Water restrictions under climate change: a Rhone-Mediterranean perspective combining 'bottom up' and 'top-down' approaches"

Sauquet et al.

Anonymous Referee #1

The paper "Water restrictions under climate change: a Rhone-Mediterranean perspective combining 'bottom-up' and 'top-down' approaches" presents a study that uses decision scaling (Borwn et al., 2012) to evaluate future water restrictions pattern in southeast France. I think the topic fit the scope of this journal, but I have several major concerns on this manuscript.

First, the novelty of the paper is questionable. Applying a bottom-up approach such as decision scaling to evaluate climate change impact uncertainty is not a new topic in the field. Although authors might argue that presenting the climate response surface in WR (not streamflow) is relatively new, I do not see any additional information regarding policy inform that can be generated from this result. Some visualization techniques used in this paper could be attractive (such as using color to represent mean value and size to represent the s.d.) but I failed to understand the overall scientific contribution of this paper.

Second, the modeling framework is extremely unclear. Authors use Section 4 to explain their method but they spent a lot of space to explain decision scaling which is other people's work. They briefly mention the rainfall-runoff model they used but no details about the actual water restriction level modeling framework (Section 4.3). They explain their concept of computing WR in fair details (which is helpful) but I still do not understand how they build the WRL model. What are the input and output of this model? What parameters can be calibrated in this model? How to authors link this model with the rainfall-runoff model? Information about these is partly provided in Section 4.3 but hard to follow from a reader's perspective.

➔ Authors agree with this remark and the section explaining the method has been rewritten.

Inputs of the WRL model are daily discharges and precipitation. Outputs are WRL for each of the 21 10-day periods for each year spanning the April-to-October period. VC3(t) is first computed from daily discharge Q(t) every day t, WRL(t) is then deduced by comparing VC3(t) to the four regulatory thresholds and finally a unique representative WR level is assigned to each of the 21 10-day periods, as the median of WRL(t) observed or simulated within that 10-day period. To best match the whole monitoring process stated in most of the DMPs, a simple precipitation correction was applied ("Pcorr", in Fig. 5). It consists to give a 'no alert' when precipitation during the preceding 10 days exceeds 70% of inter-annual precipitation average, regardless of the WR simulation results. The WRL framework is applied to observed and simulated data of both discharge and precipitation. To assess the performance of the WRL model under current condition against stated WR decisions, the WRL model is run with observed daily discharges extracted from the HYDRO database (named "HYDRO" in the text) and with daily discharges simulated by the rainfall-runoff model GR6J forced by the SAFRAN reanalysis (named "GR6J" in the text). In the context of climate change the WRL model is run with daily discharges obtained with GR6J forced by one of the 1350 sets of perturbed precipitation, temperature and PET time series. In this later case the regulatory thresholds are calculated on the simulated discharge time series to limit the possible effect of bias in rainfall-runoff modeling.

Third, lack of in-depth discussion on the policy implementation. Given that authors use WR in the climate response surface, one can expect that authors should use a lot of space to link their results to drought policy implementation or some information about the adaptation action. However, only a short discussion of WR has been provided at Section 5.5. Given that this is not a methodological paper, these in-depth discussions become the critical point to prove that this paper is worth to be published because readers around the world can learn from this study and apply it to their own drought management policy.

➔ Discussing the policy implementation is out of the scope of this article. This paper presents a first attempt to simulate water restrictions over a large area in France. This paper aims at promoting the approaches developed in parallel by Brown (named 'Decision Tree Framework") and Prudhomme (named "Scenario neutral approach") and one of the challenges was to define critical thresholds of unacceptable number of days with legally-binding WR for irrigation use. This paper suggests using information provided by insurance (here from a national system of compensation) at the regional scale.

Finally, the structure of the manuscript and English is extremely difficult for readers to follow. The general outline of the paper follows a typical modeling paper while authors introduce their study area and data than their model. However, as I mentioned above, the modeling framework especially for the "Water restriction level modeling framework" is not clear at all. Also, there are general equations list in the results section (Section 5) and irrelevant results (Line 432-474) presented in the result section.

➔ The scenario-neutral approach is applied at both local and regional scales and results discussed in Sect. 5 before drawing general conclusions in Sect. 6.

There are A LOT of grammar errors and typos that make the manuscript hard to read. This is surprising that one of the co-authors is from the UK.

➔ The text has be screened to correct grammar errors and typos.

Line 34 - What do you mean by "changes" Climate or human activities?

➔ We mean both since we are dealing with global change issues.

Line 35 -What kind of drought? Climatic? Hydrologic? Or economic?

➔ The intensity of the changes is still uncertain, however, climate models agree on significant future increase in frequency and intensity of meteorological, agricultural and hydrological droughts in Southern Europe

Line 86 and 88 - You are arguing with yourself. In Line 86 you said water is abundant globally but Line 88 you said water resources are under high stress.

➔ At the regional scale, water resources are abundant. However during low flow periods there is an intense competition for water between different users and needs—agricultural, municipal, industrial, the environment—resulting in tradeoffs between human demands and environmental needs. The French RM Water Agency has identified areas with persistent imbalance between water supply and water demand (around 40% of the RM district, http://www.rhone-mediterranee.eaufrance.fr/gestion/gestion-quanti/problematique.php).

Line 90 - Why 43% is high proportion? It is less than the half.

➔ Water abstraction for irrigation needs is ranked first in terms of volume; that is why we have considered that 43 is high proportion. We have made changes in Section 2.1.

Line 96 - You never explain what is "Drought management plan?"

➔ Drought management plans define specific actions to be undertaken to enhance preparedness and increase resilience to drought. This definition is included in Section 2.2.

Line 111 and 115 - You are arguing with yourself agian. If water restriction decisions are frequent (Line 115), why these catchments are with minor human influence? Water restriction decisions are human influence.

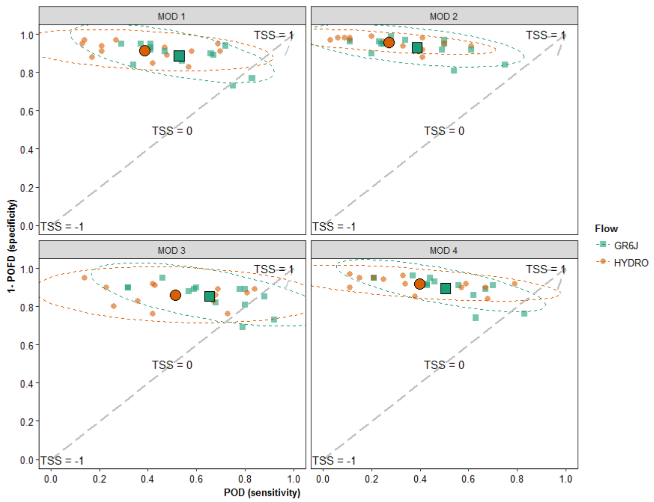
➔ The 15 catchments are benchmark catchments where near natural drought event can be observed. Water can be taken in another nearby catchment. This has been added in Section 2.3 to avoid misinterpretation.

Line 173 to 174 - Will the selection of index affects all of your results? You should discuss this in the discussion section.

➔ Indeed choosing the same definitions for the monitoring indicator and regulatory thresholds may partly explain the deviations to the stated WR. This was a simplification assumption. Before stating for VC3 and 10d-VCN3 the four prevalent modalities have been chosen to implement WR simulations:

Modality	Monitoring variable	Threshold variable	Benchmark period
MOD1	QC7	10d-VCN3(T)	1958 – 2013
MOD2		m-VCN3(T)	
MOD3	VC3	10d-VCN3(T)	
MOD4		m-VCN3(T)	

where m-VCN3(T) refers to quantiles defined by monthly. Results show a weak sensitivity to the choice of these variables. In terms of sensitivity, MOD3 on average performed best than other modalities for both HYDRO and GR6J simulations on the 15 catchments. MOD3 was finally considered for all the catchments.



Skill scores obtained for the WR level model over the period 2005-2013. Large dots show the mean values of the skill scores. Colored dotted lines are confidence interval.

Line 186 - Why cross a threshold is unsustainable? How do you know it won’t come back? Quantify sustainability is a difficult challenge and if you don’t know what it is, you should not use the word. Otherwise, you should define sustainability.

➔ Sustainability - like vulnerability - has no universal definition. Sustainability assessment is based on the analysis of failures or unacceptable conditions that lead to low crop yield and quality, and consequently to economic losses at such a level that the national system of compensation is initiated. In this application,

- we assumed that irrigated farming is not sustainable if restrictions during drought periods are , on average, too severe - i.e. duration with limited or suspended abstraction for irrigation above a critical threshold - to ensure enough water for crops;
- since it was not possible to compute the effect of water restrictions on crop yield and quality (no crop modelling was considered here) and on economic losses, we used ‘agricultural disaster’ notifications as proxies to identify the conditions that would be unacceptable/damaging for farmers activities.

This sustainability is thus indirectly related to agricultural economy (not directly related to losses expressed in euros).

Line 190 - What do you mean by intersection?

➔ Each component contributes to the vulnerability assessment of the system (including its management) to systematic climatic deviation.

Line 215 - I don't see any calculation related to irrigation water use in your 4.3? How you do this?

➔ Only the impact of WR on irrigation has been examined here. Irrigation is selected since it is the sector which consumes most water at the regional scale. Water needs are not computed. The impact of WR is highlighted by the 'agricultural disaster' status notified at the department scale and we have assumed that when the total number of days with legally-binding water restrictions exceeds a fixed threshold (defined using data from the year 2011), the situation for farmers is unacceptable (significant losses) and as a consequence the national system of compensation is initiated.

Line 254 - Don't understand what you mean.

➔ The physical components (drought severity) that lead to WR decisions are only considered in the WRL model and no socio-political factor was taken into account to reproduce water restrictions.

Line 262 - Why not use the worst WRL as indicators? And also why not just use daily time step as your rainfall-runoff model? Why change it to 10-day?

➔ Water restrictions are decided after consulting drought committees that convene irregularly. The time-step for modelling WRL was chosen to be compatible with the frequency of drought committees estimated from the analysis of the water restriction orders: WRL is thus computed at a regular time step of ten days.

Line 302 to 303 - I do not understand what is your point here. If you know this, then why don't you model that? This means you understand that just a hydrologic model is not enough to do this type of modeling but you still do it and write a paper about it. This just implies that your model is not only WRONG (as all models are) but also not very USEFUL.

➔ The model is not totally wrong. The WRL framework is able to reproduce the physical bases in the making-decision process and thus can simulate 68% of the stated restrictions over the period 2005-2013 (performance obtained with "GR6J", section 4.3); reaching 68% is not so bad.

Results of our study (conclusions based on the 15 catchments) show that: (i) surprisingly there are noticeable deviations between the drought severity perceived on discharge data and the final decisions to order restrictions but the decisions are not totally uncorrelated with drought conditions, and (ii) most of the catchments are subject to deviations. The performance is judged acceptable to be applied in the scenario-neutral approach. We are aware that the WRL model is far to be perfect and we are convinced that the WR framework will be improved if relevant socio-economical controls are introduced and it will be certainly a challenging task. Just keep in mind that this study is a first attempt to simulate WR decisions at the regional scale.

Line 357 - What drivers? I thought in climate change studies, T and P changes are drivers.

➔ Indeed temperature and precipitation are the main physical drivers. Here we wanted to assess if WR is more sensitive to P and T over a specific period.

Line 358 to 359 - I don't understand your English.

➔ Response surfaces have been displayed for different pairs of potential climate drivers (X and Y related to temperature and to precipitation, respectively). Their shapes were first examined (a flat response surface combined with high values of Sd is an evidence of no link between WR and (X, Y)). In addition we have used metrics which measure globally the dispersion around the response surface: the median and the maximum of Sd (small values mean small deviation and thus strong links between WR and (X, Y)). The drivers are (X, Y) for which the dispersion is minimal and with the most contrasted surface response.

Line 402 - Typo.

➔ "tree" should read "three": "Finally the vulnerability resulting from the combination of the three components sensitivity, sustainability and exposure"

Line 432 to 474 - I do not understand why you have these results here which are not related to WR.

➔ This section details the result of the classification carried out on the 106 individual WR response surfaces, which is consistent with the title "5.4 Response surface analysis at the regional scale".

Line 788 - There is no need for Figure 2.

➔ Indeed this figure could be deleted.

Line 797 – The explanation of Figure 5 is unclear. This result in my second major comment regarding the modeling framework. A better explanation needed.

➔ Inputs of the WRL model are daily discharges and precipitation. Outputs are WRL for each of the 21 10-day periods for each year spanning the April-to-October period. VC3(t) is first computed from daily discharge Q(t) every day t, WRL(t) is then deduced by comparing VC3(t) to the four regulatory thresholds and finally a unique representative WR level is assigned to each of the 21 10-day periods, as the median of WRL(t) observed or simulated within that 10-day period. To best match the whole monitoring process stated in most of the DMPs, a simple precipitation correction was applied ("Pcorr", in Fig. 5). It consists to give a 'no alert' when precipitation during the preceding 10 days exceeds 70% of inter-annual precipitation average, regardless of the WR simulation results. The WRL framework is applied to observed and simulated data of both discharge and precipitation. To assess the performance of the WRL model under current condition against stated WR decisions, the WRL model is run with observed daily discharges extracted from the HYDRO database (named "GR6J" in the text) and with daily discharges simulated by the rainfall-runoff model GR6J forced by the SAFRAN reanalysis (named

“GR6J” in the text). In the context of climate change the WRL model is run with daily discharges obtained with GR6J forced by one of the 1350 sets of perturbed precipitation, temperature and PET time series. In this later case the regulatory thresholds are calculated on the simulated discharge time series to limit the possible effect of bias in rainfall-runoff modeling.

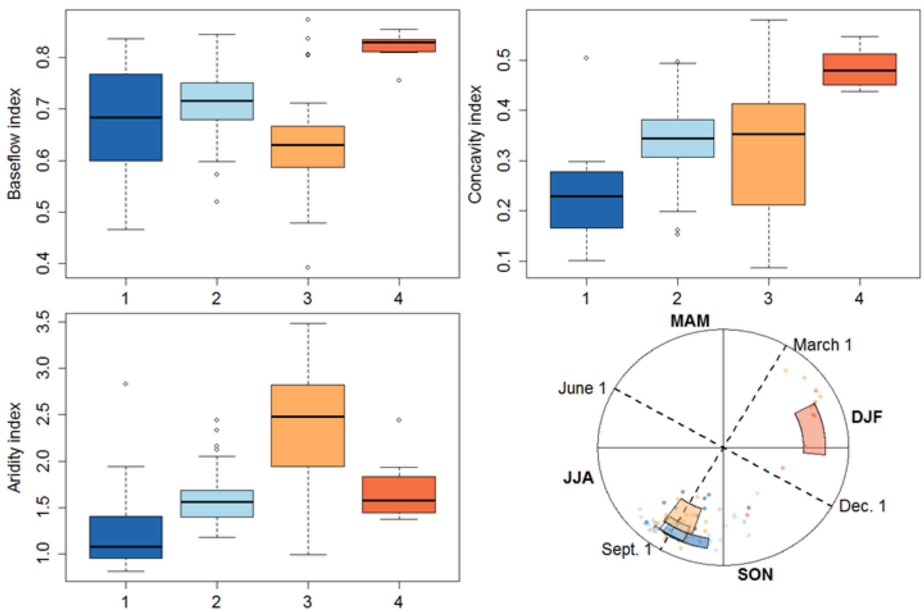
Line 801 - The results are weird here. If your GR67 model is good according to your NSE and Kling–Gupta efficiency, why GR67 and HYDRO show different results in a lot of place in this figure? Does not make sense.

➔ The GR6J model is not perfect (both criteria < 1). Small deviations to the observed discharge lead to difference in results obtained by the WR model.

Line 819 - If “2” and “3” are similar, why you need to separate them into two categories?

➔ This division into two classes have been suggested by the hierarchical clustering and the response surface representative of Class 2 is more contrasted than that of Class 3.

Line 822 - The figure at the lower-right corner is unreadable.



➔ Done

⇨ The authors would like to thank Reviewer1 for his helpful comments.

Water restrictions under climate change: a Rhone-Mediterranean perspective combining 'bottom up' and 'top-down' approaches"

Sauquet et al.

Anonymous Referee #2

Sauquet and colleagues applied a scenario neutral approach to evaluate the implementation of water use restrictions and their impacts on irrigated agriculture. They applied this approach to 15 catchments in the Rhone-Mediterranean region with minimal human influence. Their methods included calibration of a hydrological model to each catchment, sensitivity analyses, assessment of exposure and clustering to identify basins with common characteristics. Strengths of this work include comparison of results regionally and identification of catchment classes, as well as high quality graphics presenting the results. Areas to for improvement include problem framing, the implementation and communication of the sustainability assessment, and explanation of the clustering process and its value. With a clearer problem framing and improved sustainability assessment I believe the scientific and practical contributions of this work would be clearer.

➔ Authors agree with this remark and the section explaining the method has been rewritten.

The topic is of interest to HESS readers, and subject to major revision I believe that it would be suitable for publication.

Comments

1. The authors make a strong case for why we care about drought risk under climate change. However, the case for why we need to simulate the implementation of water use restrictions should be stronger. The main question I would like to see the authors address here is: how does the simulation of water use restrictions give us a different picture of impacts or ways to mitigate impacts than simulating streamflow alone?

➔ Water restrictions simulations complement studies on the impact of climate change on water resources availability and on water use needs. Indeed water needs can only be met first if water resources are available and second if water abstractions are allowed. Regulatory rules are pieces of the puzzle that should be examined. Roughly speaking studying water restrictions is a way to identify additional future constraints on water users. The regulatory aspects have never been deeply examined in France, perhaps due to the recent implementation of DMPs.

2. The authors thoroughly review the literature in the scenario neutral and decision scaling methods for assessing climate vulnerability in a bottom-up manner. However, the literature on robust decision making is complementary and should be included in this review. Specifically, there are a few robust decision making studies that assess the performance of existing

water management plans [e.g. Lempert and Groves, 2010; Bloom et al., 2013]. The authors should note how their work builds upon or goes beyond these prior works.

➔ Many thanks. We have added one of the references in the conclusion to make links with RDM.

3. The sustainability assessment is the key link between the occurrence of water use restrictions and impacts. The authors use critical thresholds as a way to measure sustainability. First, I'm not convinced that is a measure of sustainability. Is it serving as a measure of the sustainability of an agricultural economy? Or something else? Please clarify how it meets a reasonable definition of sustainability.

➔ Sustainability - like vulnerability - has no universal definition. Sustainability assessment is based on the analysis of failures or unacceptable conditions that lead to low crop yield and quality, and consequently to economic losses at such a level that the national system of compensation is initiated. In this application,

- we assumed that irrigated farming is not sustainable if restrictions during drought periods are, on average, too severe - i.e. duration with limited or suspended abstraction for irrigation above a critical threshold - to ensure enough water for crops;
- since it was not possible to compute the effect of water restrictions on crop yield and quality (no crop modelling was considered here) and on economic losses, we used 'agricultural disaster' notifications as proxies to identify the conditions that would be unacceptable/damaging for farmers activities.

This sustainability is thus indirectly related to agricultural economy (not directly related to losses expressed in euros). We have changed sustainability for failure analysis to clarify the text.

Second, it is not clear how this critical threshold was defined. The authors state that a single critical threshold is applied to all catchments. Is this reasonable given the substantial differences in elevation (and therefore temperatures)? And is the local precipitation factored into this threshold?

➔ Data are collected by the French ministry of agriculture and they are confidential. The year 2011 was the only year when the national system of compensation has been activated with available data between 1958 and 2013 and the duration of water restrictions were derived individually for each catchment and converted in anomalies $\Delta WR^*(2011)$ with respect to the benchmark value (mean over the period 1958-2013). This dispersion is due to heterogeneity in crops, in irrigation systems, in climate (precipitation, PET, temperature)… at the regional scale leading to locally differentiated sensitivity to water restrictions as well as to biases in WR modelling. Since only the year 2011 it is difficult to conclude on the origin of the dispersion (natural or non-natural). We are convinced that this information is valuable. Finally, simplifying but realistic assumptions are imposed by the lack of detail information; thus only one value was considered despite high dispersion in $\Delta WR^*(2011)$ values (Table 6): the critical threshold was set to the average $\Delta WR^*(2011)$ computed on all catchments of the region under agricultural disaster status in 2011 (6.6 10-day periods), and was used for all classes. Note that this value seems realistic: 6.6 10-day periods = 66 days with restrictions = 30% of the time between between the 1st April and the 31st October.

Lastly, do irrigators or other water users in these catchments have access to other water sources to mitigate impacts (e.g. farm ponds, groundwater)? If so, how does that influence the conclusions?

➔ More details are given in Section 2.1. In France 80% and 20% of water abstraction are taken from surface water and from groundwater, respectively. In the RM district 10% of water used for irrigation originate from groundwater. Irrigators may have access to small reservoirs (storage capacity usually < 1 Mm^3). There is actually a wide discussion about these hydraulic structures in France since their impacts on the ecosystem and their efficiency are not well known (Habets *et al*.: The cumulative impacts of small reservoirs on hydrology: A review. Science of The Total Environment, 643, 850-867, https://doi.org/10.1016/j.scitotenv.2018.06.188, 2018). Most of the small reservoirs are filled by surface water in winter and release water later in summer for irrigation purposes. Water restrictions are not imposed to these reservoirs but we assume here that during severe droughts most of them are empty and thus the influence of auxiliary water sources on the conclusions is limited.

4. On lines 274 to 275 the authors state that GR6J and HYDRO correctly reproduce water use restrictions but are inconsistent with observation. Do the authors mean that the GR6 and HYDRO produce consistent results, but they are incorrect (i.e. don't match observations)?

➔ There is obviously a problem with the phrasing on these lines. "Both GR6J and HYDRO simulations are generally consistent with OBS, even if misses are found (*e.g.*, basins 9 to 11 during the year 2005). There is no systematic bias, with some overestimations (e.g., 2005 using GR6J in basins 1 and 15; 2007 using HYDRO in basin 15), underestimations (e.g. 2009 in basin 6, 7, and 8) and misses (e.g. 2005 using HYDRO in basin 1)."

5. On line 287 the authors state that the simulated streamflow (from GR6J) produces more accurate water use restriction simulations than the observed streamflow. This strikes me as a case where the model may be right for the wrong reasons – which casts doubt on the later results. How is this counter-intuitive result explained and what are the implications for the interpretation of the results?

➔ The discharges simulated by GR6J introduced in the WRL model lead to higher *Sensitivity* scores than those obtained with observed discharges extracted in the HYDRO database. The reasons for this unexpected result have been investigated. In particular we have compared the observed and simulated temporal variability in the time series VCN3. A "smoothing" effect in the GR6J simulations compared to observations was initially suspected. Finally no obvious difference in autocorrelation functions was found between observed and simulated time series. One reason could that the period of interest 2005-2013 – with for some basins only three years with stated water restrictions – may be too short to analyse accurately the relative performance of WRL obtained with OBS and with HYDRO, respectively.

The two scores gives a global insight on the performance of the WRL modelling framework and too much weight should not been given to the differences between scores. In this case, we should conclude that the developed WRL modelling framework leads to similar results (moderate performance in detecting stated water restrictions during the period 2005-2013) with both data sources HYDRO and GR6J. The WRL modelling framework provides an overview of the on-going drought and the drought committees are partly free to account for this information to state or to postpone water restrictions. The developed framework is a useful tool to predict water restrictions with no interference of lobbies, i.e. only based on the physical processes.

6. The authors state that the CART analysis can aid sensitivity assessment at unmodelled catchments. Please address in the conclusions if and how this classification can be helpful for water managers or other scientists.

➔ The CART algorithm creates the best homogeneous group when splitting the data using through a set of “if-then” logical conditions applied to the most relevant factors, i.e. the decision variables. The result is a decision tree with nodes separating the data into two subgroups. The decision variables known at unmodelled but gauged catchments can be introduced in the chain of rules obtained by CART to finally predict – in this application – the assignment to one of the four classes.

7. Lastly, there are some typographic errors and awkward phrasing in the manuscript and it would benefit from a thorough review. See a few examples below:

Typographic errors have been corrected.

References

Bloom, E., A. Draper, D. Groves, B. Joyce, M. Rayej, and D. Yates (2013), Evaluating Resource Management Strategies for Update 2013 of the California Water Plan, in World Environmental & Water Resources Congress, pp. 2391–2403.

Lempert, R. J., and D. G. Groves (2010), Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west, Technol. Forecast. Soc. Change, 77(6), 960–974, doi:10.1016/j.techfore.2010.04.007.

⇨ The authors would like to thank Reviewer2 for his helpful comments.

Water restrictions under climate change: a Rhone-Mediterranean perspective combining 'bottom up' and 'top-down' approaches"

Sauquet et al.

Anonymous Referee #3

The objective of the study is to develop a risk-based framework to simulate water restrictions (WRs) under climate change in Rhone-Mediterranean district in order to evaluate the vulnerability of current Drought Management Plans (DMPs) to future climate conditions. The proposed framework is based on the assessment of three components: sensitivity of WRs to changes in different climate factors, sustainability of WRs for users and exposure in terms of climate response surfaces. General comments The paper presents an interesting topic. Although the applied methodology seems appropriate to some extent, it is rather unclear in some parts. Overall, I believe that further details should be added to the paper in order to support the interpretations and conclusions drawn from the analyses carried out by the authors.

➔ Authors agree with this remark and the section explaining the method has been rewritten.

Major comments

Section 3 For the sake of better understanding, I suggest to report the equations of low flow indicators and regulatory thresholds used in the manuscript.

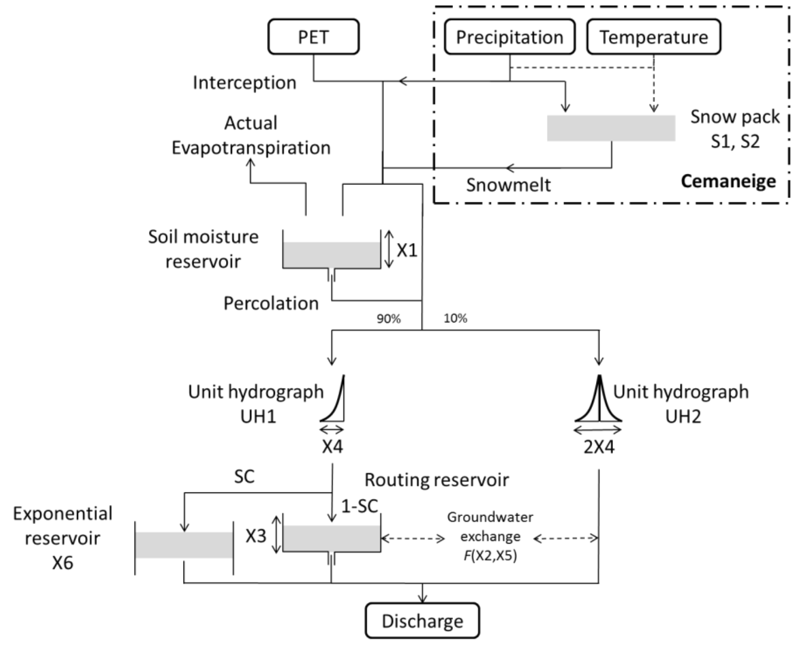
➔ Changes have been made in Section 3 to better define the variables of interest:

- "The low-flow monitoring indicators usually considered are: the daily discharge *Qdaily*, the *d*-day maximum discharge *QCd*, $QCd(t)=\max\left(Qdaily(t'),t'\in\left[t-d+1,t\right]\right)$ and the *d*-day mean discharge *VCd*, $VCd(t)=\int_{t-d+1}^{t}Qdaily(t')dt'$, with duration *d* associated with WR decision varying between 2 and 10 days depending on DMPs."
- "The threshold associated with WR also varies, generally associated with statistics derived from low-flow frequency analysis, but some being fixed to locally-defined ecological requirements. In the context of DMPs, series of minimum *QCd* or *VCd* are calculated by the block minima approach and thereafter fitted to the lognormal distribution. The block is not the year but the month or given by the division of the year into 10-day time-window. The regulatory thresholds are given by quantiles with four different recurrence intervals associated to the four restriction levels. For example, let us consider thresholds based on the annual monthly minima of *VCNd*. The block minima approach is carried out on the *N* years of records for each month *i*, *i*=1…,12 leading to twelves datasets {*min*{*VCNd*(*t*), *month*(*t*)=*i*, *year*(*t*)=*j*},

j=1,…,N}. The twelve fitted distribution allows the calculation of 48 values of thresholds (=12 months × 4 levels) with four T-year recurrence intervals. To enable comparison of results across all catchments, the same definitions for the monitoring variables and the regulatory thresholds have been adopted for all the catchments. $VC3$ was selected as the monitoring indicator and the regulatory thresholds are low flow quantiles $10d\text{-}VCN3$ based on the minimum 3-day mean discharges extracted by the block minima approach considering the fixed 10-day time-windows spanning the year as blocks with return periods, as they are the most common single indicators used in the 28 DMPs of the RM district. Lastly return periods T of 2, 5, 10 and 20 years will be associated with the "vigilance", "alert", "reinforced alert" and "crisis" restriction levels, respectively, due to their prevalence in the DMPs"

Section 4.2 Details on the rainfall-runoff model should be added, with special reference to the way how the influence of reservoirs is taken into account.

➔ The GR6J model has six parameters to be fitted (see Figure below): the capacity of soil moisture reservoir (X1) and of the routing reservoir (X3), the time base of a unit hydrograph (X4), two parameters of the groundwater exchange function F (X2 and X5) and a coefficient for emptying exponential store (X6). GR6J is combined with the daily snow module Cemaneige. The catchment is divided into five altitudinal bands of equal area on which snowmelt and snow accumulation processes are represented. For each band, daily meteorological inputs – including solid fractions of precipitation - are extrapolated using elevation as covariate and the snow routine is calculated separately. Finally, its outputs are then aggregated at the catchment scale to feed GR6J. The two parameters of Cemaneige are: the parameter controlling snowpack inertia (X1) and the degree-day coefficient controlling snowmelt (X2). No routine to simulate water management (e.g. reservoir) was considered here since discharges of the 106 gauging stations are weakly altered by human actions or naturalized discharges.



Section 4.3 The description of the water restriction level modelling is unclear in some parts. For instance, I would expect that the comparison between simulated WRLs driven by GR6J data and historical WRs will provide a lower sensitivity score than the comparison with simulated WRLs driven by HYDRO data (considered as benchmark), but it's not (see Lines 287-290). Could it be a consequence of the fact that the model disregards socio-political aspects of the decision making-process?

➔ Inputs of the WRL model are daily discharges and precipitation. Outputs are WRL for each of the 21 10-day periods defined between the 1st April and the 31st October. VC3(*t*) is first computed from daily discharge Q(*t*) every day *t*, WRL(*t*) is then deduced by comparing VC3(*t*) to the four regulatory thresholds and finally a unique representative WR level is assigned to each of the 21 10-day periods, as the median of WRL(*t*) observed or simulated within that 10-day period. To best match the whole monitoring process stated in most of the DMPs, a simple precipitation correction was applied ("Pcorr", in Fig. 5). It consists to give a 'no alert' when precipitation during the preceding 10 days exceeds 70% of inter-annual precipitation average, regardless of the WR simulation results. The WRL framework is applied to observed and simulated data of both discharge and precipitation. To assess the performance of the WRL model under current condition against stated WR decisions, the WRL model is run with observed daily discharges extracted from the HYDRO database (named "HYDRO" in the text) and with daily discharges simulated by the rainfall-runoff model GR6J forced by the SAFRAN reanalysis (named "GR6J" in the text). In the context of climate change the WRL model is run with daily discharges obtained with GR6J forced by one of the 1350 sets of perturbed precipitation, temperature and PET time series. In this later case the regulatory thresholds are calculated on the simulated discharge time series to limit the possible effect of bias in rainfall-runoff modeling.

➔ The discharges simulated by GR6J introduced in the WRL model lead to higher *Sensitivity* scores than those obtained with observed discharges extracted in the HYDRO database. The reasons for this unexpected result have been investigated. In particular we have compared the observed and simulated temporal variability in the time series VCN3. A "smoothing" effect in the GR6J simulations compared to observations was initially suspected. Finally no obvious difference in autocorrelation functions was found between observed and simulated time series. One reason could that the period of interest 2005-2013 – with for some basins only three years with stated water restrictions – may be too short to analyse accurately the relative performance of WRL obtained with OBS and with HYDRO, respectively.

The two scores gives a global insight on the performance of the WRL modelling framework and too much weight should not been given to the differences between scores. The developed WRL modelling framework leads to similar results (moderate performance in detecting stated legally-binding water restrictions during the period 2005-2013) with both data sources HYDRO and GR6J. The WRL modelling framework provides an overview of the on-going drought and the drought committees are partly free to account for this information, i.e. to state or to postpone water restrictions. The developed framework is a tool to predict water restrictions with no interference of lobbies, i.e. only based on the physical processes.

These sentences must be better explained:

- lines 295-296- “Furthermore, GR6J performance under low-flow conditions show no statistical link with its WRL modelling performance” ➔ Furthermore, there is no significant link between the GR6J efficiency in simulating low flows (NSE_{LOG}) and the performance of the WRL (*Sensitivity* and *Specificity* scores), since the determination coefficients between NSE_{LOG} and *Sensitivity*, and between NSE_{LOG} and *Sensitivity* are lower than 7%.
- lines 300-301 “possible biases in rainfall-runoff modeling does not affect much the ability of the WR modeling framework to simulate correctly declared or not declared WRs” It seems that despite the difficulties of GR6J model in simulating low-flows accurately, the results of WRL modelling driven by GR6J data are good anyway. How do the authors explain that? ➔ The WRL framework is applied to observed and simulated discharge data available before 31st December 2013. In this later case the regulatory thresholds are calculated on the simulated discharge time series to limit the possible effect of bias in rainfall-runoff modelling. The possible reasons of comparable performance between GR6J and OBS is that the WRL framework is carried out using regulatory thresholds derived from GR6J outputs and that even if the discharge data are not exactly reproduced by GR6J, their ranking and their relative position to the regulatory thresholds is correctly reproduced.

Section 5.3 Vulnerability is computed against a critical threshold. The latter is defined as the difference between the number of WRs simulated by the WR GR6J modelling framework for 2011 and over the baseline period. On the other hand, the Vulnerability Index is computed as the proportion (frequency) of RCM-based simulations that fail above the critical threshold. It sounds like a frequency is compared to a number. I believe that this step must be described in details.

➔ Indeed there are two measures of vulnerability. Given one specific climate change projection, a catchment could be judged vulnerable if on average the critical threshold is exceeded. The Vulnerability Index is a proportion reflecting the fraction of RCM leading to critical situations on average. This index is introduced here to account for the uncertainty in climate projections in vulnerability assessment. It should be interpreted as conditional probability (risk) with respect to a set of possible future climates and only used as a relative measure to rank the regions, from the less to the most likely impacted regions.

For the same reason, it is not clear how the black dotted lines representing the critical threshold are drawn in Figures 10 and 14.

➔ The dotted black lines are isopleths connecting points of the response surface with ΔWR*= ΔWR*(2011). Their location in the response surface depends on the shape of the response surface; this is why the dotted lines differ from one catchment to another in Figure 10, and later from one class to another in Figure 14.

Section 5.4 With regard to the hierarchical cluster analysis for catchment classification at regional scale, the authors should specify the catchment characteristics considered to investigate similarity through the Euclidean distance (see line 421-424). Details on the CART model and its implementation should be added.

➔ CART methods perform successive binary splittings of a given dataset according to decision variables. The algorithm identifies automatically through a set of “if-then” logical conditions the best possible predictors, starting from the most discriminating decision variable to the less important factors, to predict the membership to the one of the four groups. The optimal choices are fixed recursively by increasing the homogeneity within the two resulting clusters. At each step one of the clusters (node) is divided into two nonoverlapping parts.

The list of the potential decision variables by type is:

- Severity:
  - Flow exceeded 95% of the time (*Q*95);
  - Annual minimum 10-day daily mean low flows with a 5-year recurrence interval;
  - Annual maximum deficit below threshold *Q*95 exceeded 20% of time;
- Duration:
  - Annual maximum maximal duration of the continuous sequence of zero flow within the year, exceeded on average every five years (*D*80). Maximum duration of consecutive zero flows (*D*) are sampled by block maxima approach and *D*80 is defined as the empirical 80th percentile of cumulative distribution function of *D*;
  - Seasonal recession time scales (*DT* and *Drec*). This duration based on the hydrograph defined by the 1-day and 30-day moving average of the 365 long term mean daily discharges, *d*= 1,…, 365 (*Qd* and *Q*30*d*,

respectively). *Drec* is defined by the time lapse between the median $Qd50$ and the 90th quantile $Qd90$ of Qd on the falling limb of the hydrograph defined by $Q30d$ and $DT = \ln(Qd50/Qd90)/Drec$;

- Rate of change:
  - Ratio $Q95/Q50$;
  - Concavity index derived from flow duration curve $(Q10 - Q99)/(Q1 - Q99)$ (Sauquet and Catalogne, 2011). This descriptor is a dimensionless measure of the contrast between low-flow and high-flow regimes derived from quantiles of the Flow Duration Curve;
  - Baseflow index (*BFI*). *BFI* is a measure of the proportion of the baseflow component to the total river flow, calculated by the separation algorithm separation suggested by Lyne and Hollick (1979);
  - Class of river flow regime based on average monthly runoff pattern defined by Sauquet *et al*. (2008) (between 1 and 12)
  - Seasonality ratio (*SR*) $SR = Q95_{AMJJASON}/Q95_{DJFM}$ ($SR > 1$ for mountainous catchment);
- Frequency:
  - Proportion of years with at least one value $Q < Q95$;
- Timing:
  - Mean day of first occurrence of low flow $< Q95$;
  - Mean and dispersion of the occurrence of flows $< Q95$ within the year (θ and r, $r\sin(\theta)$ and $r\cos(\theta)$). These two variables are circular statistics. Each day i with zero flow is converted into an angular (ti) and represented by a unit vector with rectangular coordinates ($\cos(ti)$; $\sin(ti)$). The mean of the cosines and sines defines a representative vector. The value for θ is obtained by calculating the inverse tangent of the angle of the mean vector and the norm of the mean vector provides a measure of the regularity in the dates (a value close to one indicates a high concentration around θ while a value close to zero indicates no seasonality).

We have included this list in a table.

Technical comments

In Line 260, “VC3 is with 10d-VCN3(T) each day . . .”, something is missing.

➔ “VC3 is compared with 10d-VCN3(T) each day . . .”. The sentence has been totally rewritten.

In lines 273-274 “OBS WRLs are correctly reproduced by both GR6J and HYDRO simulations, but also can be consistent with OBS” (???). This sentence is rather misleading, I wonder if “OBS” at the beginning of the sentence could be a mistake and could be deleted.

➔ There is a problem with the phrasing on these lines. “Both GR6J and HYDRO simulations are globally consistent with observed WRLs (OBS). However GR6J and HYDRO results may differ from OBS (*e.g.* basins 9 to 11 in the Lozère department during the year 2005).”

In line 420: “. . . a classification (of what?) was conducted on to define typical response surfaces, . . .”. Please specify.

➔ A classification of the 106 gauging stations based on the 1350 values of ΔWR* was conducted on to define typical response surfaces.

In line 482: “come catchment” to be replaced by “some catchments”.

➔ “are found for ~~come~~ some catchments”.

In line 540: replace “precipitations” with “precipitation”.

➔ “more accurately temperature and/or precipitation~~s~~”

Missing references:

Brekke et al., 2009: Brekke L.D., Maurer E.P., Anderson J.D., Dettinger M.D., Townsley E.S., Harrison A., and Pruitt T.: Assessing reservoir operations risk under climate change. Water Resour. Res., 45, W04411, doi:10.1029/2008WR006941, 2009.

Gupta et al., 2009: Gupta H. V., Kling H., Yilmaz K., and Martinez G. F.: Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. J. Hydrol., 377, 80–91, https://doi.org/10.1016/j.jhydrol.2009.08.003, 2009.

Kay et al., 2014: Kay A. L., Crooks S. M., and Reynard N. S.: Using response surfaces to estimate impacts of climate change on flood peaks: assessment of uncertainty. Hydrol. Process., 28, 5273–5287, https://doi.org/10.1002/hyp.10000, 2014.

Schlef et al., 2018: Schlef K.E., Steinschneider S., and Brown C.M.: Spatiotemporal Impacts of Climate and Demand on Water Supply in the Apalachicola-Chattahoochee-Flint Basin. J. Water Resour. Plann. Manage., 2018, 144(2): 05017020, 2018.

Weib, 2011: Weiß M.: Future water availability in selected European catchments: a probabilistic assessment of seasonal flows under the IPCC A1B emission scenario using response surfaces. Nat Hazards Earth Syst Sci 11:2163–2171, 2011.

⇨ The authors would like to thank Reviewer3 for his helpful comments.

Water restrictions under climate change: a Rhone-Mediterranean perspective combining 'bottom up' and 'top-down' approaches"

Sauquet et al.

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This comment was written by a student in the MSc course ESS 401 Current topics in Earth System Science at the University of Zurich, Department of Geography. The students were given the task to select a manuscript in review at one of the EGU journals and to write a review. I discussed this review with the student, and find the comments actually quite valuable. Therefore, I post the review here in the hope editor and authors will find them useful to improve the manuscript.

Best regards, Jan Seibert

In the study of Sauquet et al. the vulnerability of current drought management plans (DMPs) in the Rhône-Méditerranée (RM) are evaluated under future climate. To do so water restrictions (WR) from 2005 and 2016 and hydrological data from 1958 to 2013 were analyzed in 106 catchments to derive a framework to reproduce water restriction durations based on low-flow indicators. As the authors write in this framework socio-political factors that can influence the imposition of water restriction are not included. Based on the drought of 2011 a critical threshold of acceptable WR was defined to decide if the DMPs in the future will still be effective. The study aims to assess the effectiveness of current DMPs under climate change to be able to revise the DMPs for the most vulnerable basins. They find out that in temperature-sensitive catchments the water restrictions will increase significantly in the short term and that for this reason there is a need to adapt the DMPs. In the catchments where the precipitation determines the water restriction, they see difficulties to adapt the DMPS as the uncertainties in precipitation is high. They state in the conclusion section several points they did not include in their study but could play an additional role besides the analyses of water restriction duration influenced by temperature and precipitation. These are for example socio-economic system stressors like agricultural practices, population growth, water demand, etc. which also should be considered in the DMPs. In my opinion, it is an important topic to discuss the reliability of current decision-making rules regarding water scarcity in the future when climate changes. The method used in this study can give a good overview of where there is a need to rethink the DMPs. But in my opinion, it would be quite important to take the socio-political factors into account in the framework to reproduce water restrictions. A further improvement would be if the economic system stressors would be included to evaluate the DMPs. Therefore the current method has still a lot to improve, and that's why it is not fully clear what the substantial contribution of this paper is.

Further, I think the description of the method of the hydrological modeling and the framework to reproduce the water restrictions could be more detailed.

➔ Authors agree with this remark and the method needs to be more explained. Water restrictions simulations complement studies on the impact of climate change on water resources availability and on water use needs. Indeed water needs can only be met first if water resources are available and second if water abstractions are allowed. Regulatory rules are pieces of the puzzle that should be examined. Roughly speaking studying water restrictions is a way to identify additional future constraints on water users. The regulatory aspects have never been deeply examined in France, perhaps due to the recent implementation of DMPs. This paper presents a first attempt to simulate water restrictions over a large area in France. This paper aims at promoting the approaches developed in parallel by Brown (named 'Decision Tree Framework") and Prudhomme (named "Scenario neutral approach") and one of the challenges was to define critical thresholds of unacceptable number of days with legally-binding WR for irrigation use. This paper suggests using information provided by insurance (here from a national system of compensation) at the regional scale.

Comments

P1-L22 and P16-L423: The four classes could be explained in P16-L423. The same for Figure 11 and 14, it would be easier to understand if each class would be shortly explained in the figure description.

➔ Climate response surface of WR* legally-binding water restrictions level anomalies ΔWR* is a graphic representation summarizing the sensitivity of ΔWR* to climatic drivers. They all suggest an increase in the occurrence of legally-binding water restrictions when precipitation decreases or when temperature increases. Additional temperature increase and its associated PET increase can compensate for precipitation increase and lead to decrease in ΔWR*. The response surfaces differ by their flatness (e.g. the response surface of Class 3 displays the less contrasted shape).

P2-L54: Is the scenario-neutral approach the same as a bottom-up approach? The authors could use the word "bottom up" as well, as they use it also in the title and it is not used in the rest of the paper. Please clarify difference or similarity.

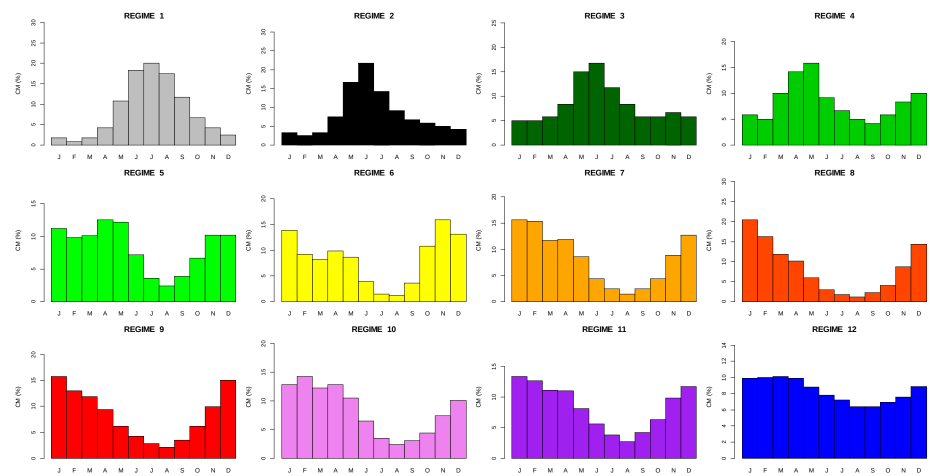
➔ According to Culley et al. (2016), "Bottom-up approaches are an alternative to the top-down procedure […], and have been designed to identify performance thresholds independently from climate models' projections". The approach developed here and based on previous published studies (Prudhomme et al., 2010) does not use downscaled GCMs to describe future climate (scenario-led approaches) but relies on sensitivity-based analyses to a wide range of climate changes, making it scenario-neutral. Ex ante climate projections are considered in the last stages of the procedure to assess the risk of failure. The sentence "specifying relevant critical thresholds is the main task involved in bottom-up approaches" was added in section 4.1.

P4-L106 to P5-L120: In section "2.3 Hydrological data" it would be good if the 15 regimes suggested by Sauquet et al. (2008) could be shortly explained.

➔ The classification could be given in Appendix.

Sauquet et al. (2008) have defined a classification based on the mean monthly runoff pattern and a map has been published showing the assignment to one class for each basin with drainage area > 50 km².

Groups 1 to 6 are pluvial river flow regimes. The groups mainly differ by the contrast between the maximum and the minimum of monthly streamflow. Nearly uniform flows through most of the year (Group 1) are found where large aquifers moderate flows whereas Group 6 is characterized by very low flow in summer, reflecting the lack of deep groundwater storages in the catchment. Group 7 is representative of Mediterranean river flow regimes where small rivers basins experience hot and dry summers and intense rainy events in autumn. Their runoff pattern therefore exhibits severe low flow in summer and high flow in November. In mountainous areas, uppermost basins display snowmelt-fed regimes (Groups 10, 11 and 12). The lower the outlet is, the lower the contributions of snowmelt to runoff. Groups 8 to 9 are in the transition regime. The seasonal variation of streamflow is affected as much by precipitation timing as by air temperature and topographic influences (on snowpack formation and snowmelt timing). Typically, high flows are observed in spring.



Reference hydrographs representative of the classification of river flow regime for France (after Sauquet et al., 2008)

P5-L121 to P5-L126: In section “2.4 Climate data” Table 2 the RCP2.6, RCP4.5, RCP8.5 scenarios could be explained. And why is Terray and Boé (2013) not listed there as his projections are used in section “5.1 Definition of perturbed climate conditions to build WR response surfaces”?

➔ I am not totally sure to understand the question. RCPs are namely “Representative Concentration Pathways” (van Vuuren et al.: The Representative Concentration Pathways: An Overview. Climatic Change, 109 (1-2), 5-31, https://doi.org/10.1007/s10584-011-0148-z, 2011). The study published by Terray and Boé (2013) is based on global climate simulations. This study was used to define the spectrum of changes in temperature and precipitation. Here regional climate projections available in the DRIAS portal are used.

P6-L163: Is duration *d*, the time used for deciding if water restrictions are imposed? In this case, I do not understand what is meant by 10d-VCNd(T) in p7-L171. In Figure 5 VC3 has a value for every day. Is it calculated from the last three days? Please clarify.

➔ We have modified the paragraph to improve the presentation of the WRL modelling framework: "Water restrictions are decided after consulting drought committees that convene irregularly. The time-step for modelling WRL was chosen to be compatible with the frequency of drought committees estimated from the analysis of the water restriction orders: WRL is thus computed at a regular time step of ten days. VC3(*t*) is first computed from daily discharge Q(*t*) every day *t*, WRL(*t*) is then deduced by comparing VC3(*t*) to the four regulatory thresholds and finally a unique representative WR level is assigned to each of the 21 10-day periods defined between the 1st April and the 31st October, as the median of WRL(*t*) observed or simulated within that 10-day period."

P7-L173: VC3 was selected, as it is the most common single indicators used in DMPs of the RM district. I might have missed something, but this seems not to be the case for the 15 test catchments chosen for the evaluation of the WR modeling framework. It is not clear for me how you can compare these different low-flow monitoring indicators with each other. This should be described clearer.

➔ Indeed the decision that lead to selecting VC3 as monitoring variable is was made considering the 28 DMPs and this modality is not prevalent within the 15 test catchments (Figure 3). We have made it clearer in the final version. *VC*3 was selected as the monitoring indicator and the regulatory thresholds are low flow quantiles 10*d-VCN*3 based on the minimum 3-day mean discharges extracted by the block minima approach considering the 37 fixed 10-day time-windows as blocks with return periods, as they are the most common single indicators used in the 28 DMPs of the RM district.

P9-L244: Are the 15 catchments used for calibration or only for evaluation? Please clarify.

➔ They were used both for calibration and for evaluation.

P13-L343: It is not clear for me if the perturbation of the climate is based on different climate scenarios as RCP2.6, RCP4.5, RCP8.5 or which exact projection is used. In the reference Terray and Boé, 2013 the authors are using they are also talking of different projections. This needs to be clarified.

➔ The "delta-change" method was used to provide a set of perturbed climates in scenario-neutral approach. Following Prudhomme *et al.* (2010), monthly correction factors ΔP and ΔT were considered:

$$\Delta \mathrm{P}(i) = \mathrm{P}_0 + \mathrm{A_P} \cdot \cos\left[(i - \varphi_{\mathrm{P}}) \cdot \frac{\pi}{6}\right]. \quad (1)$$

$$\Delta \mathrm{T}(i) = \mathrm{T}_0 + \mathrm{A_T} \cdot \cos\left[(i - \varphi_{\mathrm{T}}) \cdot \frac{\pi}{6}\right]. \quad (2)$$

P_0 and $T_0 + A_T$ are respectively the mean annual changes in equations (1) and (2), with i referring to month 1 to 12, φ_P the phase parameter and A_p the semi-amplitude of change (*e.g.* half the difference between highest and lowest values) in equation (1). The parameters P_0, φ_P, T_0 and φ_T of single-phase harmonic function were fixed with respect to the range of changes suggested by Terray and Boé (2013). Finally 45 precipitation scenarios were created using 9 values of P_0 *i.e.* [-20; -13.3; -6.6; 0; 6.6; 13.3; 20; 26.6; 33.3] $mm.an^{-1}$, by 5 values of Ap *i.e.* [0; 6.6; 13.3; 20; 26.6] $mm.season^{-1}$, while φ_P parameter is fixed to 1 to consider minimum change in January and maximum change in July. Likewise, 30 temperature scenarios were set up with 6 values of T_0 *i.e.* [0; 1; 2; 3; 4; 5]$°C.an^{-1}$ by 5 values of A_T *i.e.* [-0.5; 0.5; 1.5; 2.5; 3.5]$°C.season^{-1}$ while φ_T is fixed to 2°C to get maximum change in August. These details are now given in the new version.

P19-L513 to P19-L518: The first two sentences of the conclusion would better fit in the introduction.

➔ Done

Minor comments:

P3-L68: Why not saying Rhone-Méditerranée district in southeastern France to be consistent?

P3-L78 to P4-L95: In section “2.1 Study area” a map or a cross-reference to Figure 1 would help to get an overview of the area.

P10-L268: Figure 6 in the figure description: “Table 2” should be “Table 1”.

P4-L106: “2.3 Hydrological data” should be in bold.

➔ Changes have been made in that sense.

P4-L90: Why just speaking about the irrigation needs? It might be interesting to get the whole picture for what the water is used.

➔ The total net water withdrawal is around 6 billion of m^3 in the period 2008-2013 (water abstraction for cooling nuclear plants and hydropower is excluded) with a high proportion of them to support irrigation needs (3.4 billion of m^3, including 2 billion of m^3 for channel conveyance). Only 10% of water abstracted for irrigation originate from groundwater. Total annual abstracted volumes for drinking water and for water for industrial uses represent 1.6 and 1 billion of m^3, respectively.

P4-L109: I do not understand what the authors mean with “Time series including null values or gaps in the data records above 30% of time were disregarded”. Does this mean one null value or 30% null values? Please clarify.

➔ “Time series with more than 30% of missing values or more than 30% of zero flows were disregarded.”

P16-L426: In Table 5 in the table description please add where this standard deviation Sd is taken from.

➔ Table 5 is now referred in Section 5.2.

⇨ The authors would like to thank Jan Seibert and his students for their helpful comments.

Water restrictions under climate change: a Rhone-Mediterranean perspective combining 'bottom up' and 'top-down' approaches

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Abstract Drought management plans (DMPs) require an overview of future climate conditions for ensuring long term relevance of existing decision-making processes. To that end, impact studies are expected to best reproduce decision-making needs linked with catchment intrinsic sensitivity to climate change. The objective of this study is to apply a risk-based approach through sensitivity, exposure and ~~sustainability~~ performance assessments~~-~~ to identify where and when, due to climate change, access to surface water constrained by legally-binding water restrictions may question agricultural activities~~to evaluate the vulnerability of current DMPs operating in the Rhône-Méditerranée (RM) district to future climate projections~~. After inspection of legally-binding water restrictions (WR) from the DMPs in the Rhône-Méditerranée (RM) district, a framework to derive WR durations was developed based on harmonized low-flow indicators. Whilst the framework could not perfectly reproduce all WR ordered by state services, as deviations from socio-political factors could not be included, it enabled to identify most WRs under current baseline, and to quantify the sensitivity of WR duration to a wide range of perturbed climates for 106 catchments. Four classes of responses were found across the RM district. ~~Using t~~The information provided by the national system of compensation to farmers during the 2011 drought ~~of 2011~~ was used to define a critical threshold of acceptable WR, related to the current activities over the RM district.~~,~~ ~~the analysis~~The study ~~showed~~ finally concluded that catchments in mountainous areas, highly sensitive to temperature changes, are also the most predisposed to future restrictions under projected climate changes considering current DMPs, whilst catchments around the Mediterranean Sea, were found mainly sensitive to

precipitation changes and irrigation use, were was less vulnerable to projected climatic changes. The tools developed enable a rapid assessment of the effectiveness of current DMPs under climate change, and can be used to prioritize review of the plans for those most vulnerable basins.

Keywords Climate change; drought management plan; low-flow; France; scenario-neutral approach; response surface; vulnerability; water restriction.

1 Introduction

The Mediterranean region is known as one of the “hot spots” of global change (Giorgi, 2006; Paeth *et al.*, 2017) where environmental and socio-economic impacts of climate change and human activities are likely to be very pronounced. The intensity of the changes is still uncertain, however, climate models agree on significant future increase in frequency and intensity of meteorological, agricultural and hydrological droughts in Southern Europe (Jiménez Cisneros *et al.* 2014; Touma *et al.* 2015), with climate change likely to exacerbate the variability of climate with regional feedbacks affecting Mediterranean-climate catchments (Kondolf *et al.* 2013). Facing more severe low-flows and significant losses of snowpack, southeastern France will be subject to substantial alterations of water availability: Chauveau *et al.* (2013) have shown a potential increase in low-flow severity by the 2050’s with a decrease in low-flow statistics to 50% for the Rhône River near its outlet. Andrew and Sauquet (2017) have reported that global change will most likely result in a decrease in water resources and an increase both in pressure on water resources and in occurrence of periods of water limitation within the Durance River basin, one of the major water tower of Southeastern France. In addition Sauquet *et al.* (2016) have suggested the need to open the debate on a new future balance between the competing water uses. More recently, based on climate projections obtained from Coupled Model Intercomparison Project Phase 5 (Taylor *et al.* 2012), Dayon *et al.* (2018) have shown a significant increase in hydrological drought severity with a meridional gradient (up to -55% in southern France for both the annual minimum monthly flow with a return period of 5 years and the mean summer river flow) while a more uniform increase in agricultural drought severity is projected over France for the end of the 21st century.

The challenges associated with possible impact of climate change on droughts have received increasing attention by researchers, stakeholders and policy makers in the last decades. To date climate change impact studies are usually dedicated to water resources (*e.g.*, Vidal *et al.* 2016, Collet *et al.* 2018, Hellwig and Stahl 2018, Samaniego *et al.* 2018) or water needs for the competing users (*e.g.*, Bisselink *et al.*, 2018). However, examining the suitability of regulatory instruments, such as Drought Management Plans, is also essential to establish successful adaptation strategies. These plans state which type of water restrictions should be imposed to non-priority uses during severe low-flow events; under climate change, those water restrictions and stakeholders' access to water resources might need to be revised as drought patterns and severity might change. In most climate change impact studies, analyses on the regulatory measures are often limited to maintaining environmental flows – especially when assessing future hydropower potential. To date, no climate change impact on water regulatory measures have yet been assessed at the regional scale, highlighting a gap in developing robust adaptation plans. This study aims to address this gap by suggesting a framework, applying it to southeastern France and publishing the associated results.(Prudhomme *et al.* 2012; Prudhomme *et al.* 2014; Vidal *et al.* 2012). Drought management plans require an overview of future climate conditions to ensure the long term reliability of current decision-making rules. With poor predictability of initiation and termination (Weisheimer and Palmer 2014), droughts are challenging water managers who have to cope with climate change impact issues, and need to downscale to a scale adapted to drought management decisions (Ekström *et al.* 2015), uncertainties in future drought in response to global change, etc.

Historically, most of hydrologic impact studies are based on the "top-down" (scenario-driven) approaches for ease of interpretation, but conclusions can fast become dated as new climate projections are produced. In addition scenario-based studies fail to match decision-making needs since the implication in terms of water management is usually ignored (Mastrandrea *et al.* 2010). As a substitute to scenario-driven approach, the scenario-neutral approach (Brekke *et al*. 2009, Prudhomme *et al*. 2010, 2013a, 2013b, 2015, Brown *et al*. 2012, Brown and Wilby 2012, Culley *et al*. 2016, Danner *et al.* 2017) has been developed to better address risk-based decision issues. The suggested framework shifts the focus on the current vulnerability of the system affected by changes and on the critical thresholds above which the system starts to fail. Applied to water management issues, the scenario-neutral studies (*e.g*. Weiß 2011, Wetterhall *et al.* 2011, Brown *et al.* 2011, Whateley *et al.* 2014) aim at improving the knowledge of the system's vulnerability to changes and at bridging the gap between scientists and stakeholders facing needs in relevant adaptation strategy. Prudhomme *et al*. (2010) have suggested combining of the sensitivity framework with 'top-down' projections through climate response surfaces. This approach has been applied to low-flows in the UK (Prudhomme *et al*. 2015) and its interests have been discussed as a support tool for drought management decisions.

~~Climate change impact studies are usually dedicated to water resources or water needs for the competing users. There are also interests in examining regulatory instruments, such as Drought Management Plans, since these plans state water restrictions imposed to non-priority uses during severe low flows, and climate change is likely to affect water restrictions and modify the access of stakeholders to water resources.~~

The paper develops a framework to simulate legally-binding water restrictions (WR) under climate change in the Rhone-Méditerranée district (southeastern France) and ~~establish the level of predisposition t~~to assess the likelihood of future restrictions depending on their sensitivity, ~~sustainability~~ performance and exposure to climate deviations. The approach is ~~an adaptation~~adapted ~~of~~from the risk-based approaches such as developed in parallel by Brown *et al.* (2011) – named "Decision Tree Framework" – and Prudhomme *et al.* (2010) – named "Scenario neutral approach" – ~~developed by Prudhomme *et al.* (2015)~~ and aims to establish a ranking of ~~catchments and their DMP~~ areas in terms of vulnerability to climate change in terms of access to water for agricultural uses. This research is a scientific contribution to the ongoing decade 2013–2022 entitled "Panta Rhei – Everything Flows" initiated by the International Association of Hydrological Sciences and more specifically to the "Drought in the Anthropocene" working group (https://iahs.info/Commissions--W-Groups/Working-Groups/Panta-Rhei/Working-Groups/Drought-in-the-Anthropocene.do, Van Loon *et al.* 2016). Legally-binding water restrictions and their associated decision-making processes are important for the blue water footprint assessment at the catchment scale.

The paper is organized in four parts. Sect. 2 introduces the area of interest and the source of data. Sect. 3 is a synthesis of the mandatory processes for managing drought condition implemented within the Rhône-Méditerranée district and the related water restriction orders adopted over the period 2005-2016. Sect. 4 describes the general modelling framework developed to simulate WR decisions. The approach ~~Results~~ is implemented at both local and regional scales ~~are presented~~ and results discussed in Sect. 5 before drawing general conclusions in Sect. 6.

2 Study area and materials

2.1 Study area

The Rhone-Méditerranée district covers all the Mediterranean coastal rivers and the French part of the Rhône River basin, from the outlet of Lake Geneva to its mouth (Fig. 1). Climate is rather varied with a temperate influence in the north, a continental influence in the mountainous areas and a Mediterranean climate with dry and hot summers dominating in the south and along the coast. In the mountainous part (in both the Alps and the Pyrenees) the snowmelt-fed regimes are observed in contrast to the northern part under oceanic climate influences, where seasonal variations of evaporation and precipitation drive the monthly runoff pattern (Sauquet *et al.* 2008).

Water is globally abundant but ~~unbalanced~~ unevenly between the mountainous areas, the northern and southern parts of the Rhône-Méditerranée (RM) district and~~.~~ water resources are under high pressure due to water abstractions. ~~Around 40% of the RM district is suffering from water stress and scarcity. Water resources are under high pressure due to water abstractions for human activities. This pressure is significant in the Mediterranean regions due to high variability of precipitation.~~ For the period 2008-2013, ~~The~~ annual total ~~net~~ water withdrawal was~~is~~ around ~~7~~ 6 billion of m^3 in the ~~period 2008-2013~~ (excluding any water abstraction for energy such as cooling nuclear plants and hydropower) with a more than ~~high proportion~~used for~~-of them to support~~ irrigation ~~needs~~ (3.4 billion of m^3~~43%~~, including 2 billion of m^3 for channel conveyance). Use for public and industrial supply is of 1.6 and 1 billion of m^3, respectively. Because of an intense competition for water between different users — agricultural, municipal, and industrial — and the environment, some areas within the RM district can be vulnerable during low-flow periods. Around 40% of the RM district sufferis from water stress and scarcity (http://www.rhone-mediterranee.eaufrance.fr/gestion/gestion-quanti/problematique.php) and has been identified by the French RM Water Agency as areas with persistent imbalance between water supply and water demand.

~~Water management in the RM district is a long-standing issue. Reservoirs have been built to produce energy, to sustain low flows and to cope with drought effects. As an example, the Serre-Ponçon multi-purpose reservoir located in the Durance River basin is the second largest impoundment in Europe in terms of storage capacity (1.2 billion m^3) with objectives to supply water for cropland irrigation and drinking water to southeastern France, as well as for hydropower production (Andrew and Sauquet 2017).~~

2.2 Drought management plan

Drought management plans (DMPs) define specific actions to be undertaken to enhance preparedness and increase resilience to drought. In France DMPs include ~~Past and operating~~ regulatory frameworks to be applied in case of drought, named ~~in French~~ "arrêtés cadres sécheresse"~~, were inspected in the 28 departments of the RM~~

district. The past and operating DMPs and the water restriction orders were inspected in the 28 departments of the RM district. They were obtained from:

- The database of the *DREAL Auvergne-Rhône-Alpes (*"*Direction Régionale de l'Eau, de l'Alimentation et du Logement" in French)* including WR levels and duration at the catchment scale available over the period 2005-2016 within the RM district;
- The online national database PROPLUVIA (http://propluvia.developpement-durable.gouv.fr) with WR levels and dates of adoption at the catchment scale for the whole France available from 2012.

The most recent consulted documents date from January 2017.

2.3 Hydrological data

The hydrological observation dataset is a subset of the 632 French near-natural catchments identified by Caillouet *et al.* (2017). Daily flow data from 1958 to 2013 were extracted from the French HYDRO database (http://hydro.eaufrance.fr/). Time series with more than 30% of missing values or more than 30% of null values were disregardedTime series including null values or gaps in the data records above 30% of time were disregarded. Finally the total dataset consist of 106 gauged catchments located in the RM district with minor human influence and with high quality data. The selected catchments are benchmark catchments where near natural drought events are observed and current water availability is monitored. Water can be abstracted from other nearby streams.

A selection of 15 evaluation test catchments (Table 1) were used to calibrate and to evaluate the WR Water Restriction Level modelling framework (Sect. 4), selected because (*i*) they have complete records of stated water restriction, including dates and levels of restrictions - which was not the case of other catchments, and (*ii*) they are located in areas where water restriction decisions are frequent. To facilitate interpretation, the 15 test catchments have been ordered along the north-south gradient. The Ouche and Argens River basins (n°1 and 15 in Table 1) are the northernmost and the southernmost gauged basins, respectively. The 15 test catchments encompass a large variety of river flow regimes according to the classification suggested by Sauquet *et al.* (2008) (see Appendix A) that can be observed in the RM district (*e.g.*, the Ouche (1 in Table 1, pluvial regime), Roizonne (3, transition regime) and Argens (15, snowmelt-fed regime) River basins).

2.4 Climate data

Baseline climate data were obtained from the French near-surface Safran meteorological reanalysis (Quintana-Seguí *et al.*, 2008; Vidal *et al.* 2010) onto an 8-km resolution grid from 1 August 1958 to 2013. Exposure data was based on the regional projections for France (Table 2) available from the DRIAS French portal (www.drias-climat.fr, Lémond *et al*. 2011). Catchment-scale data were computed as weighted mean for temperature and sum for precipitation based on the river network elaborated by Sauquet (2006).

3 Operating Drought Management Plans in the Rhône-Méditerranée district

The French Water Act amended on September 24, 1992 (decree n°92/1041) defines the operating procedures for the implementation of drought management plan (DMP). Following the 2003 European heat wave, drought management plans including water restrictions have been gradually implemented in France (MEDDE 2004). Water restrictions fall within the responsibility of the prefecture (one per administrative unit or department), as mentioned in article L211-3 II-1° of the French environmental code. Their role in drought management is to ensure that regulatory approvals for water abstraction continuously meet the adequate balance between water resource availability and water uses or ecosystems resilience. *De facto*, legally-binding water restrictions have to fulfill three principles: (*i*) being gradually implemented at the catchment scale in regard with low-flow severity observed at various reference locations, (*ii*) ensuring users equity and upstream-downstream solidarity and (*iii*) being time-limited to fix cyclical deficits rather than structural deficits. The prefecture is in charge of establishing and monitoring the DMP operating in the related department.

Past and current drought management plans were analyzed to identify the past and current modalities of application, the frequency of water restriction orders and the areas affected by water restrictions. Gathering and studying the regulatory documents was a tedious in particular because of their lack of clear definition of the hydrological variables used in the decision-making process.

This analysis shows that the implementation of the DMPs has evolved for many departments since 2003, *e.g.*, with changes in the terminology and a national scale effort to standardize WR levels. Now severity in low-flows is classified into four levels which are related to incentive or legally-binding water restrictions. These measures affect recreational uses, vehicle washing, lawn watering and domestic, irrigation and industrial uses (Table 3). Level 0 (named "vigilance") refers to incentive measures, such as awareness campaign to promote low water consumption from public bodies and general public. Levels 1 to 3 are incrementally legally-binding restriction levels; level 1 (named "alert") and 2 (named "reinforced alert") enforcing reductions in water abstraction for agriculture uses, or several days a week of suspension; level 3 (named "crisis") involves a total suspension of water abstraction for non-priority uses, including abstraction for agricultural uses and home gardening, and authorizes only water abstraction for drinking water and sanitation services. Due to change in the naming of WR levels since their creation one task was dedicated to restate the WR decisions (hereafter "OBS") since 2005 with respect to the current classification into four WR levels.

For all catchments, a WR decision chronology was derived, showing a large spatial variability in WR (Fig. 1) - note that the 15 evaluation catchments (Table 1) are located in the most affected areas. Between 2005 and 2012, WR decisions were mainly adopted between April and October (98% of the WR decisions, Fig. 2), with 62% in July or August, peaking in July.

Decisions for adopting, revoking or upgrading a WR measure are taken after consultation of "drought committees" bringing the main local stakeholders together, the meeting frequency of which is irregular and depends on hydrological drought development. The adopted restriction level is mainly based on the ~~current~~ existing hydrological conditions at the time, i.e., ~~according to~~based on ~~the values of~~ low-flow monitoring ~~low-flows~~ indicators measured at a set of reference gauging stations and their departure ~~against~~ from a set of regulatory thresholds. This varies greatly across the RM district (Fig. 3). The low-flow monitoring indicators usually considered are:

- the daily discharge *Qdaily*,
- the *d*-day maximum discharge *QCd*, $QCd(t)=\max\left(Qdaily(t'),t'\in[t-d+1,t]\right)$ and
- the *d*-day mean discharge *VCd*, $VCd(t)=\int_{t-d+1}^{t} Qdaily(t')dt'$ ~~the *d*-day maximum discharge *QCd*, the *d*-day mean discharge *VCd* and the daily discharge *Qdaily*,~~

with duration *d* associated with WR decision varying between 2 and 10 days depending on DMPs. *VC*3 (40% of DMPs) and *QC*7 (17% of DMPs) are the most commonly used, but other single indicators include *Qdaily* (17%), *QC*5 (14%), *QC*10 (8%), *QC*2 (3%), *VC*10 (3%), and with mixed indicators also used (*e.g.*, 14% of *VC*3 and *Qdaily* together.

The threshold associated with WR also varies within the district, generally associated with statistics derived from low-flow frequency analysis~~the minimum *QCd* observed or the minimum *VCd* observed with a *T*-year recurrence interval (or *QCNd*(*T*) and *VCNd*(*T*) respectively)~~, but also ~~some being~~ fixed to locally-defined ecological requirements. ~~Generally, return periods *T* of 2, 5, 10 and 20 years are associated with the "vigilance", "alert", "reinforced alert" and "crisis" restriction levels, respectively.~~

In the context of DMPs, series of minimum *QCd* or *VCd* are calculated by the block minima approach and thereafter fitted to a statistical distribution. T~~t~~he ~~monitoring indicators~~block ~~are~~ is not ~~calculated annually~~the year but ~~by~~ the month ~~(*m-VCN*(*T*) and *m-QCNd*(*T*))~~ or ~~on~~ given by the division of the year into 37 ~~fixed~~ 10-day time-window~~ basis (10*d-VCNd*(*T*) and 10*d-QCNd*(*T*))~~. The regulatory thresholds are given by quantiles with four different recurrence intervals associated to the four restriction levels. Generally, return periods *T* of 2, 5, 10 and 20 years are associated with the "vigilance", "alert", "reinforced alert" and "crisis" restriction levels, respectively. For example, let us consider thresholds based on the annual monthly minima of *VCNd*. The block minima approach is carried out on the *N* years of records for each month *i*, i=1…,12 leading to twelves datasets {*min*{*VCNd*(*t*), *month*(*t*)=*i*, *year*(*t*)=*j*}, *j*=1,…,*N*}. The twelve fitted distribution allows the calculation of 48 values of thresholds (=12 months × 4 levels) with four *T*-year recurrence intervals.

The meteorological situation is also examined in terms of precipitation deficit and likelihood of significant rainfall event considering available short to medium-range weather forecasts. There are heterogeneities in the drought monitoring variables, the time period on which deficit is calculated and the permissible deviation from long term average values.

Where appropriate other supporting local observations such as groundwater levels, reservoir water levels, field surveys provided by the ONDE network (Beaufort *et al*., 2018) or feedbacks from stakeholders can be used to inform final decisions.~~Generally, return periods *T* of 2, 5, 10 and 20 years are associated with the "vigilance", "alert", "reinforced alert" and "crisis" restriction levels, respectively. To enable comparison of results across all catchments, *VC*3 was selected as the monitoring indicator and 10*d-VCN*3 as the regulatory threshold, as they are the most common single indicators used in DMPs of the RM district.~~

4 Risk-based framework and the related tools

4.1 The scenario neutral concept

Traditionally, hydrological impact studies are often based on "top down" (scenario-driven) approaches, easy to interpret, but with associated conclusions becoming outdated as new climate projections are produced. In addition scenario-based studies may fail to match decision-making needs since the implication in terms of water management is usually ignored (Mastrandrea *et al.* 2010). As a substitute to scenario-driven approach, the scenario-neutral approach (Brekke *et al*. 2009, Prudhomme *et al*. 2010, 2013a, 2013b, 2015, Brown *et al*. 2012, Brown and Wilby 2012, Culley *et al*. 2016, Danner *et al*. 2017) has been developed to better address risk-based decision issues. The suggested framework shifts the focus on the current vulnerability of the system affected by changes and on critical thresholds above which the system starts to fail to identify possible maladaptation strategies (Broderick *et al*. 2019). Applied to water management issues, the scenario-neutral studies (*e.g.*, Weiß 2011, Wetterhall *et al.* 2011, Brown *et al.* 2011, Whateley *et al.* 2014) aim at improving the knowledge of the system's vulnerability to changes and at bridging the gap between scientists and stakeholders facing needs in relevant adaptation strategy. Prudhomme *et al*. (2010) have suggested combining of the sensitivity framework with 'top-down' projections through climate response surfaces. This approach has been applied to low-flows in the UK (Prudhomme *et al*. 2015) and its interests have been discussed as a support tool for drought management decisions.

The risk-based framework adopted contains three independent components (Fig. 4):

(i) Sensitivity analysis (Fronzek *et al*., 2010) based on simulations under a large spectrum of perturbed climates to (a) quantify how policy-relevant variables respond to changes in different climate factors, and (b) identify the climate factors to which the system is the most sensitive. Addressing (a) and (b) may help modelers to check the relevance of their model (*e.g.*, unexpected sensitivity to a climate factor regarding the know processes influencing the rainfall-runoff transformation). From an operational viewpoint, it may encourage stakeholders to monitor in priority the variables that affect the system of interest (reinforcement of the observation network, literature monitoring, etc.),

(ii) Sustainability or performance assessment, aiming to identify under which climate (or others) conditions (e.g., no rain period in spring, heat wave in summer, etc.) the system fails. A key-challenge in bottom-up framework is to define performance metrics and associated critical thresholds relevant for the system of interest. In the case of our study, this would be acceptable or not water restrictions for usersSustainability is evaluated through quantitative critical thresholds which, if crossed, could generate unacceptable water restrictions for users,

(iii) Exposure, as defined by state-of-the-art regional climate trajectories superimposed to the climate response surface The exposure measures the probability of changes occurring for different lead times based on available regional projections..

All the components of the framework together contribute to ~~The intersection of all three components defines~~ the vulnerability of the system (including its management) to systematic climatic deviations.

The sensitivity analysis was conducted applying a water restriction modelling framework. Climate conditions were generated applying incremental changes to historical data (precipitation and temperature) and introduced as inputs in the developed models to derive occurrence and severity of water restriction under modified climates. The tool chosen here to display the interactions between water restriction and the parameters that reflect the climate changes is a two-dimensional response surface, with axes represented by the main climate drivers. This representation is commonly used in scenario neutral approach. For example, in both Culley *et al.* (2016) and Brown *et al.* (2012) the two axes were defined by the changes in annual precipitation and temperature. When changes affect numerous attributes of the climate inputs, additional analyses (*e.g.*, elasticity concept combined with regression analysis (Prudhomme *et al*. 2015), Spearman rank correlation and Sobol' sensitivity analyses (Guo *et al*. 2017)) may be required to point out the key variables with the largest influence on water restriction that form thereafter the most appropriate axes for the response surfaces.

~~Sustainability~~ Performance assessment is a challenging task for hydrologists since ~~its assessment~~it requires information on the impact of extreme hydrometeorological past events on stakeholders' activities. Simonovic (2010) used observed past events selected with local authorities on a case study in southwestern Ontario (Canada), chosen for their past impact (flood peak associated with a top-up of the embankments of the main urban center; level II drought conditions of the low water response plan). Schlef *et al*. (2018) set the threshold to the worst modelled event under current conditions. Whateley *et al.* (2014) assessed the robustness of a water supply system and the threshold is fixed to the cumulative cost penalties due to water shortage evaluated under the current conditions. Brown *et al*. (2012) and Ghile *et al*. (2014) suggested selecting thresholds according to expert-judgment of unsatisfactory performance of the system by stakeholders, whilst Ray and Brown (2015) use results from benefit-cost analyses. The spatial coverage of a large area, such as the RM district, and the heterogeneity in water use (domestic needs, hydropower, recreation, irrigation, etc.) makes it challenging for a systematic, consistent and comparable stakeholder consultation to be conducted and for a relevant critical threshold T_c to be fixed for all the users. Facing this complexity, only the irrigation water use ~~has~~ will been examined here, since it is the sector which consumes most water at the regional scale, with a critical threshold defined for this single water use.

~~The last component of the risk-based framework is the e~~Exposure to changes here~~.~~ ~~The exposure measures the probability of changes occurring for different lead times based on available regional projections. It~~ is ~~assessed~~ measured using regional projections, visualized graphically by positioning the regional projections in the coordinate system of the climate response surfaces and identifying the associated likelihood of failure relative to T_c~~the critical threshold~~. Note that, to update the ~~vulnerability~~ risk assessment, only the exposure component has to be examined (including the latest climate projections available onto the response surfaces).

4.2 The ~~R~~rainfall-runoff modelling

The conceptual lumped rainfall-runoff model GR6J was adopted for simulating daily discharge at 106 selected catchments of the RM district. The GR6J model is a modified version of GR4J originally developed by Perrin *et al.* (2003), well suited to simulate low-flow conditions (Pushpalatha *et al.* 2011). It was selected for its good performance across a large spectrum of river flow regimes (*e.g.*, Hublart *et al.* 2016, Poncelet *et al*. 2017).

~~The GR6J model is combined here with the CemaNeige semi-distributed snowmelt runoff component (Valéry *et al*. 2014).~~ The GR6J model has six parameters to be fitted (Fig. 5): the capacity of soil moisture reservoir (X1) and of the routing reservoir (X3), the time base of a unit hydrograph (X4), two parameters of the groundwater exchange function F (X2 and X5) and a coefficient for emptying exponential store (X6). The GR6J model is combined here with the CemaNeige semi-distributed snowmelt runoff component (Valéry *et al.* 2014). The catchment is divided into five altitudinal bands of equal area on which snowmelt and snow accumulation processes are represented. For each band, daily meteorological inputs – including solid fractions of precipitation - are extrapolated using elevation as covariate and the snow routine is calculated separately. Finally, its outputs are then aggregated at the catchment scale to feed GR6J. The two parameters of Cemaneige are: the parameter controlling snowpack inertia (X1) and the degree-day coefficient controlling snowmelt (X2). No routine to simulate water management (*e.g.*, reservoir) was considered here since discharges of the 106 gauging stations are weakly altered by human actions or naturalized discharges. ~~There are, in total~~The~~,~~ eight parameters ~~to be fitted~~ (six from the GR6J model and two from the CemaNeige module)~~. The parameters~~ were calibrated against the observed discharges using the baseline Safran reanalysis as input data and the Kling–Gupta efficiency criterion (Gupta *et al.*~~,~~ 2009) KGE_{SQRT} calculated on the square root of the daily discharges as objective function. The KGE_{SQRT} criterion was used to give less emphasis of extreme flows (both low and high flows). As the climate sensitivity space includes unprecedented climate conditions (including colder climate conditions around the current-day condition), the CemaNeige module was run for all the 106 catchments even for those not currently influenced by snow.

The two step procedure suggested by Caillouet *et al.* (2017) was adopted for the calibration: first the eight free parameters were fitted only for the catchments significantly influenced by snowmelt processes – *i.e.*, when the proportion of snowfall to total precipitation > 10% - and second, for the other catchments, the medians of the CemaNeige parameters were fixed and the six remaining parameters are then calibrated. Calibration is carried out over the period 1 January 1973 to 30 September 2006 with a 3-year spin-up period to limit the influence of reservoir initialization on the calibration results. The criterion KGE_{SQRT} and the Nash-Sutcliffe efficiency criterion on the log transformed discharge NSE_{LOG} (Nash and Sutcliffe 1970) were calculated over the whole period 1958-2013 for the subset of 15 evaluation catchments (Table 1), showing KGE_{SQRT} and NSE_{LOG} values are above 0.80 and 0.70 respectively. These two goodness-of-fit statistics indicate that GR6J adequately reproduces observed river flow regime, from low to high flow conditions. The less satisfactory performances of GR6J are observed for the Tarn and Roizonne River basins, both characterized by smallest drainage areas and highest elevations of the dataset. These lowest performances are likely to be linked to their location in mountainous areas (snowmelt processes are difficult to reproduce) and to their size (the grid resolution of the baseline climatology fails to capture the climate variability in the headwaters).

4.3 The ~~W~~water restriction level modelling framework

The Water Restriction Level (WRL) modelling framework developed ~~(Fig. 5)~~ aims to identify periods when the hydrological monitoring indicator is consistent with legally-binding water restrictions. ~~It only focuses on the physical aspects (river flow) and excludes any other socio-political aspects of the decision making process.~~ Only physical components (mainly hydrological drought severity) leading to WR decisions are considered, with no socio-political factor accounted for to model water restrictions.

To enable comparison of results across all catchments, the same drought monitoring indicators and regulatory thresholds were adopted in all the catchments (see Section 3 for details), selected as most commonly used in the 28 DMPs across the RM district, specifically *VC*3 as monitoring indicator and 10*d*-*VCN*3 with return periods *T* of 2, 5, 10 and 20 years as regulatory thresholds. Each regulatory threshold is defined for a 10-day calendar period between 1st April and 31st October, resulting in 21 sets of four thresholds. ~~By design, the time step of~~

analysis is ten days, consistently with prefectural decision-making time frame. Results are analyzed over the period April to October when water restrictions are numerous and when irrigation takes place.

Daily discharge time series Q were used to derive the low-flow monitoring indicator $VC3$ and the regulatory thresholds $10d\text{-}VCN3(T)$, both estimated from the full period of records prior to 31[st] December 2013. In the WRL modelling framework, $VC3$ is with $10d\text{-}VCN3(T)$ each day and transformed in a 'no alert' to 'crisis' WRL indicator. Water restrictions are decided after consulting drought committees that convene irregularly depending on hydrological conditions over a time window, i.e. the last N days. Here a time window for analysis of N= 10 days was decided, which is consistent with the prefectural decision-making time frame (frequency of updates in water restriction statements). The WRL modelling time-step is finally fixed to 10 days and a representative value of WRL is given to the 21 10-day calendar periods from April to October. Thus WRL is thus computed as follows: The WRL time series is then examined for all 21 10-day periods defined between the 1[st] April and the 31[st] October. For each 10-day period, a

- $VC3(t)$ is computed from daily discharge $Qdaily(t)$ every day t;
- $VC3(t)$ is compared to the corresponding regulatory thresholds to create time series of daily water restriction level wrl, with $wrl(t)$ ranging from 0 ('no alert') to 3 ('crisis'):
    - if $10d\text{-}VCN3(2) \geq VC3(t) > 10d\text{-}VCN3(5)$, $wrl(t)=0$
    - if $10d\text{-}VCN3(5) \geq VC3(t) > 10d\text{-}VCN3(10)$, $wrl(t)=1$
    - if $10d\text{-}VCN3(10) \geq VC3(t) > 10d\text{-}VCN3(20)$, $wrl(t)=2$
    - if $10d\text{-}VCN3(20) \geq VC3(t)$, $wrl(t)=3$
- A dekad $WRL(d)$ time series is created as the median of $wrl(t)$ for each 10-day period;
- The $WRL(d)$ value is set to zero if To best match the whole monitoring process stated in most of the DMPs, a simple precipitation correction was applied ("Pcorr", in Fig. 5). It consists to give a 'no alert' when precipitation during the preceding 10--day precipitation totals exceeds 70% of inter-annual precipitation average(precipitation correction), regardless of the WR simulation results.

Inputs of the WRL model are daily discharges and precipitation. Outputs are WRL dekad time series. Modelling is only applied to the period April-to-October, the irrigation period and unique WR level is defined as the median of WRL indicators when most water restrictions are put in place.within that period. The low-flow monitoring indicator $VC3$ and the regulatory thresholds $10d\text{-}VCN3(T)$ are computed from daily discharge time series *Qdaily* based on full period of records prior to 31st December 2013. The log-normal distribution is used to assess the return periods.

To best match the whole monitoring process stated in most of the DMPs, a simple precipitation correction was applied ("Pcorr", in Fig. 5). It consists to give a 'no alert' when precipitation during the preceding 10 days exceeds 70% of inter-annual precipitation average, regardless of the WR simulation results. The WRL modelling framework is can be applied to both observed and simulated time series. For the later, outputs from GR6J are used for simulations under current and modified climate conditions. Regulatory thresholds are derived from simulated discharge using the Safran baseline meteorological reanalysis as input, to moderate the possible effect of bias in rainfall-runoff modelling.

In order to evaluate tThe WRL modelling framework was verified in the 15 evaluation catchments (Table 1). methodology, WRL simulations results based on GR6J outputsmodelled (hereafter "GR6J") and observed (hereafter 'HYDRO') discharge were compared graphically to official WR measures adopted by Prefectures ("OBS") for the 15 test catchments (Table 1) (Fig. 6). A further assessment of the WRL modelling framework was conducted over the period 2005-2013 using the *Sensitivity* and *Specificity* scores (Jolliffe and Stephenson, 2003) to examine how well it the WRL modelling framework can discriminate WR severity levels (Table 4). The *Sensitivity* score assesses the probability of event detection; the *Specificity* score calculates the proportion of "No" events that are correctly identified. An event was defined as any legally-binding Water Restriction of at least level 1, and 'non-event' a period where WRL is 0 or without WR. Comparisons are were made over the 2005-2013 period, corresponding to the common period of availability for OBS, HYDRO and GR6J from 1st April to 31st October. Information on the dates of the revised DMPs was also provided to assess the frequency of revisions in their implementation at the department scale.

Fig. 6 For the 15 test catchments,shows years the WRL modelling framework can reproduce the alternation between dry years withwith severe simulated WRLs (*e.g.*, 2005 and 2011) and wet years with no or only few simulated WRs (*e.g.*, 2010 and 2013). OBS WRLs are correctly reproduced by bBoth GR6J and HYDRO simulations are generally consistent with OBS, even if misses are found, but also can be inconsistent with OBS (*e.g.*, basins 9 to 11 in the Lozère department during the year 2005). There is no systematic bias, with . For example, simulations using HYDROsome overestimateions (e.g., WRL compared to OBS in 2005 using GR6J in basins 1 and 15; 2007 using HYDRO at in the Argens River basin 15), underestimations (e.g. 2009 in basin 6, 7, and 8) and misses ~~but have missed OBS WRs in 2005 at the Ouche River basin~~(e.g. 2005 using HYDRO in basin 1).

Sensitivity~~Results~~ and *Specificity* scores computed with OBS considered as benchmark (Fig. 7) show a large variation ~~in skill scores~~ across the catchments, in particular ~~when looking at~~for *Sensitivity*. *Specificity* scores are around 0.85 for both GR6J and HYDRO, suggesting that more than 85% of the observed non-events were correctly simulated by the W~~L~~RL modelling framework. The median of ~~HYDRO~~ WRL *Sensitivity* score using HYDRO is around 45%, indicating that for half the ~~test~~ catchments, less than 45% of observed events are detected based on HYDRO discharges, but this raises to 68% of events detected when W~~L~~RL~~S~~s are simulated based on GR6J discharge. ~~There is n~~No evidence of systematic bias ~~due~~ associated ~~to~~with ~~the location of the~~ catchment locations or ~~to the~~ river flow regime was found: northern (blue) and southern (red) catchments are uniformly distributed in the *Sensitivity*/*Specificity* space.

Sensitivity and *Specificity* scores using HYDRO as benchmark in the contingency table were also used to compare ~~results~~ simulations from GR6J discharge with those obtained from HYDRO discharge ~~(considered as benchmark)~~. Median ~~scores~~ values reach 84% (*Sensitivity*) and 92% (*Specificity*), showing high consistency ~~in the outputs~~between HYDRO and GR6J. ~~Furthermore, GR6J performance under low-flow conditions show n~~No statistical link ~~with its~~between hydrological model and WRL ~~modelling performance~~ model performance was found, with R^2 between NSE_{LOG} and *Sensitivity*, or NSE_{LOG} and *Specificity* ~~being~~ lower than 7%. In addition, ~~Despite the known difficulty for hydrological models to simulate accurately low flows (*e.g.* Staudinger *et al.* 2011; Huang *et al.* 2017), here~~ the similar skill scores ~~associated with WR simulations based on HYDRO (observed) and GR6J (simulations) discharge~~of GR6J and HYDRO modelling suggest ~~are very similar, suggesting that any possible~~that possible biases in rainfall-runoff modelling does not ~~affect much~~impact on the ability of the WRL modelling framework to correctly simulate ~~correctly~~ declared or not declared WRs. No evidence was found that the slightly higher *Sensitivity* scores for GR6J was due to a "smoothing" introduced by the hydrological modelling (similar autocorrelation between observed and GR6J simulated *VC*3 time series VC3), but the relatively short verification period (only three years with legally-binding water restrictions in some catchments) and the frequency of DMP updates (black vertical segments in Fig. 6) might result in not truly representative scores.

Discrepancy between simulated and adopted WR measures is most likely due to the other factors involved in the making-decision process. When regulatory thresholds are crossed, restrictive measures should follow the

DMPs. In reality, the measures are not automatically imposed, but are the result of a negotiating process. This process includes for example some expert-judgment factors such as (i) the evolution of low-flow monitoring indicators and thresholds over the years (*e.g.*, annual revision for the Ouche, and irregular revision for the Isère (38), Gard (30), Alpes-de-Haute-Provence (04) and Lozère (48) departments (last one in 2012); (ii) the role of drought committees in negotiating a delay in WR level applications to limit economic damages or to harmonize responses across different administrative sectors sharing the same water intake; (iii) the local expertise especially regarding the uncertainty in flow measurements (Barbier *et al*. 2007) impacting on the low-flow monitoring indicators, *e.g.*, Cote d'Or (21) and Lozère (48) in the northern and southwestern parts of the RM district, respectively. Note that where WR decisions are not uniquely based on hydrological indicators but also involve a negotiation process, the results of the WRL modelling framework should be interpreted as potential hydrological conditions for stating water restrictions.

Results of our sample study on 15 evaluation catchments show deviations for most catchments, but links between order restrictions and hydrological drought severity. These deviations may partly be attributed to the use of the same monitoring indicator and regulatory thresholds across the catchments in the modelling (whilst it is not true in reality), as a necessary assumption for a region scale analysis. Tests with *QC*7 as low-flow monitoring variable combined with the two dominant modalities for the regulatory thresholds show a weak sensitivity of the WRL modelling skill to the choice of the indicators (with a slight increase in *Specificity* score (~ 90%) while *Sensitivity* score is reduced (< 50%) using GR6J). Whilst the developed WRL modelling framework does not account for expert-decision brought by drought committees - and hence is not designed to simulate the exact WR decisions - its ability to simulate 68% of the stated restrictions over the period 2005-2013 demonstrates its usefulness as a tool to objectively simulate the potential of drought restrictions based on hydrological drought physical processes. The methodology was applied to the 106 catchments of the RM district under climate perturbations to assess the potential impact of climate change on water restriction in the region. The resulting analysis focuses on water restriction level higher than 1, denoted thereafter WR*. ~~Results show an acceptable skill in predicting WR over the 15 catchments and that the WRL modelling framework, although not perfect, is reasonably well suited to provide hydrological support to WR decisions. In the following, the same WRL modelling framework is applied under climate perturbations to the 106 catchments to assess the potential impact of climate change on Water Restrictions in the region. In addition we will concentrate on events with Water Restriction of at least level 1, denoted WR*, since these events result in limited use of water currently in place.~~

5.14.4 The Definitiongeneration of perturbed climate conditions to build WR response surfaces

The generation of climate response surfaces relies on synthetic climate time series representative of each explore climate condition, and used as input to the impact modelling chain (here hydrological model and WRL modelling framework). Methods based on stochastic weather simulation have been used (*e.g.*, Steinschneider and Brown 2013, Cipriani *et al.* 2014, Guo *et al.* 2016, 2017), but they can be complex to apply in a region with such heterogeneous climate as the RM district. Alternatively, the simple "delta-change" method (Arnell 2003) has been commonly used to provide a set of perturbed climates in scenario-neutral approach (*e.g.*, Paton *et al.* 2013, Singh *et al.* 2014), and was used here, similarly to (Prudhomme *et al.* 2010, 2013a, 2013b, 2015).

Following Prudhomme *et al.* (2015), monthly perturbationcorrection factors ΔP and ΔT were summarizedare calculated using by single-phase harmonic functions.:

$$\Delta \mathrm{P}(i) = \mathrm{P}_0 + \mathrm{Ap} \cdot \cos\left[(i - \varphi_{\mathrm{P}}) \cdot \frac{\pi}{6}\right]. \qquad (1)$$

$$\Delta \mathrm{T}(i) = \mathrm{T}_0 + \mathrm{A}_{\mathrm{T}} \cdot \cos\left[(i - \varphi_{\mathrm{T}}) \cdot \frac{\pi}{6}\right]. \qquad (2)$$

with P_0 and T_0 + A_T mean annual changes in precipitation (1) and temperature (2), respectively; i indicator of the month (from 1 to 12); φ_P the phase parameter and A_p the semi-amplitude of change (*e.g.*, half the difference between highest and lowest values). These corrections factors were and applied to the baseline climate data sets to create perturbed daily forcings:

$$\mathrm{P}^*(d) = \mathrm{P}(d) \cdot [\overline{\mathrm{PM}}(\mathrm{month}(d)) + \Delta\mathrm{P}(\mathrm{month}(d))]/\overline{\mathrm{PM}}(\mathrm{month}(d)) \qquad (13)$$

$$\mathrm{T}^*(d) = \mathrm{T}(d) + \Delta\mathrm{T}(\mathrm{month}(d)) \qquad (24)$$

with $P(d)$ and $T(d)$ are the baseline precipitation and temperature values for day d;, with $P^*(d)$ and $T^*(d)$ the the perturbcorrected (or perturbed) associated time seriesvalues for day d;. $\overline{PM}(\mathrm{month}(d))$ is the average monthly baseline precipitation for month(d) in mm. PerturbCorrected potential evapotranspiration PET^*time series were derived from temperature datavalues using the formula suggested by Oudin *et al* (2005):

$$\mathrm{PET}^*(d) = \max\left[\mathrm{PET}(d) + \frac{Ra}{28.5}\frac{\Delta T(\mathrm{month}(d))}{100}; 0\right]. \qquad (35)$$

with $\mathrm{PET}(d)$ is the baseline potential evapotranspiration values for day d; in mm. Ra is the extra-terrestrial global radiation for the catchment in MJ m^{-2}day^{-1}.

The baseline climate (precipitation and temperature) time series waswere extracted from the Safran reanalysis over the period 1958-2013 (56 years), and perturbed time series generated for the same length. The range of climate change factors to generate the perturbed series were chosen to encompass both the range and the seasonality of RCM-based changes. based on recent projections suggested by Terray and Boé (2013) in France. A set of 45 precipitation and 30 temperature scenarios was created (Fig. 8), spanning the range of potential future climate suggested by Terray and Boé (2013) and combined independently, resulting in a total of 1350 precipitation and temperature perturbations pairs used to define the climate sensitivity space. In this application,

- P_0, (mm.an^{-1})= -20 +20/3× (j-1) , j= 1,.., 9 ,
- Ap (mm.season^{-1}) = 20/3× (j-1) , j= 1,.., 5 ,
- T_0 (°C.an^{-1}) = j-1 , j= 1,…, 6 ,
- A_T (°C.season^{-1}) = -0.5 +2×(j-1) , j= 1,…,5 ,
- φ_P parameter is fixed to 1 to consider minimum change in January and maximum change in July and
- φ_T is fixed to 2 to get maximum change in August. Finally, 45 precipitation and 30 temperature perturbations were independently generated and combined (Fig. 8), leading to a total of 1350 precipitation and temperature perturbations pairs used to define the climate sensitivity space.

5 Drought management plans under climate change and their impact on irrigation use

5.1 Definition of perturbed climate conditions to build WR response surfaces

The generation of climate response surfaces relies on synthetic climate time series representative of each explore climate condition, and used as input to the impact modelling chain (here hydrological model and WRL modelling framework). Methods based on stochastic weather simulation have been used (*e.g.* Steinschneider and Brown 2013, Cipriani *et al*. 2014, Guo *et al*. 2016, 2017), but they can be complex to apply in a region with such heterogeneous climate as the RM district. Alternatively, the simple "delta-change" method (Arnell 2003) has been commonly used to provide a set of perturbed climates in scenario-neutral approach (*e.g.* Paton *et al*. 2013, Singh *et al*. 2014), and was used here, similarly to (Prudhomme *et al*. 2010, 2013a, 2013b, 2015).

Following Prudhomme *et al.* (2015), monthly perturbation factors ΔP and ΔT were summarized by single-phase harmonic functions and applied to the baseline climate data sets to create perturbed daily forcings:

$$P^* = P \cdot /(month) \quad (1)$$

$$T^* = T + \Delta T \quad (2)$$

P(*d*) and *T*(*d*) are the baseline precipitation and temperature for day *d*, with *P**(*d*) and *T**(*d*) the perturbed associated time series. $\overline{PM}$(month(*d*)) is the average monthly baseline precipitation for month(*d*) in mm. Perturbed potential evapotranspiration *PET** were derived from temperature data using the formula suggested by Oudin *et al* (2005):

$$\mathrm{PET}^*(d) = \max. \qquad (3)$$

PET(*d*) is the baseline potential evapotranspiration for day *d* in mm. *Ra* is the extra-terrestrial global radiation for the catchment in MJ $m^{-2}day^{-1}$.

The baseline climate was extracted from the Safran reanalysis over the period 1958-2013 (56 years), and perturbed time series generated for the same length. The range of climate change factors were chosen to encompass both the range and the seasonality of RCM-based changes based on recent projections suggested by Terray and Boé (2013) in France. Finally, 45 precipitation and 30 temperature perturbations were independently generated and combined (Fig. 8), leading to a total of 1350 precipitation and temperature perturbations pairs used to define the climate sensitivity space.

5.12 Generation of The Water Restriction response surfaces

The 1350 sets of perturbed precipitation, temperature and PET time series were each fed into the WRL modelling framework for each 106 catchments**.** Both *VC*3 (monitoring indicators) and 10*d*-*VCN*3(*T*) (regulatory thresholds) were computed from GR6J 56 years discharge simulations. For each scenario, the number of 10-day periods under Water Restriction of at least level 1 (WR*) were calculated, and expressed as deviation from the simulated baseline value: ΔWR*, hence removing the effect of any systematic bias from the WRL modelling framework. Results are shown as WR response surfaces built with *x*- and *y*-axes representing key climate drivers. Because different climate perturbation combinations share the same values of the key climate drivers, hence represented at the same location of the response surface, the median ΔWR* from all relevant combinations is displayed as color gradient, with the standard deviation *Sd* of ΔWR* showed as size of the symbol.

Response surfaces based on different climate variables for *x* (precipitation) and *y* (temperature) were generated over full or part of the water restriction period (April to October "AMJJASO", March to June "MAMJ"; and July to October "JASO", the latter coinciding with the highest temperatures) and visually inspected to identify the greatest signal pattern, combined with the smallest dispersion around the surface response (i.e., analysis of the median and the maximum of *Sd* values over the grid cells). ~~The identification of the drivers was based on the visual examination of responses surfaces for different pairs of potential climate drivers (one related to temperature, the other to precipitation) and supported by a measure of the dispersion around the median response surface by grid cell (the smaller the dispersion, the stronger the link). This measure is given by the median and the maximum of *Sd* values of the grid. Different climate indices ΔP(x) and ΔT(y) calculated over the full or part of the water restriction period (April to October "AMJJASO", March to June "MAMJ"; and July to October "JASO", the latter coinciding with the highest temperatures) have been tested as candidates for the two axes.~~

The response surfaces are exemplified on three of the 15 evaluation catchments (Table 1, Fig. 9):

- ~~The sensitivity analysis of Water Restriction to climate perturbations is illustrated on three contrasting catchments. The Roizonne River basin, located in the Alps, has a summer flow regime controlled by snowmelt. This means that spring to summer climate conditions influence most of the low-flow changes and are the main drivers of reaching critical WR thresholds. In the~~ The Argens River basin, ~~located~~ along the Mediterranean coast, severe low-flows occur in summer and actual evapotranspiration is limited by water availability in the soil,
- ~~. T~~The Ouche River basin, in the northern part of the RM district, has a typical pluvial river flow regime under oceanic climate influences ~~in the northern part of the RM district~~, where runoff generation is less bounded by evapotranspiration processes, ~~and ΔWR is influenced by climatic deviations over the entire period of potential water restriction orders.~~
- The Roizonne River basin, in the Alps, typical of summer flow regime controlled by snowmelt, with spring to summer climate conditions dominating changes in low-flows.

~~The response surfaces for three example catchments (Fig. 9) show:~~The visual inspection of response surfaces shows that:

- ΔWR* are differently driven by the changes in precipitation Δ*P* and in temperature Δ*T*:~~.~~ ΔWR* is very sensitive to Δ*P* ~~For~~ in the Argens River basin (~~, the response surface displays a~~ horizontal stratification in the response surface) and to Δ*T* ~~ΔWR* is highly sensitive to ΔP, whereas for~~in the Roizonne River basin (vertical stratification in the response surface) ~~the response surface displays a vertical stratification and the main driver is ΔT.~~whilst being controlled by both drivers in ~~ΔWR* for~~ the Ouche River basin ~~looks equally influenced by both changes in precipitation and temperature~~;

- There is a high likelihood of increase in the duration of water restriction in ~~proportion of the response surface associated with ΔWR*<0 is very limited for~~ the Roizonne River basin, as showed a response surface dominated by positive ΔWR*~~indicating that most of the climate projections lead to an increase in the duration of WR restrictions~~;

- *Sd* values may vary significantly from one graph to another (Table 5). For both the Argens and Roizonne River basins, largest *Sd* are found when the response surfaces are displayed with climate variables ~~considering ΔP and ΔT~~ computed over the whole period April-to-October (AMJJASO) while smallest *Sd* are associated with ΔP and ΔT drivers from March to June. ~~Results suggest that c~~Changes in mean spring to early summer precipitation and temperature mainly govern changes in WR* ~~occurrence~~for these two basins. Conversely ~~anomalies~~ changes in precipitation ΔP and temperature ΔT over the ~~total~~ full period April-to-October seem the dominant drivers of changes in WR* for the Ouche River basin.

5.2 Response surface analysis at the regional scale

Following (Köplin *et al.* 2012, Prudhomme *et al.* 2013a), the 106 response surfaces were classified to define typical response surfaces, designed as tools to help prioritizing actions for adapting water management rules to future climate conditions in the RM district. Here a hierarchical clustering based on Ward's minimum variance method and Euclidian distance as similarity criteria (Ward 1963) was applied and four classes were identified after inspection of the agglomeration schedule and silhouette plots (Rousseeuw 1987). A manual reclassification was conducted for the few catchments with negative individual silhouette coefficients to ensure higher intra-class homogeneity. For each class, a mean response surface and associated *Sd* was computed, and main climate drivers associated with WR changes identified (Table 5).

All suggest an increase in the occurrence of legally-binding water restrictions when precipitation decreases or when temperature increases (Fig. 10). Additional temperature increase and its associated *PET* increase can compensate for precipitation increase and lead to decrease in ΔWR* with intra-class differences emerging in the magnitude of changes. The identified four typical Water Restriction response surfaces show a weak regional pattern and common features. Class 4 (including the Roizonne River basin) regroups snowmelt-fed river flow regimes in the Alps, whilst basins of Class 1 are mainly Mediterranean river flow regimes. Class 2 (including the Ouche River basin) and Class 3 catchments are partly influenced by both precipitation and temperature, with ΔWR* in Class 2 catchments less sensitive to climatic changes (flatter WR response surface) than catchments of

Class 3. Flow regime of Classes 2 to 3 ranges from rainfall-fed regimes with high flow in winter and low flow in summer in the northern part of the RM district to regimes partly influenced by snowmelt with high-flows in spring in the Alps and in the Cevennes.

To further the regional analysis and help sensitivity assessment at un-modelled catchments, basin descriptors were investigated as possible discriminators of the four classes. A set of potential discriminators - which included measures of the severity, frequency, duration, timing and rate of change in low-flow events (Table 6), the drainage area and the median elevation for the catchment and one climate descriptor (mean annual precipitation and mean annual potential evapotranspiration used to compute an aridity index) – were introduced in a CART model (Classification And Regression Trees, Breiman *et al*., 1984), aimed at performing successive binary splits of a given data set according to decision variables. Through a set of "*if-then*" logical conditions the algorithm automatically identifies the best possible predictors of group membership, starting from the most discriminating decision variable to the less important factors. The optimal choices are fixed recursively by increasing the homogeneity within the two resulting clusters. At each step one of the clusters (node) is divided into two non-overlapping parts. Here, to free results from catchment size influence, descriptors related to severity were expressed in mm/year, mm/month or mm/day.

Results show three top discriminators, the aridity index being the strongest:

- Aridity index *AI* given by the mean annual precipitation divided by the mean annual potential evapotranspiration (UNEP, 1993),
- Baseflow index *BFI*, a measure of the proportion of the baseflow component to the total river flow, calculated by the separation algorithm separation suggested by Lyne and Hollick (1979),
- Concavity Index *IC* (Sauquet and Catalogne 2011) to characterize the contrast between low-flow and high-flow regimes derived from quantiles of the flow duration curve,

CART overall misclassification (18%) suggests a satisfactory performance in classification method, characterized by a parsimonious algorithm (five nodes and three variables) with potential for a first guess assessment of the WR response to disruptions and evaluation of the robustness of existing water restriction at the department-level scale. For each class, Fig. 11 shows the empirical distribution of the three main discriminators, the mean timing θ of daily discharge below $Q95$ and its dispersion r, based on circular statistics, where $Q95$ is the 95^{th} quantile derived from the flow duration curve.

The classification discriminates catchments primarily on the seasonality of low-flow conditions and the aridity index, with the extreme classes (1 and 4) being particularly well discriminated.

Geographically, Class 1 catchments are mainly located along the Mediterranean coast and include the Argens River basin; ΔWR* is mainly driven by changes in precipitation in spring and early summer. Class 1 gathers water-limited basins with small values of *AI* and a weak sensitivity to climate change in summer. In these dry water-limited basins, the mid-year period exhibits the minimal ratio *P*/*PET* and changes in summer precipitation has hence only a moderate impact on low-flows; spring is the only season when *PET* changes are likely to result in both actual evapotranspiration and discharge changes. WR levels are more likely controlled by antecedent soil moisture conditions in spring and early summer. This behavior is typical of the basins under Mediterranean conditions and was discussed in the context of a scenario-neutral study in Australia (Guo *et al.* 2016). For those catchments, climate drivers computed in spring (over the period MAMJ) are used to describe the x- and y-axes of the response surface, fully consistent with water-limited basin processes.

Catchments of both Class 2 and 3 have similar *IC*, hence suggesting that flow variability is not a proxy for low-flow response to climatic deviation. However, *BFI* values for Class 3 are lower than for Class 2 while Class 3 is characterized by high values for *AI*. Despite higher capability to sustain low-flows (see *BFI* values) the response surface representative of Class 2 is more contrasted than that of Class 3; a possible reason could be drier conditions under current conditions (the median of *AI* equals 2.5 for Class 3 against 1.6 for Class 2). The monthly perturbation factors (see Sect. 5.1) are the same for all the classes but the changes in relative terms are less significant regarding the current climate conditions for Class 3 than for Class 2, and may explain the limited changes in river flow patterns.

Class 4 regroups catchments with low flows in winter and significant snow storage. The *BFI* values are high and due to smooth flow duration curves, *IC* demonstrates also high values.

5.3 ~~Vulnerability~~ Risk assessment at the basin scale

The risk-based framework has been applied to the irrigation water use since annual net total water withdrawal for agriculture purposes is ranked first at the regional scale. Note that in the Rhône-Méditerranée district around 90% and 10% of water used for irrigation originate from surface water and groundwater, respectively. To complement water needs irrigators may also have access to small reservoirs (storage capacity usually less than 1 Mm^3). Most of the reservoirs are filled by surface water in winter and release water later in the following summer. Water restrictions are not imposed to these reservoirs but it is assumed here that during severe drought events the majority of them are empty and thus the existence of potential sources auxiliary to surface water on the conclusions has limited influence on the conclusions.

We assumed here that irrigated farming is globally under failure if the duration with limited or suspended abstraction is above a critical threshold T_c that causes insufficient water for crops. The catchment or area *i* will be considered more vulnerable than the catchment or area *j* if the likelihood of failure (i.e., exceeding T_c) for catchment or area *i* is more than the likelihood of failure for catchment or area *j*. The critical threshold T_c is a value of total number of days with legally-binding water restrictions that needs to be fixed. To move closer to reality and following Simonovic (2010), the value of T_c is based on the analysis of past events. A possible way to fix T_c is to simulate historic drought events observed during the period 2005-2012 and the effects of water restrictions on crop yield and quality and on economic losses. Computing water deficits was considered rather tricky at the farming scale - partly due to the high heterogeneity in crop and soil types, watering systems, conveyance efficiencies, etc. across the RM district - and we have investigated the use of 'agricultural disaster' notifications as proxies to identify the damaging conditions instead. To define the critical threshold used for the assessment of vulnerability to climate change of the test catchments, we used a national system of compensation to farmers for uninsurable damages due to extreme hydro-meteorological events.

Specifically the 'agricultural disaster' notifications are, issued to each affected department by the agriculture ministry following recommendations from the Prefecture to each department affected by extreme hydro-meteorological events, and applied uniformly over the RM district. Whilst 'agricultural disaster' status is a global index that may mask heterogeneity in crop losses within each department, and that reflects losses related to both agricultural and hydrological droughts, it has the advantage of being directly related to economic impact, and uniformly applied across the RM district, hence suitable for a regional-scale analysis. The national system of compensation to farmers is initiated for areas notified under 'agricultural disaster' status.

Over 2005-2012, only one agriculture disaster was declared, in 2011, and applied to 70 of the 95 departments in continental France, and to 16 of the 28 departments fully or partly located in the RM district (source: French Ministry of Agriculture and Food). Data are collected by the French Ministry of Agriculture and Food and they are not publically available. The year 2011 was the only year when the national system of compensation has been triggered between 1958 and 2013 and the analysis of simulated water restrictions for this year fixed the value for T_c. The duration of water restrictions was calculated individually for each catchment and converted into anomalies $\Delta WR^*(2011)$ with respect to the benchmark value (mean over the period 1958-2013). ~~That year, 2011, was selected to define the WR* critical threshold; f~~For consistency with the indicators used in the response surfaces, this threshold $\Delta WR^*(2011)$ is derived ~~defined as the difference between the number of WR events simulated by the WR~~from ~~GR6 modelling framework~~GR6J outputs ~~for 2011 and over the baseline period, $\Delta WR^*(2011)$~~.

The RCM-based projections of all the catchments of the class for the three time slices 2021-2050, 2041-2070 and 2071-2100 were superimposed to the representative response surfaces to assess the risk of failure (Fig. ~~4~~6). Finally the vulnerability resulting from the combination of the three components sensitivity, ~~sustainability~~ performance and exposure was measured by the proportion of RCM-based projections leading to critical situations ~~that fail above the critical threshold~~, similarly to Prudhomme *et al*. (2015). Technically this Vulnerability Index (*VI*) calculated as the proportion of exposure simulations that fail below the critical threshold T_c is the complement to the “climate-informed” robustness index (*CRI*) (Whateley *et al*., 2014) ~~calculated as the proportion of exposure simulations that fail below the critical threshold~~. Given one specific climate projection, a catchment or a group of catchments could be judged vulnerable if on average T_c is exceeded. *VI* is introduced here to account for the uncertainty in climate projections in risk assessment. This index should be interpreted as conditional probability (risk) with respect to a specified ensemble of future climates. ~~*VI* informs on the risk of the studied system to fail over a specified ensemble of future climates.~~

Fig. ~~10~~ 12 shows an application to ~~the example of~~ the Ouche River basin, North of the RM district (1, Fig. 1, Table 1) and declared under agricultural disaster status in 2011. The black dotted line are isopleths connecting points of the response surface with $\Delta WR^*=$ ~~shows the critical threshold~~ $\Delta WR^*(2011) = T_c$ (= 7 10-day periods for this catchment), and delimits the climate space leading to median climatic situations more severe than 2011 ($\Delta WR^* >$ ~~more~~ $\Delta WR^*(2011)$, ~~(~~above left) or less severe than 2011 ~~fewer (~~$\Delta WR^* < \Delta WR^*(2011)$, ~~(~~below right) ~~Water Restrictions above level 1~~ $\Delta WR^*(2011)$~~compared with 2011~~. As reference, the black solid line ($\Delta WR^* = 0$) delimits the climate space associated with more (above left) or less (bottom right) water restrictions compared with the whole period average (1958-2013). Basin-scale exposure projections (Table 2) were plotted onto the WR response surface for three time-slices 2021-2050, 2041-2070 and 2071-2100 (grey symbols), showing a warmer trend but no total precipitation signal. Whilst by the end of the century, projections move towards the critical threshold $\Delta WR^*(2011)$ climate space, pointing out a significant increase in more severe low-flows, there remain a large spread in signal (dispersion of the grey symbols) and the vulnerability index equals zero for this catchment.

5.4 Response surface analysis at the regional scale

To better exploit the results from the 106 response surfaces and to develop tools to help prioritizing actions for adapting water management rules to future climate conditions in the region, a classification of the 106 gauging stations based on the 1350 values of ΔWR* was conducted on to define typical response surfaces, following (Köplin *et al*. 2012, Prudhomme *et al*. 2013a). Here a hierarchical clustering based on Ward's minimum variance method and Euclidian distance as similarity criteria (Ward 1963) was applied and four classes were identified after inspection of the agglomeration schedule and silhouette plots (Rousseeuw 1987). A manual reclassification was conducted for the few catchments with negative individual silhouette coefficients to ensure higher intra-class homogeneity. For each class, a mean response surface and associated *Sd* was computed, and main climate drivers associated with WR changes identified (Table 5).

The analysis of the Water Restriction response surfaces from 106 catchments identified four classes of catchments organized regionally (Fig. 11). Class 4 regroups snowmelt-fed river flow regimes in the Alps, whilst basins of Class 1 are mainly Mediterranean river flow regimes. Flow regime of Classes 2 to 3 ranges from rainfall-fed regimes with high flow in winter and low flow in summer in the northern part of the RM district to regimes partly influenced by snowmelt with high-flows in spring in the Alps and in the Cevennes.

A moderate geographic signal in the classified catchments is visible. To go further in the regional analysis and to help sensitivity assessment at un-modelled catchments along, basin descriptors were investigated as possible discriminators of the four classes. A set of 23 potential discriminators – which included 17 measures of the severity, frequency, duration, timing and rate of change in low flow events, the drainage area and the median elevation for the catchment and four climate descriptors (mean annual temperature, mean annual precipitation, mean annual potential evapotranspiration and aridity index) – were introduced in a CART model (Classification And Regression Trees, Breiman *et al*., 1984). Note that all descriptors related to magnitude were expressed in mm/year, mm/month or mm/day to allow comparisons between catchments free of scale effect. The results of the CART model show a prevalence of the aridity index to the other descriptors, with three descriptors kept for the best fit:

- Aridity index *AI* given by the mean annual precipitation divided by the mean annual potential evapotranspiration (UNEP, 1993),

- Baseflow index *BFI*, a measure of the proportion of the baseflow component to the total river flow, calculated by the separation algorithm separation suggested by Lyne and Hollick (1979),

- Concavity Index *IC* (Sauquet and Catalogne 2011) to characterize the contrast between low-flow and high-flow regimes derived from quantiles of the flow duration curve,

The performance of the CART model is satisfactory with a misclassification rate of 18%, is parsimonious (five nodes and three variables) and may help as a first guess to assess the sensitivity where discharge levels are used to characterize current hydrological conditions and thereafter to state Water Restriction at the department scale.

The empirical distribution of each catchment descriptor is displayed (Fig. 12) for each class, along with that of the mean timing θ of daily discharge below *Q*95 and its dispersion *r*, based on circular statistics, where *Q*95 is the 95th quantile derived from the flow duration curve (see Prudhomme *et al*. 2015 for calculation details). For the later, a particular representation equivalent to the classical boxplot was adopted.

The four classes discriminate well rivers primarily on the basis of the seasonality of low-flow conditions and the aridity index, with the extreme classes (1 and 4) being particularly well discriminated.

Class 1 gathers water-limited basins with small values of *AI* and a weak sensitivity to climate change in summer. In these dry water-limited basins, the mid-year period exhibits the minimal ratio *P*/*PET* and changes in summer precipitation has hence only a moderate impact on low-flows; spring is the only season when *PET* changes are likely to result in both actual evapotranspiration and discharge changes. WR levels are more likely controlled by antecedent soil moisture conditions in spring and early summer. This behavior is typical of the basins under Mediterranean conditions and was discussed in the context of a scenario-neutral study in Australia (Guo *et al*. 2016). For those catchments, climate drivers computed in spring (over the period MAMJ) are used to describe the x- and y-axes of the response surface, fully consistent with water-limited basin processes.

Catchments of both Class 2 and 3 have similar *IC*, hence suggesting that flow variability is not a proxy for low-flow response to climatic deviation. However, *BFI* values for Class 3 are lower than for Class 2 while Class 3 is characterized by high values for *AI*. Despite higher capability to sustain low-flows (see *BFI* values) the response surface representative of Class 2 is more contrasted than that of Class 3; a possible reason could be

~~drier conditions under current conditions (the median of *AI* equals 2.5 for Class 3 against 1.6 for Class 2). The monthly perturbation factors (see Sect. 5.1) are the same for all the classes but the changes in relative terms are less significant regarding the current climate conditions for Class 3 than for Class 2, and may explain the limited changes in river flow patterns.~~

~~Class 4 regroups catchments with low flows in winter and significant snow storage. The *BFI* values are high and due to smooth flow duration curves, *IC* demonstrates also high values.~~

5.4~~5~~ A regional perspective for prioritizing adaptation strategies

Following the methodology applied to the Ouche River basin, ΔWR*(2011) were calculated for individual catchments and averaged to produce a value of T_c~~class critical threshold~~ relevant for each Class~~,~~ (Table ~~6~~7). Class variation in ΔWR*(2011) is large, with Class 2 and 3 showing thresholds of at least 7 10-day periods, whilst they are close to zero for Class 1 and Class 4. The scatter in the ΔWR*(2011) values is certainly due to heterogeneity in crops, in irrigation systems, in climate conditions, etc. at the regional scale leading to locally differentiated sensitivity to water restrictions as well as to biases in WR modelling. Since only the year 2011 it is now difficult to conclude on the origins of the dispersion (natural or non-natural). However t~~T~~he distribution and absolute values of the critical thresholds reflect well the spatial pattern of WR enforced from May to September 2011, with Southern regions and the French Alps moderately affected by lack of rainfall in spring compared to the Northern and Western regions of the RM district (Fig. 13). Surprisingly negative values for ΔWR*(2011) are found for ~~come~~ some catchments of Classes 1 and 4, providing no evidence to support their agricultural disaster status that year. At the RM scale, average ΔWR*(2011) equals 38 days when considering all catchments, and increases to 66 days when considering only catchments under agricultural disaster status. ~~Anomalous values for ΔWR*(2011) suggests that one year may not be enough to derive a reliable and representative critical threshold for each class; instead an average ΔWR*(2011) was computed on all catchments of the region under agricultural disaster status in 2011 (6.6 10-day periods), and was used as regional critical threshold applied to all classes.~~Simplifying but realistic assumptions are imposed by the lack of detail information; thus only one value was considered at the regional scale despite high dispersion in ΔWR*(2011) values (Table 7): the critical threshold T_c was set to the average of the ΔWR*(2011) values computed on all catchments in departments under agricultural disaster status in 2011 (6.6 10-day periods), and was used thereafter for all classes. Note that this value of T_c seems realistic: it represents a significant period with restrictions (66 days or 30% of the time between the 1st April and the 31st October).

~~The response surfaces of each class (Fig. 14) show water restrictions highly (Class 1) to weakly (Class 4) sensitive to precipitation and weakly (Class 1) to highly (Class 4) sensitive to temperature, as suggested by the slopes of WR thresholds (black solid and dashed lines). The portion of the WR response surface associated with ΔWR*<0 is gradually lower from Class 1 to Class 4 suggesting that catchments of Class 4 are more subject to an increase in water restriction occurrence than catchments of the other classes. Classes 1 and 4, the most extreme responses classes, contain fewer catchments, whilst class 2 and 3, characterized by an intermediate response, have the most of the catchments.~~

~~Geographically (Fig 1), Class 1 catchments are mainly located along the Mediterranean coast and include the Argens River basin; ΔWR* is mainly driven by changes in precipitation in spring and early summer. Class 2 (including the Ouche River basin) and Class 3 catchments are partly influenced by both precipitation and temperature, with ΔWR* in Class 2 catchments less sensitive to climatic changes (flatter WR response surface) than catchments of Class 3. Because of the large geographical spread of catchments of Class 2 and 3, an expert-based division was done to distinguish catchments with continental (northern sectors) and Mediterranean (southern sectors) climate. This is to better capture the predominantly north–south gradient in future projections of both temperature and rainfall, as they differing impact on the river flow regime (*e.g.* Boé *et al*. 2009; Chauveau *et al*. 2013; Dayon *et al*. 2018). Finally, Class 4 catchments are found exclusively in mountainous regions, where the flow regime is likely to be influenced by snow processes with low flows in winter and summer. The Roizonne River basin belongs to this group.~~

Using the Class WR response surface as diagnostic tools, exposure information (grey symbols) and thresholds (ΔWR*=0, solid, ΔWR*(2011), dashed black lines) were displayed (Fig. 14), and *VI* calculated (Table ~~6~~7). The location of the two isopleths ΔWR*= ΔWR*(2011) (black dotted line) and ΔWR*= 0 (black straight line) in the WR response surface depends on the shape of the response surface and differ from one class to another. The portion of the WR response surface associated with ΔWR*<0 is gradually lower from Class 1 to Class 4 suggesting that catchments of Class 4 are more subject to an increase in water restriction occurrence than catchments of the other classes. Classes 1 and 4, the most extreme responses classes, contain fewer catchments, whilst Classes 2 and 3, characterized by an intermediate response, have the most of the catchments. Because of the large geographical spread of catchments of Class 2 and 3, an expert-based division was done to distinguish catchments with continental (northern sectors) and Mediterranean (southern sectors) climate in terms of exposure. This is to better capture the predominantly north–south gradient in future projections of both temperature and rainfall, as they differing impact on the river flow regime (*e.g.*, Boé *et al*. 2009; Chauveau *et al*. 2013; Dayon *et al*. 2018). For all classes, vulnerability increases with lead time, with Class 4 showing the largest vulnerability and Class 1 being the less vulnerable despite its location in the Mediterranean area. In the two classes 2 and 3, vulnerability increases from North to South in the RM district (*e.g.*, *VI* = 13% for ~~Group~~ Class 2-N against 32.9% for Class 2-S at the end of the century). These contrasted results are mainly explained by the difference between exposure characterizations since a common value of the threshold T_c was adopted.

These preliminary results may support recent initiatives taken at different scales to develop adaption strategies to climate change are developing in France:

- In 2011, France adopted a general framework for action—the French National Climate Change Impact Adaptation Plan ("Plan National d'Adaptation au Changement Climatique (PNACC)" in French)—with numerous recommendations related to research and observation. Five priorities of the first PNACC related to water resources have been highlighted. The PNACC has been recently reviewed and the PNACC2 published in December 2018 confirms the place of DMPs as tools for monitoring water resources and water allocation, and for driving greater public and stakeholder awareness. Results here show that the climate change effects could be felt more acutely during the irrigation period by an increase in water restriction, relying on surface water to compensate deficits is highly hazardous, current agricultural practices should be revised (probably in catchments of Class 4 from the short perspective, and later for the other areas) and any change in the current DMPs should be examined in terms of consequence for all uses.
- The RM Water Agency has initiated an unprecedented major initiative that provides guidance for the River Basin Management Plan (2016–2021). The strategy partly relies on an analysis of the vulnerability in different water-related sectors (water resources, soil-moisture, biodiversity, and water quality) within the RM district to climate change. The study here complements this analysis by focusing on agricultural uses and introducing the bottom-up concept.

6 Conclusions

~~This research is a scientific contribution to the ongoing decade 2013–2022 entitled "Panta Rhei – Everything Flows" initiated by the International Association of Hydrological Sciences and more specifically to the "Drought in the Anthropocene" working group (https://iahs.info/Commissions--W-Groups/Working-Groups/Panta-Rhei/Working-Groups/Drought-in-the-Anthropocene.do, Van Loon *et al.* 2016). Legally-binding water restrictions and their associated decision-making processes are important for the blue water footprint assessment at the catchment scale.~~ This paper presents a first attempt to analyse and simulate water restrictions over a large area in France applying an alternative approach to the classical "top-down" approach. The risk-based approach developed here relies on sensitivity-based analyses to a wide range of climate changes, making it scenario-neutral. However ex ante climate projections are introduced in the last stage of the framework to assess the likelihood of failure.

The analysis of the past and current DMPs in the RM district shows a decision-making processes highly heterogeneous both in terms of low-flow monitoring variable and regulatory thresholds. In reality, the WR statements follow a set of rules defined in the DMPs (which can be simulated and reproduced automatically) but also expert judgment or lobbying from key stakeholders - which are not accounted for in the WRL modelling framework put in place here. However, the post-processing of GR6J outputs allows detecting more than 68% of severe alerts (more severe than level 1), making the developed framework a useful tool. Our study is a first step towards a comprehensive accounting of physical processes, but does not capture socio-economic factors, also critically important and reaches out to interdisciplinary for completing the modelling framework designed here. The study at the regional scale illustrates an expected difficulty to simulate accurately a regulatory framework. Further improvement is not expected in enhancing hydrological models but in reproducing decision-making processes. The overall performance could be improved by scrutinizing the minutes of the drought committees to better understand the weight of the stakeholders in the final statement.

~~Synthetic scenarios were created from parametric variation of forcing data and integrated in a risk-based framework to derive climate response surfaces showing water restrictions deviations.~~

~~Our results~~The sensitivity analysis and the related response surfaces suggest that basins located in the Southern Alps are the most ~~vulnerable~~ responsive basins to climate change and that those experiencing a high ratio *P/PET* are found the less ~~vulnerable~~responsive. The classification method CART has been applied to 106 responses surfaces associated with 106 gauged basins and leads to four classes with different sensitivity. The key-variables known at un-modelled but gauged catchments can be introduced in the decision-tree to finally predict the assignment as a first guess to one of the four classes. Water managers are thus encouraged to monitor in priority and more accurately temperature and/or precipitation when and where the sensitivity of their catchments is found the highest. This may mean efforts to reinforce field instrumentation within these key catchments, but also an opportunity to implement awareness and participatory methods to initiate or to consolidate dialogues between stakeholders from a long term perspective.

The impact of climate change on the river flow is expected to be gradual, thus offering opportunities to update, to harmonize and to adapt Drought Management Plans to changes in climate conditions and water needs. ~~Results of our Water Restriction framework show that t~~As a consequence, the ~~sustainability~~ need for adaptation of existing drought action plans could differ much from one catchment to another and should take into account intrinsic sensibility to climate change besides ‘top-down’ projections. Results also show needs to firstly adapt DMPs in temperature sensitive catchments more subject to a significant increase in legally-binding restrictions in the short term. In contrast, the capacity to anticipate new regulations will be challenging where water restrictions are largely driven by precipitation. Regarding long-term relevance of DMPs, robustness of DMPs in these catchments is not warranted given the large uncertainties in precipitation regional projections.

~~Water managers are thus incited to monitor in priority and more accurately temperature and/or precipitations when and where the sensitivity of their catchments is found the highest. This may mean efforts to reinforce field instrumentation within these key catchments, but also an opportunity to implement awareness and participatory methods to initiate or to consolidate dialogues between stakeholders from a long term perspective.~~

~~The study at the RM scale illustrates the difficulty to simulate accurately a regulatory framework. The overall performance of the WR modelling framework under current conditions is found satisfactory with a probability of detecting events more severe than “alert” (level 1) above 50% but could be improved by scrutinizing the minutes of the drought committees to better understand the weight of the stakeholders in the final statement. A better assessment of the sustainability is required.~~ The risk-based approach was applied to assess the vulnerability of irrigation due to regulatory instruments under modified climate. Evaluating the impact of climate change on irrigation was not the objective of the suggested framework; it has been applied to estimate the likelihood of failure for irrigation at various lead times, instead. Usually, a failure can be stated when irrigation water needs are not fully satisfied. This case study suggests the use of a proxy obtained from a national system of compensation to define a critical threshold (maximum acceptable duration with water restriction). Analysis, however, was based on limited data (one year) and a better failure assessment is required using other years (e.g., 2015 and 2017. The higher the probability, the more vulnerable the irrigation use within the department. A more complete dataset of WR measures would be beneficial, to complement existing sources (*e.g.* http://www.bnpe.eaufrance.fr/ for water abstractions, http://propluvia.developpement-durable.gouv.fr for water restrictions order). Finally, socio-economic system stressors like agricultural practices, population growth, water demand, etc. should be considered to highlight combinations that would lead to unacceptable conditions and to assess the performance of various adaptation strategies under an extended set of future climate conditions (Poff *et al.* 2016).

Climate response surface appears as a convenient tool for simulating and discussing future perspectives locally on the basin scale or more broadly on a given management territory. For example, they can support implement adaptive strategies (see - as an example - the Robust Decision Making framework suggested by Lempert and Groves (2010)): response surfaces can be drawn for different adaptation scenarios combined with periodic updates of DMPs including rules for defining regulatory thresholds and monitoring variables evolving over time, etc.

Note that all results are based on a single hydrological model, but a multi-model approach could be applied as the magnitude of the rainfall-runoff response was shown vary with different hydrological models (*e.g.*, Vidal *et al.* 2016; Kay *et al.* 2014). Finally, an extension of the area of interest to the whole France may bring to light a more complete typology of response surfaces and a wider range of sensitivity.

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N°	River basin	Department (department number)	Station number	Elevation (m.a.s.l.)	Area (km^2)	Regime class	NSE_{LOG}	KGE_{SQRT}
1	Ouche	Côte d'Or (21)	U1324010	243	651	6	0.84	0.94
2	Bourbre	Isère (38)	V1774010	202	703	1	0.85	0.92
3	Roizonne	Isère (38)	W2335210	936	71.6	11	0.71	0.84
4	Bonne	Isère (38)	W2314010	770	143	12	0.80	0.91
5	Buëch	Hautes-Alpes (05)	X1034020	662	723	9	0.84	0.93
6	Drôme	Drôme (26)	V4214010	530	194	3	0.81	0.89
7			V4264010	263	1150	9	0.85	0.88
8	Roubion	Drôme(26)	V4414010	264	186	9	0.83	0.93
9	Lot	Lozère (48)	O7041510	663	465	3	0.88	0.94
10	Tarn	Lozère (48)	O3011010	905	67	8	0.73	0.90
11			O3031010	565	189	9	0.81	0.91
12	Hérault	Hérault (34)	Y2102010	126	912	8	0.83	0.88
13	Asse	Alpes de Haute-Provence (04)	X1424010	605	375	9	0.80	0.86
14	Caramy	Var (83)	Y5105010	172	215	2	0.85	0.94
15	Argens	Var (83)	Y5032010	175	485	2	0.80	0.92

Table 1: Main characteristics of the 15 catchments used for validation of water restriction simulations. Station number refers to the catchment number in the HYDRO database and regime class to the classification suggested by Sauquet *et al*. (2008) with a gradient from Class 1- pluvial fed regime moderately contrasted to Class 12- snowmelt fed regime.

Data source	Representative Concentration Pathway			Reference
	RCP2.6	RCP4.5	RCP8.5	
ALADIN	A	A	NA	Bubnová et al. (1995). Radnoti (1995)
First quartile, median and last quartile of the ensemble EURO-CORDEX results	NA	A	A	Jacob et al. (2014)
WRF	NA	A	NA	Skamarock et al. (2008)

Table 2: Regional climate projections available in the DRIAS portal (A: available; NA: not available).

Level	Name	Water restriction: Recreational	Vehicle washing	Lawn watering	Swimming-pool filling	Urban washing	Irrigation	Industry	Drinking water and sanitation
0	Vigilance	×	×	×	×	×			
1	Alert	×	×	×	×	×	×	×	
2	Reinforced alert	×	×	×	×	×	×	×	
3	Crisis	×	×	×	×	×	×	×	×

Table 3: Uses affected by water restriction according to the drought severity

WR* event		WR level ≥ 1 (Benchmark): *Yes*	*No*
WR level ≥ 1 (Prediction)	*Yes*	hits	false alarms
	No	misses	correct negatives

Table 4: Contingency table for legally-binding restriction (WR*).

	Sd	Period		
		AMJJASO	JASO	MAMJ
Argens River basin (Class 1)	median	1.59	1.65	**0.19**
	max	3.32	3.69	**1.21**
Ouche River basin (Class 2)	median	**0.63**	0.78	1.10
	max	**1.03**	1.52	1.99
Roizonne River basin (Class 4)	median	1.12	1.32	**0.64**
	max	1.98	2.49	**0.91**
All	median	**0.69**	0.80	0.70
	max	1.45	1.70	**1.24**
Class 1	median	1.16	1.24	**0.25**
	max	2.70	2.96	**1.17**
Class 2	median	**0.72**	0.85	0.89
	max	1.45	1.81	**1.43**
Class 3	median	**0.41**	0.49	0.64
	max	**0.88**	0.97	1.06
Class 4	median	0.91	1.14	**0.81**
	max	1.78	2.15	**1.28**

Table 5: Summary statistics for standard deviation *Sd* of the grid for different axes.

Component of the river flow regime	Hydrological indices
Severity	Flow exceeded 95% of the time (*Q*95) Annual minimum 10-day daily mean low flow with a 5-year recurrence interval Annual maximum deficit below threshold Q95 exceeded 20% of time
Duration	Annual maximum maximal duration of the continuous sequence of zero flow within the year, exceeded on average every five years (*D*80). Maximum duration of consecutive zero flows (*D*) are sampled by block maxima approach and *D*80 is defined as the empirical 80th percentile of cumulative distribution function of *D* Seasonal recession time scales (*DT* and *Drec*). This duration based on the hydrograph defined by the 1-day and 30-day moving average of the 365 long term mean daily discharges, *d*= 1,…, 365 (*Qd* and *Q*30*d*, respectively). *Drec* is defined by the time lapse between the median *Qd*50 and the 90th quantile *Qd*90 of *Qd* on the falling limb of the hydrograph defined by *Q*30*d* and $DT = \ln(Qd50/Qd90)/Drec$
Rate of Change	Ratio *Q*95/*Q*50 Concavity index derived from flow duration curve (*Q*10 − *Q*99)/(*Q*1 − *Q*99) (Sauquet and Catalogne, 2011). This descriptor is a dimensionless measure of the contrast between low-flow and high-flow regimes derived from quantiles of the flow duration curve Baseflow index (*BFI*). *BFI* is a measure of the proportion of the baseflow component to the total river flow, calculated by the separation algorithm separation suggested by Lyne and Hollick (1979) Class of river flow regime based on average monthly runoff pattern defined by Sauquet *et al.* (2008) (between 1 and 12) Seasonality ratio (*SR*) $SR = Q95_{AMJJASON}/Q95_{DJFM}$ ($SR > 1$ for mountainous catchment) with $Q95_{AMJJASON}$ and $Q95_{DJFM}$ computed on seasonal flow duration curves
Frequency	Proportion of years with at least one value below *Q*95
Timing	Mean day of first occurrence of flow below *Q*95 Mean and dispersion of the occurrence of flows below *Q*95 within the year (θ and *r*, $r\sin(\theta)$ and $r\cos(\theta)$. These two variables are circular statistics. Each day *i* with zero flow is converted into an angular (t_i) and represented by a unit vector with rectangular coordinates ($\cos(t_i)$; $\sin(t_i)$). The mean of the cosines and sines defines a representative vector. The value for θ is obtained by calculating the inverse tangent of the angle of the mean vector and the norm of the mean vector provides a measure of the regularity in the dates (a value close to one indicates a high concentration around θ while a value close to zero indicates no seasonality)

Table 6: Hydrological metrics considered to investigate similarity in CART.

Class		Number of catchments (with agricultural disaster status)	Mean ΔWR*(2011) (with agricultural disaster status) (× 10 days)	Vulnerability index *VI* (%)		
				2021-2050	2041-2070	2071-2100
1	**All**	**15 (2)**	**-1.2 (-2.3)**	**6.1**	**11.5**	**6.7**
2	**All**	**44 (22)**	**5.0 (7.1)**	**6.4**	**11.8**	**21.6**
	N	25 (18)	6.1 (6.2)	0	0	13
	S	19 (4)	3.4 (11.3)	14.8	27.3	32.9
3	**All**	**38 (13)**	**5.4 (8.7)**	**1.7**	**4.5**	**7.9**
	N-E	25 (4)	3.7 (3.8)	0.4	0	4.5
	S-W	13 (9)	8.5 (10.8)	4.19	13.3	14.4
4	**All**	**9 (3)**	**0 (-0.7)**	**18.2**	**45.4**	**47.2**
All		**106 (40)**	**3.8 (6.6)**	**5.8**	**12**	**16.7**

Table ~~6~~ 7: Summary statistics for the mean anomaly ΔWR*(2011) and for the measure of vulnerability *VI* estimated at the regional scale.

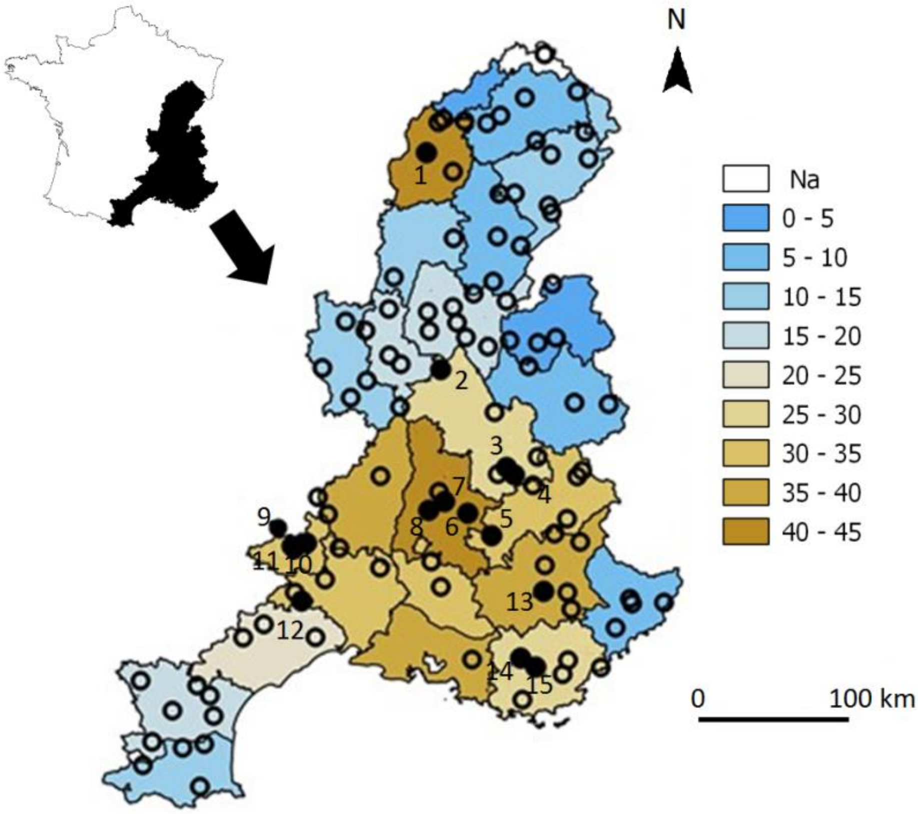


Figure 1: The Rhône-Méditerranée water district, the total number of WR decisions stated by department over the period 2005-2016 and the gauged catchments ○ where WR decisions are simulated (● denotes the subset of the 15 ~~gauging station~~catchments used for evaluation purposes and the figures are the related ranks presented in Table 1).

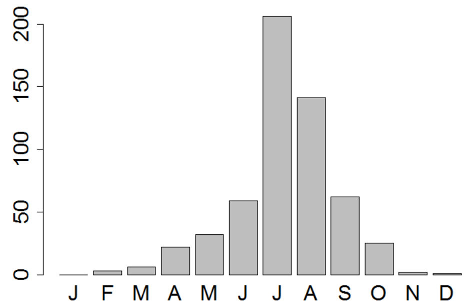


Figure 2: Total number of ~~water restriction~~ stated WR decisions over the RM district per month over the period 2005-2016.

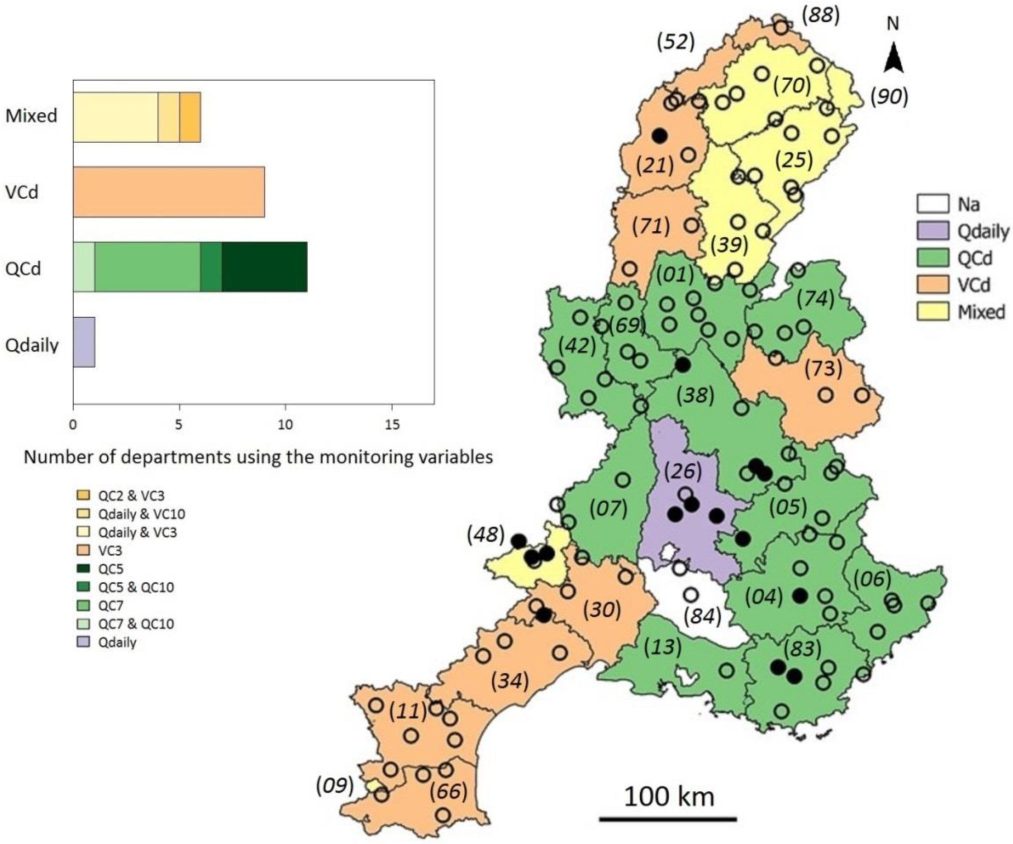


Figure 3: Low-flow monitoring variables used in the current drought management plans. *Qdaily* denotes daily streamflow, *QCd* the *d*-day maximum discharge; *VCd* the *d*-day mean discharge and *Mixed* refers to combinations of the aforementioned variables. Department codes are given into brackets.

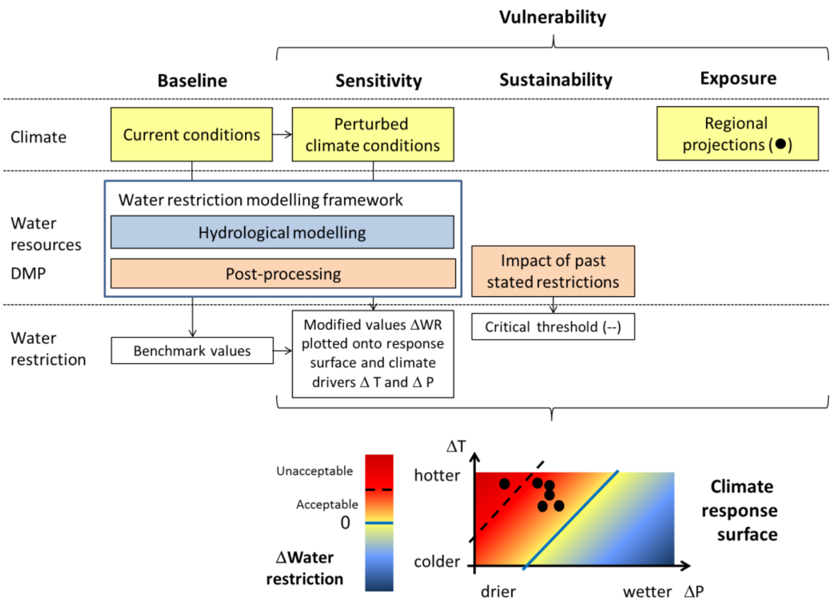


Figure 4: Schematic framework of the developed approach to assess the vulnerability of the DMPs under climate change.

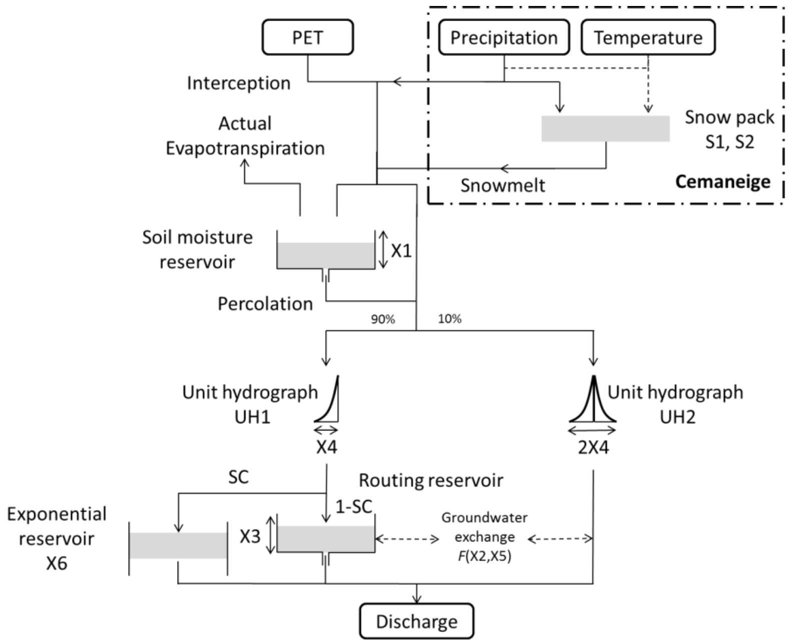
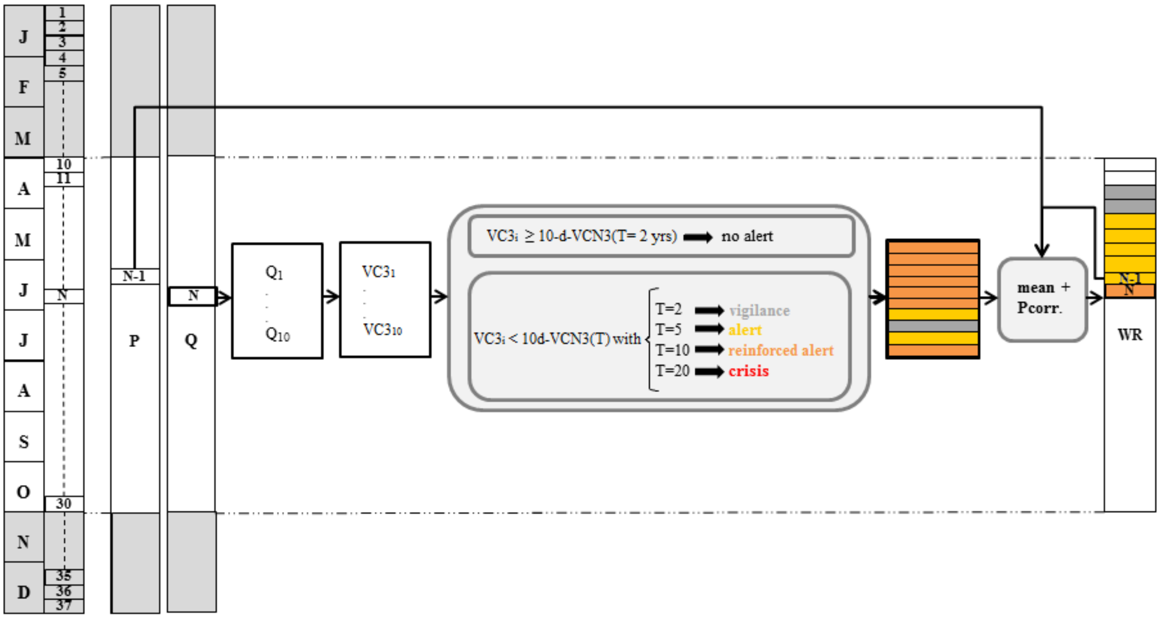


Figure 5: Schematic of the rainfall-runoff Model GR6J combined with the CemaNeige snowmelt runoff component (after Pushpalatha *et al*. 2011).



~~**Figure 5: Schematic detailing the post-processing that supports the decision for water restrictions. *Qi* is *i*th daily discharge of the fixed ten-day period *N* and *Pcorr*. refers to the precipitation correction based on the analysis of the total precipitation over the previous ten-day period *N*-1. Colors refer to the simulated water restriction levels.**~~

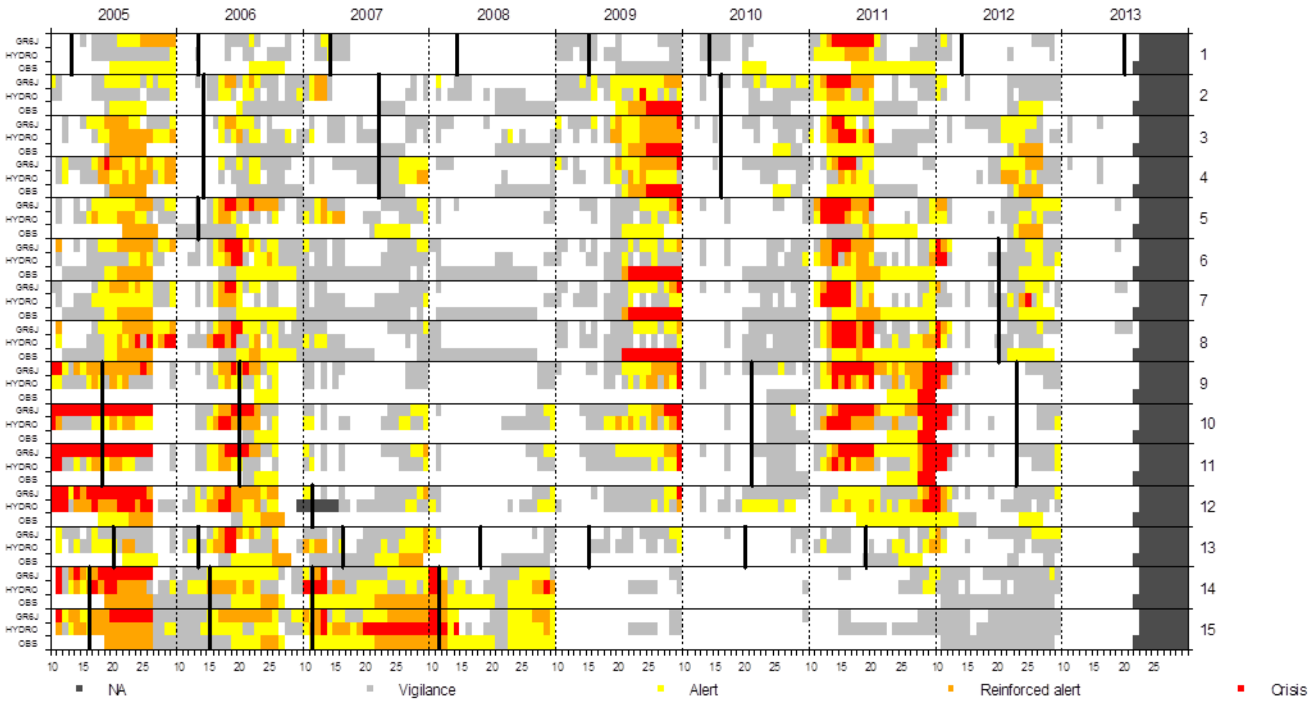


Figure 6: Observed and simulated water restriction levels considering the two sources of discharge data GR6J and HYDRO for each of the 15 evaluation catchments ~~listed in~~(Table ~~2~~1). The x-abscissa is divided into ten-day periods for each year spanning the period April-to-October~~ period~~. Black segments identify updated DMPs.

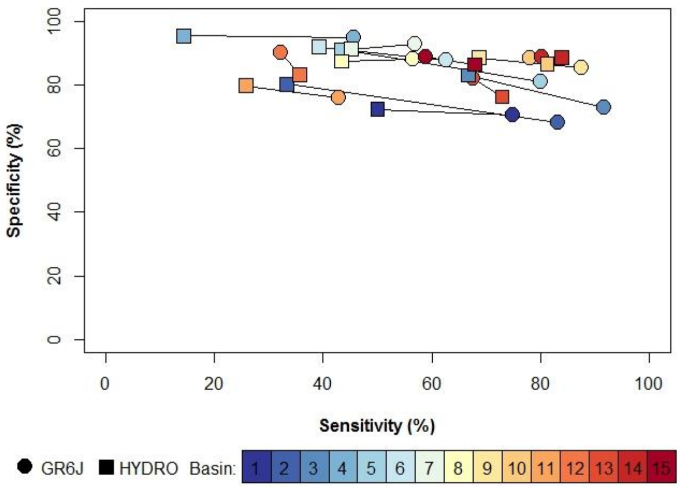


Figure 7: Skill scores obtained for the WR level model over the period 2005-2013. Each segment is related to one of the 15 catchments listed in Table 2. The endpoints refer to the source of discharge data (GR6J or HYDRO).

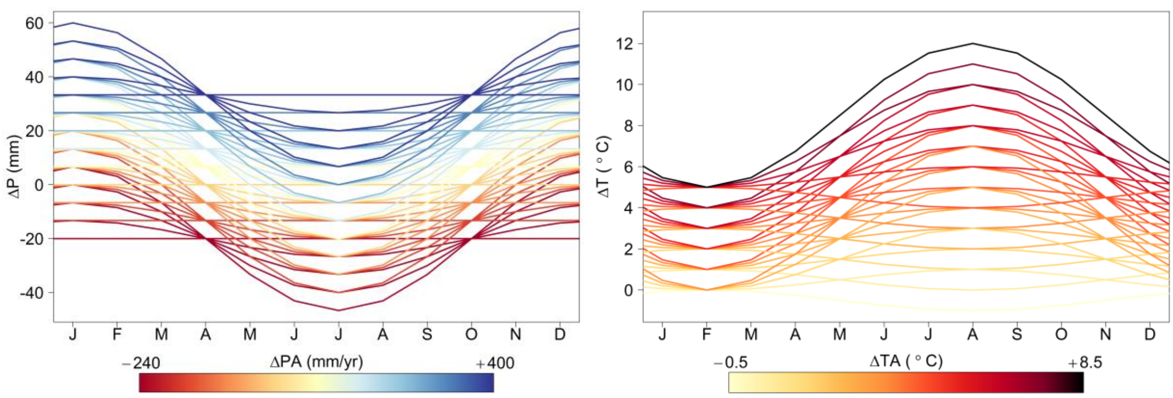


Figure 8: Monthly perturbation factors ΔP and ΔT associated with the climate sensitivity domain. The color of the line is related to the intensity of the annual change ΔPA and ΔTA.

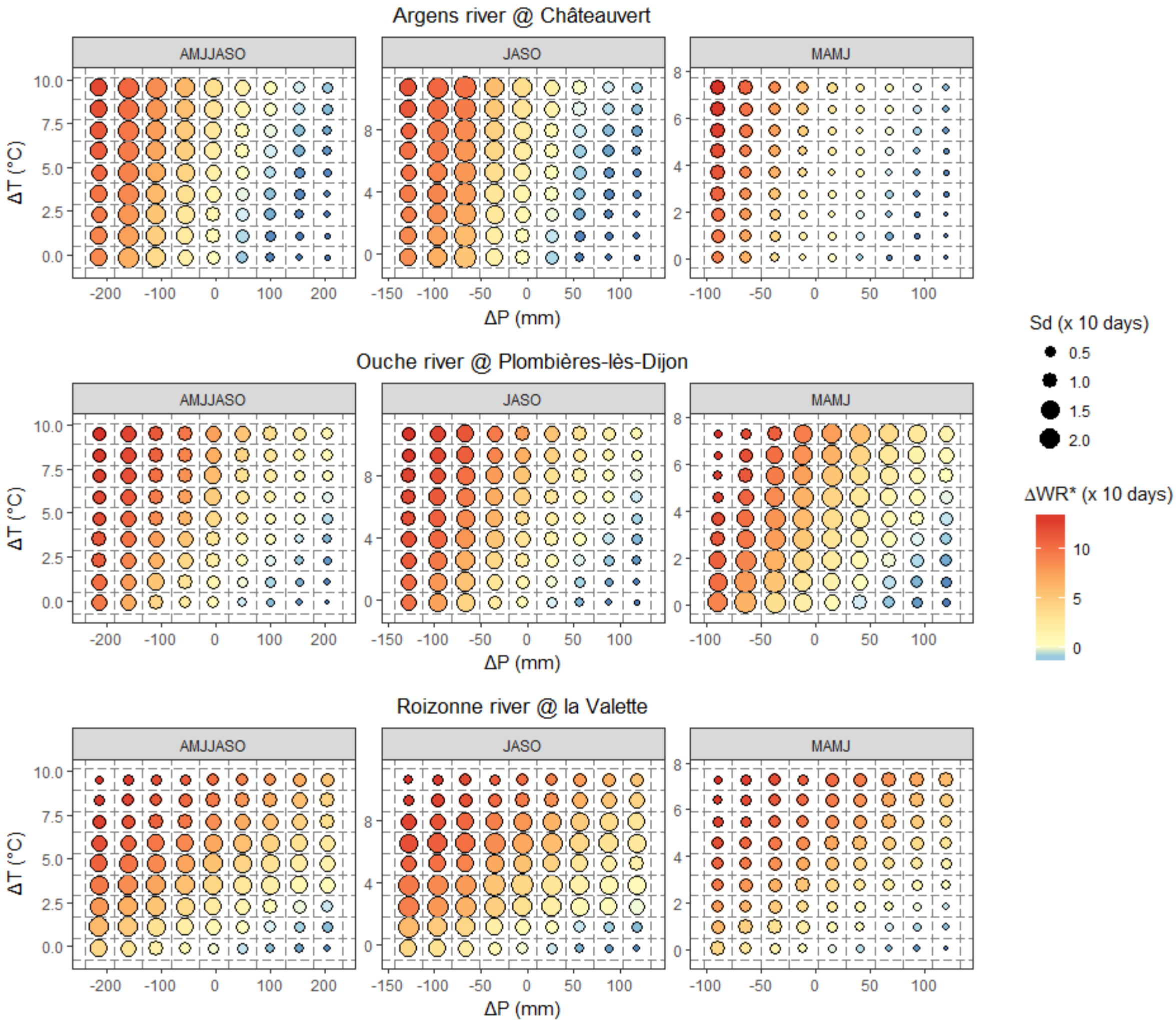
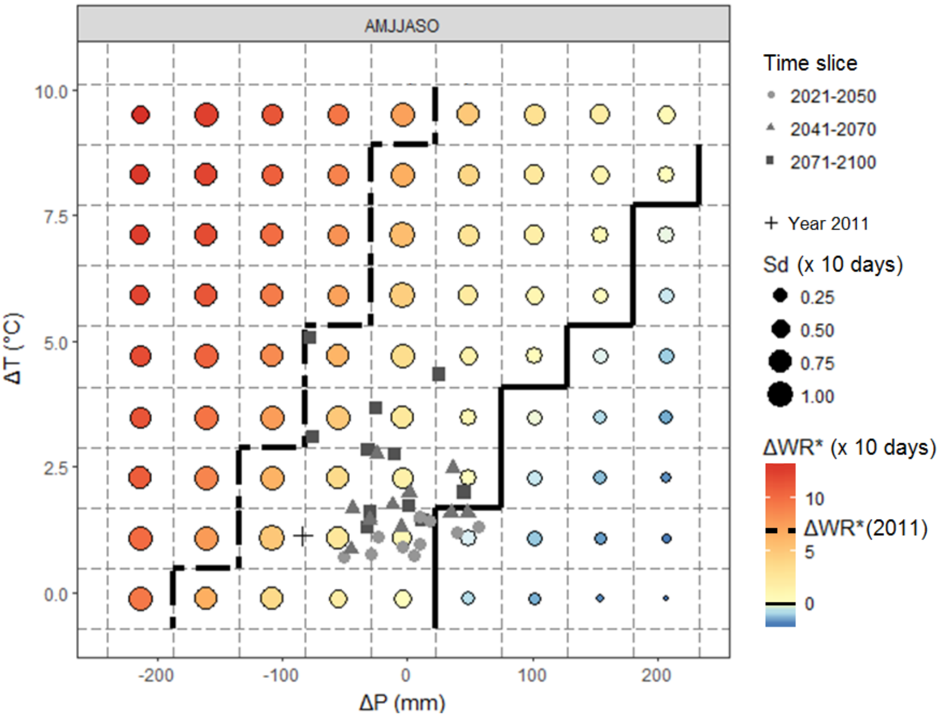


Figure 9: <u>Climate response surface of legally-binding water restrictions level anomalies ΔWR* </u>~~Climate response surfaces~~ for the Argens, Ouche and Roizonne River basins. Each graph is obtained considering changes in mean precipitation ΔP and temperature ΔT over a specific ~~season~~ period as x- and y-axis.



~~**Figure 10: Climate response surface WR* level anomalies for the Ouche River basin including both exposure and sustainability characterizations.**~~

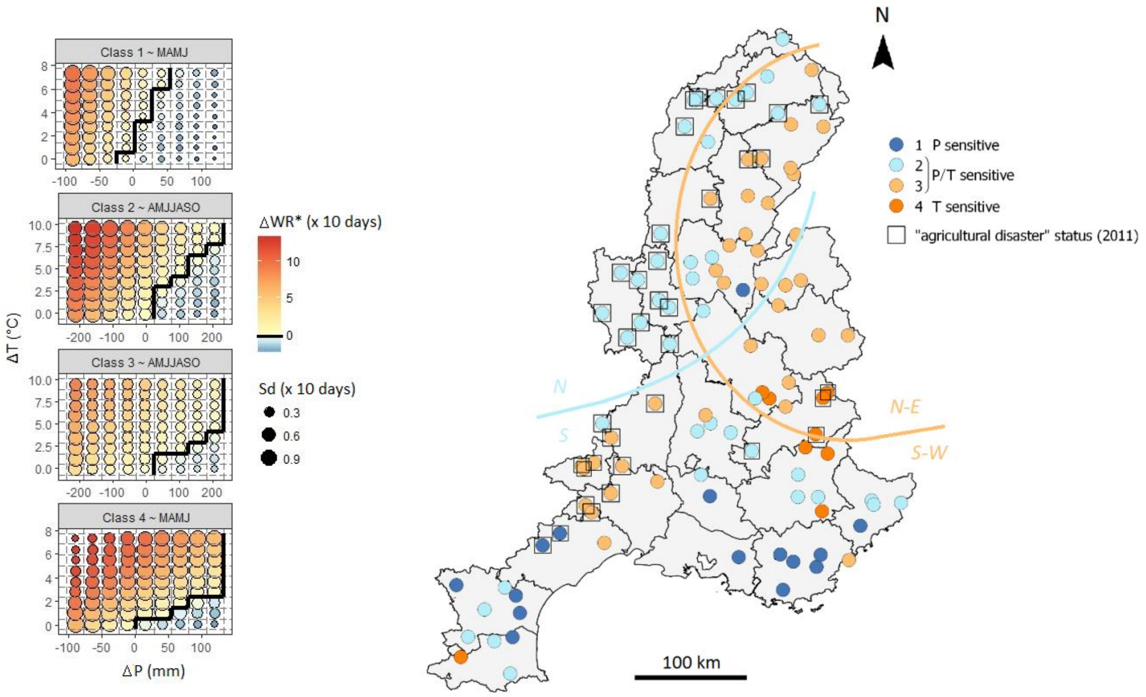


Figure ~~11~~10: Results of the hierarchical cluster analysis applied to the climate response surface WR* level anomalies ΔWR*

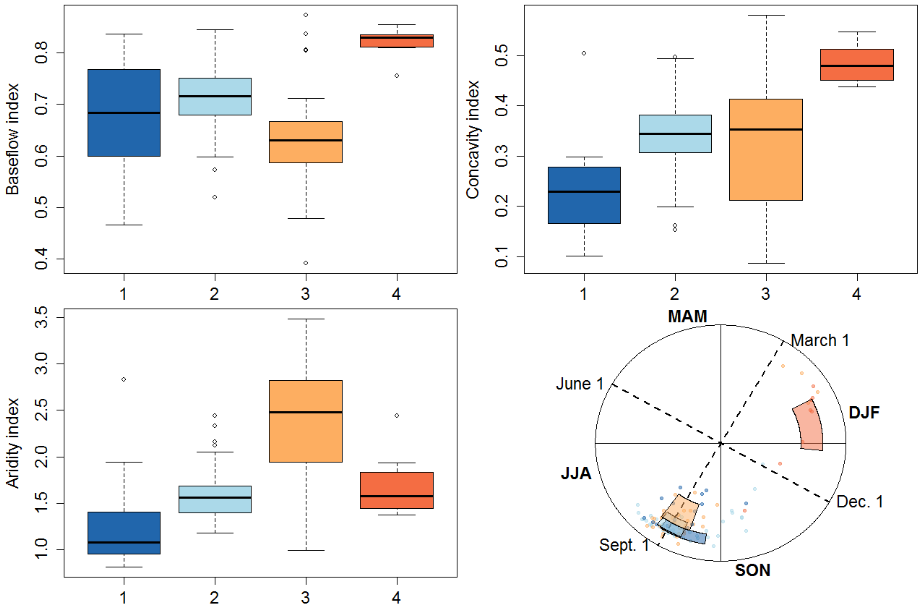


Figure 11~~2~~: Statistical distribution of the discriminating factors identified by the CART algorithm (top level, top left and bottom left) and the mean timing θ of daily discharge below $Q95$ and its dispersion r (bottom right). ~~Statistical distribution of the seven basin descriptors.~~ The boxplots are defined by the first quartile, the median and the third quartile. The whiskers extend to 1.5 of the interquartile range; open circles indicate outliers. The color is associated to the membership to one class and the name of the class is given along the x-axis. The colored areas in the lower right figure are defined by the first quartile and the third quartile of r and θ. Each dot is related to one gauged basin. The doted lines indicate the start of four meteorological seasons.

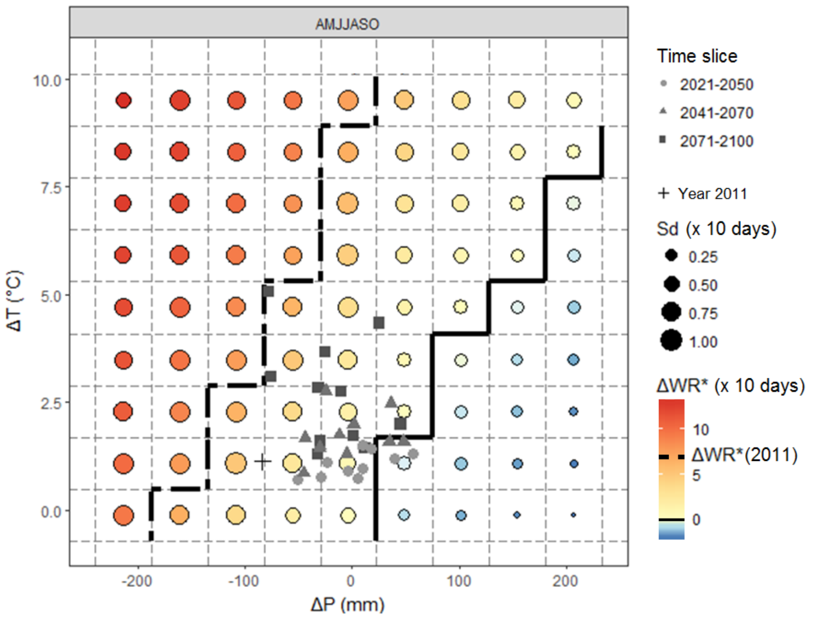


Figure 12: Climate response surface of legally-binding water restrictions level anomalies ΔWR* for the Ouche River basin including both exposure and performance characterizations.

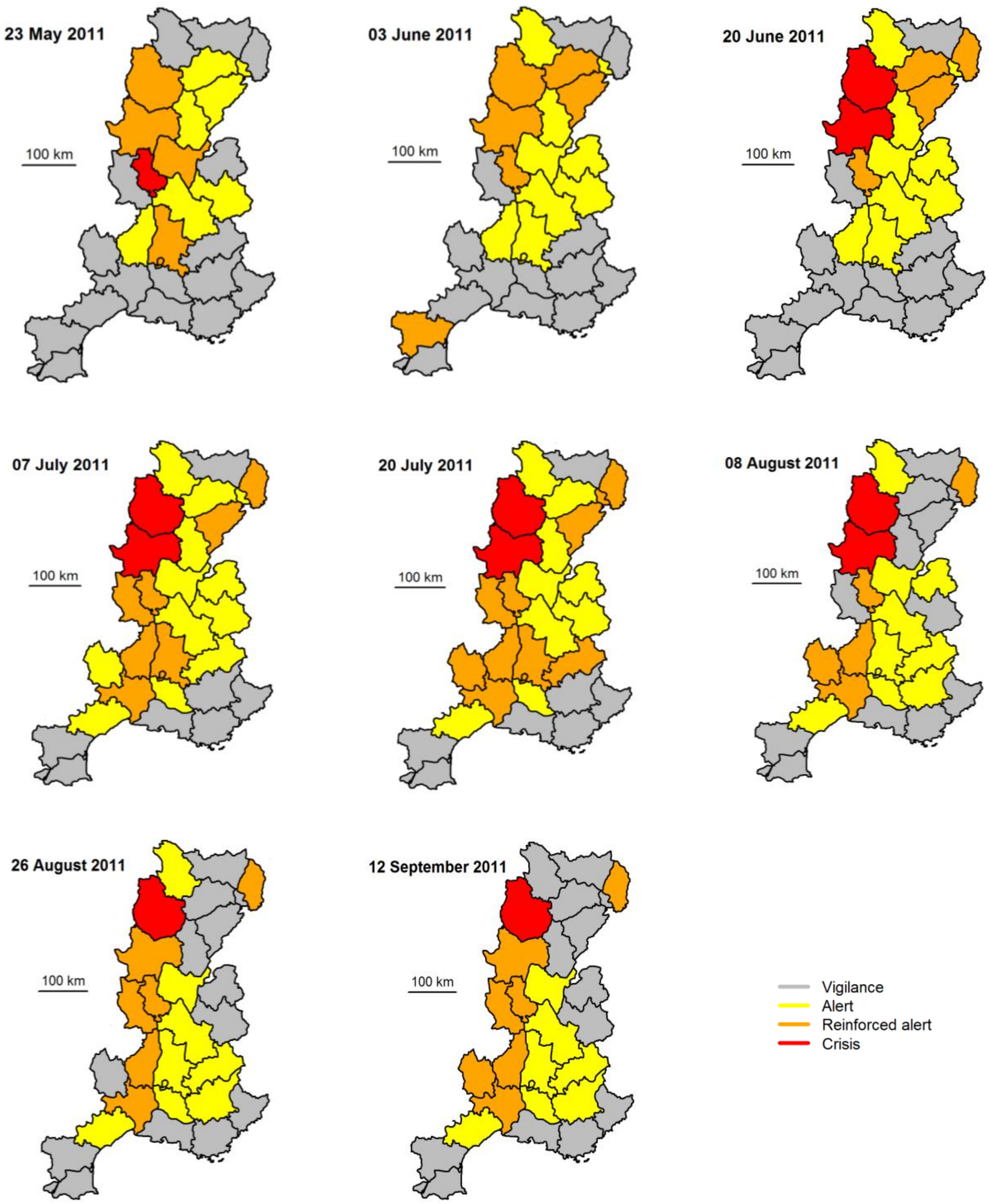


Figure 13: Most severe water restriction level adopted at the department-level scale for several dates between May and September 2011 (Source: French ministry of Ecology)

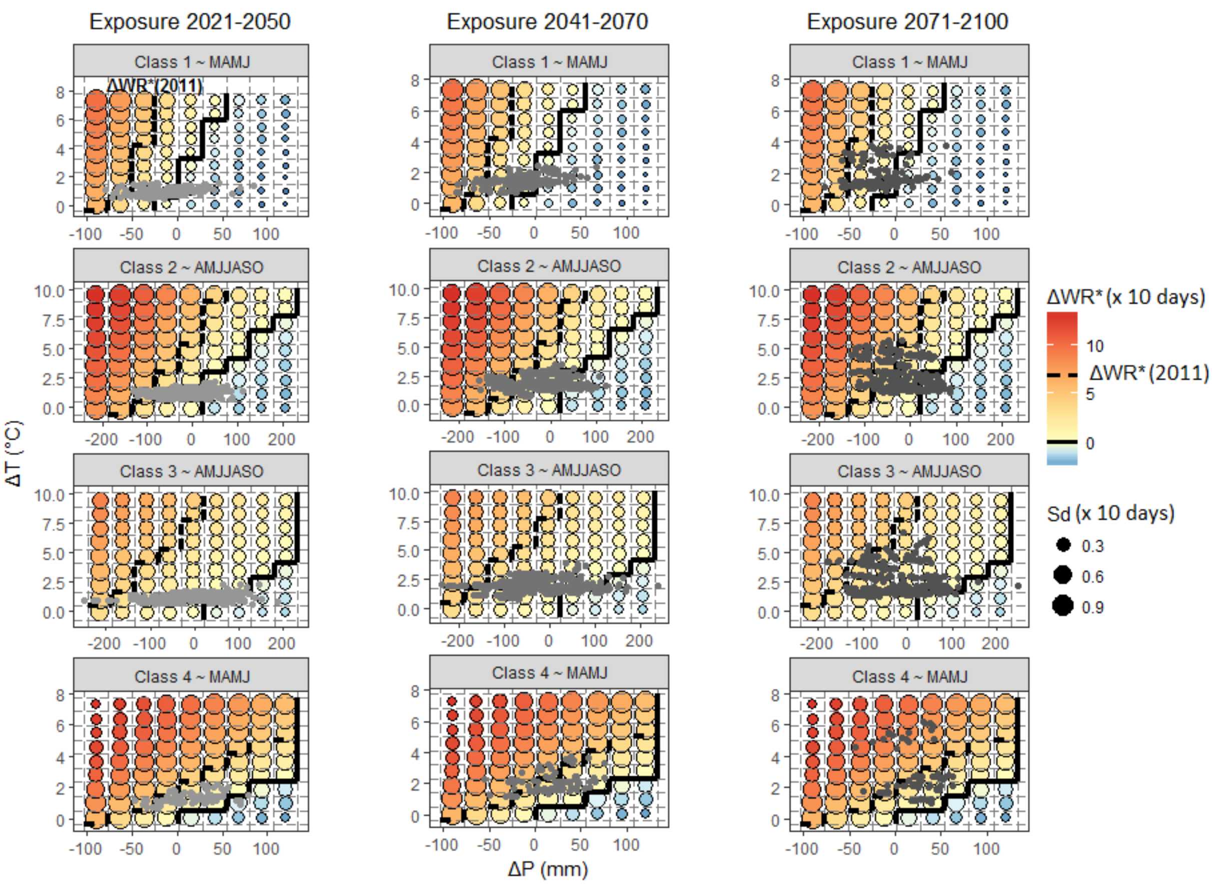


Figure 14: ~~Mean~~ Representative climate response surfaces for each class including both exposure and ~~sustainability~~ performance characterizations.

Appendix A: Classification of river flow regime for France

Sauquet *et al.* (2008) have defined a classification based on the mean monthly runoff pattern (Fig. A1) and a map has been published showing the assignment to one class along the main river network. The twelve dimensionless coefficients *CM* are the twelve values of mean monthly runoff (mm) divided by the mean annual runoff).

Groups 1 to 6 are pluvial river flow regimes. The six groups mainly differ by the contrast between the maximum and the minimum of the monthly discharges. Nearly uniform flows through most of the year (Group 1) are found where large aquifers moderate flows whereas Group 6 is characterized by very low flow in summer, reflecting the lack of deep groundwater storages in the catchment. Group 7 is representative of Mediterranean river flow regimes where small rivers basins experience hot and dry summers and intense rainy events in autumn. Their runoff pattern therefore exhibits severe low flow in summer and high flow in November. In mountainous areas, uppermost basins display snowmelt-fed regimes (Groups 10, 11 and 12). The lower the outlet is, the lower the contributions of snowmelt to runoff. Groups 8 to 9 are in the transition regime. The seasonal variation of streamflow is affected as much by precipitation timing as by air temperature and topographic influences (on snowpack formation and snowmelt timing). Typically, high flows are observed in spring.

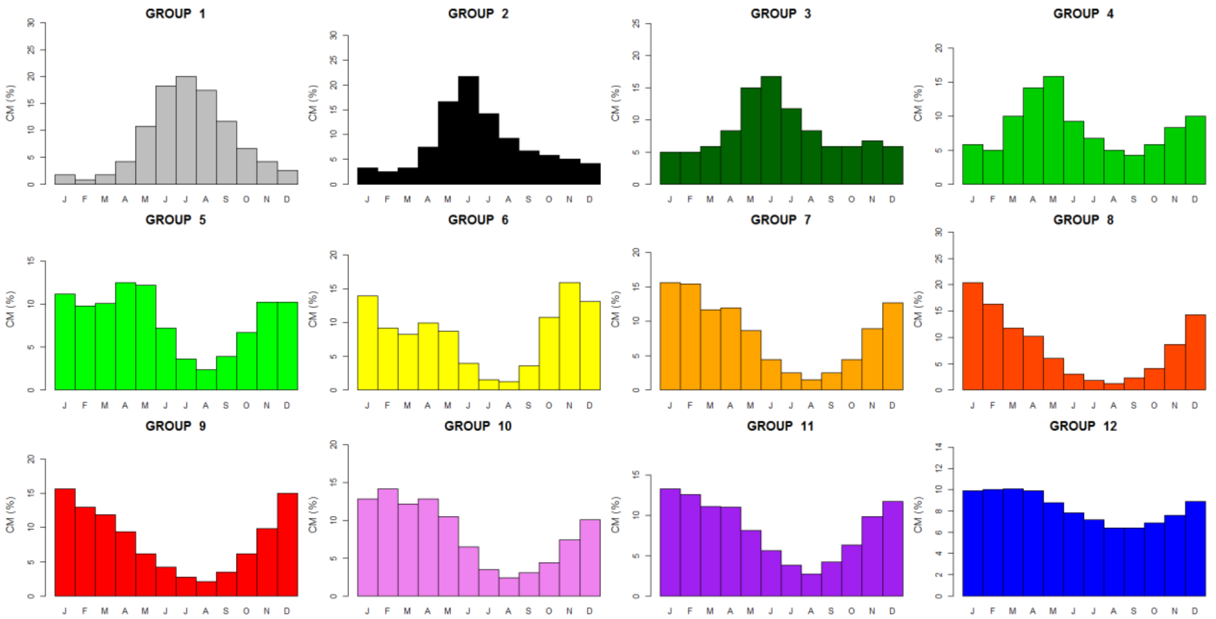


Figure A1 : Reference dimensionless hydrographs representative of the classification of river flow regime for France (after Sauquet *et al*. 2008)