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# 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 assessments 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 RM, 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 the drought of 2011 to define a critical threshold of acceptable WR, the analysis showed 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, mainly sensitive to precipitation changes, were 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 droughts in Southern Europe (Jiménez Cisneros *et al.* 2014), 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.

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 (Prudhomme *et al.* 2012; Prudhomme *et al.* 2014; Vidal *et al.* 2012), 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

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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 southeastern France and establish the level of predisposition to future restrictions depending on their sensitivity, sustainability and exposure to climate deviations. The approach is an adaptation of the risk-based approach developed by Prudhomme *et al*. (2015) to rank catchments and their DMP in terms of vulnerability.

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. Results at both local and regional scales are presented and 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. 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 between the mountainous areas, the northern and southern parts of the Rhône-Méditerranée (RM) district. 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. The total net water withdrawal is around 7 billion of $m^3$ in the period 2008-2013 with a high proportion of them to support irrigation needs (43%). 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

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 DMPs and the water restriction orders 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 including null values or gaps in the data records above 30% of time were

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disregarded. Finally the total dataset consist of 106 gauged catchments located in the RM district with minor human influence and with high quality data.

A selection of 15 test catchments (Table 1) were used to evaluate the WR 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) that can be observed in the RM district (*e.g.* the Ouche (1 in Table1, 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 adopted restriction level is based on the current hydrological conditions, *i.e.* according to the values of monitoring low-flows indicators against regulatory thresholds. This varies greatly across the RM district (Fig. 3). The low-flow monitoring indicators usually considered are 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. $VC3$

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(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, generally associated with the minimum *QCd* observed or the minimum *VCd* observed with a *T*-year recurrence interval (or *QCNd*(*T*) and *VCNd*(*T*) respectively), but some being fixed to locally defined ecological requirements. In the context of DMPs, the monitoring indicators are not calculated annually but by month (*m*-*VCN*(*T*) and *m*-*QCNd*(*T*)) or on the fixed 10-day time-window basis (10*d*-*VCNd*(*T*) and 10*d*-*QCNd*(*T*)). 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

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 assessment. Sustainability 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 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 is a challenging task for hydrologists since its assessment 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 to be fixed for all the users. Facing this complexity, only the irrigation water use has 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 exposure to changes. The exposure measures the probability of changes occurring for different lead times based on available regional projections. It is assessed graphically by positioning the regional projections in the coordinate system of the climate response surfaces and identifying the associated likelihood of failure relative to the critical threshold. Note that, to update the vulnerability assessment, only the exposure component has to be examined (including the latest climate projections available onto the response surfaces).

### 4.2 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). There are, in total, 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 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 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. 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 31st 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. The WRL time series is then examined for all 21 10-day periods defined between the 1st April and the 31st October. For each 10-day period, a unique WR level is defined as the median of WRL indicators within that 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.

In order to evaluate the WRL modelling framework methodology, WRL simulations results based on GR6J outputs (hereafter "GR6J") and observed (hereafter 'HYDRO') discharge were compared to WR measures adopted by Prefectures ("OBS") for the 15 test catchments (Table 1) (Fig. 6). Comparisons are 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.

For the 15 test catchments, the WRL modelling framework can reproduce the alternation between dry years with severe WRLs (*e.g.* 2005 and 2011) and wet years with no or only few WRs (*e.g.* 2010 and 2013). OBS WRLs are correctly reproduced by both GR6J and HYDRO simulations, but also can be inconsistent with OBS (*e.g.* basins 9 to 11 in the Lozère department during the year 2005).

Generally, there is no systematic bias. For example, simulations using HYDRO overestimate WRL compared to OBS in 2007 at the Argens River basin, but have missed OBS WRs in 2005 at the Ouche River basin. Simulated WRLs using GR6J are overestimated in 2005 at the Argens and Ouche River basins but underestimated in 2005 at the Roizonne River basin.

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 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. Results (Fig. 7) show a large variation in skill scores across the catchments, in particular when looking at *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 WLR modelling framework. The median of HYDRO WRL *Sensitivity* score 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 WLRS are simulated based on GR6J discharge. There is no evidence of systematic bias due to the location of the catchments or to the river flow regime: northern (blue) and southern (red) catchments are uniformly distributed in the *Sensitivity*/*Specificity* space.

*Sensitivity* and *Specificity* scores were also used to compare results from GR6J discharge with those obtained from HYDRO discharge (considered as benchmark). Median scores reach 84% (*Sensitivity*) and 92% (*Specificity*), showing consistency in the outputs. Furthermore, GR6J performance under low-flow conditions show no statistical link with its WRL modelling performance, with $R^2$ between $NSE_{LOG}$ and *Sensitivity*, or $NSE_{LOG}$ and *Specificity* being lower than 7%. Despite the known difficulty for hydrological models to simulate accurately low-flows (*e.g.* Staudinger *et al*. 2011; Huang *et al*. 2017), here the skill scores associated with WR simulations based on HYDRO (observed) and GR6J (simulations) discharge are very similar, suggesting that any possible biases in rainfall-runoff modelling does not affect much the ability of the WR modelling framework to simulate correctly or not declared WRs.

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 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 WR modelling framework should be interpreted as potential hydrological conditions for stating water restrictions.

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 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 $\Delta P$ and $\Delta T$ were summarized by single-phase harmonic functions and applied to the baseline climate data sets to create perturbed daily forcings:

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$$\mathrm{P}^*(d) = \mathrm{P}(d) \cdot [\overline{\mathrm{PM}}(\mathrm{month}(d)) + \Delta\mathrm{P}(\mathrm{month}(d)]/\overline{\mathrm{PM}}(\mathrm{month}(d)) \quad (1)$$

$$\mathrm{T}^*(d) = \mathrm{T}(d) + \Delta\mathrm{T}(\mathrm{month}(d)) \quad (2)$$

*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. $\overline{PM}(\mathrm{month}(d))$ 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):

$$\mathrm{PET}^*(d) = \max\left[\mathrm{PET}(d) + \frac{Ra}{28.5}\frac{\Delta T(\mathrm{month}(d))}{100}; 0\right]. \quad (3)$$

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.

### 5.2 Generation of Water Restriction response surfaces

The 1350 sets of perturbed precipitation, temperature and PET time series were each fed into the WR 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 mean ΔWR* from all relevant combinations is displayed as color gradient, with the standard deviation *Sd* of ΔWR* showed as size of the symbol.

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 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 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. The Ouche River basin 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 response surfaces for three example catchments (Fig. 9) show:

- ΔWR* are differently driven by the changes in precipitation Δ*P* and in temperature Δ*T*. For the Argens River basin, the response surface displays a horizontal stratification and ΔWR* is highly sensitive to Δ*P*, whereas for the Roizonne River basin the response surface displays a vertical stratification and the main driver is Δ*T*. ΔWR* for the Ouche River basin looks equally influenced by both changes in precipitation and temperature;
- The proportion of the response surface associated with ΔWR*<0 is very limited for the Roizonne River basin, 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. For both the Argens and Roizonne River basins, largest *Sd* are found when 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 changes in mean spring to early summer precipitation and temperature mainly govern changes in WR* occurrence. Conversely anomalies over the total period April-to-October seem the dominant drivers for the Ouche River basin.

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### 5.3 Vulnerability assessment at the basin scale

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, issued to each affected department by the agriculture ministry following recommendations from the Prefecture, 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. 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). That year, 2011, was selected to define the WR* critical threshold; for consistency with the indicators used in the response surfaces, this threshold is defined as the difference between the number of WR events simulated by the WR GR6 modelling framework for 2011 and over the baseline period, ΔWR*(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. 6). Finally the vulnerability resulting from the combination of the tree components sensitivity, sustainability and exposure was measured by the proportion of RCM-based projections that fail above the critical threshold, similarly to Prudhomme *et al*. (2015). Technically this Vulnerability Index (*VI*) 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. *VI* informs on the risk of the studied system to fail over a specified ensemble of future climates. Fig. 10 shows 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 shows the critical threshold ΔWR*(2011) (7 10-day periods for this catchment), and delimits the climate space leading to more (above left) or fewer (below right) Water Restrictions above level 1 compared with 2011. As reference, the black solid line (ΔWR*= 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 ΔWR*(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 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 $\theta$ of daily discharge below *Q*95 and its dispersion *r*, based on circular statistics, where *Q*95 is the 95$^{th}$ 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.

### 5.5 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 class critical threshold for each Class, (Table 6). 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 distribution and absolute values of the critical thresholds reflect well the spatial pattern of Water Restrictions 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 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.

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.

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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). 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, vulnerability increases from North to South in the RM district (*e.g. VI* = 13% for Group 2-N against 32.9% for the end of the century).

## 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. 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 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 WR modelling framework put in place here. However, the post-processing of GR6J outputs allows detecting more than 68% of severe alerts, 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. Further improvement is not expected in enhancing hydrological models but in reproducing decision-making processes.

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 suggest that basins located in the Southern Alps are the most vulnerable basins to climate change and those experiencing a high ratio *P/PET* are found the less vulnerable. 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 the sustainability 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. This case study suggests the use of a proxy obtained from a national system of compensation. Analysis, however, was based on limited data (one year). 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*. 2015). 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* for different axes.**

| 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 Summary statistics for the mean anomaly ΔWR*(2011) and for the measure of vulnerability *VI* estimated at the regional scale.**

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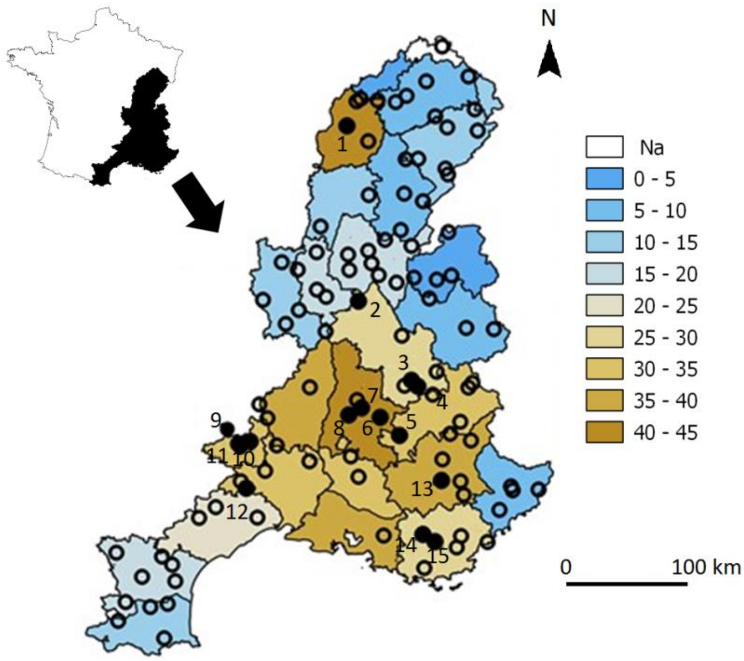


**Figure 1: The Rhône-Méditerranée water district, the total number of WR decisions stated by department over the period 2005-2016 and the gauged catchments O where WR decisions are simulated (● denotes the subset of the 15 gauging stations used for evaluation purposes and the figures are the related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

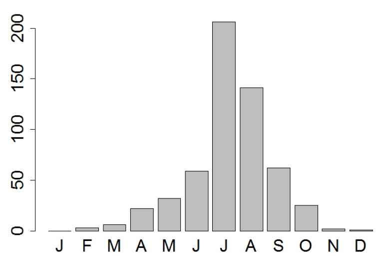


**Figure 2: Total number of water restriction decisions over the RM district per month over the period 2005-2016.**

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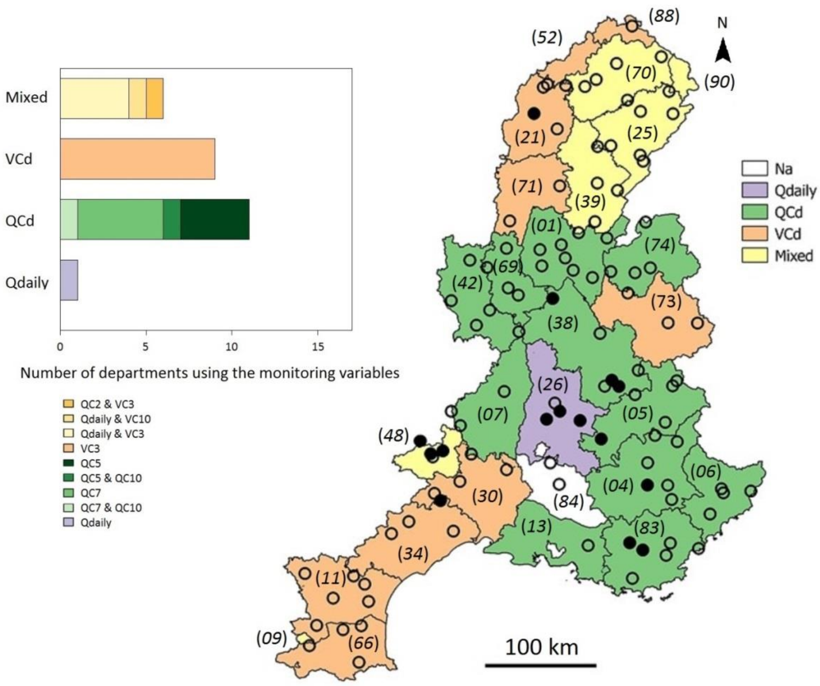


**Figure 3: Low-flow monitoring variables used in the current drought management plans. *Qdaily* denotes daily streamflow, *QCd* the *d*-day maximum discharge; *VCd* the *d*-day mean discharge and *Mixed* refers to combinations of the aforementioned variables. Department codes are given into brackets.**

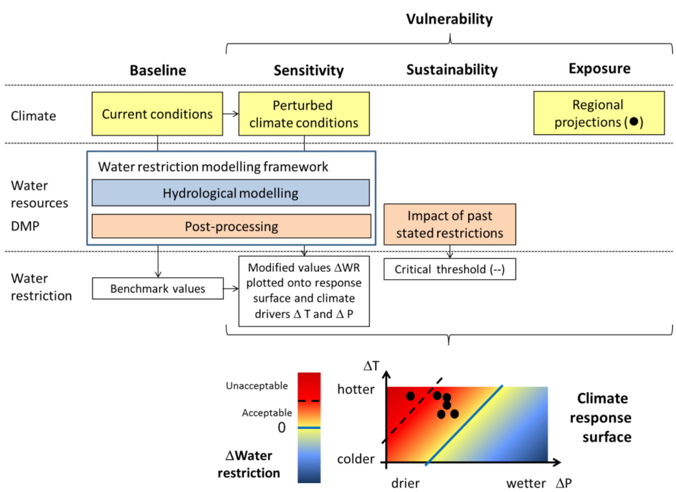


**Figure 4: Schematic framework of the developed approach to assess the vulnerability of the DMPs under climate change.**

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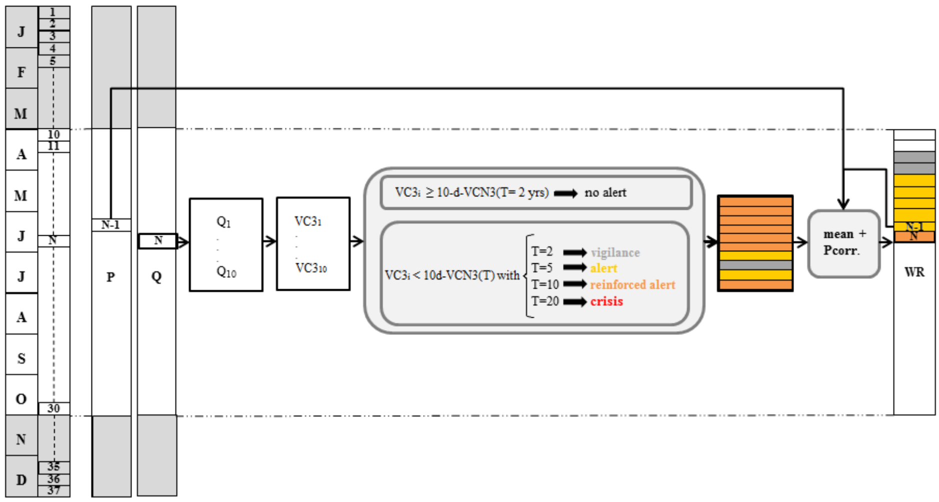


**Figure 5: Schematic detailing the post-processing that supports the decision for water restrictions. *Qi* is *i*$^{th}$ daily discharge of the fixed ten-day period *N* and *Pcorr.* refers to the precipitation correction based on the analysis of the total precipitation over the previous ten-day period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

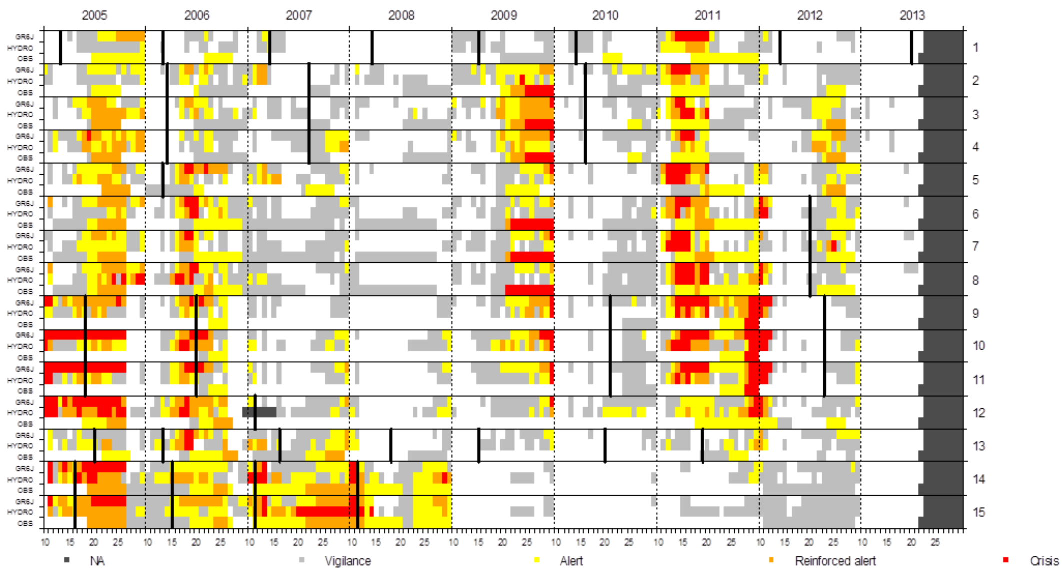


**Figure 6: Observed and simulated water restriction levels considering the two sources of discharge data GR6J and HYDRO for each of the 15 catchments listed in Table 2. The x-abscissa is divided into ten-day periods for each year spanning the April-to-October period. Black segments identify updated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

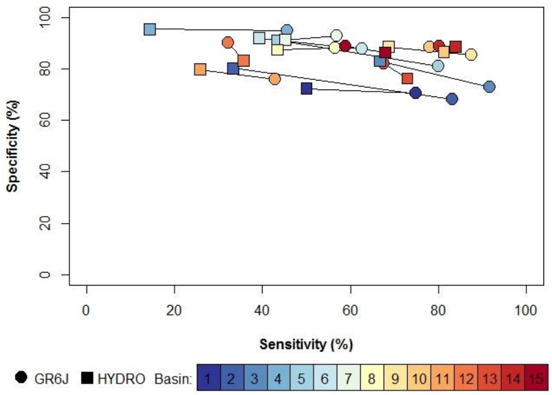


**Figure 7: Skill scores obtained for the WR level model over the period 2005-2013. Each segment is related to one of the 15 catchments listed in Table 2. The endpoints refer to the source of discharge data (GR6J or HYDRO).**

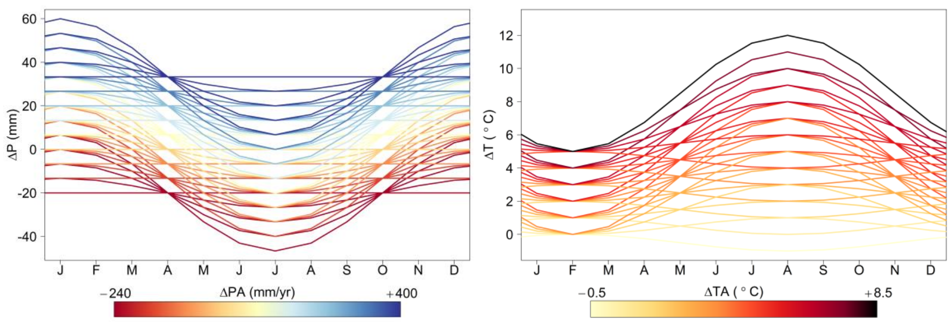


**Figure 8: Monthly perturbation factors ΔP and ΔT associated with the climate sensitivity domain. The color of the line is related to the intensity of the annual change ΔPA and ΔTA.**

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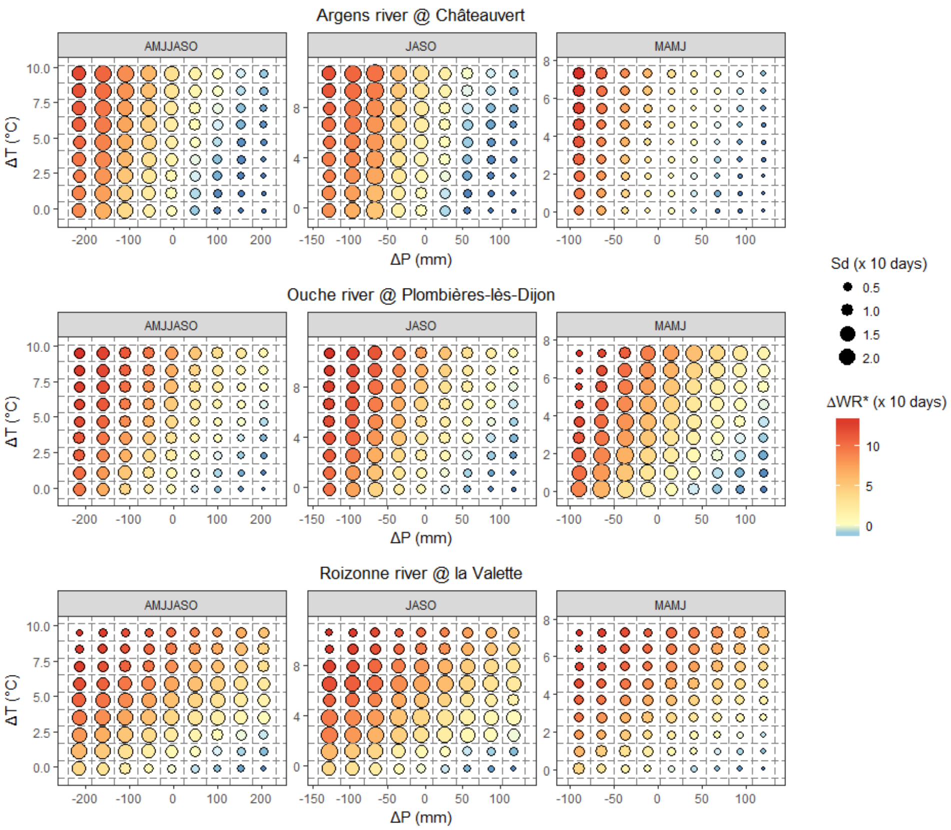


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812 **Figure 9: Climate response surfaces for the Argens, Ouche and Roizonne River basins. Each graph is obtained**
813 **considering changes in mean precipitation ΔP and temperature ΔT over a specific season period as x- and y-axis.**

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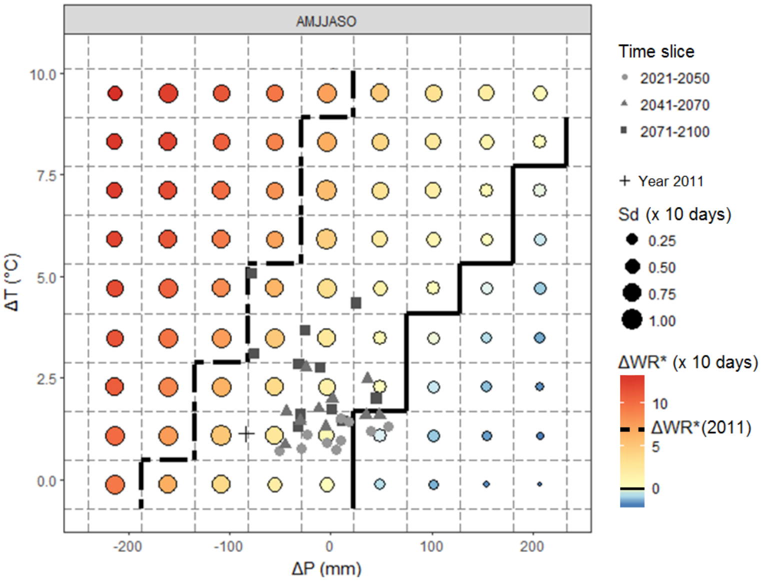
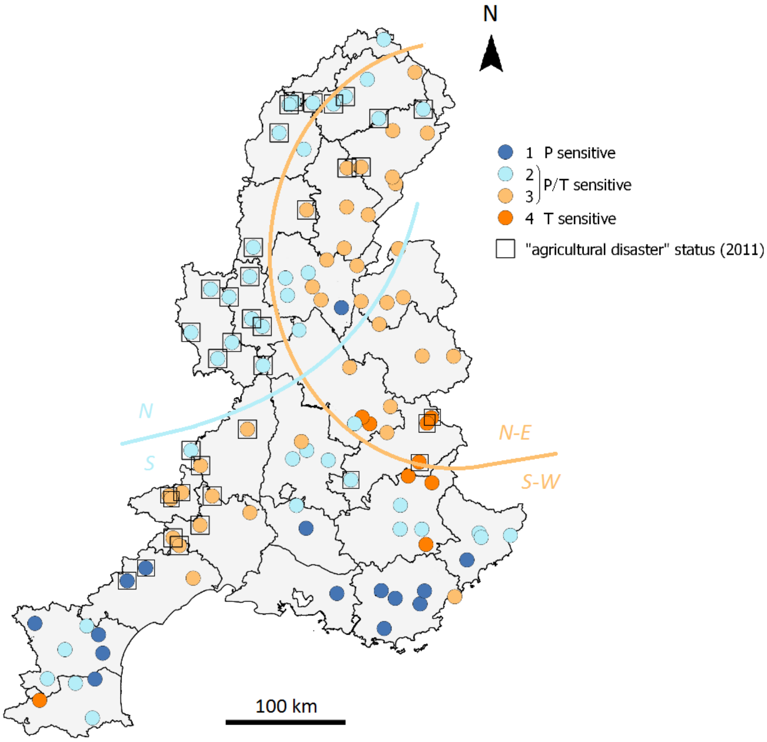



**Figure 10: Climate response surface WR* level anomalies for the Ouche River basin including both exposure and sustainability characterizations.**

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

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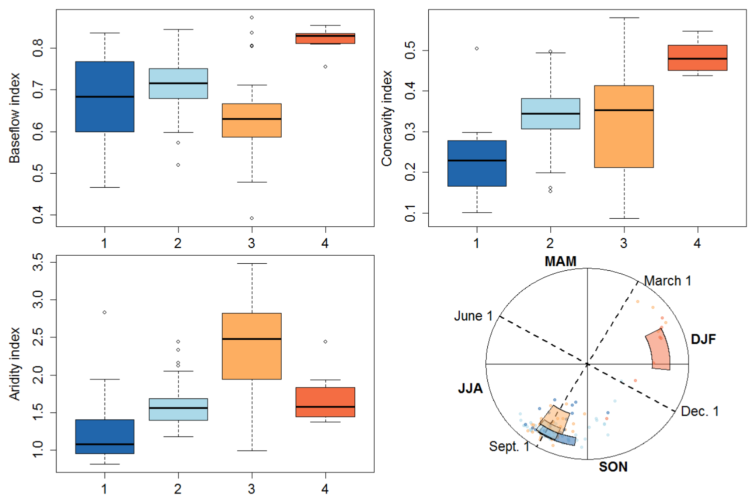


**Figure 12: Statistical distribution of the seven basin descriptors. The boxplots are defined by the first quartile, the median and the third quartile. The whiskers extend to 1.5 of the interquartile range; open circles indicate outliers. The color is associated to the membership to one class and the 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.**

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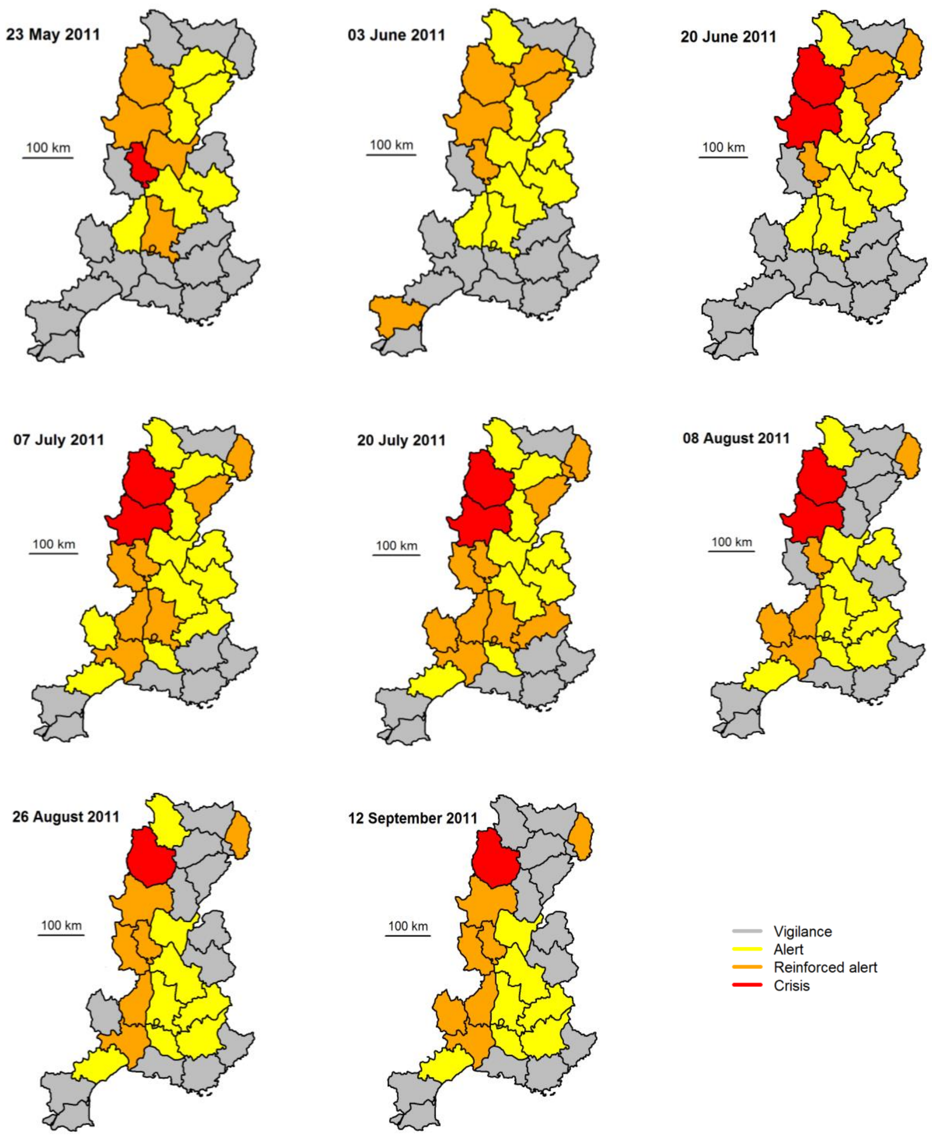


829 **Figure 13: Most severe water restriction level adopted at the department scale for several dates between May and**
830 **September 2011 (Source: French ministry of Ecology)**

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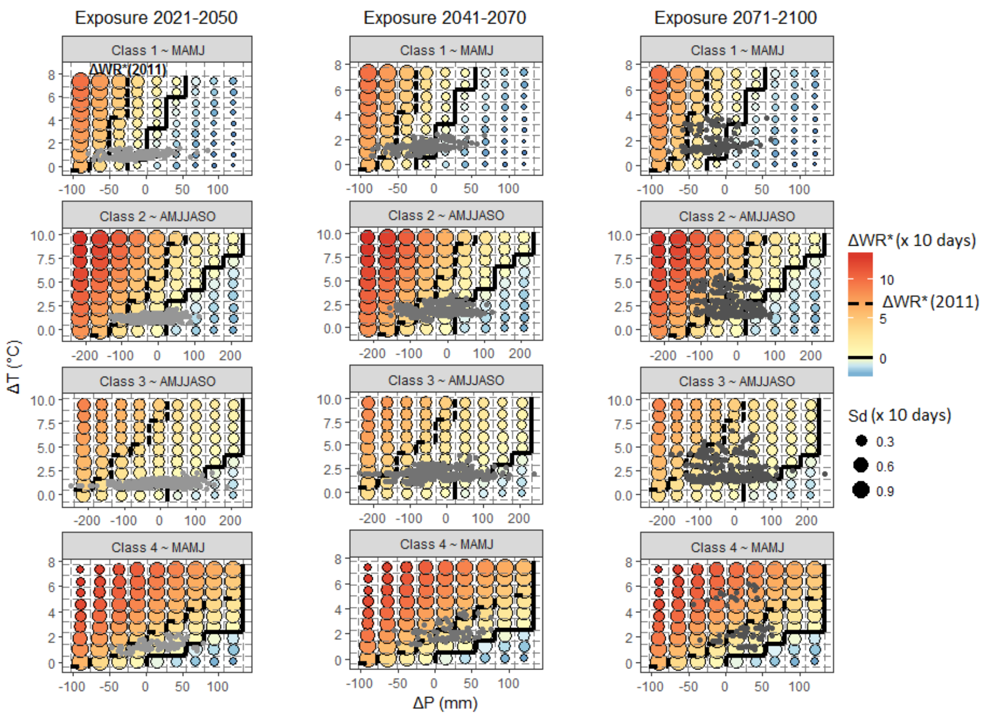


833 **Figure 14: Mean climate response surfaces for each class including both exposure and sustainability**
834 **characterizations.**

835