month filling period, respectively.

Filling period	SFD ratio D%	V_{max} Mm^3	catchment to SFD ratio R	A_{catch} km^2	Catchment ratio C %	Impact on the annual discharge %	Storage ratio driest year %	Impact discharge driest year %
5 m	1	2.79	100	930	100	−17.3	57.7	−57.2
5 m	0.5	1.395	200	930	100	−9.0	85.6	−40.6
5 m	0.5	1.395	100	465	50	−8.6	59.0	−29.0
5 m	0.5	1.395	20	93	10	−6.4	13.5	−6.9
3 m	1	2.79	100	930	100	−16.7	31.9	−34.9
3 m	0.5	1.395	200	465	100	−8.7	63.1	−28.6
3 m	0.5	1.395	100	465	50	−8.4	42.9	−20.0
3 m	0.5	1.395	20	93	10	−5.4	8.7	−4.0

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Table 3. Simulated present-day precipitation and riverflow according to the climate models, and projections for 2050: PRCP: annual precipitation; D no dams: annual discharge without small farm dams; D 3 m and D 5 m: annual discharge with small farm dams covering and area of 0.5 %, with a dam catchment of 50 %, and the 3 month and 5 month filling periods, respectively. The river discharge evolution in 2050 was computed using two references, either without or with (in brackets) dams in present day; Sto: mean annual maximum storage over maximum storage of the dams for the two filling periods. Two values are computed over France: the average is computed over the whole of France and, in bold, only on the grid cells below 1250 m. The results obtained using the Safran analysis are given as a baseline.

	Layon			France		
	ARPEGE	GFDL0	MRI	ARPEGE	GFDL0	MRI
			1970–2000			
PRCP		SAFRAN = 660			SAFRAN = 950	
mm yr^{-1}	638.8	692.6	690.0	930	961	963
D no dam		SAFRAN = 4.7			SAFRAN = 77.7	
m^3 s^{-1}	3.7	4.1	4.6	70.0	74.2	74.4
D with dam						
5 m m^3 s^{-1}	3.3	3.7	4.2	67.4	71.5	71.7
3 m m^3 s^{-1}	3.4	3.7	4.2	67.4	71.6	71.8
			2046–2065			
PRCP %	−6.3	+3.7	−0.1	−13.6	−3.7	−5.1
D no dam %	−22.9	−7.3	−34.6	−30.6	−14.8	−20.7
D 5 m %	−32.4 (−24.8)	−17.2 (−8.2)	−42.2 (−36.6)	−34.3 (−31.7)	−18.4 (−15.5)	−24.2 (−21.4)
D 3 m %	−31.7 (−24.4)	−16.3 (−7.6)	−41.2 (−35.7)	**−34.1** −31.6	**−18.3** −15.3	**−24.0** −21.4
sto 5 m %	−2.2	+0.1	−2.4	**−3.5** +14.2	**−0.9** +3.2	**−1.4** +5.9
sto 3 m %	−3.7	−0.2	−6.4	**−5.0** +19.6	**−3.0** +11.5	**−5.2** +18.6

Fig. 1. Domain under study. The Pays de la Loire region is shaded in green, and the Layon river is plotted in red.

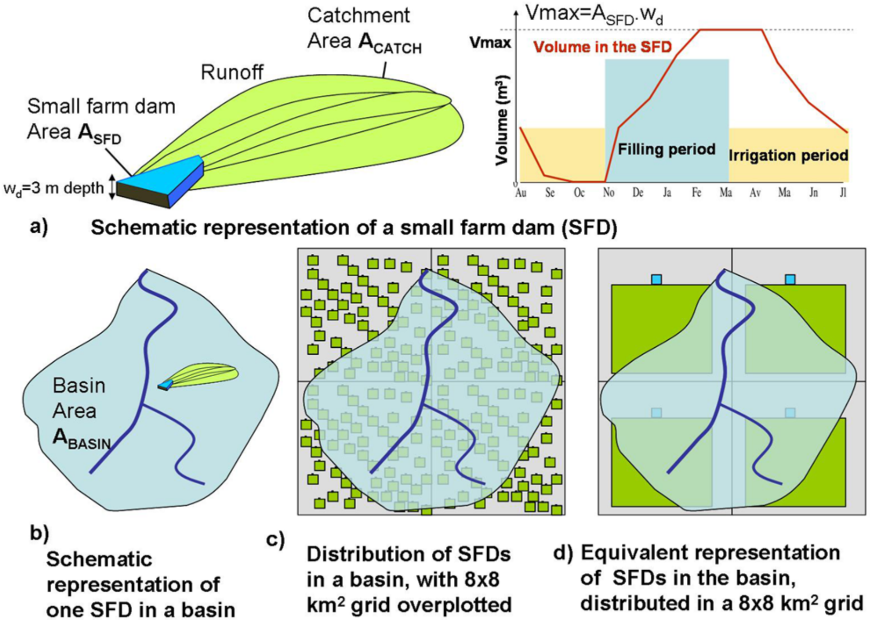

Fig. 2. Schematic representation of a small farm dams (SFD) and of its coupling with the hydrometeorological model: **(a)** representation of the small farm dam (in blue) and its catchment area (in green), with a time evolution of its volume according to the filling period, **(b)** schematic representation of an SFD in a river basin **(c)** schematic representation of numerous SFDs in a basin situated in four 8 km × 8 km cells **(d)** equivalent representation of the SFD in the 8 km × 8 km cells of the hydrometeorological model.

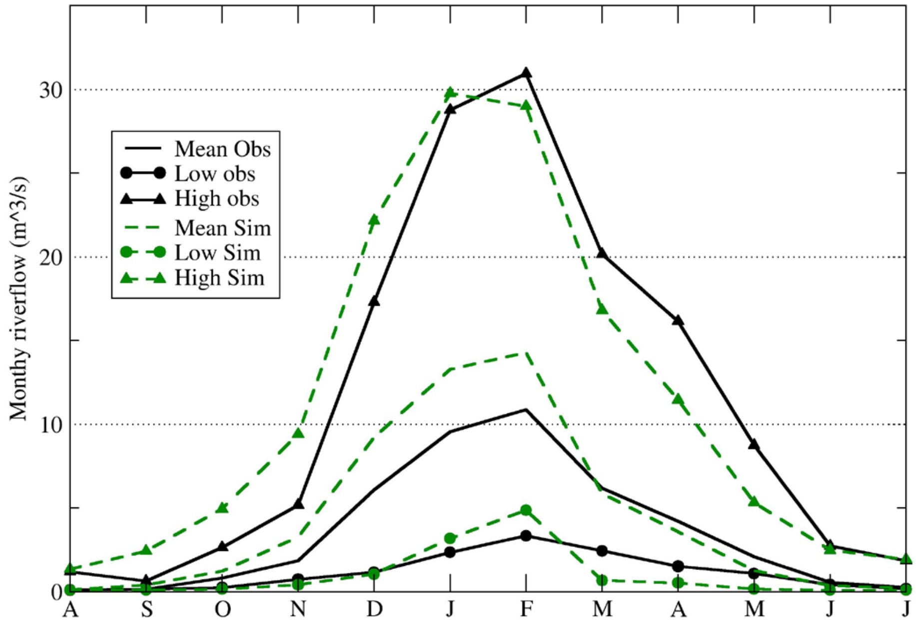

Fig. 3. Comparison between observed and simulated monthly mean, high (VCX3) and low (VCN3) riverflows of the Layon at St. Lambert on average on the period 1970–2000.

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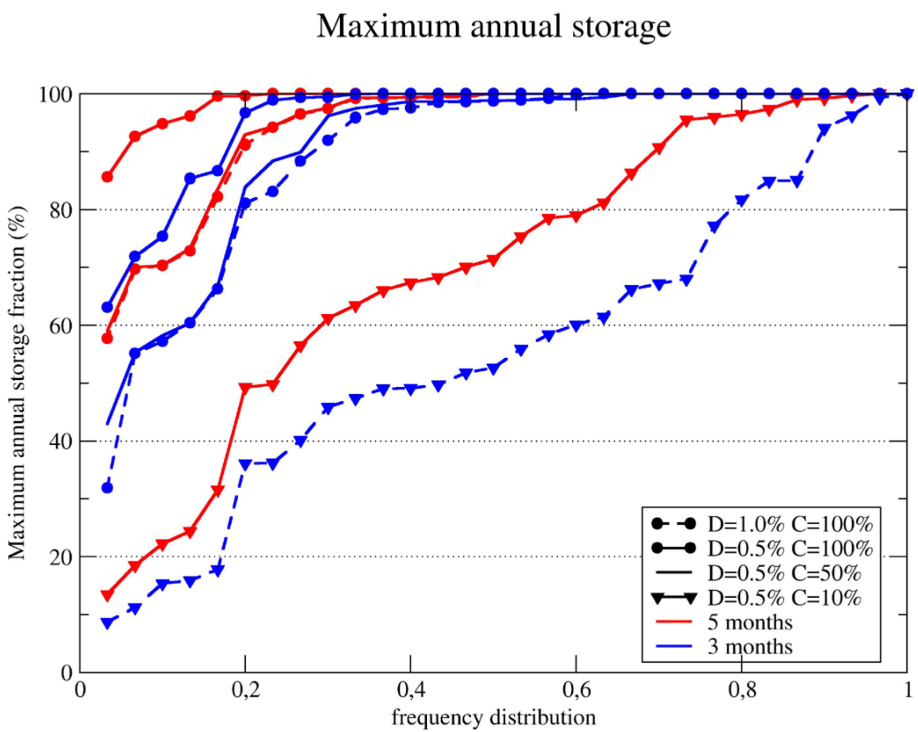

Fig. 4. Frequency distribution of the maximum annual dam storage expressed as a fraction of the maximum capacity according to the filling period (3 or 5 months), the spatial extent of the dams (D = 1 % or 0.5 %) and the size of the catchments (C = 10, 50 or 100 %).

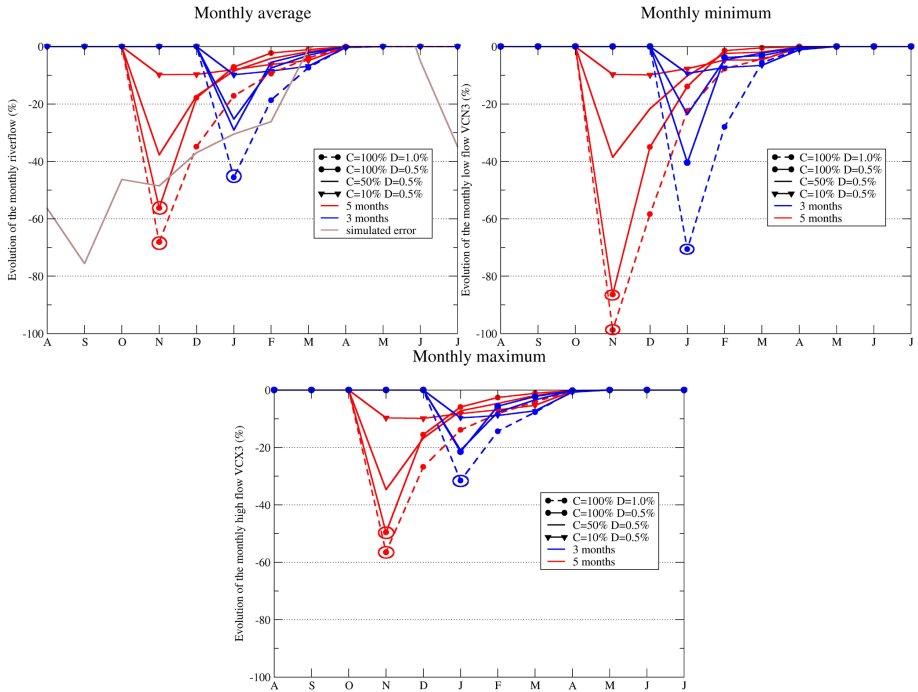

Fig. 5. Impact of the irrigation dams on the mean monthly riverflow (top) mean monthly low flow (bottom left) and mean monthly high flow (bottom right) of the Layon at St. Lambert according to the filling period (3 or 5 months), the spatial extent of the dams ($D = 1\,\%$ or $0.5\,\%$) and the size of the filling catchments ($C = 10$, 50 or 100 %). The grey line represents the error on the monthly discharge of the 10 yr reference simulation. A circle indicates that the impact is significant at 95 %.

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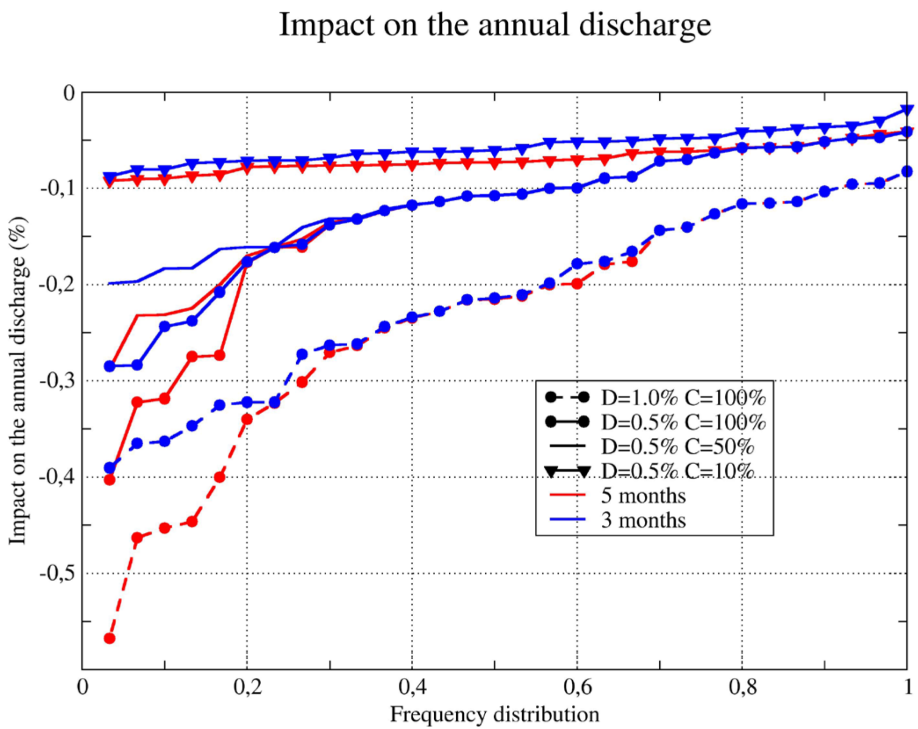

Fig. 6. Frequency analysis of the impact of the small farm dams on the annual river flow according to their storage capacities and impact of the size of the filling catchment.

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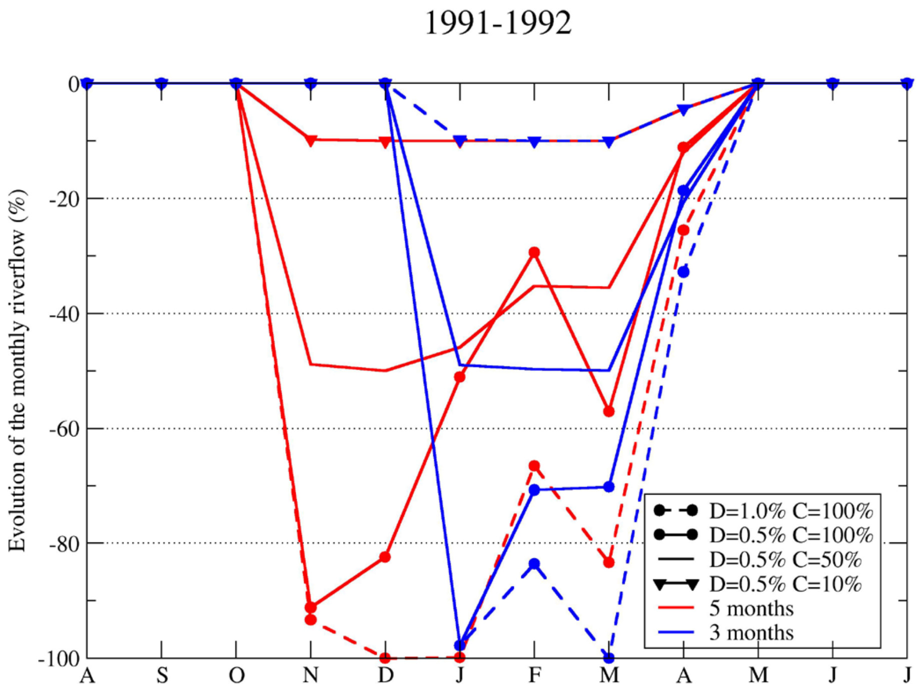

Fig. 7. Impact of the small dams on the monthly river flows of the Layon at St. Lambert for the dry year of 1991–1992.

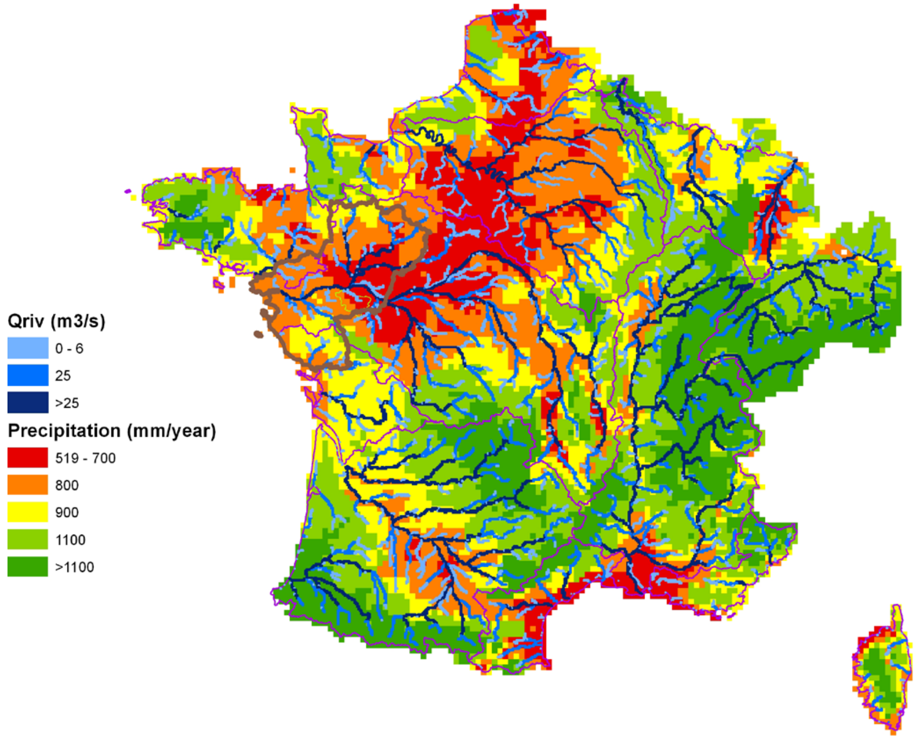

Fig. 8. Mean annual precipitation from the Safran analysis ($mm\,yr^{-1}$) and mean annual river flow ($m^3\,s^{-1}$) simulated by SIM for the period 1970–2000. The Pays de la Loire region is plotted in brown.

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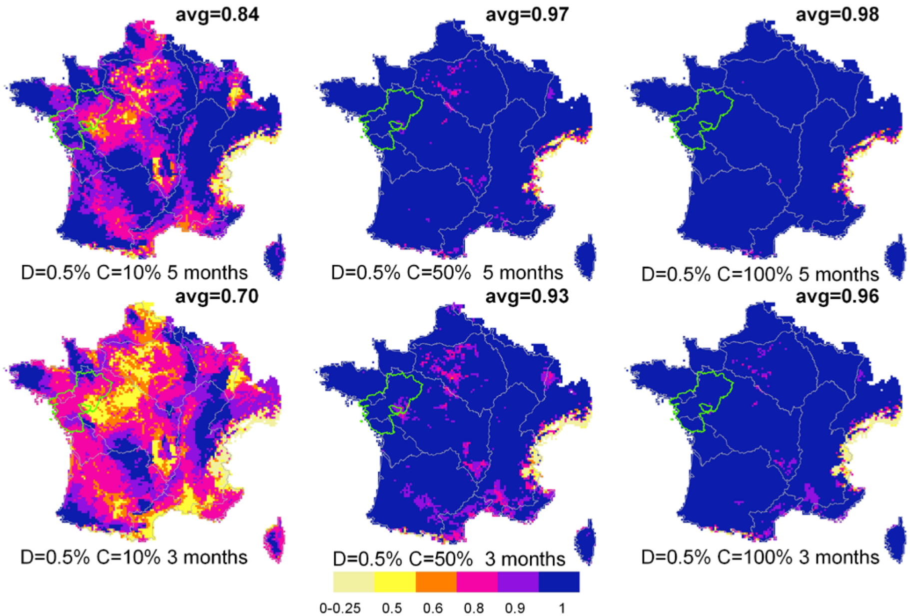

Fig. 9. Mean maximum storage fraction of the dams over the 30 yr period for 5 month (top) and 3 month (bottom) filling periods. The Pays de la Loire region and the Layon basin are plotted in green.

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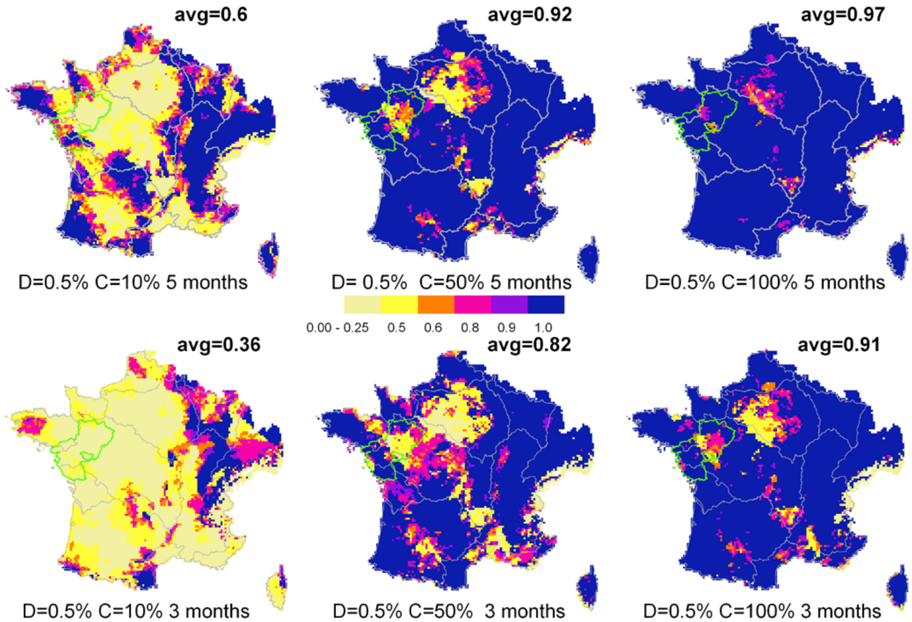

Fig. 10. Mean maximum storage fraction of the dams over the dry year of 1991–1992 for 5 month (top) and 3 month (bottom) filling periods. The Pays de la Loire region and the Layon basin are plotted in green.

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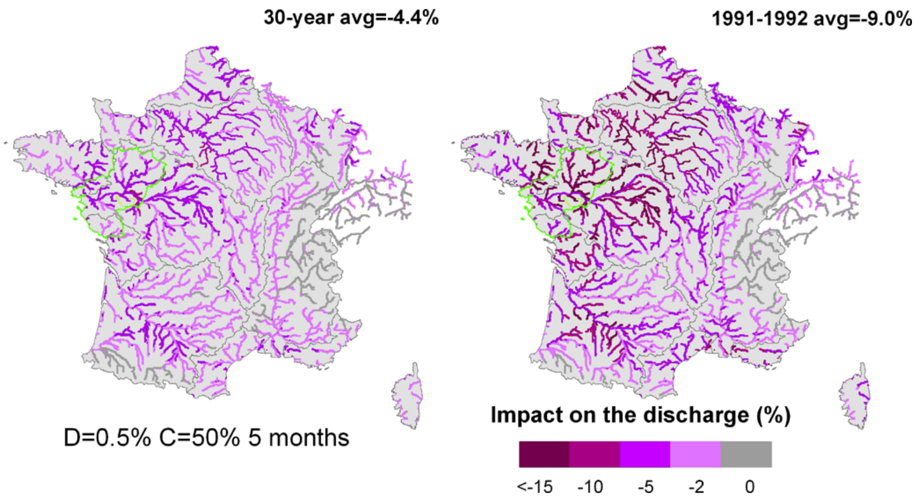

Fig. 11. Mean impact of the small farm dams on the annual discharge for a 5 month filling period, a 0.5 % coverage, and a dam catchment of 50 %. The Pays de la Loire region is plotted in green.

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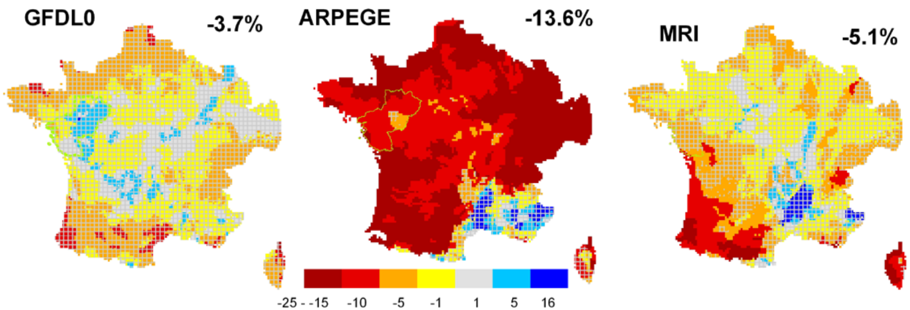

Fig. 12. Evolution of the precipitation (in %) on annual average for the period 2045–2065 compared to 1970–2000 for the three climate projections. Evolutions that are not significant at the 95 % level are hatched.

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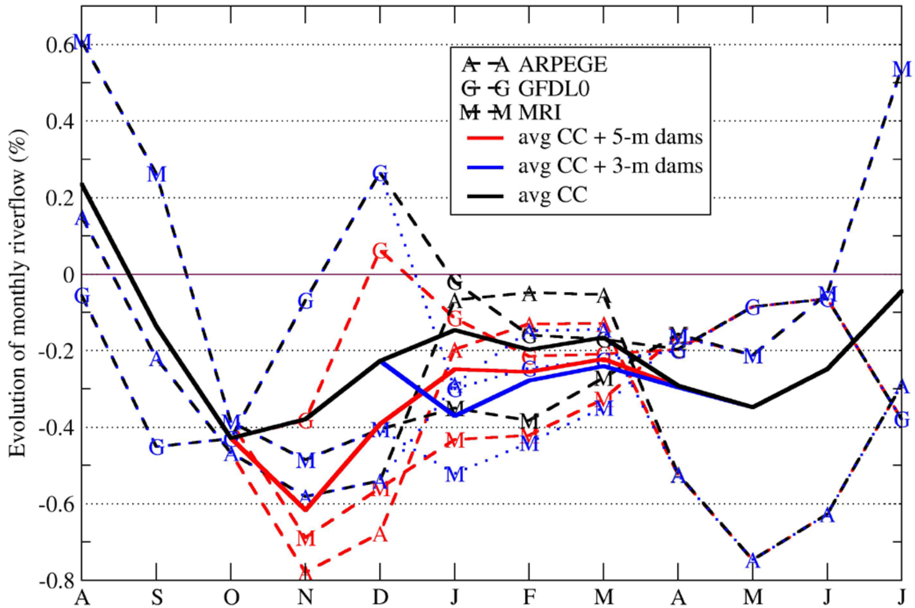

Fig. 13. Evolution of the Layon monthly riverflows according to 3 climate projections with (black) and without small farm dams (blue for the 3 month filling period, red for the 5 month filling period). The thick lines are averages over the 3 climate projections.

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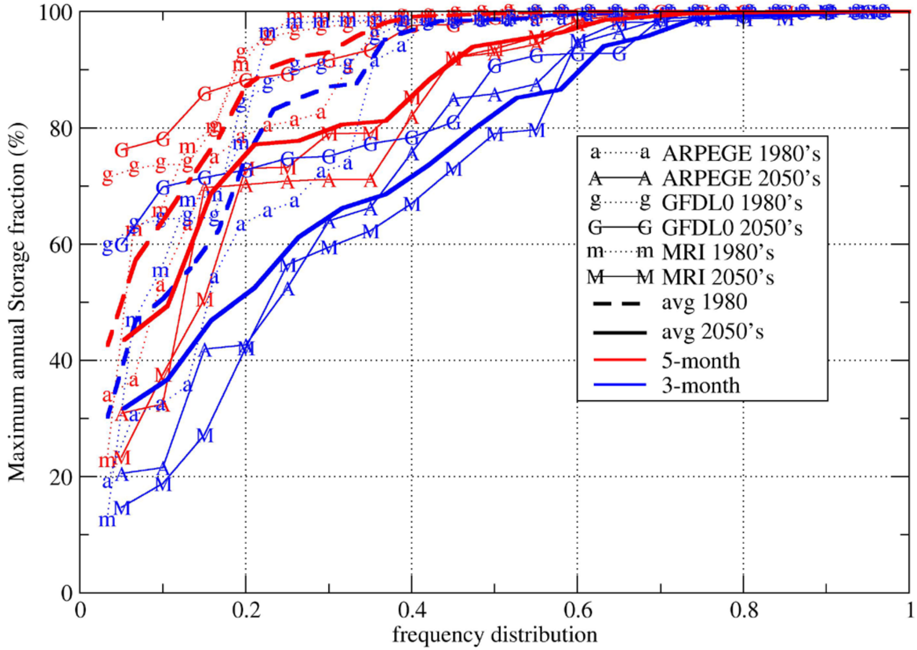

Fig. 14. Comparison of the frequency distribution of the maximal annual storage of the small farm dams in the Layon in the 1980's and 2050's as simulated using 3 downscaled climate projections, for the 5 month (red) and 3 month (blue) filling period. The letter corresponds to the climate model (lower case for 1980's, upper case for 2050's), and the averages in 1980 and 2050 are plotted in thick dashed and plain lines respectively.

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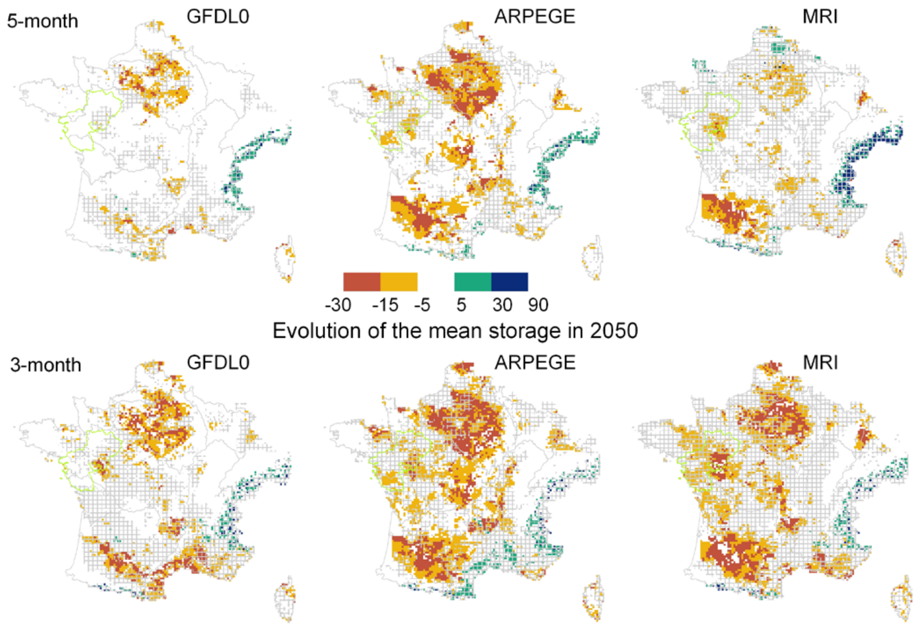

Fig. 15. Evolution of the mean maximum storage of the small farm dams in 2050 as projected using 3 downscaled climate projections for the two filling periods. Results that are not significant at the 95 % level are hatched.

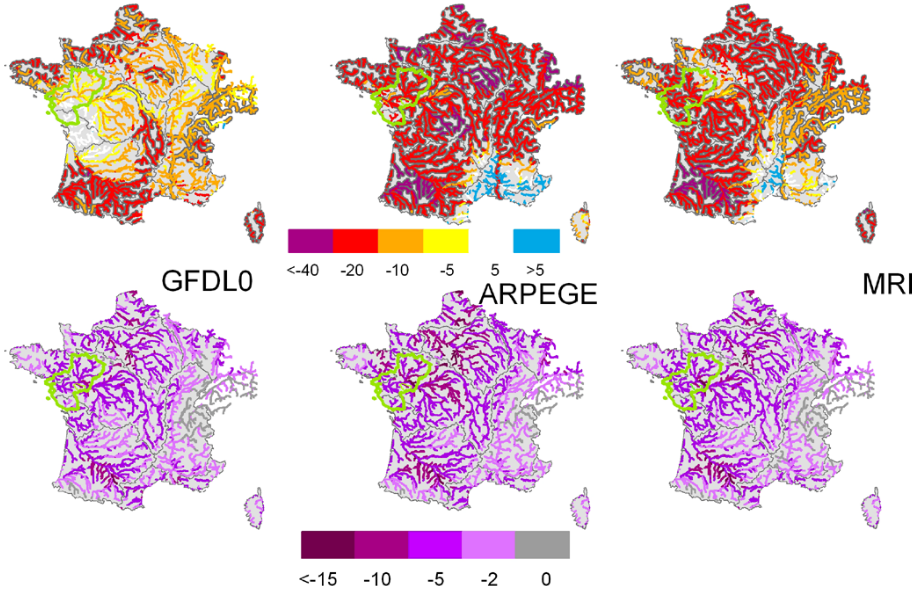

Fig. 16. Impact of climate change (top) and small farm dams (bottom) on the annual discharge in 2050 as projected using three downscaled climate projections in %. The small farm dams are assumed to cover 0.5 % of the domain, with a catchment that covers half the basins, and the filling period is taken as 5 months. Top, evolutions that are significant at the 95 % level are outlined in black. Bottom, the distinction is not made as only a few river cells gave results significant at the 95 % level.