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Additional Information

# 1 Integrating top-down and bottom-up approaches to design global 2 change adaptation at the river basin scale

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## 13 14 **Abstract:**

15 The high uncertainty associated with the effect of global change on water resource systems calls for a  
16 better combination of conventional top-down and bottom-up approaches, in order to design robust  
17 adaptation plans at the local scale. The methodological framework presented in this article introduces  
18 “bottom-up meets top-down” integrated approach to support the selection of adaptation measures at  
19 the river basin level by comprehensively integrating the goals of economic efficiency, social  
20 acceptability, environmental sustainability and adaptation robustness. The top-down approach relies  
21 on the use of a chain of models to assess the impact of global change on water resources and its  
22 adaptive management over a range of climate projections. Future demand scenarios and locally  
23 prioritised adaptation measures are identified following a bottom-up approach through a participatory  
24 process with the relevant stakeholders and experts. The optimal combinations of adaptation measures  
25 are then selected using a hydro-economic model at basin scale for each climate projection. The  
26 resulting adaptation portfolios are, finally, climate checked to define a robust least-regret programme  
27 of measures based on trade-offs between adaptation costs and the reliability of supply for agricultural  
28 demands.

29 This innovative approach has been applied to a Mediterranean basin, the Orb river basin (France).  
30 Mid-term climate projections, downscaled from 9 General Climate Models, are used to assess the  
31 uncertainty associated with climate projections. Demand evolution scenarios are developed to project  
32 agricultural and urban water demands on the 2030 time horizon. The results derived from the  
33 integration of the bottom-up and top-down approaches illustrate the sensitivity of the adaptation  
34 strategies to the climate projections, and provide an assessment of the trade-offs between the  
35 performance of the water resource system and the cost of the adaptation plan to inform local decision-  
36 making. The article contributes new methodological elements for the development of an integrated  
37 framework for decision-making under climate change uncertainty, advocating an interdisciplinary  
38 approach that bridges the gap between bottom-up and top-down approaches.

## 39 40 **Highlights:**

- 41 • Top-down and bottom-up approaches are combined to define water management strategies to  
42 adapt to global change at the river basin scale. Economic efficiency, social acceptability,

1 environmental sustainability and climate robustness are taken into account in the integrated  
2 approach.

- 3 • Least-cost programme of adaptation measures are identified through integrated modelling and  
4 their performance is assessed under various future climate projections.
- 5 • A regret analysis is performed to contribute elements for adaptation decision-making faced  
6 with uncertainties.

7  
8 **Key words:** Climate change; Adaptation measures; River basin model; climate check; top-down,  
9 bottom-up.

### 10 11 **Acknowledgements:**

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20

## 1. Introduction

21 The Mediterranean basin is identified as a climate change “Hot Spot” at the global scale (Giorgi and  
22 Lionello, 2008; Mariotti et al., 2008), and significant impacts are expected on its water resources  
23 (Iglesias et al., 2007; Bates et al., 2008) and related ecosystem services (Bangash et al., 2013).  
24 Adaptation strategies are needed, but raise policy and scientific challenges (Smith, 1997; Hallegatte,  
25 2009; Biesbroek, et al., 2010; Haasnoot et al., 2013) that generate an increasing number of research  
26 initiatives and policy recommendations in the water sector in particular (Ludwig et al., 2011; EC, 2013;  
27 Quevauviller, 2014). Adaptation is expected to be flexible, adaptive, and based on an integrated water  
28 resources management framework. The capacity to adapt is dynamic and influenced by economic and  
29 natural resources, social networks, entitlements, institutions and governance, human resources, and  
30 technology (IPCC, 2007). Therefore, effective adaptation pathways would require a mix of structural  
31 and non-structural measures, including regulatory and economic instruments as well. To design the  
32 appropriate mix, adaptation measures should be “cost-effective”, but also “environmentally  
33 sustainable, culturally compatible and socially acceptable”, and their selection should be based on the  
34 results of “vulnerability assessments, costs and benefits assessments, development objectives,  
35 stakeholder considerations and the resources available” (UNECE, 2009).

36 Two main approaches are commonly applied to design climate change adaptation plans at the river  
37 basin scale: “top-down” and “bottom-up” approaches. Top-down (or ‘scenario-centred’) methods  
38 involve downscaling climate projections from General Circulation Models (GCM) under a range of  
39 emissions scenarios, providing inputs for hydrologic and management models to estimate potential  
40 impacts and, finally, to analyse adaptation measures (e.g., Caballero et al., 2007, Sperna-Weiland et  
41 al., 2012, Milano et al., 2012, Pulido-Velazquez et al., 2014). Nevertheless, the vast majority of  
42 existing top-down studies stop at the impact assessment phase (Wilby and Dessai, 2010). The term  
43 “top-down” is used because information is cascaded from one step to the next, with uncertainty

1 expanding at each step of the process. However, as uncertainties increase along the top-down  
2 modelling chain, at best it provides an “uncertain outlook”, which complicates the definition of  
3 adaptation strategies; at worst, it provides results too uncertain for decision-makers to even consider  
4 them. Despite this unavoidable propagation of uncertainty (Dessai et al., 2005; Ekström et al., 2013),  
5 this should not be used as an excuse for delays or inaction in adaptation, as water resource systems  
6 can be greatly affected (UNECE, 2009). Improving the top-down approach would require, on the one  
7 side, addressing the challenges of a more complex probabilistic multi-model ensemble forecast (Knutti  
8 et al., 2010) or, on the other side, addressing the uncertainty propagation through all steps involved in  
9 the regional climate downscaling and hydrological modelling (Ekström et al. 2013). The case for or  
10 against probabilistic approaches is made by biophysical and social vulnerability scholars respectively,  
11 the latter challenging the relevance of climate change probabilities in defining adaptation strategy  
12 (Dessai and Hulme, 2004).

13 The bottom-up approaches analyse social vulnerability and adaptive capacity to climate variations to  
14 make adaptation decisions (decision-centred approaches). These methods start with a range of  
15 possible local responses as a portfolio for coping with global change-related threats at the level of the  
16 different stakeholders (individuals, households and communities). Adaptation strategies are not  
17 presumed by the researcher but rather identified empirically from the community, using semi-  
18 structured interviews and focus group discussions, information from experts and local stakeholders,  
19 and available literature (Smith and Wandel, 2006; Barthel et al., 2008; Adger et al., 2009; Bhave et al.,  
20 2013). The robustness of various possible adaptation strategies can then be assessed by evaluating  
21 their performance against a wide range of plausible scenarios (Groves et al., 2008), and, in some  
22 cases, without relying on emission scenarios but focusing on sensitivity analysis or stress tests  
23 (scenario-neutral approaches, Prudhomme et al., 2010). Many vulnerable systems are already coping  
24 with current climate change variability, which also provides a range of options on which to base  
25 adaptation and increases adaptation capacity (Dovers et al., 2009).

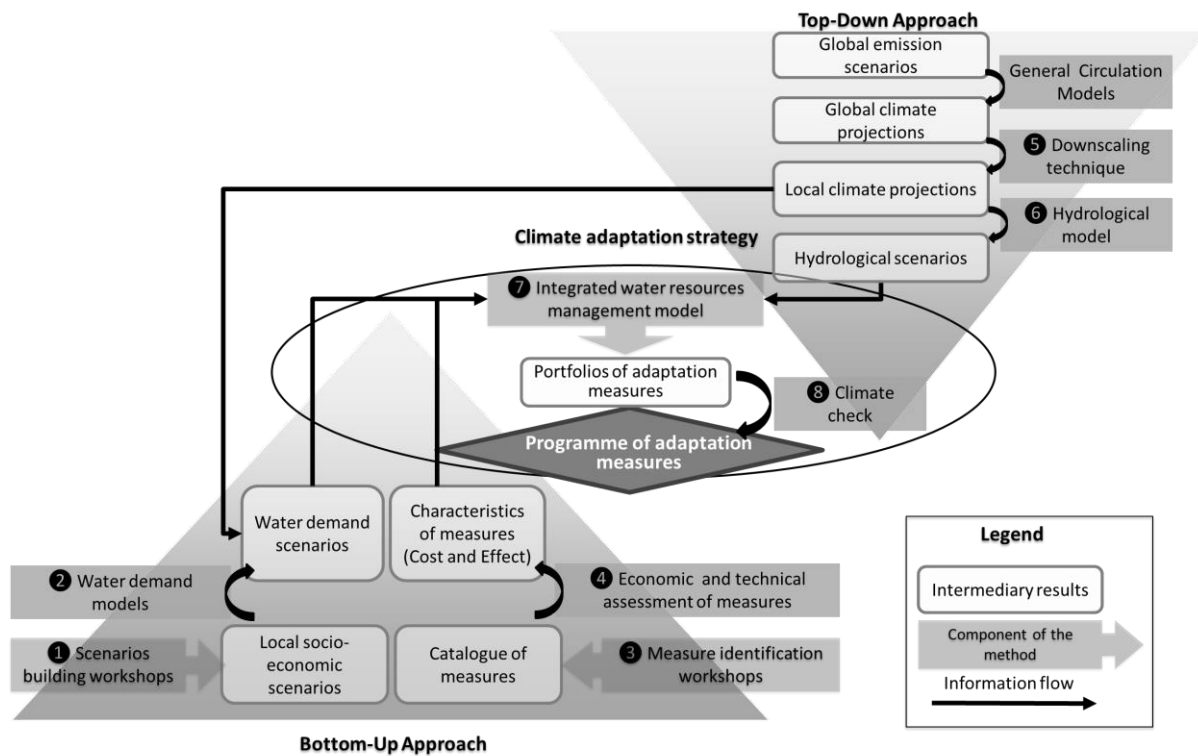
26 These two attitudes toward the “drama of uncertainty” (Mearns, 2010) can be summarised as: on the  
27 one side the “necessity-of-reducing-uncertainty camp” that would further investigate via a top-down  
28 approach in order to narrow down uncertainties and support adaptation from a “predict-then-act”  
29 perspective; and, on the other side, the “vulnerability-and-response camp” that develops tools and  
30 methods to analyse the risks associated with adaptation strategies. The distinction between the two  
31 camps is not straightforward, and scientists do not always belong to one camp only (Meyer, 2012).  
32 Several authors have already discussed the benefits of integrating both approaches in the adaption  
33 process (e.g. Barthel et al., 2008, Wilby and Dessai, 2010; Ekström et al., 2013), although only a few  
34 studies have combined them in practice (Mastrandrea et al., 2010; Bhave et al., 2013). Our interest  
35 lies in the interface between the two aforementioned approaches, leading to our investigation of a  
36 “bottom-up meets top-down” perspective, where the focus is on the water resource system under  
37 study and GCM projections are used to inform rather than direct adaptation strategies (Brown and  
38 Wilby, 2012).

39 Our first motivation was the requirement to ensure that the new river basin management plans and  
40 Programme of Measures (PoM) in the European Water Framework Directive (EU-WFD) will be

1 “climate proof” (EC, 2009). In order to formulate an adaptation plan in response to current vulnerability  
2 and future climate risks, we need to identify and select a set of adaptation measures and form them  
3 into a coherent integrated strategy. For that purpose, we propose an approach combining top-down  
4 strategic assessments and context-sensitive bottom-up analyses in a consistent framework,  
5 integrating the goals of economic efficiency, social acceptability, environmental sustainability and  
6 climate robustness at the basin scale, what we define as a bottom-up meet top-down approach. The  
7 objectives of the paper are then to provide a general framework to integrate top-down and bottom-up  
8 approaches (section 2), to describe the components of this framework and their integration through  
9 integrated water resources management models (section 3) and to illustrate how this integration can  
10 be performed in a real case study and which kind of results can be provided (section 4).  
11 The method is implemented in the Orb river basin, a Mediterranean basin located in the Southern  
12 France, where global change is expected to exacerbate the difficulty in meeting growing demands and  
13 the EU-WFD environmental in-stream flow requirements. Indeed, last assessment realised using  
14 CMIP5 (Coupled Model Intercomparison Project) scenario ensembles (Taylor et al., 2012), Terray and  
15 Boé (2013) showed that projections for the near-future (2020-2049) over the French Mediterranean  
16 rim, lead to a warmer climate compared to present (temperature increase greater than 1.5°C). While  
17 more uncertain, a summer precipitation decrease is projected, together with an increase of extreme  
18 precipitation in autumn.  
19

## 2. GENERAL FRAMEWORK

20 An overview of the framework adopted to combine top-down and bottom-up approaches and of the  
21 different tasks performed to select and assess programs of adaptation measures is presented below  
22 (Figure 1). The top-down approach provides local climate projections, down-scaled from general  
23 circulation models, to force the hydrological impact simulation models. The bottom-up approach allows  
24 us to define future demand scenarios and a catalogue of locally feasible and prioritised adaptation  
25 measures. The costs and effectiveness of the potential measures has to be systematically compiled,  
26 integrating expert knowledge when needed. Finally, results from bottom-up and top-down approaches  
27 are integrated in a Least-Cost River Basin Optimisation Model (LCRBOM) that identifies an optimal  
28 PoM at basin scale to meet the water planning objectives under each given climate projection. The  
29 PoMs are then climate checked through a least-regret analysis across the different climate projections.  
30



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**Figure 1 Combining Top-Down and Bottom-Up approaches to support the design of climate change adaptation programme of measures.** The components of the method are numbered in order to be described in section 2.

## 2.1. Bottom-up approach

6 The bottom-up approach component of our framework consists of eliciting stakeholders' vision of how  
7 global change may affect the territory under study, and the range of adaptation that could be  
8 implemented to cope with the changing conditions. Participatory foresight techniques are first used to  
9 progressively engage stakeholders in an exploration of possible alternative future economic  
10 development for the territory under study (1), considering a large number of economic, regulatory,  
11 social, and environmental factors of change. The output of this task consists of one or several  
12 scenarios characterized by assumptions in terms of land use, economic production, demographic  
13 growth, etc. Deterministic forecasting models are then used to estimate sector-level long term water  
14 demands associated with the scenarios considered (2). Agricultural models typically simulate the  
15 impact of changes in cropping patterns, irrigation technologies, farming practices and climate (for  
16 examples see Rinaudo et al., 2013a; Wriedt et al., 2009). Urban water demand forecast are generally  
17 based on population growth and per capita water consumption, also related to the derived  
18 socioeconomic scenarios. Econometric models combined with evolution scenarios are commonly used  
19 for long-term strategic planning for urban water services (Donkor et al., 2014). The combined use of  
20 participatory foresight and demand forecasting models helps anticipating future water stress levels,  
21 setting the ground for a discussion of required adaptation measures. This part of the approach is  
22 strongly inspired by the literature using scenario analysis for determining robust adaptation options in

1 natural resource management problems considering the uncertainty attached to future evolution  
2 (Carpenter et al., 2006; Lempert et al., 2006; Berkhout, et al., 2002, March, et al., 2012; Hatzilacou et  
3 al., 2007, Alcamo et al., 2007; Rinaudo et al., 2013a, Faysse et al., 2014). Participatory approaches  
4 are also used to identify and evaluate the local suitability of a range of adaptation options (3). In this  
5 way, assessing some of the soft components which form the social capital of the stakeholders group,  
6 considered as a determinant for the success of the adaptation process (Adger, 2003; Barron and Noel,  
7 2011).

8 Systematic and complete information on the cost and effectiveness of measures then has to be  
9 gathered, integrating expert criteria where needed (4). Herein, effectiveness is initially defined based  
10 solely on the impact of the measures on the system pressures (the real assessment of the measures'  
11 effectiveness will come after the application of the hydrological and water management models).

## 2.2. Top-down approach

12 The top-down approach starts by choosing one or several climate projections, defined as the  
13 simulated response of the climate system to a scenario of future emission or concentration of  
14 greenhouse gases and aerosols, generally derived using climate models (IPCC, 2014). To account for  
15 uncertainty, several projections can be used, considering one or more emission scenarios and several  
16 Global Circulation Models. These climate projections are then downscaled (5) to construct local  
17 climate change projections; several dynamic or statistical downscaling techniques can be applied  
18 (Fowler et al., 2007). Local climate change projections are used as input to hydrological models (6)  
19 to simulate the impact on the available resources (Leavesley, 1994; Praskievicz et al., 2009). The  
20 local climate projections are also the input for the agro-climatic models (2).

21

## 2.3. Bottom-up meets top-down

22 The two approaches meet and feed each other through the development of an integrated water  
23 resources management model (7) to support the definition of a climate adaptation strategy for global  
24 change. Simulation and optimisation models have been long applied to river basin planning and  
25 management (Jacoby and Loucks, 1972, Labadie, 2004; Singh, 2012). For instance, hydro-economic  
26 models enable economically efficient adaptation strategies to be defined, by integrating hydrologic,  
27 engineering, environmental and economic aspects of water resources systems within a coherent  
28 framework (Heinz, et al., 2007; Harou et al., 2009). The approach allows for the comprehensive  
29 integration of economic efficiency (when introducing an economic objective in the optimisation for the  
30 selection of a programme of measures at the basin scale) and environmental goals (once  
31 environmental requirements have been included within the model constraints), while social  
32 acceptability is addressed through the identification of local adaption measures through the bottom-up  
33 process. Finally, to address the uncertainty of the global-change scenarios, it is essential to evaluate  
34 how robust water management plans are in relation to the uncertain future (Moody and Brown, 2013).  
35 To test the robustness of the adaptation plan (8), their performance is assessed across a range of



1 different climate projections (climate check), and then compared by applying a multi-criteria decision  
2 making approach (e.g. Srdjevic, et al., 2003; Huang, et al., 2011).

3

### 3. Material and method

4 The precedent framework has been applied to a real case study, the Orb river basin (France), to  
5 illustrate how each step of the method can be applied in a real context.

#### 3.1. Case study description: the Orb River Basin (France)

6 The Orb River basin is a Mediterranean river basin in the south of France (Figure 2 2, 1580 km<sup>2</sup>), at  
7 the heart of local and regional water management issues. The annual average natural flow is 850  
8 Mm<sup>3</sup>, with the lowest flows in summer and flash flood events in autumn, typical of the Mediterranean  
9 costal area.

10 The region experiences the highest population growth rate in the country (1.6 % per year), associated  
11 with important seasonal variation due to a tourist population in the sum  
12 mer. The agricultural sector encompasses more than 6,000 ha of irrigated cultivated area, half of  
13 which corresponds to irrigated vineyards. The demand to irrigate the vineyards is skyrocketing in a  
14 process of converting from intensive wine production to higher-standard wines. Supplying urban water  
15 demand is competing in space and time with agricultural and environmental water demand. In the  
16 future, the combined effect of the increase in urban, agricultural and environmental water demand and  
17 of the impact of climate change is expected to further increase the pressure on the Orb's water  
18 resources.

19 Since the 1960s, under a supply-side management approach, first the state and then local authorities  
20 have developed hydraulic infrastructures in the region. In the Orb basin, the Monts d'Orb reservoir (30  
21 Mm<sup>3</sup> of useful capacity) has regulated the flow of the Orb river since 1964 to compensate the water  
22 transfers from the Réals pumping station to tourist and agricultural areas of the Mediterranean coast  
23 (Aude's littoral), but these infrastructures may reach their capacity limits in the adaptation to climate  
24 change.

25 In the last two decades, the local stakeholders have teamed up in a unique stakeholder platform, the  
26 Orb Watershed Council ("Syndicat Mixte de la Vallée de l'Orb" in French). The last two action plans of  
27 the Orb Watershed Council clearly appeal for the improvement of the quantitative management of  
28 water resources as a priority (SMVO, 2013). At the same time, the river basin management plan has  
29 classified the water bodies of the Orb river basin as at risk of not meeting the good status required by  
30 the EU-WFD due to a quantitative imbalance in water abstractions. This risk is one of the challenges  
31 to be addressed by the PoM defined at the basin scale (AERMC, 2009). At the national level, one of  
32 the flagship measures of the French adaptation strategy for climate change is a 20 % water saving  
33 target on water abstraction by the time horizon 2020 (MEDDTL, 2011) opening the way to demand  
34 management strategy in order to cope with global change; what is known as the soft-path solution  
35 (Gleick, 2003).

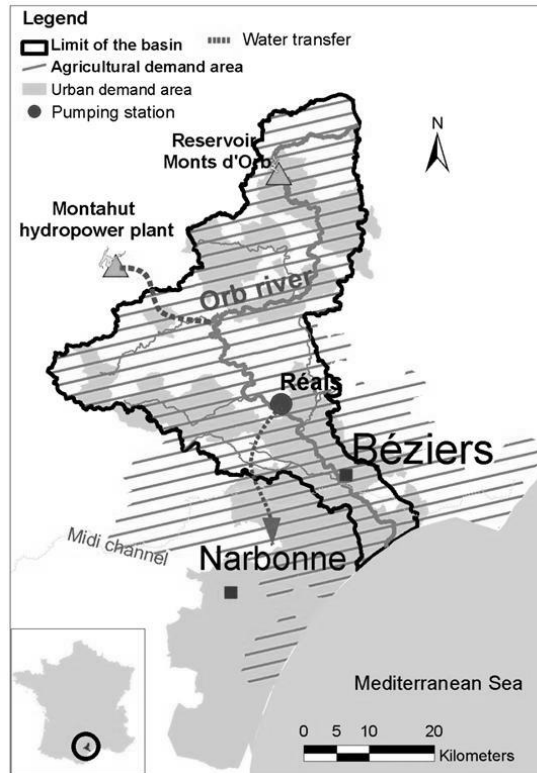


Figure 2 Case study area: the Orb River basin

### 3.2. Applying the top-down approach

#### 3.2.1. Downscaling techniques

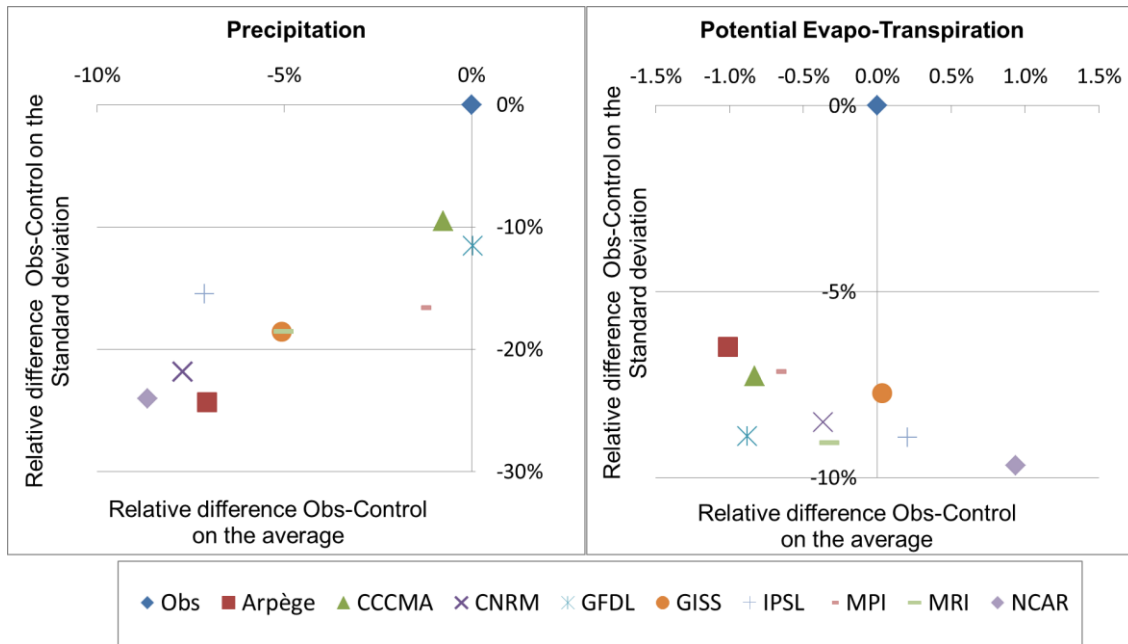
In order to further address the uncertainty of climate change projections, we use climate scenarios downscaled from 9 General Climate Models (5), ((GCM) -CCCMA CGCM3 (Canada); CNRM CM3 (Météo-France); CNRM Arpege (Météo-France); GFDL CM2 (NOAA, USA); GISS MODELER (NASA, USA); IPSL CM4 (IPSL, France); MPI ECHAM5 (Germany); MRI CGCM2 (Japan); NCAR CCSM3 (NCAR, USA)). These GCMs belong to the wider set of GCM outputs available in the framework of the CMIP3 experiment (Climate of the 20th Century Experiment Phase 3, CMIP3, Meehl et al., 2007), considered as able to capture both regional precipitation and temperature climatology for the Mediterranean region (Mariotti et al., 2008). The models used correspond to nine different research centres and show a wide range of uncertainties in precipitation and temperature anomalies among them (Figure 3), and therefore have been selected to illustrate the large span of uncertainty associated to climate modelling. The GCMs are forced by one greenhouse gases emission scenario (A1B), considered as an average emission scenario amongst the various possible futures (IPCC, 2007). This emission scenario is similar to the new Representative Concentration Pathways (RCP) 6.0 used in the 2013 IPCC report .

The statistical downscaling technique used here (weather-type method, Boe and Terray, 2008) statistically link the large-scale circulation (predictor variables) and the local-scale climate variables to disaggregate the output from coarse spatial resolution climate models of both temperature and precipitation (DSCLIM: Pagé and Terray, 2010), considering their physical link. The method aims at

1 finding groups of days exhibiting similar large-scale atmospheric circulations (weather type) that are  
2 the most discriminating regarding a local climatic variable of interest over a specific region and  
3 season. The considered large-scale variables are the mean sea level pressure and the average  
4 temperature at two meters. Each season is processed separately because the atmospheric circulation  
5 differs significantly between seasons. Once the major weather-types (accounting for most of the  
6 observed variance) have been derived using an automated classification algorithm for each season,  
7 each day of the learning period is classified according to its distance to each weather-type. A  
8 regression equation is then built combining the distances to weather-types and the local scale  
9 variables (precipitation, and also temperature for the summer season). These regression coefficients  
10 are then used for downscaling future local-scale conditions simulated by climate models. The control  
11 period is defined from 1971 to 2000, and the future period from 2046 to 2065. The climate data are  
12 provided on a daily time step with a spatial resolution of 8 km that fits the grid of the historical local  
13 meteorological data set SAFRAN (Quintana-Segui, et al., 2008), since it is used in the learning phase  
14 of the downscaling technique.

15 To illustrate this variability of the GCMs in reproducing the existing climate, the following graphs  
16 (Figure 3, up and down) show the relative differences between the observed (SAFRAN) and the  
17 control period of the different models for potential evapotranspiration (PET) and rainfall (P). An  
18 increase of PET by 13.2 % per year is projected on average (across the considered climate  
19 projections) over the Orb river basin, ranging from 8.4% to 18.2 %, in comparison with the control  
20 period. Regarding precipitation, a large dispersion is observed between the models' results: an  
21 average 8 % decrease in the annual rainfall is expected, ranging from – 18.6 % to + 5.8 %. Whereas a  
22 trend appears in PET according to the multi-model average, anomalies in rainfall are less  
23 homogenous. The models that best represent current precipitation (CCMA and GFDL) are different  
24 from the ones with the best reproduction of the PET (GISS, IPSL). The NCAR model seems to be the  
25 poorest one in both cases. In any case, the quality of the simulation of the control period does not  
26 necessarily ensure the quality of the simulation of the future period under a non-stationary climate  
27 (Teutschbein and Seibert, 2012). Similarly, a good performance of a downscaling method in the  
28 control period does not guarantee good performance under changed future conditions. It can only be  
29 assumed that the method is more likely to perform better under changed conditions than one that  
30 already performs poorly under current conditions. Neither can the range of results be considered as a  
31 probability distribution function, since the number of samples is very low. Therefore, working on a  
32 selection of these models or following an ensemble approach would not allow the variability of the  
33 projections of the GCMs to be accounted for in the next steps of the methods. In order to capture the  
34 range of impacts introduced by climate change, the results of all the climate projections were  
35 considered and given the same weight and probabilities of occurrence. A reason that can explain the  
36 large range of variations is that there are great uncertainties concerning France with respect to  
37 precipitation trends under climate change, as shown in Kjellström et al. (2013) and Boé et al. (2009),  
38 because the general trend in Northern and Southern Europe is the opposite. This is consistent with the  
39 resulting down-scaling trends.

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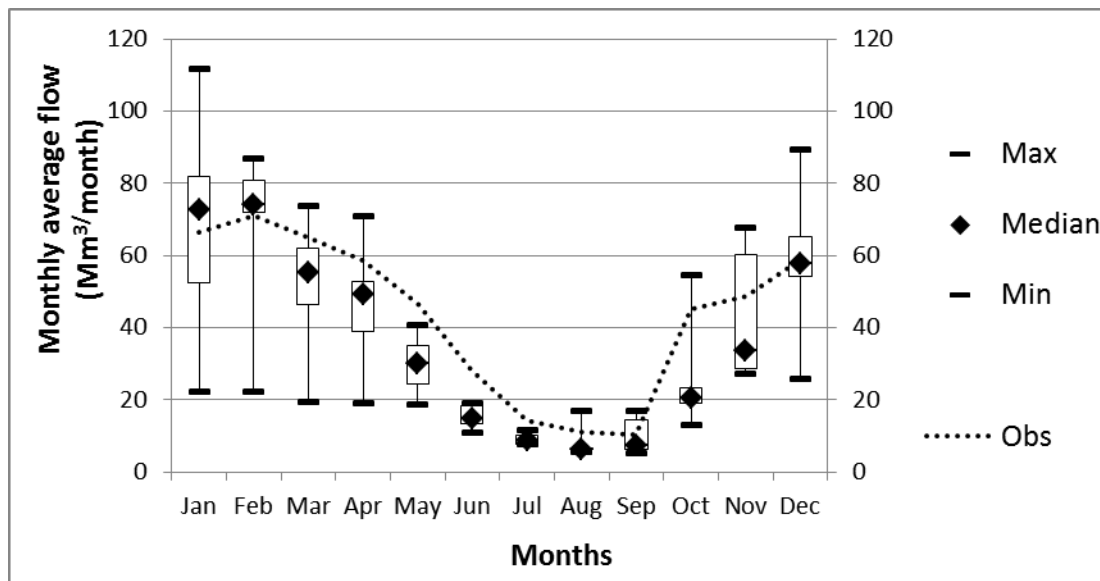


2

3 **Figure 3 Statistical analysis of climate data (average annual Potential Evapotranspiration, (PET)**  
 4 **and Precipitation over the river basin) for 9 climate projections.**

### 3.2.2. Hydrological model

5 A monthly lumped two-parameter rainfall-runoff model (GR2M, Mouelhi et al., 2006), forced by  
 6 historical climatic data (precipitation and potential evapotranspiration) was calibrated and validated on  
 7 each sub-basin with the observed monthly discharge for 38 years, from 1970 to 2000 for the  
 8 calibration and from 2001 to 2007 for the validation (6). The Nash-Sutcliffe (1970) efficiency criteria  
 9 calculated are above 0.5 in the majority of the basins and considered as acceptable (Girard, et al.,  
 10 under review). The models for each of the 11 sub-basins are used to simulate future natural river  
 11 discharge at their respective outlets, using the forcing data from the 9 downscaled climate projections  
 12 (Caballero and Girard, 2012). The future monthly time flow series presents large variations between  
 13 the different climate change scenarios (Figure 4). Looking at the monthly time step, the dispersion  
 14 between the climate projections is higher in the high-flow season than in summer, due to uncertainties  
 15 in climate modelling. The summer low-flow seems to decrease in the future in comparison to the  
 16 observed historical data. However, the average, or even a single low-flow indicator, are not enough for  
 17 the selection of the adaptation measures as time series are needed in order to address how the water  
 18 resource system behaves in a succession of dry and high-flow periods. Therefore, a future monthly  
 19 time series over 20-years is used to account for the intra- and inter-annual reservoir management. The  
 20 obtained discharge time series for each climate projection at selected locations across the basin were  
 21 then integrated in the water management model built at the Orb river basin scale.



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3

**Figure 4 Future mid-term (2046-2065) monthly average flow statistics across the 9 climate change scenarios vs. historical (1970-2000) monthly averages (Obs)**

### 3.3. Applying the bottom-up approach

#### 3.3.1. The participatory process

4 At the beginning of the project, we set up an advisory group comprising experts and stakeholders with  
 5 representatives from two government agencies, the regional and the county councils, two local  
 6 watershed councils (Orb river basin and astian sand aquifer) and the Rhone Mediterranée and Corsica  
 7 river basin district authority. The members met about ten times over six years. The stakeholder  
 8 advisory group accompanied the different steps of the study. It more specifically contributed to the  
 9 development of future agricultural and urban water demand scenarios and to the identification of  
 10 adaptation measures relevant for the basin. Additional experts and users' representatives were invited  
 11 to participate to meetings and workshops dealing with agricultural issues, including a major public  
 12 water company and the regional agricultural chamber<sup>1</sup>.

#### 3.3.2. Scenario building workshops

13 Stakeholders were first involved in the construction of 2030 agricultural water demand scenarios  
 14 through semi-structured interviews, followed by workshops (①). Because we recognise the limitation  
 15 of forecasting techniques, we decided to elicit stakeholder's vision of alternative possible futures  
 16 (exploratory approach) before trying to creating a consensus on the most likely outcome at the 2030  
 17 time horizon. The 2030 time horizon was chosen a compromise between the time horizon used by  
 18 climate scientist (2045-2060) and the time horizon that makes sense for stakeholders when  
 19 considering future scenarios (20-25 years maximum) and adaptation strategy at the local level.

20 Stakeholders first debated on major factors of change (drivers), which they hierarchized (see figure 5).  
 21 They then discussed possible trends associated with each driver and formulated quantitative

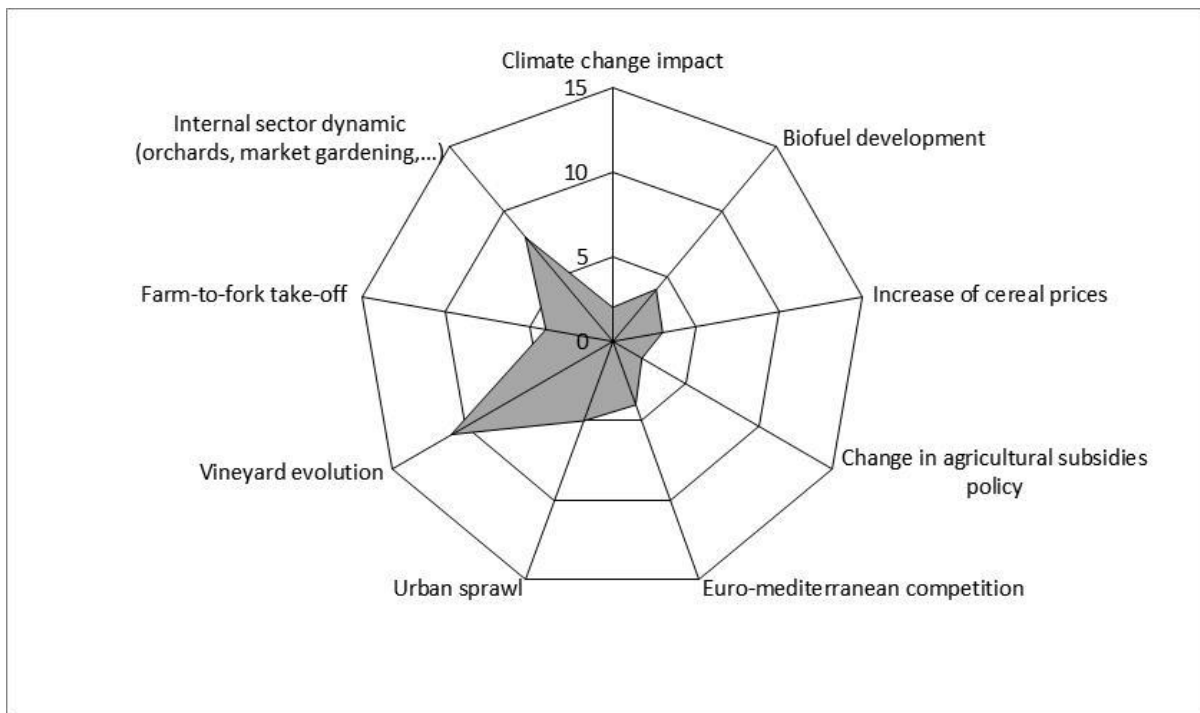
<sup>1</sup> Additional information on the selection of stakeholders and their contribution is presented in the supplementary material

1 assumptions that were used to frame three contrasted scenarios. We then tried to find a consensus on  
2 the most likely trends to build a baseline scenario, corresponding to a negotiated vision of future  
3 irrigated agriculture and considered as plausible and somehow desirable by participating stakeholders.  
4 The output of the workshop, of course, has a clear subjective dimension and we acknowledge that  
5 contradictory visions could have been expressed by other components of the civil society. However,  
6 because our stakeholders were considered as representative of actors whose decisions will shape the  
7 future in the Orb river basin, we used it as a baseline scenario.

8 The workshop output consisted of a series of assumptions on future irrigated areas, crops and  
9 technologies This was then used to quantify the corresponding future irrigation water demand (Maton  
10 et al., 2007 and 2012) using a methodology used by the authors in a different case study (Rinaudo et  
11 al., 2013).

12

13



14

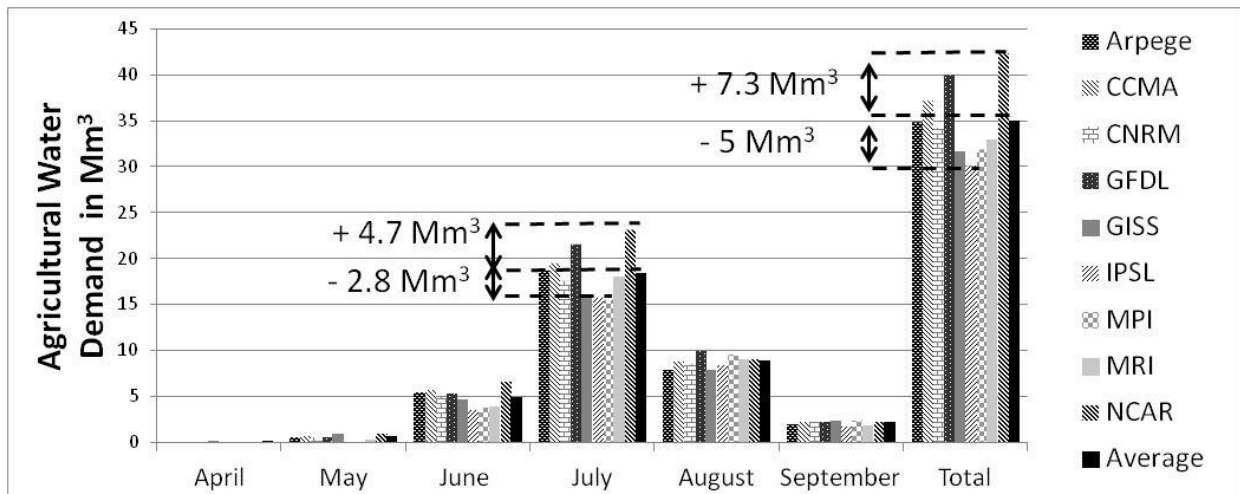
15 **Figure 5 Factors of change identified by consulted stakeholders as main drivers of future**  
16 **agricultural water demand (the score represents the number of experts that consider that the**  
17 **factor will strongly determine future evolution).**

18 Regarding urban development, the scenario was based on an in-depth analysis of past and present  
19 demographic and housing trends, on forecasts made by the National Institute for Statistical Studies  
20 (INSEE, France) and on interviews with urban planning experts. Because the uncertainty associated  
21 to future evolution of urban and demographic development is lower (at the 2030 time horizon  
22 considered), only one baseline scenario was constructed, what did not generate much controversy.  
23 The output from the scenario specifies population growth rate and new housing patterns at the

1 municipal level at the 2030 time horizon, for which a new urban water demand was assessed (Vernier  
 2 and Rinaudo, 2012).

### 3.3.3. Agricultural and urban demand models

3 An agro-climatic crop water requirement model, based on Allen et al. (1998), was developed to assess  
 4 future water demand associated with the scenario developed during the workshop (2). The model  
 5 simulates the impact of climate change on irrigation demand for the climate projection of the 9 GCMs  
 6 (Hoang et al., 2012). Monthly average water demand values are computed for the 9 climate  
 7 projections in combination with the 2030 cultivated areas at the agricultural demand unit level (Girard  
 8 and Rinaudo, 2013). Figure 6 presents the aggregated values at the basin scale. The dispersion  
 9 between climate models is limited. Therefore, the multi-model average is adopted for the rest of the  
 10 study.



11

12 **Figure 6 Monthly average agricultural water demands at the basin scale for 9 futures mid-term**  
 13 **(2046-2065) climate change scenarios**

14 Future urban water demand was also estimated for each of the 62 Urban Water Demand Units of the  
 15 basin, using an econometric model (Rinaudo et al., 2012) which predicts water demand as a function  
 16 of population growth, average household income, water price and climate, based on the evolution  
 17 scenario (3.3.1). Results predict an increase in the annual demand of 4.4 Mm³ a year on average  
 18 (Vernier and Rinaudo, 2012).

### 3.3.4. Identification and local selection of adaptation measures

19 After developing a socio-economic scenario depicting the most likely evolution of urban and  
 20 agricultural water use in the basin at the 2030 time horizon, the expert group assisted the research  
 21 team in screening a range of possible responses for coping with global change (3). A first catalogue  
 22 of measures was elaborated by combining literature reviews (peer-review journals, technical reports  
 23 and case study description-grey literature, as well as planning documents), personal communication  
 24 with local experts (water managers, local authorities), and stakeholder consultation workshops. The

1 three main evaluation criteria used to characterize local suitability were (i) technical, institutional and  
 2 legal feasibility at the time horizon considered; (ii) capabilities of the actors to uptake the measures  
 3 and (iii) societal and political acceptability (see supplementary material for more details).  
 4 Two types of responses were considered: planned and autonomous adaptation measures. Planned  
 5 adaptation measures is the result of a deliberate policy decision, based on an awareness that conditions have  
 6 changed or are about to change and that actions are required to return to, maintain, or achieve a desired state. By  
 7 contrast, autonomous adaptation does not constitute a conscious response to climatic stimuli but is triggered by  
 8 ecological changes in natural systems, by market, public policy or welfare changes in human systems (IPCC,  
 9 2007).  
 10 In the study, the planned adaptation measures include: the optimisation of reservoir operation, further  
 11 development of groundwater resources (new boreholes and water conveyance infrastructure),  
 12 desalination, improved efficiency of large public agriculture irrigation schemes, reduction of leaks in  
 13 municipal water distribution networks, and the implementation of tariffs that provide water conservation  
 14 incentives. Autonomous adaptation measures consist of water conservation actions that can be  
 15 implemented by households, municipal services and commercial activities (hotels, sea resorts) if they  
 16 are provided with the right incentives (subsidies, technical information). The stakeholder consultation  
 17 process led to the identification of a list of priority measures (13 type measures corresponding to 462  
 18 possible measures to be applied at the local level, Table 1 and supplementary material), while other  
 19 measures were eliminated (i.e. rainwater harvesting, reuse) based on the results of technical,  
 20 economic legal or acceptability criteria.

### 3.3.5. Economic and technical assessment of measures

21 The measures were characterised in terms of their cost and effectiveness (as volume of water saved  
 22 or mobilised) for the different demand units of the basin (4). The calculations were made at the  
 23 municipal level (Urban Demand Unit) for all urban water conservation measures, considering the  
 24 heterogeneity of water users (type of houses, income) and water services (current tariffs, current level  
 25 of leakage, etc.). Agricultural water conservation measures were evaluated at the irrigation district  
 26 level (Agricultural demand Unit). Finally, water resource development (groundwater exploitation,  
 27 desalination) was assessed at the project level. Annual costs were estimated considering investment  
 28 and maintenance costs, the technical lifespan for the equipment, and a 4% discount rate (Rinaudo, et  
 29 al., 2013b, 2013c). Table 1 shows the average cost per unit of water (€/m<sup>3</sup>) and maximum volume of  
 30 water that can be saved or mobilised with each measure.

31

Description of measure		Maximum annual volume available in 2030 (Mm <sup>3</sup> )	Average annualised unit cost (€/m <sup>3</sup> )
<b>Code</b>	<b>Planned adaptation measures</b>		
MA1	Conversion of gravity irrigation systems to pressurised / sprinkler irrigation.	0.81	0.16
MU1	Reduction of leaks in urban water distribution networks	3.28	0.77
MU8	Replacement of water intensive landscapes with xeric	0.59	0.68



	vegetation (public gardens)		
MU9	Replacement of irrigated lawns with artificial turf for sport grounds	0.43	1.95
GW	Substitution of water intakes in the Orb river (and alluvial aquifer) with other groundwater resources	3.60	0.58
DS	Substitution of water intakes in the Orb river with desalinated water (coastal municipalities)	3.60	1.22
<b>Autonomous adaptation measures</b>			
MA2	Development of drip irrigation at farm level in all pressurised irrigation systems	1.56	0.54
MU2	Installation of water conservation devices (tap aerators, shower flow reducer, etc.) in households	0.36	0.56
MU3	Water consumption audits for single family houses & changes in appliances	0.52	1.16
MU4	Same as U2 for multi-family housing units	0.51	1.64
MU5	Installation of automated reading meters & use of seasonal water tariffs to reduce peak-season demand	0.83	0.66
MU6	Installation of water saving devices in hotels (tap aerators, toilet flushes)	0.04	0.61
MU7	Water consumption audits of campsites and holiday parks. Installation of low-flow flushes / showers, leakage detection in campsite distribution network, etc.	0.18	1.55

1 **Table 1 Characteristics of planned and autonomous adaptation measures considered**

### 2 **3.4. When bottom-up meets top-down**

3 The bottom-up and the top-down approaches are integrated through an ad-hoc river basin  
4 management model that optimises the selection of the measures for the future hydrological and demand scenarios.

#### 5 **3.4.1. Least-cost river basin optimisation model**

6 The Least-Cost River Basin Optimisation Model (LCRBOM) selects the combination of adaptation  
7 measures that minimises the total annualised cost of the adaptation PoM while meeting the demand  
8 targets and minimum in-stream flow constraints (7) (Girard, et al., 2013). Economic elements are  
9 integrated in the optimization model: on one side the adaptation measures are characterised by their  
10 cost and effectiveness for each demand unit (as detailed in section 3.3.5), and on the other side  
11 constraints are defined to ensure the supply of the urban and agricultural demands (defined in section  
12 3.3.3). The hydrological side of the modelling framework is then integrated as the optimisation is  
13 carried out over a 20-year monthly inflow time series provided by the hydrological model (section  
14 3.2.2) for the future scenarios corresponding to the 9 GCMs.

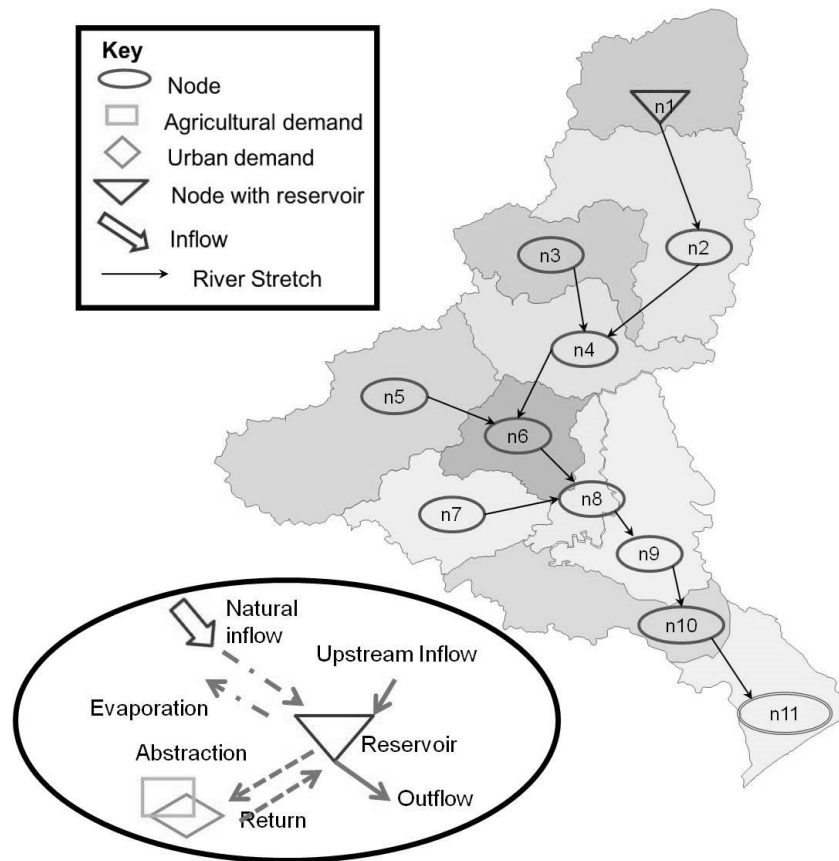
15 Measures can then be selected simultaneously in the optimization model except for some that are defined as mutually exclusive for technical reasons (for instance the incompatibility of different

1 irrigation technologies). The effect of the combination of the measures on their effectiveness is not  
2 quantified at this stage to limit the calculation burden (non-linearity).

3 In the quantitative management of water resources at the river basin level, environmental aspects can  
4 be represented in terms of exogenous constraints such as minimum-instream flow requirements.  
5 These constraints are assumed to capture in their definition the environmental aspects involved in the  
6 quantitative management of water resources at the river basin scale. In the case study area,  
7 environmental flows are defined as a minimum monthly in-stream flow threshold for the 11 sub-basins,  
8 following the legal requirements to ensure the environmental functions of the river. The thresholds  
9 have been defined in previous studies by combining hydraulic and habitat methods (Vier and Aigoui,  
10 2011)

11 The system is represented as a flow network comprising 11 nodes (diversions and/or storage nodes)  
12 one for each sub-basin, linked through arcs representing the river stretches (Figure 7). The 64 Urban  
13 Demand Units and 19 Agricultural Demand Units of the Orb river basin are connected to the node of  
14 the sub-basin from which water is abstracted, or to which it returns. The model has been developed  
15 using GAMS (General Algebraic Modelling System, Rosenthal, 2012) and applying Mixed Integer  
16 Programming with the solver from the Cplex Callable Library from IBM ILOG CPLEX.

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1  
2 **Figure 7 Conceptual model of the Orb River with the flow network on the map of sub-basins,**  
3 **and details of mass balance at reservoir node n1.**

4 The LCRBOM yields a least-cost PoM of adaptation measures for each global change scenario. In  
5 order to assess the performance of the system under each PoM we have used a modified version of  
6 the Demand Reliability Index (DRI) proposed by Martin-Carrasco et al. (2013). The reliability index  $I$  is  
7 defined as the ratio of the demand supplied for a given acceptable level of reliability divided by the  
8 total annual water demand. We define this for the agricultural water sector by considering reliability as  
9 referring to a monthly failure of the supply associated with a return period of 5 years, as required by  
10 the French legislation (MEEDDT, 2008). Therefore,  $I_r^a = S_r^a / D^a$ , where  $I_r^a$  is the demand reliability  
11 index for the agricultural annual demand, "a", and a reliability, "r";  $S_r^a$  is the acceptable supply, or  
12 average amount of water supplied to agricultural demand with reliability greater or equal to the  
13 acceptable value "r", in  $\text{Mm}^3/\text{yr}$ ; and  $D^a$  is the multi-model average agricultural water demand, in  
14  $\text{Mm}^3/\text{yr}$  (defined in section 3.3.3).

15 For each of the 9 climate projections we obtain an optimum adaptation PoM through the use of the  
16 LCRBOM. However, given the high level of uncertainty corresponding to the climate projections  
17 (Figure 3), a large range of variation is expected across PoMs. Stopping at this stage would provide  
18 little practical information for decision-making, given that, one adaptation PoM needs to be selected in  
19 the end, to overcome the "drama of uncertainty". To provide insights into the definition of the final  
20 adaptation strategy, we suggest assessing the performance of each of the 9 PoMs successively  
21 through the other climate projections, so that we can assess the robustness of the performance of the  
22 PoMs under conditions that they have not been designed for.

### 3.5. Climate check

1 We adapted the TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) approach  
 2 to identify the least-regret adaptation PoM (8). TOPSIS is a simple multi-criteria analysis method that  
 3 has already been applied in many contexts (Hwang and Yoon, 1981; Huang et al., 2011) aiming to  
 4 minimise the distance to the ideal alternative and maximising the distance from the worst one. It  
 5 follows a three-step process. First, performances are calculated for each PoM and evaluation criteria  
 6 in order to create a performance matrix; then, relative performance indices (regret) are computed  
 7 based on their distance from the best and the worst solutions; finally, weights are defined for each  
 8 criteria to calculate an indicator of the overall regret in the selection of the PoM.

#### 3.5.1. Performance matrix

9 Using the LCRBOM, we assess two types of performance indicators in connection with each PoM: the  
 10 cost of adaptation, previously obtained for a fixed set of measures, and the DRI index calculated for  
 11 the PoM under a given climate projection. From a general point of view, if  $n$  is the number of climate  
 12 change scenarios and  $m$  the number of criteria for the evaluation of the performance of a PoM, a  
 13 performance matrix,  $P = [x_{ij}]$ , can be defined as (Eq. 1)

$$14 \quad P = \begin{pmatrix} PoM_1 \\ \vdots \\ PoM_n \end{pmatrix} \begin{pmatrix} w_1 & \cdots & w_{m-1} & w_m \\ x_{11} & \cdots & x_{1m-1} & x_{1m} \\ \vdots & \ddots & \vdots & \vdots \\ x_{n1} & \cdots & x_{nm-1} & x_{nm} \end{pmatrix} \quad (Eq.1)$$

15 Where, in our case study, the number of PoMs to evaluate corresponds to the  $n$  climate change  
 16 scenarios ( $PoM_1, PoM_2, \dots, PoM_n$ ); the performance criteria,  $x_{i1}$  to  $x_{im-1}$ , corresponds to the agricultural  
 17 demand reliability index calculated for each climate projection, and the last  $x_{im}$  criteria are the cost of  
 18 the evaluated PoM. Weights ( $w_1, \dots, w_m$ ) correspond to each of the  $m$  performance criteria, as defined  
 19 in section 3.5.3.

#### 3.5.2. Regret matrix

20 The regret matrix,  $R = (r_{ij})$ , is derived from the performance matrix by calculating regret indices  $r_{ij}$   
 21 (relative normalised performance index). Each regret index quantifies how much each performance  
 22 ( $x_{ij}$ ) of a  $PoM_i$  deviates from the best performance of the  $j$  criteria ( $x_j^*$ ). To compare performance  
 23 criteria that do not have commensurable units, the performance indices are normalised (Eq. 2).

$$24 \quad r_{ij} = |x_j^* - x_{ij}| / |x_j' - x_j^*|, \quad (Eq.2)$$

25 Where  $x_j'$  is the worst performance for each criteria. The higher the index value, the more the  
 26 performance deviates from the best one, which has an index of 0.

#### 3.5.3. Weights for ranking

27 The value of the weights associated with each criterion can be defined by stakeholders, expert  
 28 judgment or information theory methods (Srdjevic et al., 2003). As a starting point, the weight of each

1 agricultural DRI under a climate change scenario ( $x_{i1}, x_{i2}, \dots, x_{im-1}$ ) are stated as equal (Eq. 3), as we  
 2 assume that none of the scenarios have been found to perform better than another (section 3.2.1).

$$3 \quad w_k = w_j, \forall k, j \text{ from } 1 \text{ to } m - 1 \quad (\text{Eq. 3})$$

4 Then, two situations can be considered: first, it can be decided, arbitrarily in a first step, to assign the  
 5 same weight to the agricultural demand reliability (DRI) and to the cost of the PoM (i.e., the sum of the  
 6 weight of the agricultural DRI is equal to the weight for the cost of the PoM,  $w_m$ ). The sum of all the  
 7 weights must be equal to 1 (Eq. 4). Solving equations 3 and 4 gives the weight  $w_m = 1/2$ ; and  $w_j = 1/18$   
 8  $= (1/2) \times (1/9)$  for  $i = 1$  to  $n$ .

$$9 \quad \sum_{j=1}^{m-1} w_j = w_m ; \sum_{j=1}^{m-1} w_j + w_m = 1 ; w_j > 0 ; w_m > 0 \quad (\text{Eq. 4})$$

10 Alternatively, different values could be assigned to the agricultural and cost weights, in order to reflect  
 11 the potential preferences of the stakeholders. This has been done by defining, firstly, that  $w_m = 1/4$  and  
 12  $\sum_{j=1}^{m-1} w_j = \frac{3}{4}$  to give more importance to the agricultural DRI and, subsequently, that  $w_m = 3/4$  and  
 13  $\sum_{j=1}^{m-1} w_j = 1/4$  to give more importance to the cost criteria.

14 Aggregated regret indicators ( $R_i$ ) are finally calculated as the sum of the weighted regrets, in order to  
 15 rank the PoMs by increasing order (Eq.5) to identify the least-regret solution.

$$16 \quad R_i = \sum_{j=1}^m w_j \times r_{ij} \quad \forall i \text{ from } 1 \text{ to } n \quad (\text{Eq.5})$$

## 4. RESULTS

### 4.1. Least-cost adaptation programmes of measures

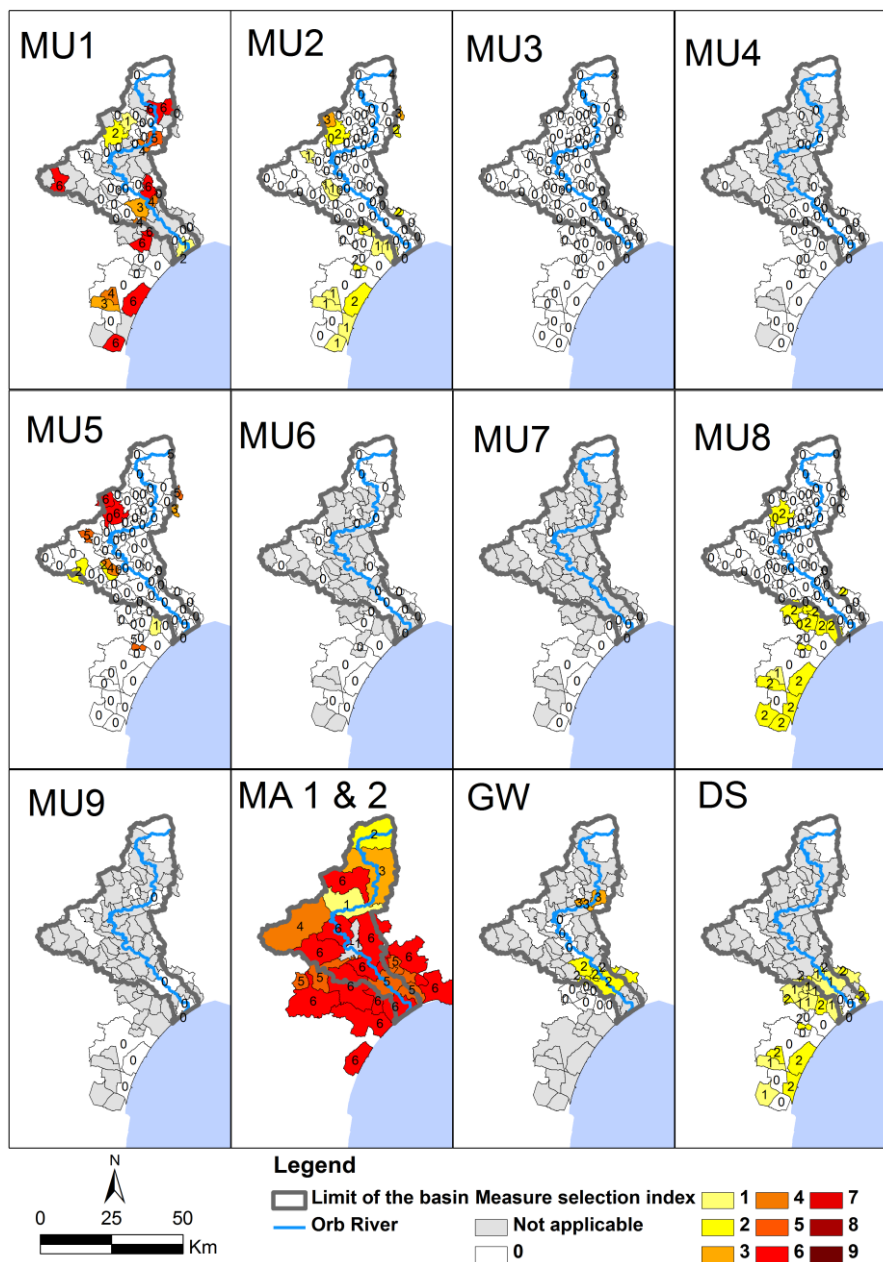
Climate projection	DRI without PoM	Cost of the PoM (€)
IPSL	1.000	-
MPI	1.000	-
MRI	1.000	-
CCMA	0.987	213,500
GISS	0.961	771,800
Arpège	0.940	1,565,500
GFDL	0.941	2,730,500
CNRM	0.863	2,905,200
NCAR	0.871	6,701,500

17 **Table 2 Demand Reliability Index without programme of measures (PoM) and cost of the**  
 18 **optimal PoM for the 9 climate projections.**

19 9 different adaptation PoMs are defined through the LCRBOM, one for each climate projection (7).  
 20 The programmes have been characterised in terms of their cost and the agricultural DRI under each  
 21 climate projection, assuming business-as-usual (BAU), i.e. without adaptation measures (Table 2). In  
 22 3 cases out of 9 there was no need for a PoM in the future situation, while in the 6 remaining cases

1 the annual cost of the PoM ranged from 0.2 M € (CCMA scenario) to 6.7 M € in the worst case (NCAR  
 2 scenario). The relation between the cost of the PoM and the DRI without adaptation is not direct, given  
 3 that some scenarios with similar DRI (0.940 and 0.941 for Arpège and GFDL respectively) lead to  
 4 different PoM costs (2.7 M€ and 1.5 M€ respectively). In the following sections, the different PoMs are  
 5 identified by the name of the GCM for which they have been optimised (i.e. the PoM GFDL is the  
 6 least-cost PoM optimised for the climate projection coming from the GFDL general circulation model).

7 To illustrate the variability and uncertainty concerning the definition of least-cost adaptation measures  
 8 for climate change, we have compared the measures selected in the different climate change  
 9 scenarios (Figure 8).



10

11 **Figure 8 Distribution of the measures applied in the Orb river basin.** The number and colours  
 12 indicate the level of confidence in the selection of the measure, ranging from 0 (white) to 9 (dark red),

1 adding 1 each time the measure is selected under one of the 9 climate projections. The agricultural  
2 measures MA1 and 2, mutually exclusive, are presented together (measures described in Table 1).

3 The level of confidence is higher for the selection of the agricultural measures, up to 6 in most of the  
4 irrigated areas, meaning that irrigation modernisation measures should be prioritised. Regarding urban  
5 demand, the measure most applied is that of improving network efficiency (MU1), with levels of  
6 confidence reaching up to 6 over the whole urban demand area. The other measures, such as MU2,  
7 MU3, MU5 and MU8, are also selected, but with lower level of confidence. Some urban measures  
8 such as MU4, MU6, MU7 and MU9 do not present that much interest in the scenarios considered and  
9 could be discarded from an adaptation PoM. Groundwater measures (GW), even if spatially limited,  
10 present some interest locally, to alleviate the burden on some Urban Demand Units, with confidence  
11 levels reaching up to 3. Desalination measures (DS) are included in the PoMs in only two cases,  
12 corresponding to the driest climate projections.

13

## 4.2. Climate check results

### 4.2.1. Assessing the performance matrix

14 The first element of the climate check (8) is to assess the performance matrix (Table 3) that presents  
15 the result of the optimisation for a given PoM (row) under different climate projections (column) in  
16 terms of agricultural demand, reliability and cost. The results have been ordered in rows according to  
17 increased cost of the PoM, and in columns by the corresponding climate projection. In the  
18 performance matrix, the shaded bold numbers of the diagonal of DRI equal to 1 correspond to the  
19 cases where the PoM is checked against the climate projection for which it has been optimised (i.e.  
20 the PoM Arpège has been optimised for the climate projection Arpège). Therefore, the DRI is equal to  
21 1, as this was one of the constraints of the optimisation. DRIs lower than 1 mean that the level of  
22 demand that can be supplied for the given reliability is below the legal requirement (i.e. the deficit in  
23 water supply to the agricultural sector is higher than that allowed). The lower the DRI, the greater the  
24 deficit is. We have considered 3 categories of DRI as illustrative guidelines for the state of the system.  
25 Ideally this should be linked to the impact of the deficit on agricultural production but this was beyond  
26 the scope of the study. Below the diagonal (green area), DRIs are equal to 1 and, above it, DRIs  
27 decrease by row – from left to right, and by column – from bottom to top. It can be seen that the  
28 greater the cost of the PoM, the higher the DRI, with the lowest DRI obtained in the cases where no  
29 PoMs are applied (IPSL, MPI and MRI) and the highest DRI observed for the most expensive PoM  
30 (NCAR). Some irregularities to that rule are observed between the PoM designed under the GFDL and  
31 Arpège climate projections (even though it is more expensive, the GFDL PoM results in a lower DRI  
32 than the Arpège scenario for the Arpège climate projection). A trade-off appears between the cost of  
33 the PoM and an acceptable level of reliability of irrigated agriculture supply.

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PoM/ Climate projection	Demand reliability index (0 to 1)									Cost of the PoM (€)
	MPI									
	IPSL	ECHAM	MRI	CCMA	GISS	Arpège	GFDL	CNRM	NCAR	
Without PoM	1.00	1.00	1.00	0.99	0.96	0.94	0.94	0.86	0.87	0
IPSL	<b>1.00</b>	1.00	1.00	0.99	0.96	0.94	0.94	0.86	0.87	0
MPI ECHAM	1.00	<b>1.00</b>	1.00	0.99	0.96	0.94	0.94	0.86	0.87	0
MRI	1.00	1.00	<b>1.00</b>	0.99	0.96	0.94	0.94	0.86	0.87	0
CCMA	1.00	1.00	1.00	<b>1.00</b>	0.97	0.95	0.95	0.89	0.89	213,497
GISS	1.00	1.00	1.00	1.00	<b>1.00</b>	0.98	0.98	0.94	0.94	771,784
Arpège	1.00	1.00	1.00	1.00	1.00	<b>1.00</b>	0.99	0.97	0.95	1,565,466
GFDL	1.00	1.00	1.00	1.00	1.00	0.99	<b>1.00</b>	0.96	0.95	2,730,458
CNRM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	<b>1.00</b>	0.98	2,905,221
NCAR	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	<b>1.00</b>	6,701,525

7 **Table 3 Performance matrix of the 9 programmes of measures under the 9 climate projections**

8 The categories are represented by the colours (DRI=1 (Green), between 1 and 0.95 (Yellow), from  
9 0.95 to 0.90 (Orange) and below 0.9 (Red)).

#### 4.2.2. Regret Matrix

10 Drawn from the performance matrix, the regret matrix enables the comparison of different criteria  
11 (Table 4). It illustrates how the best performing PoMs for one criterion are not those of least-regret.  
12 The decision to not apply any PoM is the best-performing strategy according to the cost criterion  
13 (regret =0) but the worst in regard to the agricultural DRI (regret=1). In the opposite, the most  
14 expensive PoM obtained under the NCAR climate projections is the best-performing strategy in terms  
15 of DRI (regret=0) but the worst in terms of cost (regret=1). Given the weight assigned to the different  
16 performance criteria, the least-regret option would be to apply the PoM defined under the GISS  
17 climate change scenario corresponding to an aggregated regret of 0.15 balancing the cost of the PoM



1 (0.7 M€) with an average DRI of 0.98. The PoM corresponding to the climate change scenario Arpège  
 2 with aggregated regrets of 0.16 also seems to be worthy of further consideration.

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PoM/scenario CC	IPSL	MPI	MRI	CCMA	GISS	Arpège	GFDL	CNRM	NCAR	Regret on the Cost of the PoM	Average Regret Agri DRI	Weighted regret
Without PoM	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.67	0.33
IPSL	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.67	0.33
MPI ECHAM	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.67	0.33
MRI	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.67	0.33
CCMA	0.00	0.00	0.00	0.00	0.70	0.81	0.81	0.80	0.83	0.03	0.44	0.24
GISS	0.00	0.00	0.00	0.00	0.00	0.37	0.36	0.42	0.49	0.12	0.18	0.15
Arpège	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.24	0.37	0.23	0.09	0.16
GFDL	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.32	0.41	0.41	0.08	0.25
CNRM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.43	0.02	0.22
NCAR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.50

7 **Table 4 Regrets matrix calculated to compare the performance of the 9 programmes of**  
 8 **measures according to agricultural Demand Reliability Index and annual costs**

### 4.2.3. Analysis of preferences

9 The final selection of a PoM will depend on the respective importance given to each criterion in line  
 10 with the preferences of the stakeholders and decision-makers. The preference matrix illustrates the  
 11 range of variation in the aggregated regret for different preferences. Three different preference arrays  
 12 are considered corresponding to: 1. an equal importance given to agricultural demand and to  
 13 adaptation PoM cost, 2. a preference to the cost of the adaptation PoM, and 3. A preference to the  
 14 agricultural demand ( $w_c=1/2$ ;  $w_c=1/4$ ,  $w_c=3/4$  respectively, see Table 5). When more importance is  
 15 given to the cost indicator, the less expensive PoMs present less regret. Correspondingly, the PoMs  
 16 with lower agricultural deficit also have a lower aggregated regret. The extreme programmes in terms  
 17 of cost and DRI are also the most sensitive to the weighting of the regrets (variation of 0.33 and 0.5 for  
 18 the No PoM and NCAR respectively), whereas the PoM least affected by the variation of the weights is  
 19 the GISS PoM (0.04). These elements could be useful in terms of discussion and negotiations with the

1 stakeholders on the selection of the adaptation PoM, given that it provides an assessment of the  
 2 different choices and performances possible in terms of cost and the reliability of agricultural demand.

3  
 4  
 5

Weighted regret (%)			
PoM	1.	2.	3.
	25 C/75 A	50 C/50 A	75 C/25 A
Without PoM (IPSL, MPI, MRI)	0.50	0.33	0.17
CCMA	0.34	0.24	<b>0.13</b>
GISS	0.17	<b>0.15</b>	<b>0.13</b>
Arpège	<b>0.12</b>	0.16	0.20
GFDL	0.16	0.25	0.33
CNRM	<b>0.12</b>	0.22	0.33
NCAR	0.25	0.50	0.75

6

7 **Table 5: Preference Table of the aggregated regret** for different combinations of weight between  
 8 the agricultural DRI (% A) and the cost of the PoM (% C), the least-regret option is indicated in bold for  
 9 each weighting, the colours are decided arbitrarily to provide four categories (below 0.20 (Green);  
 10 From 0.2 to 0.3 (Yellow); from 0.3 to 0.4 (orange); more than 0.40 (red)).

11

## 5. Discussion and conclusions

1 The methodological framework presented integrates conventional top-down and bottom-up  
2 approaches in an innovative and useful way to support the design of climate change adaptation  
3 strategies at the river basin scale. It combines computer-based and scenario-planning techniques in a  
4 bottom-up meets top-down perspective that accounts for economic efficiency, social acceptability,  
5 environmental sustainability and climate adaptation robustness. The bottom-up approach involves a  
6 multilevel scenario-building approach, applying participatory forecasting techniques in combination  
7 with agricultural and urban demand simulations to estimate future demand scenarios. Local adaptation  
8 measures are identified and prioritised through multi-level stakeholder workshops (catalogue of  
9 measures), and systematically characterised in terms of cost and effectiveness. In the top-down  
10 approach, climate data are downscaled from a general climate model to hydrological impact to assess  
11 the future flow regime under climate uncertainty. The bottom-up approach meets the top-down when  
12 least-cost adaptation PoMs are identified using a hydro-economic optimisation model. Economic and  
13 reliability indicators of water resource system performance are evaluated under different future climate  
14 projections and for different adaptation programmes of measures. The resulting adaptation portfolios  
15 are then submitted to a climate check to address climate uncertainty, in order to assess the  
16 robustness of the potential decisions and to select the least-regret option.

17 The framework has been successfully implemented in a real case study, in the Orb River basin, in  
18 Southern France, to inform adaptation strategy defined at the local level on the best water  
19 management measures to be applied. Demand management measures, such as network efficiency  
20 improvement in irrigation and urban supply, seem to be the least-regret options. The need for supply-  
21 side capacity expansion measures, such as desalination plants or ground water exploitation, is limited  
22 given their high inversion cost; they are less cost-effective in a context of climate change uncertainty.  
23 The trade-offs between the cost of the adaptation plan and the reliability on the supply of agricultural  
24 demand have been identified. Depending on the preferences of the decision-makers, the appropriate  
25 level of adaptation can be defined to adapt to climate change. Without adaptation measures, the  
26 deficit in agricultural supply remains at what could be considered an acceptable level, in the driest  
27 regions of the world, challenging the need for adaptation in the Orb river basin. One reason for the  
28 relatively good adaptive capacity of the Orb river basin has to be linked to the storage capacity of the  
29 reservoir located up-stream of the basin, able to regulate the variations in runoff. On the contrary,  
30 meeting the legal requirement to supply agricultural demand under each scenario could be far too  
31 expensive to be assumed by the local actors. These variations highlight the interest of the framework  
32 presented. If the programme of adaptation measures is designed under only one climate projection,  
33 clearly, it could be inefficient, either by being over-designed at a very high cost, or under-designed at a  
34 low cost, but failing to provide the level of reliability required on the supply of demand. In this way,  
35 fruitful insights for adaptation decision-makers are provided for the design and discussion of  
36 adaptation plans with stakeholders. In this case study, the trade-offs between the planning objectives  
37 are limited to the cost of the programme of measures and the agricultural deficit, considering  
38 environmental issues as exogenous and defined by the legislator as “minimum in-stream flow

1 requirements". A stronger emphasis could be put on investigating different environmental  
2 considerations and their influence on the other parts of the problem. The definition of environmental  
3 objectives could be included as well in the bottom-up process. More performance indicators could be  
4 used to assess the performance of the system under uncertainty, or be incorporated as objectives  
5 through many objective optimisation techniques (Kasprzyk et al., 2013).

6 By combining top-down and bottom-up approaches, the framework presented helps to overcome the  
7 "drama of uncertainty" that delays adaptation planning. On the one hand, by working with the local  
8 stakeholders in the definition of the measures and development scenarios, and including local  
9 contributions from economists, hydrologists, climate scientists, water resource engineers, water  
10 managers, stakeholders and planning authorities, the approach takes root in the local context,  
11 fostering dialogue on a common basis to ensure the design of adaptation strategies, which is essential  
12 for the definition of relevant, credible and acceptable adaptation options. However, bottom-up  
13 approaches focus mainly on short-term adaptation using historical or contemporary experiences,  
14 limiting their input to long-term robust infrastructure and policy planning (Ekström et al., 2013).

15 On the other hand, the complexity of physical interlinks and management strategies, and the need to  
16 consider futures scenarios representing conditions far beyond current management experience benefit  
17 from the modelling part of the framework, in order to obtain insights on the impacts, costs and benefits  
18 of adaptation at the basin scale. The proposed integration of the bottom-up and top-down information  
19 in a basin wide hydro-economic model enables a multi-criteria approach in the definition and  
20 assessment of adaptation plans, so that we can identify the trade-offs between different goals  
21 (environmental flow targets, reliability of supply, adaptation cost, etc.) and analyse the robustness of  
22 the adaptation across different climate projections without losing the relevant local information derived  
23 from the local stakeholders. The added value of this integrated top-down and bottom-up framework  
24 resides in the combination of its various components, surpassing the limitations of each module in  
25 isolation. At the frontier between science and policymaking, we think that integrating both top-down  
26 and bottom-up approaches could be the way to bridge the gap between investigating theoretical  
27 climate change impacts and designing pragmatic local adaptation strategies. The integrated  
28 assessment is, in this case, an element of integration for a common understanding of the problem,  
29 opening the way for a participatory integrated assessment of the impact of climate change at the river  
30 basin scale in order to design an adaptation strategy.

31 In any case, other kinds of uncertainties in both the modelling and the scenario planning processes  
32 still need to be addressed (Dessai et al., 2007). An improved characterisation of these uncertainties  
33 would ensure a higher level of robustness of the adaptation plan. From the top-down side, the analysis  
34 could be improved by performing the full downscaling method for the updated emission scenario with  
35 the latest Representative Concentration Pathway, considering a larger set of climate models  
36 (Rajagopalan et al., 2009), comparing results from downscaling techniques or hydrological models  
37 (Steinschneider et al., 2012), running a deeper sensitivity analysis to various components in the  
38 modelling chain (Dessai and Hulme, 2007). It could be tempting to use an ensemble-like approach,  
39 weighting each model according to their ability to simulate the past climate, hence attributing more

1 probability to one scenario or another in the future. However, the literature tells us that it is not really  
2 possible to assess a model performance in a context similar to this study, as the results of such an  
3 evaluation will depend on the region, the season, etc. (Gleckler and al., 2008). Another innovative and  
4 more appropriate approach would be the use of model genealogy (Knutti et al., 2013) models  
5 according to similarities in their dynamical and physical codes. This approach could be used in future  
6 studies to better assess model uncertainties. However, various methods already exist to manage  
7 climate uncertainty in the planning of water resources systems, as illustrated in two recent special  
8 issues (Dessai, et al., 2013; Salas, et al., 2012), applying techniques such as robust decision-making,  
9 decision-scaling, or real option analysis and relying on computational techniques such as scenario  
10 discovery, info-gap decision theory (Hassnoot, 2013).

11 Even if bottom-up approaches are less dependent on outputs from GCM scenarios and modelling  
12 uncertainties, they also suffer from method-related uncertainties, such as epistemic or linguistic  
13 uncertainties, bias in the representativeness of the stakeholders and uncertainty due to variability in  
14 the data or population sampled (Hayes, 2011; Ekström et al., 2013). These uncertainties could be  
15 addressed by considering different development scenarios and by up-dating the stakeholders involved  
16 in the planning process through a stakeholder analysis process or a social network analysis process  
17 (Prella et al., 2009). The scenario workshop and climate checks could be realised in a regular planning  
18 exercise to support and debate the adoption of new adaptation measures. In order to improve the  
19 elicitation of social acceptability, trade-offs and decision making, the pragmatic least-regret and  
20 preference analysis presented here could be extended following a fully participatory multi-criteria  
21 analysis (Madani and Lund, 2011; Munaretto et al., 2014) for planning for climate change adaptation  
22 at the river basin scale.

23 The step-by-step process (Figure 1) allows a characterization of the different elements of the problem,  
24 developing in each case an appropriate method and then combining them into a coherent framework.  
25 Thus, it ensures an interaction between bottom-up and top-down approaches beyond disciplinary  
26 boundaries and an harmonization of the temporal and spatial scales of analysis of the adaptation at  
27 river basin scale. Although the framework is presented as a step-by-step process, this does not mean  
28 that its implementation in practice must be linear. The development of the top-down and bottom-up  
29 approaches are performed in parallel. Once established the framework, the interactions between the  
30 top-down and the bottom-up approaches will continue on this common basis to feed the decision  
31 making process. Each part can be updated to integrate new information available such as learnings  
32 from the bottom-up side, or up-dated climate scenarios for the top-down side. The climate check  
33 assessment can then be performed again under improved assumptions, or modified if needed to  
34 better fit or integrate the different elements of the framework.

35 Indeed, to properly address the issue of planning for adaptation, the framework should fit into a wider  
36 management framework that accounts for what is learned as future conditions are experienced and  
37 that allows for the dynamic update of plans under an adaptive management paradigm (Walters, 1986;  
38 Johnson, 1999; Convertino, 2013). The current framework brings some insights for describing and  
39 analysing adaptation at the river basin scale, as well as for the identification of adaptation actions

1 under climate uncertainties, which are necessary first steps to frame dynamic adaptive policy  
2 pathways for instance (Hassnoot et al., 2013).

3 Finally, the proposed approach focuses clearly on the resource-based problem generated by climate  
4 change rather than addressing fully the governance dimension of adaptation. The combination of the  
5 bottom-up and top-down approaches is a first practical way to move from a normative governance  
6 framework to the development of actor's adaptive capacity to deal with uncertainty and to increase the  
7 resilience of the full socio-ecological system. Adaptation to global change will require as well changes  
8 in governance regimes, institutional innovation and the development of more social learning capacities  
9 (Pahl-Wostl, 2009).

10 As a conclusion, the proposed modelling framework combining top-down with bottom-up approaches  
11 in a step-by-step process is an innovative and useful way of exploring future adaptation strategies to  
12 global change at the river basin scale. The different steps integrated consideration of economic  
13 efficiency, social acceptability, environmental sustainability and robustness in the design of the  
14 adaptation plans. The method leads to the identification of least-cost programs of adaptation  
15 measures whose performance is assessed across future climate scenarios, providing elements for  
16 decision-making facing climate uncertainties. This work provides insight on the way to combine  
17 different analytical frameworks, tools and methods to frame adaptation strategy and planning  
18 objectives at the river basin scale, considering the integration of bottom-up and top-down approaches  
19 as necessary to further develop a full adaptive management framework.

20

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