Integrating top–down and bottom–up approaches to design global change adaptation at the river basin scale

Article *in* Global Environmental Change · September 2015

DOI: 10.1016/j.gloenvcha.2015.07.002

Corentin Girard
Universitat Politècnica de València


Manuel Pulido-Velazquez
Universitat Politècnica de València


Jean-Daniel Rinaudo
French Geological Survey


Christian Page
Centre Européen de Recherche et de Formati…

Global Environmental Change 34 (2015) 132–146

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Integrating top–down and bottom–up approaches to design global change adaptation at the river basin scale

Corentin Girard[a,*], Manuel Pulido-Velazquez[a], Jean-Daniel Rinaudo[b], Christian Pagé[c], Yvan Caballero[b]

[a] Research Institute of Water and Environmental Engineering (IIAMA), Universitat Politècnica de València, Camino de Vera s/n, Valencia 46022, Spain
[b] BRGM, French Geological Survey, 1039, Rue de Pinville, 34000 Montpellier, France
[c] CERFACS (European Center for Research and Advanced Training in Scientific Computing), CERFACS/CNRS, URA1875, 42 Ave G. Coriolis, 31057 Toulouse Cedex 1, France

ARTICLE INFO

Article history:
Received 18 May 2014
Received in revised form 1 July 2015
Accepted 6 July 2015
Available online xxx

Keywords:
Climate change
Adaptation measures
River basin model
Climate check
Top–down
Bottom–up

ABSTRACT

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

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

1. Introduction

The Mediterranean basin is identified as a climate change "Hot Spot" at the global scale (Giorgi and Lionello, 2008; Mariotti et al., 2008), and significant impacts are expected on its water resources (Iglesias et al., 2007; Bates et al., 2008) and related ecosystem services (Bangash et al., 2013). Adaptation strategies are needed, but raise policy and scientific challenges (Smith, 1997; Hallegatte, 2009; Biesbroek et al., 2010; Haasnoot et al., 2013) that generate an increasing number of research initiatives and policy recommendations in the water sector in particular (Ludwig et al., 2011; EC, 2013; Quevauviller, 2014 Quevauviller, 2014). Adaptation is expected to be flexible, adaptive, and based on an integrated water resources management framework. The capacity to adapt is dynamic and influenced by economic and natural resources, social networks, entitlements, institutions and governance, human resources, and technology (IPCC, 2007a,b). Therefore, effective adaptation pathways would require a mix of structural and non-structural measures, including regulatory and economic instruments as well. To design

* Corresponding author.
E-mail addresses: cogimar@upv.es (C. Girard), mapuve@hma.upv.es (M. Pulido-Velazquez), jd.rinaudo@brgm.fr (J.-D. Rinaudo), christian.page@cerfacs.fr (C. Pagé), y.caballero@brgm.fr (Y. Caballero).

http://dx.doi.org/10.1016/j.gloenvcha.2015.07.002
0959-3780/

the appropriate mix, adaptation measures should be "cost-effective", but also "environmentally sustainable, culturally compatible and socially acceptable", and their selection should be based on the results of "vulnerability assessments, costs and benefits assessments, development objectives, stakeholder considerations and the resources available" (UNECE, 2009).

Two main approaches are commonly applied to design climate change adaptation plans at the river basin scale: "top–down" and "bottom–up" approaches. Top–down (or 'scenario-centred') methods involve downscaling climate projections from General Circulation Models (GCM) under a range of emissions scenarios, providing inputs for hydrologic and management models to estimate potential impacts and, finally, to analyse adaptation measures (e.g. Caballero et al., 2007; Sperna-Weiland et al., 2012; Milano et al., 2012; Pulido-Velazquez et al., 2014). Nevertheless, the vast majority of existing top–down studies stop at the impact assessment phase (Wilby and Dessai, 2010). The term "top–down" is used because information is cascaded from one step to the next, with uncertainty expanding at each step of the process. However, as uncertainties increase along the top–down modelling chain, at best it provides an "uncertain outlook", which complicates the definition of adaptation strategies; at worst, it provides results too uncertain for decision-makers to even consider them. Despite this unavoidable propagation of uncertainty (Dessai et al., 2005; Ekström et al., 2013), this should not be used as an excuse for delays or inaction in adaptation, as water resource systems can be greatly affected (UNECE, 2009). Improving the top–down approach would require, on the one side, addressing the challenges of a more complex probabilistic multi-model ensemble forecast (Knutti et al., 2010) or, on the other side, addressing the uncertainty propagation through all steps involved in the regional climate downscaling and hydrological modelling (Ekström et al., 2013). The case for or against probabilistic approaches is made by biophysical and social vulnerability scholars respectively, the latter challenging the relevance of climate change probabilities in defining adaptation strategy (Dessai and Hulme, 2004).

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

These two attitudes toward the "drama of uncertainty" (Mearns, 2010) can be summarised as: on the one side the "necessity-of-reducing-uncertainty camp" that would further investigate via a top–down approach in order to narrow down uncertainties and support adaptation from a "predict-then-act" perspective; and, on the other side, the "vulnerability-and-response camp" that develops tools and methods to analyse the risks associated with adaptation strategies. The distinction between the two camps is not straightforward, and scientists do not always belong to one camp only (Meyer, 2012). Several authors have already discussed the benefits of integrating both approaches in the adaption process (e.g. Barthel et al., 2008; Wilby and Dessai, 2010; Ekström et al., 2013), although only a few studies have combined them in practice (Mastrandrea et al., 2010; Bhave et al., 2013). Our interest lies in the interface between the two aforementioned approaches, leading to our investigation of a

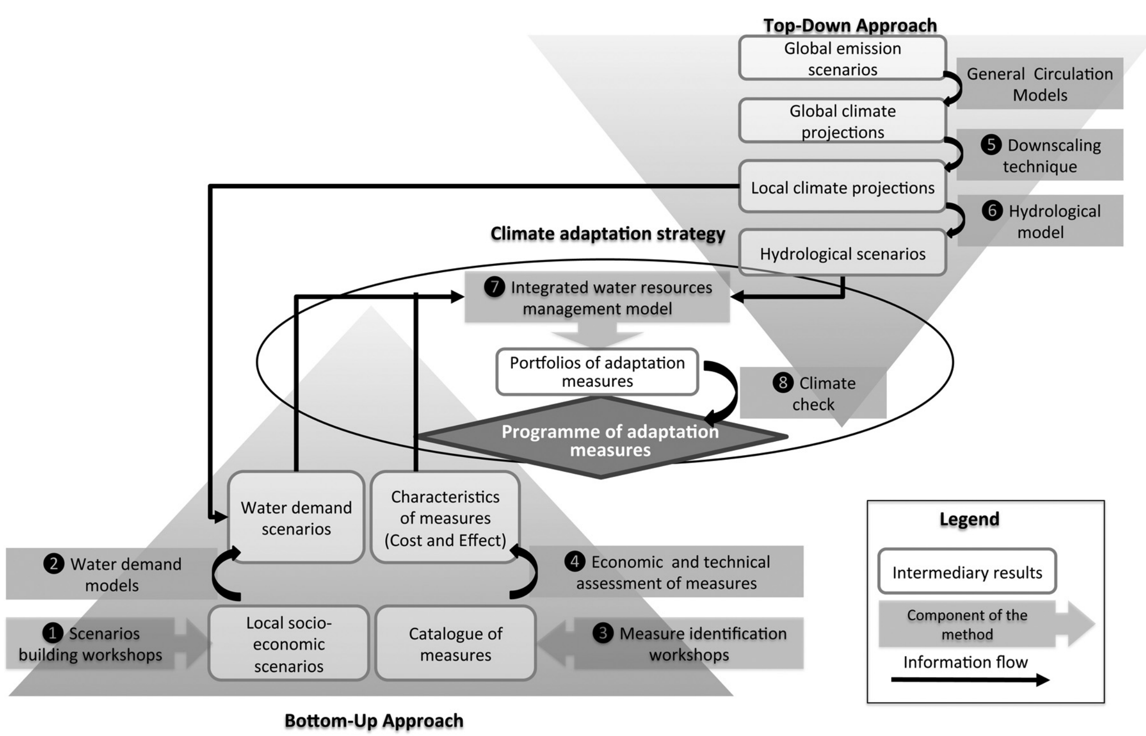

Fig. 1. Combining top–down and bottom–up approaches to support the design of climate change adaptation programme of measures. The components of the method are numbered in order to be described in Section 2.

"bottom–up meets top–down" perspective, where the focus is on the water resource system under study and GCM projections are used to inform rather than direct adaptation strategies (Brown and Wilby, 2012).

Our first motivation was the requirement to ensure that the new river basin management plans and Programme of Measures (PoM) in the European Water Framework Directive (EU-WFD) will be "climate proof" (EC, 2009). In order to formulate an adaptation plan in response to current vulnerability and future climate risks, we need to identify and select a set of adaptation measures and form them into a coherent integrated strategy. For that purpose, we propose an approach combining top–down strategic assessments and context-sensitive bottom–up analyses in a consistent framework, integrating the goals of economic efficiency, social acceptability, environmental sustainability and climate robustness at the basin scale, what we define as a bottom–up meets top–down approach. The objectives of the paper are then to provide a general framework to integrate top–down and bottom–up approaches (Section 2), to describe the components of this framework and their integration through integrated water resources management models (Section 3) and to illustrate how this integration can be performed in a real case study and which kind of results can be provided (Section 4).

The method is implemented in the Orb river basin, a Mediterranean basin located in the Southern France, where global change is expected to exacerbate the difficulty in meeting growing demands and the EU-WFD environmental in-stream flow requirements. Indeed, last assessment realised using CMIP5 (Coupled Model Intercomparison Project) scenario ensembles (Taylor et al., 2012; Terray and Boé, 2013) showed that projections for the near-future (2020–2049) over the French Mediterranean rim, lead to a warmer climate compared to present (temperature increase greater than 1.5 °C). While more uncertain, a summer precipitation decrease is projected, together with an increase of extreme precipitation in autumn.

2. General framework

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

2.1. Bottom–up approach

The bottom–up approach component of our framework consists of eliciting stakeholders' vision of how global change may affect the territory under study, and the range of adaptation that could be implemented to cope with the changing conditions. Participatory foresight techniques are first used to progressively engage stakeholders in an exploration of possible alternative future economic development for the territory under study (❶), considering a large number of economic, regulatory, social, and environmental factors of change. The output of this task consists of one or several scenarios characterized by assumptions in terms of land use, economic production, demographic growth, etc. Deterministic forecasting models are then used to estimate sector-level long term water demands associated with the scenarios considered (❷). Agricultural models typically simulate the impact of changes in cropping patterns, irrigation technologies, farming practices and climate (for examples see Rinaudo et al., 2013a; Wriedt et al., 2009). Urban water demand forecast are generally based on population growth and per capita water consumption, also related to the derived socioeconomic scenarios. Econometric models combined with evolution scenarios are commonly used for long-term strategic planning for urban water services (Donkor et al., 2014). The combined use of participatory foresight and demand forecasting models helps anticipating future water stress levels, setting the ground for a discussion of required adaptation measures. This part of the approach is strongly inspired by the literature using scenario analysis for determining robust adaptation options in natural resource management problems considering the uncertainty attached to future evolution (Carpenter et al., 2006; Lempert et al., 2006; Berkhout et al., 2002; March et al., 2012; Hatzilacou et al., 2007; Alcamo et al., 2007; Rinaudo et al., 2013a; Faysse et al., 2014). Participatory approaches are also used to identify and evaluate the local suitability of a range of adaptation options (❸). In this way, assessing some of the soft components that form the social capital of the stakeholders' groups, considered as determinant for the success of the adaptation process (Adger, 2003; Barron and Noel, 2011).

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

2.2. Top–down approach

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

2.3. Bottom–up meets top–down

The two approaches meet and feed each other through the development of an integrated water resources management model ❼ to support the definition of a climate adaptation strategy for global change. Simulation and optimisation models have been long applied to river basin planning and management (Jacoby and Loucks, 1972; Labadie, 2004; Singh, 2012). For instance, hydro-economic models enable economically efficient adaptation strategies to be defined, by integrating hydrologic, engineering, environmental and economic aspects of water resources systems within a coherent framework (Heinz et al., 2007; Harou et al., 2009). The approach allows for the comprehensive integration of economic efficiency (when introducing an economic objective in the optimisation for the selection of a programme of measures at the basin scale) and environmental goals (once environmental requirements have been included within the model constraints), while social acceptability is addressed through the identification of local adaption measures through the bottom–up process. Finally, to address the uncertainty of the global-change scenarios, it is essential to evaluate how robust water management plans are in relation to the uncertain future (Moody and Brown, 2013). To test the robustness of the adaptation plan 8, their performance is assessed across a range of different climate projections (climate check), and then compared by applying a multi-criteria decision making approach (e.g. Srdjevic et al., 2003; Huang et al., 2011).

3. Material and method

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

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

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

The region experiences the highest population growth rate in the country (1.6% per year), associated with important seasonal variation due to a tourist population in the summer. The agricultural sector encompasses more than 6000 ha of irrigated cultivated area, half of which corresponds to irrigated vineyards. The demand to irrigate the vineyards is skyrocketing in a process of converting from intensive wine production to higher-standard wines. Supplying urban water demand is competing in space and time with agricultural and environmental water demand. In the future, the combined effect of the increase in urban, agricultural

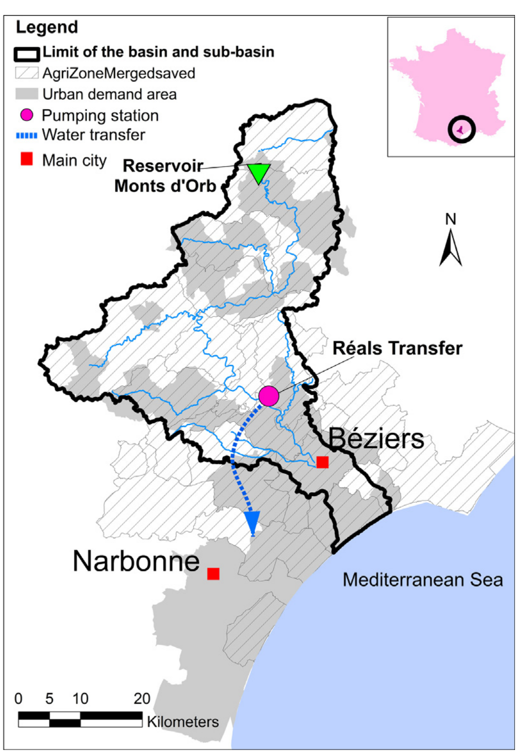

Fig. 2. Case study area: the Orb River basin.

and environmental water demand and of the impact of climate change is expected to further increase the pressure on the Orb's water resources.

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

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

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 (Fig. 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, 2007a,b). 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 finding groups of days exhibiting similar large-scale atmospheric circulations (weather type) that are the most discriminating regarding a local climatic variable of interest over a specific region and season. The considered large-scale variables are the mean sea level pressure and the average temperature at two meters. Each season is processed separately because the atmospheric circulation differs significantly between seasons. Once the major weather-types (accounting for most of the

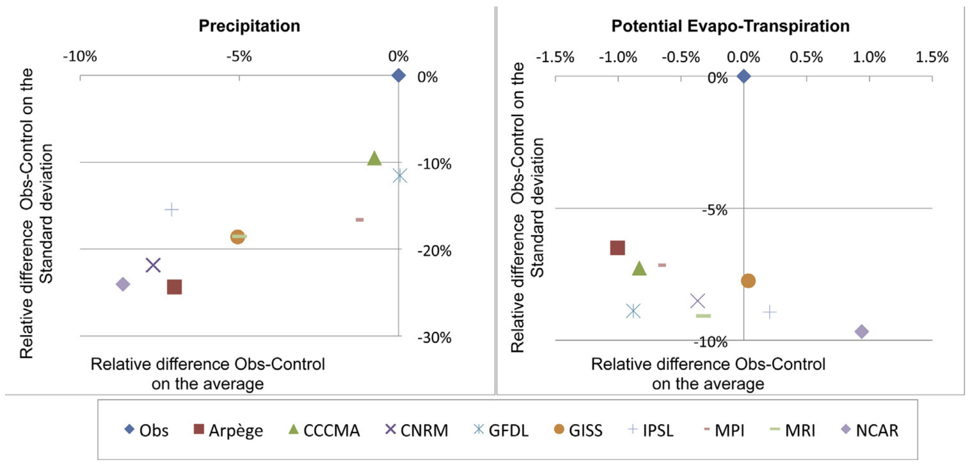

Fig. 3. Statistical analysis of climate data (average annual Potential Evapotranspiration, (PET) and Precipitation over the river basin) for 9 climate projections.

observed variance) have been derived using an automated classification algorithm for each season, each day of the learning period is classified according to its distance to each weather-type. A regression equation is then built combining the distances to weather-types and the local scale variables (precipitation, and also temperature for the summer season). These regression coefficients are then used for downscaling future local-scale conditions simulated by climate models. The control period is defined from 1971 to 2000, and the future period from 2046 to 2065. The climate data are provided on a daily time step with a spatial resolution of 8 km that fits the grid of the historical local meteorological data set SAFRAN (Quintana-Seguí et al., 2008), since it is used in the learning phase of the downscaling technique.

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

3.2.2. Hydrological model

A monthly lumped two-parameter rainfall-runoff model (GR2M, Mouelhi et al., 2006), forced by historical climatic data (precipitation and potential evapotranspiration) was calibrated and validated on each of the 11 sub-basins with the observed monthly discharge for 38 years, from 1970 to 2000 for the calibration and from 2001 to 2007 for the validation (6). The Nash and Sutcliffe (1970) efficiency criteria calculated are above 0.5 in the majority of the sub-basins and considered as acceptable (Girard, et al., 2015a). The models of each sub-basin are used to simulate future natural river discharge at their respective outlets, using the forcing data from the 9 downscaled climate projections (Caballero and Girard, 2012). The future monthly time flow series presents large variations between the different climate change scenarios (Fig. 4). Looking at the monthly time step, the dispersion between the climate projections is higher in the high-flow season than in summer, due to uncertainties in climate modelling. The summer low-flow seems to decrease in the future in comparison to the observed historical data. However, the average, or even a single low-flow indicator, are not enough for the selection of the adaptation measures as time series are needed in order to address how the water resource system behaves in a succession of dry and high-flow periods. Therefore, a future monthly time series over 20-years is used to account for the intra- and inter-annual reservoir management. The obtained discharge time series for each climate projection at selected locations across the basin were then

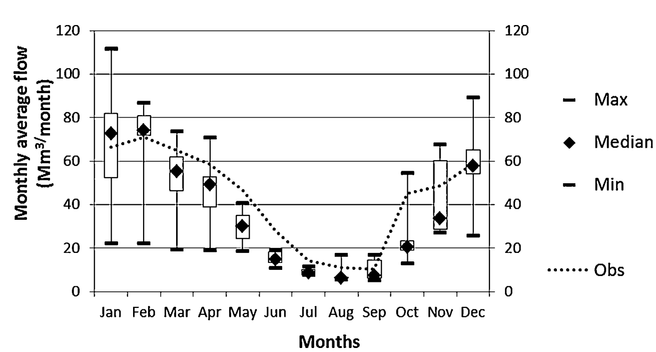

Fig. 4. Future mid-term (2046–2065) monthly average flow statistics across the 9 climate change scenarios vs. historical (1970–2000) monthly averages (Obs).

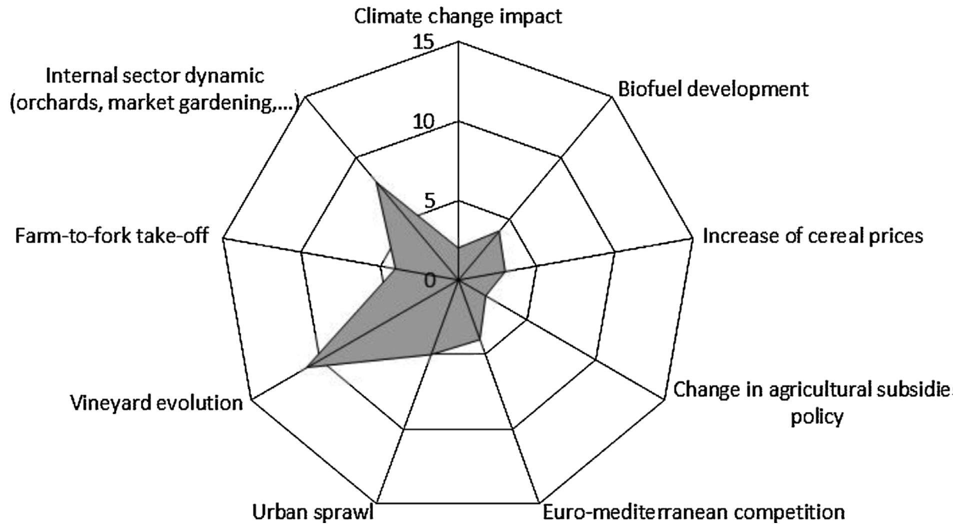

Fig. 5. Factors of change identified by consulted stakeholders as main drivers of future agricultural water demand (the score represents the number of experts that consider that the factor will strongly determine future evolution).

integrated in the water management model built at the Orb river basin scale.

3.3. Applying the bottom–up approach

3.3.1. The participatory process

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

3.3.2. Scenario building workshops

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

Stakeholders first debated on major factors of change (drivers), which they hierarchized (see Fig. 5). They then discussed possible trends associated with each driver and formulated quantitative assumptions that were used to frame three contrasted scenarios. We then tried to find a consensus on the most likely trends to build a baseline scenario, corresponding to a negotiated vision of future irrigated agriculture and considered as plausible and somehow desirable by participating stakeholders. The output of the workshop, of course, has a clear subjective dimension and we acknowledge that contradictory visions could have been expressed by other components of the civil society. However, because our stakeholders were considered as representative of actors whose decisions will shape the future in the Orb river basin, we used it as a baseline scenario.

The workshop output consisted of a series of assumptions on future irrigated areas, crops and technologies. This was then used to quantify the corresponding future irrigation water demand (Maton, 2008; Maton et al., 2012) using a methodology developed by the authors in a different case study (Rinaudo et al., 2013a).

Regarding urban development, the scenario was based on an in-depth analysis of past and present demographic and housing trends, on forecasts made by the National Institute for Statistical Studies (INSEE, France) and on interviews with urban planning experts. Because the uncertainty associated to future evolution of urban and demographic development is lower (at the 2030 time horizon considered), only one baseline scenario was constructed, what did not generate much controversy. The output from the scenario specifies population growth rate and new housing patterns at the municipal level at the 2030 time horizon, for which a new urban water demand was assessed (Vernier de Byans and Rinaudo, 2012).

3.3.3. Agricultural and urban demand models

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

Future urban water demand was also estimated for each of the 62 Urban Water Demand Units of the basin, using an econometric model (Rinaudo et al., 2012) which predicts water demand as a function of population growth, average household income, water price and climate, based on the evolution scenario (3.3.1). Results

[1] Additional information on the selection of stakeholders and their contribution is presented in the Supplementary material.

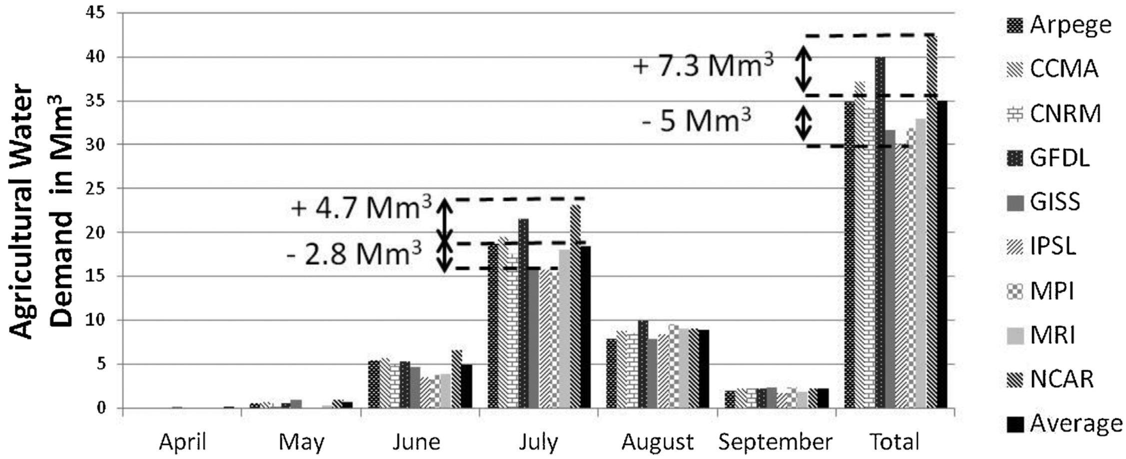

Fig. 6. Monthly average agricultural water demands at the basin scale for 9 futures mid-term (2046–2065) climate change scenarios.

predict an increase in the annual demand of 4.4 Mm^3 a year on average (Vernier de Byans and Rinaudo, 2012).

3.3.4. Identification and local selection of adaptation measures

After developing a socio-economic scenario depicting the most likely evolution of urban and agricultural water use in the basin at the 2030 time horizon, the expert group assisted the research team in screening a range of possible responses for coping with global change (3). A first catalogue of measures was elaborated by combining literature reviews (peer-review journals, technical reports and case study description-grey literature, as well as planning documents), personal communication with local experts (water managers, local authorities), and stakeholder consultation workshops. The three main evaluation criteria used to characterize local suitability were (i) technical, institutional and legal feasibility at the time horizon considered; (ii) capabilities of the actors to uptake the measures and (iii) societal and political acceptability (see supplementary material for more details).

Two types of responses were considered: planned and autonomous adaptation measures. Planned adaptation measures is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that actions are required to return to, maintain, or achieve a desired state. By contrast, autonomous adaptation does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems, by market, public policy or welfare changes in human systems (IPCC, 2007a,b).

In the study, the planned adaptation measures include: the optimisation of reservoir operation, further development of groundwater resources (new boreholes and water conveyance infrastructure), desalination, improved efficiency of large public agriculture irrigation schemes, reduction of leaks in municipal water distribution networks, and the implementation of tariffs that provide water conservation incentives. Autonomous adaptation measures consist of water conservation actions that can be implemented by households, municipal services and commercial activities (hotels, sea resorts) if they are provided with the right incentives (subsidies, technical information). The stakeholder consultation process led to the identification of a list of priority measures (13 type measures corresponding to 462 possible measures to be applied at the local level, Table 1 and supplementary material), while other measures were eliminated (i.e. rainwater harvesting, reuse) based on technical, economic, legal or acceptability criteria.

3.3.5. Economic and technical assessment of measures

The measures were characterised in terms of their cost and effectiveness (as volume of water saved or mobilised) for the different demand units of the basin (4). The calculations were made at the municipal level (Urban Demand Unit) for all urban water conservation measures, considering the heterogeneity of

Table 1
Characteristics of planned and autonomous adaptation measures considered.

Code	Description of measure	Maximum annual volume available in 2030 (Mm^3)	Average annualised unit cost (€/m^3)
	Planned adaptation measures		
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 vegetation (public gardens)	0.59	0.68
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
	Autnomous adaptation measures		
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

water users (type of houses, income) and water services (current tariffs, current level of leakage, etc.). Agricultural water conservation measures were evaluated at the irrigation district level (Agricultural demand Unit). Finally, water resource development (groundwater exploitation, desalination) was assessed at the project level. Annual costs were estimated considering investment and maintenance costs, the technical lifespan for the equipment, and a 4% discount rate (Rinaudo et al., 2013b,c). Table 1 shows the average cost per unit of water (€/m^3) and maximum volume of water that can be saved or mobilised with each measure.

3.4. When bottom–up meets top–down

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

3.4.1. Least-cost river basin optimisation model

The Least-Cost River Basin Optimisation Model (LCRBOM) selects the combination of adaptation measures that minimises the total annualised cost of the adaptation PoM while meeting the demand targets and minimum in-stream flow constraints (7) (Girard et al., 2015a,b). Economic elements are integrated in the optimization model: on one side the adaptation measures are characterised by their cost and effectiveness for each demand unit (as detailed in Section 3.3.5), and on the other side constraints are defined to ensure the supply of the urban and agricultural demands (defined in Section 3.3.3). The hydrological side of the modelling framework is then integrated as the optimisation is carried out over a 20-year monthly inflow time series provided by the hydrological model (Section 3.2.2) for the future scenarios corresponding to the 9 GCMs.

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

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

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

The LCRBOM yields a least-cost PoM of adaptation measures for each global change scenario. In order to assess the performance of the system under each PoM we have used a modified version of the demand reliability index (DRI) proposed by Martin-Carrasco et al.

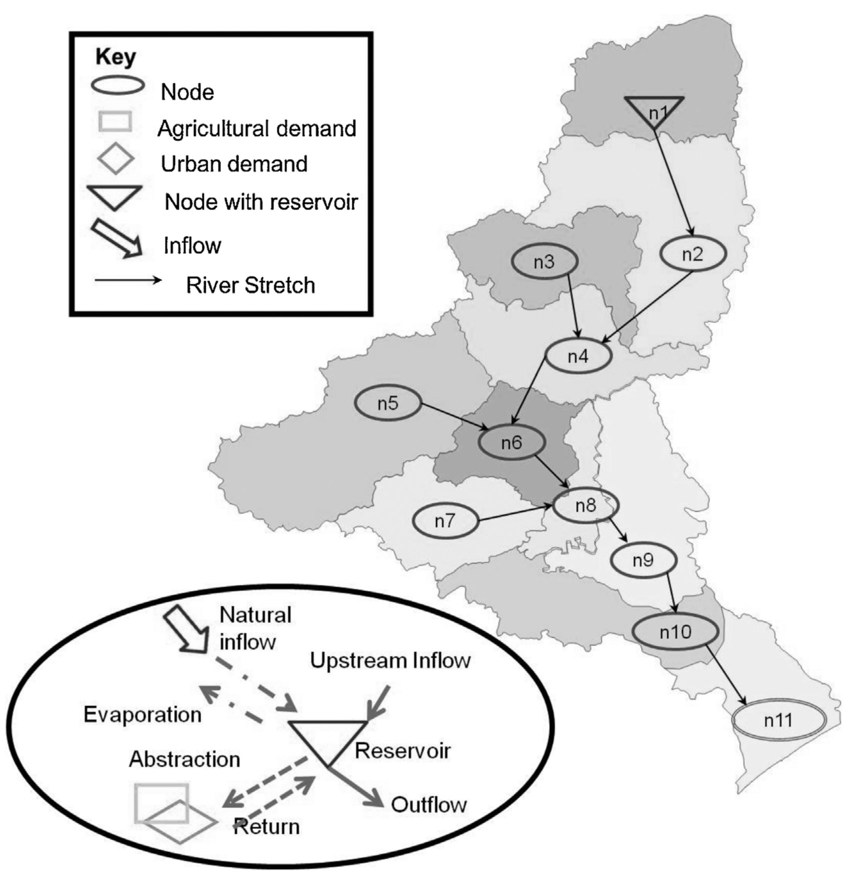

Fig. 7. Conceptual model of the Orb River with the flow network on the map of sub-basins, and details of mass balance at reservoir node n1.

(2013). The reliability index I is defined as the ratio of the demand supplied for a given acceptable level of reliability divided by the total annual water demand. We define this for the agricultural water sector by considering reliability as referring to a monthly failure of the supply associated with a return period of 5 years, as required by the French legislation (MEEDDT, 2008). Therefore, $I_r^a = S_r^a / D^a$, where I_r^a is the demand reliability index for the agricultural annual demand, “a”, and a reliability, “r”; S_r^a is the acceptable supply, or average amount of water supplied to agricultural demand with reliability greater or equal to the acceptable value “r”, in Mm^3/yr; and D^a is the multi-model average agricultural water demand, in Mm^3/yr (defined in Section 3.3.3).

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

3.5. Climate check

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

3.5.1. Performance matrix

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

$$p = \begin{pmatrix} \mathrm{PoM}_1 \\ \vdots \\ \mathrm{PoM}_n \end{pmatrix} \begin{array}{c} \begin{matrix} (w_1 & \dots & w_{m-1} & w_m) \end{matrix} \\ \begin{bmatrix} x_{11} & \dots & x_{1m-1} & x_{1m} \\ \vdots & \ddots & \vdots & \vdots \\ x_{n1} & \dots & x_{nm-1} & x_{nm} \end{bmatrix} \end{array} \quad (1)$$

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

3.5.2. Regret matrix

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

$$r_{ij} = \frac{|x_j^* - x_{ij}|}{|x_j' - x_j^*|}, \quad (2)$$

where x'_j is the worst performance for each criteria. The higher the index value, the more the performance deviates from the best one, which has an index of 0.

3.5.3. Weights for ranking

The value of the weights associated with each criterion can be defined by stakeholders, expert judgment or information theory methods (Srdjevic et al., 2004). As a starting point, the weight of each agricultural DRI under a climate change scenario (x_{i1}, x_{i2}, ..., x_{im-1}) are stated as equal (Eq. (3)), as we assume that scenarios are given the same weights and probabilities of occurrence (Section 3.2.1).

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

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

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

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

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

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

4. Results

4.1. Least-cost adaptation programmes of measures

9 different adaptation PoMs are defined through the LCRBOM, one for each climate projection (❼). The programmes have been characterised in terms of their cost and the agricultural DRI under each climate projection, assuming business-as-usual (BAU), i.e. without adaptation measures (Table 2). In 3 cases out of 9 there

Table 2
Demand reliability index without programme of measures (PoM) and cost of the optimal PoM for the 9 climate scenarios.

Climate projection	DRI without PoM	Cost of 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

was no need for a PoM in the future situation, while in the 6 remaining cases the annual cost of the PoM ranged from 0.2 M € (CCMA scenario) to 6.7 M € in the worst case (NCAR scenario). The relation between the cost of the PoM and the DRI without adaptation is not direct, given that some scenarios with similar DRI (0.940 and 0.941 for Arpège and GFDL respectively) lead to different PoM costs (2.7 M € and 1.5 M € respectively). In the following sections, the different PoMs are identified by the name of the GCM for which they have been optimised (i.e. the PoM GFDL is the least-cost PoM optimised for the climate projection coming from the GFDL general circulation model).

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

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

4.2. Climate check results

4.2.1. Assessing the performance matrix

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

4.2.2. Regret matrix

Drawn from the performance matrix, the regret matrix enables the comparison of different criteria (Table 4). It illustrates how the best performing PoMs for one criterion are not those of least-regret. The decision to not apply any PoM is the best-performing strategy according to the cost criterion (regret = 0) but the worst in regard to the agricultural DRI (regret = 1). In the opposite, the most expensive PoM obtained under the NCAR climate projections is the best-performing strategy in terms of DRI (regret = 0) but the worst in terms of cost (regret = 1). Given the weight assigned to the different performance criteria, the least-regret option would be to apply the PoM defined under the GISS climate change scenario corresponding to an aggregated regret of 0.15 balancing the cost of the PoM (0.7 M €) with an average DRI of 0.98. The PoM corresponding to the climate change scenario Arpège with aggregated regrets of 0.16 also seems to be worthy of further consideration.

4.2.3. Analysis of preferences

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

5. Discussion and conclusions

The methodological framework presented integrates conventional top–down and bottom–up approaches in an innovative and useful way to support the design of climate change adaptation strategies at the river basin scale. It combines computer-based and scenario-planning techniques in a bottom–up meets top–down perspective that accounts for economic efficiency, social acceptability, environmental sustainability and climate adaptation robustness. The bottom–up approach involves a multilevel scenario-building approach, applying participatory forecasting

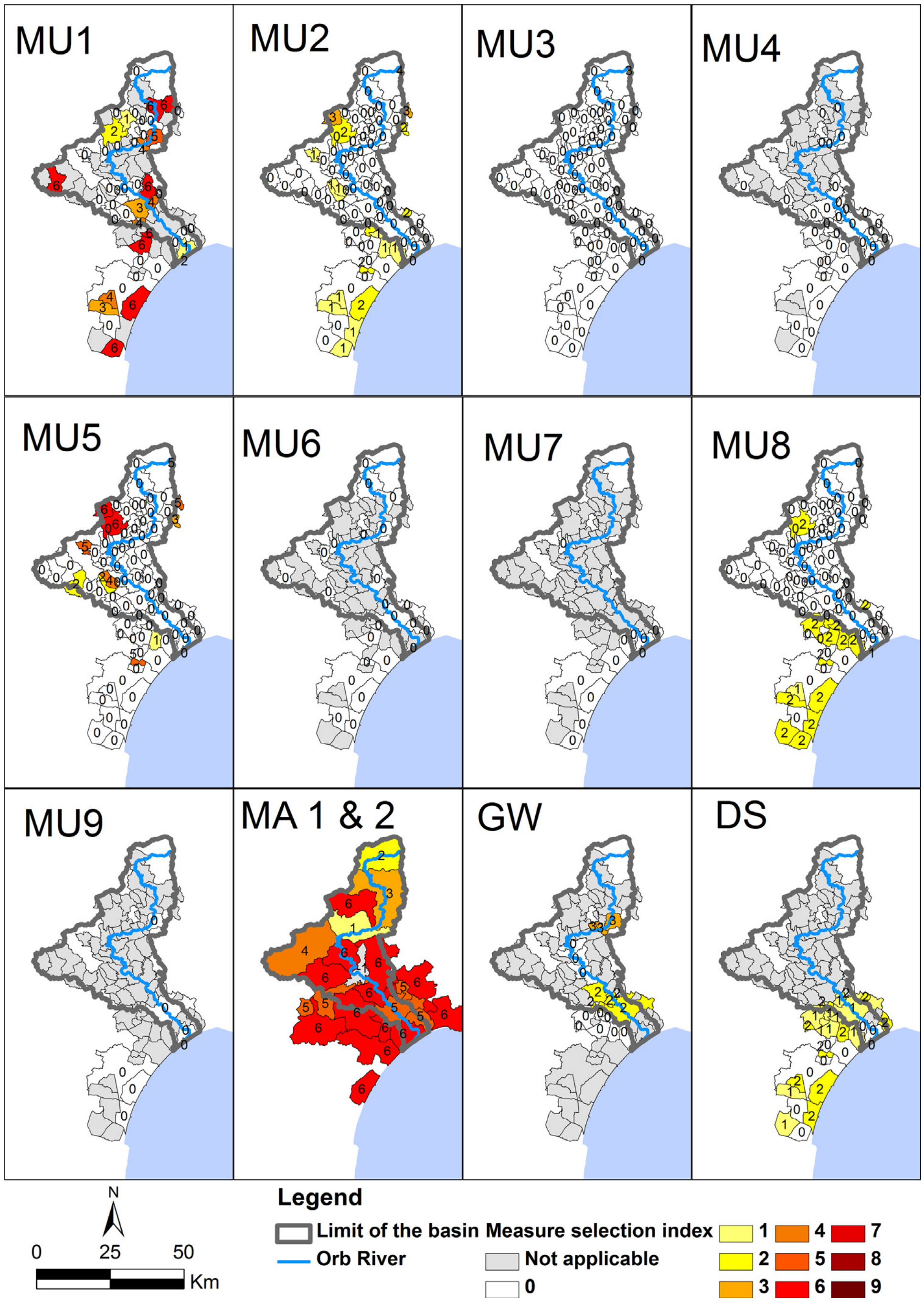

Fig. 8. Distribution of the measures applied in the Orb river basin. The number and colours indicate the level of confidence in the selection of the measure, ranging from 0 (white) to 9 (dark red), adding 1 each time the measure is selected under one of the 9 climate projections. The agricultural measures MA1 and 2, mutually exclusive, are presented together (measures described in Table 1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

techniques in combination with agricultural and urban demand simulations to estimate future demand scenarios. Local adaptation measures are identified and prioritised through multi-level stakeholder workshops (catalogue of measures), and systematically characterised in terms of cost and effectiveness. In the top–down approach, climate data are downscaled from a general climate model to hydrological impact to assess the future flow regime under climate uncertainty. The bottom–up approach meets the top–down when least-cost adaptation PoMs are identified using a hydro-economic optimisation model. Economic and reliability indicators of water resource system performance are evaluated under different future climate projections and for different adaptation programmes of measures. The resulting adaptation portfolios are then submitted to a climate check to address climate uncertainty, in order to assess the robustness of the potential decisions and to select the least-regret option.

The framework has been successfully implemented in a real case study, in the Orb River basin, in Southern France, to inform adaptation strategy defined at the local level on the best water management measures to be applied. Demand management measures, such as network efficiency improvement in irrigation and urban supply, seem to be the least-regret options. The need for supply-side capacity expansion measures, such as desalination plants or ground water exploitation, is limited given their high

Table 3
Performance matrix of the 9 programmes of measures under the 9 climate projections. (For interpretation of the references to colour in this table, the reader is referred to the web version of this article.)

PoM/CC projection	Demand reliability index (0–1)									Cost of the PoM (€)
	IPSL	MPI 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	1.00	1.00	1.00	0.99	0.96	0.94	0.94	0.86	0.87	0
MPI ECHAM	1.00	1.00	1.00	0.99	0.96	0.94	0.94	0.86	0.87	0
MRI	1.00	1.00	1.00	0.99	0.96	0.94	0.94	0.86	0.87	0
CCMA	1.00	1.00	1.00	1.00	0.97	0.95	0.95	0.89	0.89	213,497
GISS	1.00	1.00	1.00	1.00	1.00	0.98	0.98	0.94	0.94	771,784
Arpège	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.97	0.95	1,565,466
GFDL	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.96	0.95	2,730,458
CNRM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	2,905,221
NCAR	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	6,701,525

Table 4
Regrets matrix calculated to compare the performance of the 9 programmes of measures according to agricultural demand reliability index and annual costs.

PoM/CC projection	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

Table 5
Preference table of the aggregated regret for different combinations of weight between the agricultural DRI (%A) and the cost of the PoM (%C), the least-regret option is indicated in bold for each weighting, the colours are decided arbitrarily to provide four categories (below 0.20 (Green); from 0.2 to 0.3 (Yellow); from 0.3 to 0.4 (orange); more than 0.40 (red)). (For interpretation of the references to colour in this table, the reader is referred to the web version of this article.)

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

inversion cost; they are less cost-effective in a context of climate change uncertainty. The trade-offs between the cost of the adaptation plan and the reliability on the supply of agricultural demand have been identified. Depending on the preferences of the decision-makers, the appropriate level of adaptation can be defined to adapt to climate change. Without adaptation measures, the deficit in agricultural supply remains at what could be considered an acceptable level, in the driest regions of the world, challenging the need for adaptation in the Orb river basin. One reason for the relatively good adaptive capacity of the Orb river basin has to be linked to the storage capacity of the reservoir located up-stream of the basin, able to regulate the variations in runoff. On the contrary, meeting the legal requirement to supply agricultural demand under each scenario could be far too expensive to be assumed by the local actors. These variations highlight the interest of the framework presented. If the programme of adaptation measures is designed under only one climate projection, clearly, it could be inefficient, either by being over-designed at a very high cost, or under-designed at a low cost, but failing to provide the level of reliability required on the supply of demand. In this way, fruitful insights for adaptation decision-makers are provided for the design and discussion of adaptation plans with stakeholders. In this case study, the trade-offs between the planning objectives are limited to the cost of the programme of measures and the agricultural deficit, considering environmental issues as exogenous and defined by the legislator as “minimum in-stream flow requirements”. A stronger emphasis could be put on investigating different environmental considerations and their influence on the other parts of the problem. The definition of environmental objectives could be included as well in the bottom–up process. More performance indicators could be used to assess the performance of the system under uncertainty, or be incorporated as objectives through many objective optimisation techniques (Kasprzyk et al., 2013).

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

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

In any case, other kinds of uncertainties in both the modelling and the scenario planning processes still need to be addressed (Dessai et al., 2007). An improved characterisation of these uncertainties would ensure a higher level of robustness of the adaptation plan. From the top–down side, the analysis could be improved by performing the full downscaling method for the updated emission scenario with the latest Representative Concentration Pathway, considering a larger set of climate models (Rajagopalan et al., 2009), comparing results from downscaling techniques or hydrological models (Steinschneider et al., 2012), running a deeper sensitivity analysis to various components in the modelling chain (Dessai and Hulme, 2007). It could be tempting to use an ensemble-like approach, weighting each model according to their ability to simulate the past climate, hence attributing more probability to one scenario or another in the future. However, the literature tells us that it is not really possible to assess a model performance in a context similar to this study, as the results of such an evaluation will depend on the region, the season, etc. (Gleckler et al., 2008). Another innovative and more appropriate approach would be the use of model genealogy (Knutti et al., 2013), selecting models according to similarities in their dynamical and physical codes. This approach could be used in future studies to better assess model uncertainties. However, various methods already exist to manage climate uncertainty in the planning of water resources systems, as illustrated in two recent special issues (Dessai et al., 2013; Salas et al., 2012), applying techniques such as robust decision-making, decision-scaling, or real option analysis and relying on computational techniques such as scenario discovery, info-gap decision theory (Hassnoot, 2013).

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

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

Indeed, to properly address the issue of planning for adaptation, the framework should fit into a wider management framework that accounts for what is learned as future conditions are experienced and that allows for the dynamic update of plans under an adaptive management paradigm (Walters, 1986; Johnson, 1999; Convertino et al., 2013). The current framework brings some insights for describing and analysing adaptation at the river basin scale, as well as for the identification of adaptation actions under climate uncertainties, which are necessary first steps to frame dynamic adaptive policy pathways for instance (Hassnoot et al., 2013).

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

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

Acknowledgements

The study has been financially supported by BRGM-ONEMA joint project on Hydro-economic modelling and by the IMPADAPT project (CGL2013-48424-C2-1-R) from the Spanish ministry MINECO (Ministerio de Economía y Competitividad) with European FEDER funds. Corentin Girard is supported by a grant from the University Lecturer Training Program (FPU12/03803) of the Ministry of Education, Culture and Sports of Spain. We also acknowledge the CERFACS for the climate scenarios provided from the SCRATCH 2010 dataset (March 2012 release - http://www.cerfacs.fr/~page/work/scratch/). We thank as well the anonymous reviewers and the Editors of Global Environmental Change, for their useful and encouraging comments during the review process.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2015.07.002.

References

Adger, W.N., Dessai, S., Goulden, M., Hulme, M., Lorenzoni, I., Nelson, D.R., Naess, L. O., Wolf, J., Wreford, A., 2009. Are there social limits to adaptation to climate change. Clim. Change 93, 335–354.

Adger, N.W., 2003. Social capital, collective action, and adaptation to climate change. Econ. Geogr. 79 (4), 387–404.

AERMC (Agence de l'Eau Rhône Méditerranée Corse), 2009. Schéma directeur d'aménagement et de gestion des eaux du bassin Rhône-Méditerranée. Vers le bon état des milieux aquatiques. Agence de l'Eau Rhône, Méditerranée, Corse. (In French) Access at http://www.rhone-mediterranee.eaufrance.fr/docs/dce/sdage/docs-officiels/HD/sdage-2010-2015_VF.pdf.

Alcamo, J., Flörke, M., Märker, M., 2007. Future long-term changes in global water resources driven by socio-economic and climatic changes. Hydrol. Sci. J. 52, 247–275.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations, Rome, Italy ISBN 92-5-104219-5.

Bangash, R.F., Passuello, A., Sanchez-Canales, M., Terrado, M., López, A., Elorza, F.J., Ziv, G., Acuña, V., Schuhmacher, M., 2013. Ecosystem services in Mediterranean river basin: climate change impact on water provisioning and erosion control. Sci. Total Environ. 458–460, 246–255.

Barron, J., Noel, S., 2011. Valuing soft components in agricultural water management interventions in meso-scale watersheds: a review and synthesis. Water Altern. 4 (2), 145–154.

Barthel, R., Janisch, S., Schwarz, N., Trifkovic, A., Nickel, D., Schulz, C., Mauser, W., 2008. An integrated modelling framework for simulating regional-scale actor responses to global change in the water domain. Environ. Modell. Softw. 23, 1095–1121.

Berkhout, F., Hertin, J., Jordan, A., 2002. Socio-economic futures in climate change impact assessment: using scenarios as 'learning machines. Glob. Environ. Change 12, 83–95.

Bates, B.C., Kundzewicz, Z.W., Wu, S., Palutikof, J.P., 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change. IPCC, Secretariat, Geneva, pp. 210.

Bhave, A.G., Mishra, A., Raghuwanshi, N.S., 2013. A combined bottom–up and top–down approach for assessment of climate change adaptation options. J. Hydrol..

Biesbroek, G.R., Swart, R.J., Carter, T.R., Cowan, C., Henrichs, T., Mela, H., Morecroft, M.D., Rey, D., 2010. Europe adapts to climate change: comparing national adaptation strategies. Glob. Environ. Change 20, 440–450.

Boé, J., Terray, L., Cassou, C., Najac, J., 2009. Uncertainties in European summer precipitation changes: role of large scale circulation. Clim. Dynam. 33, 265–276.

Boé, J., Terray, L., 2008. A weather-type approach to analyzing winter precipitation in France: twentieth-century trends and the role of anthropogenic forcing. J. Climate 21 (13), 3118.

Brown, C., Wilby, R.L., 2012. An alternate approach to assessing climate risks. Eos 93, 401–402.

Caballero, Y., Voirin-Morel, S., Habets, F., Noilhan, J., LeMoigne, P., Lehenaff, A., Boone, A., 2007. Hydrological sensitivity of the Adour-Garonne river basin to climate change. Water Resour. Res. 43.

Caballero Y., Girard C., 2012. Impact du changement climatique sur la ressource en eau du bassin versant de l'Orb. Rapport BRGM/RP-61319-FR. 40 p., 16 ill. (In French) http://infoterre.brgm.fr/rapports/RP-61319-FR.pdf.

Carpenter, S.R., Bennett, E.M., Peterson, G.D., 2006. Scenarios for ecosystem services: an overview. Ecol. Soc. 11 (1), 29.

Convertino, M., Foran, C.M., Keisler, J.M., Scarlett, L., LoSchiavo, A., Kiker, G.A., Linkov, I., 2013. Enhanced adaptive management: integrating decision analysis, scenario analysis and environmental modeling for the everglades, scientific reports. Nat. Publ. Group 3, 2922. doi:http://dx.doi.org/10.1038/srep02922.

Dessai, S., Hulme, M., 2004. Does climate adaptation policy need probabilities. Clim. Policy 4, 107–128.

Dessai, S., Lu, X., Risbey, J.S., 2005. On the role of climate scenarios for adaptation planning. Glob. Environ. Change 15, 87–97.

Dessai, S., Hulme, M., 2007. Assessing the robustness of adaptation decisions to climate change uncertainties: a case study on water resources management in the east of England. Glob. Environ. Change 17, 59–72.

Dessai, S., O'Brien, K., Hulme, M., 2007. Editorial: on uncertainty and climate change. Glob. Environ. Change 17, 1–3.

Dessai, S., Browne, A., Harou, J.J., 2013. Introduction to the Special Issue on Adaptation and Resilience of Water Systems to an Uncertain Changing Climate. Water Resour. Manag. 27, 943–948. doi:http://dx.doi.org/10.1007/s11269-012-0254-3.

Donkor, E.A., Mazzuchi, T.A., Soyer, R., Alan Roberson, J., 2014. Urban water demand forecasting: review of methods and models. J. Water Resour. Plan. Manag. 140, 146–159.

Dovers, S., 2009. Normalizing adaptation. Glob. Environ. Change 19, 4–6.

EC (European Commission), 2009. River basin management in a changing climate. Common i Mplementation Strategy for the Water Framework Directive (2000/60/EC), Guidance Document No. 24. European Union Publications Office ISBN 978 92 79 14298 7.

Ekström, M., Kuruppu, N., Wilby, R.L., Fowler, H.J., Chiew, F.H.S., Dessai, S., Young, W. J., 2013. Examination of climate risk using a modified uncertainty matrix framework—Applications in the water sector. Glob. Environ. Change 23, 115–129.

Faysse, N., Rinaudo, J.-D., Bento, S., Richard-Ferroudji, A., Errahj, M., Varanda, M., Imache, A., Dionnet, M., Rollin, D., Garin, P., Kuper, M., Maton, L., Montginoul, M., 2014. Participatory analysis for adaptation to climate change in Mediterranean agricultural systems: possible choices in process design. Reg. Environ. Change 14, 57–70.

Fowler, H.J., Blenkinsop, S., Tebaldi, C., 2007. Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. Int. J. Climatol. 27, 1547–1578.

Giorgi, F., Lionello, P., 2008. Climate change projections for the Mediterranean region. Global Planet. Change 63, 90–104.

Girard, C., Rinaudo, J.D., 2013. Evolution des besoins en eau d'irrigation à l'horizon 2030 dans l'Ouest de l'Hérault Rapport BRGM- RP-61323-FR. 41 pages (In French) Available at http://infoterre.brgm.fr/rapports/RP-61323-FR.pdf.

Girard, C., Rinaudo, J.D., Pulido-Velazquez, M., Caballero, Y., 2015a. An interdisciplinary modelling framework for selecting adaptation measures at the river basin scale in a global change scenario. Environ. Model. Software 69, 42–54. http://dx.doi.org/10.1016/j.envsoft.2015.02.023.

Girard, C., Rinaudo, J.D., Pulido-Velazquez, M., 2015b. Index-based cost-effectiveness analysis vs. least-cost river basin optimization model: comparison in the selection of a programme of measures at the river basin scale. Water Resour. Manage. doi:http://dx.doi.org/10.1007/s11269-015-1049-0 Published online 10 July 2015.

Gleckler, P.J., Taylor, K.E., Doutriaux, C., 2008. Performance metrics for climate models. J. Geophys. Res. D 113.

Gleick, P.H., 2003. Global freshwater resources: soft-path solutions for the 21st century. Science 302, 1524–1528.

Groves, D.G., Robert Lempert, J., Debra Knopman, Sandra Berry, H., 2008. Preparing for an Uncertain Future Climate in the Inland Empire Identifying Robust Water-Management Strategies. Rand Corporation, Santa Monica, CA, pp. 98.

Haasnoot, M., Kwakkel, J.H., Walker, W.E., ter Maat, J., 2013. Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. Glob. Environ. Change 23, 485–498.

Hallegatte, S., 2009. Strategies to adapt to an uncertain climate change. Glob. Environ. Change 19, 240–247.

Harou, J.J., Pulido-Velazquez, M., Rosenberg, D.E., Medellín-Azuara, J., Lund, J.R., Howitt, R.E., 2009. Hydro-economic models: concepts, design, applications, and future prospects. J. Hydrol. 375, 627–643.

Hatzilacou, D., Kallis, G., Mexa, A., Coccosis, H., Svoronou, E., 2007. Scenario workshops: a useful method for participatory water resources planning. Water Resour. Res. 43.

Hayes, K., 2011. Uncertainty and uncertainty analysis methods. Australian Centre of Excellence for Risk Assessment (ACERA) project 0705A. Report number EP102467, 131 pp. Available online at: http://www.acera.unimelb.edu.au/materials/endorsed/0705a_final-report.pdf.

Heinz, I., Pulido-Velazquez, M., Lund, J.R., Andreu, J., 2007. Hydro-economic modelling in river basin management: Implications and applications for the European water framework directive. Water Resour. Manag. 21, 1103–1125.

Hoang, T., Maton, L., Caballero, Y. et Rinaudo J-D. Impact du changement climatique sur le besoin en eau d'irrigation dans l'Ouest de l'Hérault. Rapport Brgm RP-61311-FR. 36 pages + 2 annexes. http://infoterre.brgm.fr/rapports/RP-61311-FR.pdf.

Huang, I.B., Keisler, J., Linkov, I., 2011. Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. Sci. Total Environ. 409, 3578–3594.

Hwang, C.L., Yoon, K., 1981. Multiple Attribute Decision Making: Methods and Applications. Springer-Verlag, New York, pp. 1981.

Iglesias, A., Garrote, L., Flores, F., Moneo, M., 2007. Challenges to manage the risk of water scarcity and climate change in the Mediterranean. Water Resour. Manag. 21, 775–788.

IPCC, 2007a. Climate change 2007: synthesis report. Contribution of Working Groups I–III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, University Press, Cambridge.

IPCC, 2007. Appendix 1: Glossary in: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., Cambridge University Press, Cambridge, UK.

IPCC, (2014) Annex XX: Glossary [J., Agard, E.L.F., Schipper, J., Birkmann, M., Campos, C., Dubeux, Y., Nojiri, L., Olsson, B., Osman-Elasha, M., Pelling, M.J., Prather, M.G., Rivera-Ferre, O.C., Ruppel, A., Sallenger, K.R., Smith, A.L. St. Clair, K.J., Mach, M.D., Mastrandrea, T.E., Bilir (eds.)]. In: Climate Change 2014: Impacts, Adaptation,

and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [V.R., Barros, C.B., Field, D.J., Dokken, M.D., Mastrandrea, K.J., Mach, T.E., Bilir, M., Chatterjee, K.L., Ebi, Y.O., Estrada, R.C., Genova, B., Girma, E.S., Kissel, A.N., Levy, S., MacCracken, P.R., Mastrandrea, L.L., White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Jacoby, H.D., Loucks, D.P., 1972. Combined use of optimization and simulation models in river basin planning. Water Resour. Res. 8 (6), 1401–1414. doi:http://dx.doi.org/10.1029/WR008i006p01401.
Johnson, B.L., 1999. The role of adaptive management as an operational approach for resource management agencies. Conserv. Ecol. 3, 8.
Kasprzyk, J.R., Nataraj, S., Reed, P.M., Lempert, R.J., 2013. Many objective robust decision making for complex environmental systems undergoing change. Environ. Modell. Softw. 42, 55–71.
Kjellström, E., Thejll, P., Rummukainen, M., Christensen, J.H., Boberg, F., Christensen, O.B., Maule, C.F., 2013. Emerging regional climate change signals for Europe under varying large-scale circulation conditions. Clim. Res. 56, 103–119.
Knutti, R., Furrer, R., Tebaldi, C., Cermak, J., Meehl, G.A., 2010. Challenges in combining projections from multiple climate models. J. Clim. 23, 2739–2758.
Knutti, R., Masson, D., Gettelman, A., 2013. Climate model genealogy: generation CMIP5 and how we got there. Geophys. Res. Lett. 40, 1194–1199.
Labadie, J.W., 2004. Optimal operation of multireservoir systems: state-of-the-art review. J. Water Resour. Plan. Manag. 130, 93–111.
Leavesley, G.H., 1994. Modeling the effects of climate change on water resources—a review. Clim. Change 28, 159–177.
Lempert, R.J., Groves, D.G., Popper, S.W., Bankes, S.C., 2006. A general, analytic method for generating robust strategies and narrative scenarios. Manag. Sci. 52, 514–528.
Ludwig, R., Roson, R., Zografos, C., Kallis, G., 2011. Towards an inter-disciplinary research agenda on climate change, water and security in Southern Europe and neighboring countries. Environ. Sci. Policy 14, 794–803.
Madani, K., Lund, J.R., 2011. A Monte-Carlo game theoretic approach for multi-criteria decision making under uncertainty. Adv. Water Resour. 34, 607–616.
March, H., Therond, O., Leenhardt, D., 2012. Water futures: reviewing water-scenario analyses through an original interpretative framework. Ecol. Econ. 82, 126–137.
Mariotti, A., Zeng, N., Yoon, J., Artale, V., Navarra, A., Alpert, P., Li, L.Z.X., 2008. Mediterranean water cycle changes: transition to drier 21st century conditions in observations and CMIP3 simulations. Environ. Res. Lett. 3.
Maton, L., Girard, C., and Rinaudo, J.D., 2012. Evolution des besoins en eau d'irrigation à l'horizon 2030 dans l'Ouest de l'Hérault. Rapport BRGM-RP-61323-FR. 51 pages, 2 annexes. http://infoterre.brgm.fr/rapports/RP-61323-FR.pdf (In French).
Maton, L., 2008. Evaluation économique du programme de mesures de gestion quantitative des ressources en eau dans l'Ouest de l'Hérault. Volume 1: Scénario tendanciel et analyse coÛt-efficacité pour l'usage agricole de l'eau. Rapport BRGM-RP-56143-FR. 89 p http://infoterre.brgm.fr/rapports/RP-56143-FR.pdf.
Martin-Carrasco, F., Garrote, L., Iglesias, A., Mediero, L., 2013. Diagnosing causes of water scarcity in complex water resources systems and identifying risk management actions. Water Resour. Manag. 27, 1693–1705.
Mastrandrea, M.D., Heller, N.E., Root, T.L., Schneider, S.H., 2010. Bridging the gap: linking climate-impacts research with adaptation planning and management. Clim. Change 100, 87–101.
Mearns, L.O., 2010. The drama of uncertainty. Clim. Change 100, 77–85.
MEDDTL (Ministère de l'Ecologie du Développement Durable, des Transports et du Logement), 2011. Plan National d'adaptation au Changement Climatique, 2011–2015. Paris, 2011 (In French).
MEEDDT (Ministère de l'écologie, de l'énergie, du développement durable et de l'aménagement du teritoire), 2008. Circulaire du 30 juin 2008 relative à la résorption des déficits quantitatifs en matière de prélèvement d'eau et gestion collective des prélèvements d'irrigation NOR: DEVO0815432C, Bulletin officiel du Ministère de l'écologie, de l'énergie, du développement durable et de l'aménagement du teritoire, Paris, 2008 (In French).
Meehl, G.A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J.F.B., Stouffer, R.J., Taylor, K.E., 2007. The WRCP CMIP3 multimodel dataset—a new era in climate change research. Bull. Am. Meteor. Soc. 88, 1383–1394.
Meyer, R., 2012. Uncertainty as a science policy problem. Clim. Change 110, 1–2.
Milano, M., Ruelland, D., Fernandez, S., Dezetter, A., Fabre, J., Servat, E., 2012. Facing climatic and anthropogenic changes in the Mediterranean basin: what will be the medium-term impact on water stress. C. R. Geosci. 344, 432–440.
Moody, P., Brown, C., 2013. Robustness indicators for evaluation under climate change: application to the upper Great Lakes. Water Resour. Res. 49, 3576–3588.
Mouelhi, S., Michel, C., Perrin, C., Andréassian, V., 2006. Stepwise development of a two-parameter monthly water balance model. J. Hydrol. 318, 200–214.
Munaretto, S., Siciliano, G., Turvani, M.E., 2014. Integrating adaptive governance and participatory multicriteria methods: a framework for climate adaptation governanceEcol. Soc. 19 (2) . . 74 http://dx.doi.org/10.5751/ES-06381-190274.
Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models. J. Hydrol. 10 (3), 282–290.
Pagé, C. and Terray, L., 2010. Nouvelles projections climatiques à échelle fine sur la France pour le 21ème siècle: les scénarii SCRATCH2010. Technical Report TR/CMGC/10/58, SUC au CERFACS, URA CERFACS/CNRS No1875CS, Toulouse, France (In French). http://www.cerfacs.fr/~page/work/scratch/.
Pahl-Wostl, C., 2009. A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. Glob. Environ. Change 19 (3), 354–365. doi:http://dx.doi.org/10.1016/j.gloenvcha.2009.06.001.
Praskievicz, S., Chang, H., 2009. A review of hydrological modelling of basin-scale climate change and urban development impacts. Progress Phys. Geogr. 33, 650–671.
Prella Hubacekb, C., Hubacekb, K., Reed, M., 2009. Stakeholder analysis and social network analysis in natural resource management. Soc. Nat. Resour. Int. J. 22 (6), 501–518. doi:http://dx.doi.org/10.1080/08941920802199202.
Prudhomme, C., Wilby, R.L., Crooks, S., Kay, A.L., Reynard, N.S., 2010. Scenario-neutral approach to climate change impact studies: application to flood risk. J. Hydrol. 390, 198–209.
Pulido-Velazquez, D., García-Aróstegui, J.L., Molina, J., Pulido-Velazquez, M., 2014. Assessment of future groundwater recharge in semi-arid regions under climate change scenarios (serral-salinas aquifer, SE Spain). could increased rainfall variability increase the recharge rate? Hydrol. Process..
Quevauviller, P., 2014. European water policy and research on water-related topics—an overview. J. Hydrol..
Quintana-Seguí, P., Le Moigne, P., Durand, Y., Martin, E., Habets, F., Baillon, M., Canellas, C., Franchisteguy, L., Morel, S., 2008. Analysis of near-surface atmospheric variables: validation of the SAFRAN analysis over France. J. Appl. Meteor. Climatol. 47, 92–107.
Rajagopalan, B., Nowak, K., Prairie, J., Hoerling, M., Harding, B., Barsugli, J., Ray, A., Udall, B., 2009. Water supply risk on the Colorado River: can management mitigate? Water Resour. Res. 45.
Rinaudo, J.D., Neverre, N., Montginoul, M., 2012. Simulating the impact of pricing policies on urban water demand: a Southern France case study. Water Resour. Manag. 26 (7), 2057–2068.
Rinaudo, J.D., Maton, L., Terrason, I., Chazot, S., Richard-Ferroudji, A., Caballero, Y., 2013a. Combining scenario workshop with modelling to assess future irrigation water demands. Agric. Water Manag. 130, 103–112.
Rinaudo, J-D, Noel, Y., Marchal, J.-P., Lamotte, C., 2013b. Evaluation du coÛt de mobilisation de nouvelles ressources en eau souterraine dans l'Ouest de l'Hérault. Rapport BRGM-RP-61794-FR http://infoterre.brgm.fr/rapports/RP-61794-FR.pdf (In French).
Rinaudo JD, Girard C., Vernier de Byans C, (2013c), Analyse coÛt efficacité du programme de mesures de gestion quantitative: Application de deux méthodes au bassin versant de l'Orb Rapport BRGM. Available at http://infoterre.brgm.fr/rapports/RP-62713-FR.pdf (In French).
Rosenthal, E., 2012. GAMS, A User's Guide Tutorial by Richard E. Rosenthal. GAMS Development Corporation, Washington, D.C., USA.
Salas, J.D., Rajagopalan, B., Saito, L., Brown, C., 2012. Special section on climate change and water resources: climate non-stationarity and water resources management. J. Water Resour. Plan. Manag. 138, 385–388.
Singh, A., 2012. An overview of the optimization modelling applications. J. Hydrol. 466–467, 167–182.
SMVO (Syndicat Mixte de la Vallée de l'Orb), (2013). Contrat de rivière Orb-Libron, 2011–2015, Dossier définitif, Dossier M001 8 03 039/EV (in French).
Smit, B., Wandel, J., 2006. Adaptation, adaptive capacity and vulnerability. Glob. Environ. Change 16, 282–292.
Smith, J.B., 1997. Setting priorities for adapting to climate change. Glob. Environ. Change 7, 251–264.
Sperna-Weiland, F.C., Van Beek, L.P.H., Kwadijk, J.C.J., Bierkens, M.F.P., 2012. Global patterns of change in discharge regimes for 2100. Hydrol. Earth Syst. Sci. 16, 1047–1062.
Srdjevic, B., Medeiros, Y.D.P., Faria, A.S., 2004. An objective multi-criteria evaluation of water management scenarios. Water Resour. Manag. 18, 35–54.
Steinschneider, S., Polebitski, A., Brown, C., Letcher, B.H., 2012. Toward a statistical framework to quantify the uncertainties of hydrologic response under climate change. Water Resour. Res. 48.
Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. Bull. Am. Meteorol. Soc. 93, 485–498. http://dx.doi.org/10.1175/BAMS-D-11-00094.1.
Terray, L., Boé, J., 2013. Quantifying 21st-century France climate change and related uncertainties. C. R. Geosci. 345, 136–149.
Teutschbein, C., Seibert, J., 2012. Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. J. Hydrol. 456–457, 12–29.
UNECE (United Nations Economic Commission for Europe), 2009. Guidance on Water and Adaptation to Climate Change, ECE/MP.WAT/30, United Nations, Geneva, ISBN: 978-92-1-117010-8.
Vernier de Byans, M. and Rinaudo, J.D., 2012. Scénarios d'évolution de la demande en eau potable à l'horizon 2030 dans l'Ouest Hérault. Rapport BRGM/RP-61317-FR. Brgm Orléans. 51 p + ann. Available at http://infoterre.brgm.fr/rapports/RP-61317-FR.pdf.
Vier E. and Aigoui. F. (2011) Etude de définition des débits d'étiage de référence pour la mise en oeuvre d'une gestion quantitative de la ressource en eau dans le bassin de l'Orb. Rapport provisoire phases 1 et 2. Avril 2011. Syndicat mixte de la vallée de l'Orb. (in French).
Walters, C.J., 1986. Adaptive Management of Renewable Resources. McMillian, New York.
Wilby, R.L., Dessai, S., 2010. Robust adaptation to climate change. Weather 65, 180–185.
Wriedt, G., Van der Velde, M., Aloe, A., Bouraoui, F., 2009. Estimating irrigation water requirements in Europe. J. Hydrol. 373, 527–544.