

Answer to comments from Referee 1

On "Sustainability of water uses in managed hydrosystems: human- and climate-induced changes for the mid-21st century" by Fabre et al.

▪ **Referee comment**

This paper analyses water scarcity in two Mediterranean watersheds. For 2050 scenarios of future water availability and water demand are calculated, "water demand satisfaction indicators" are set up and compared to values from 2000. In principle the overall topic of the manuscript is highly relevant, since the Mediterranean region is facing severe water shortage already today which is accelerated by anticipated global change. Also the methods used are adequate.

However, the paper contains a high level of redundant information compared to two recent papers by the same authors: A. Grouillet et al. (2015), Journal of Hydrology 522, 684–696 deals with historic and future water demand. B. Fabre et al. (2015), Hydrol. Earth Syst. Sci., 19, 1263–1285 deals with a historic comparison between water demand and water availability. All papers use the same catchments, the same models and the same data. A manual check revealed a high level of analogy. Several figures and paragraphs of the texts are similar, some parts even identical. This is especially true for parts of the introduction, study area and methodology (Fig. 1 and 2). This means, the present paper needs to be condensed to build upon published information and needs to concentrate on really novel findings that have not been published before.

Authors' response

We would like to thank the Referee for reviewing our submission and for his interest in the topic.

However, we were surprised at the Referee's judgement on this paper's redundancy with the two published papers Grouillet et al. (2015) and Fabre et al. (2015).

While the paper from Fabre et al. (2015) presented the development of the integrated modelling chain and its validation over a past period of nearly 40 years and the paper from Grouillet et al. (2015) aimed at reconstructing historical water demand and at proposing a trend scenario of water uses according to local socio-economic projections and under 9 climate scenarios, the submitted paper relies on these two previous publications to provide an integrated analysis of the balance between water availability and water uses under both human- and climate-induced changes for the mid-21st century. Projections of water demand satisfaction were carried out according to four combinations of water use and climate scenarios. The work presented in the submitted paper made it possible to assess risks of unbalance between water uses and water availability while considering uncertainty that stems from the spread of 18 climate scenarios (9 GCMs under two Radiative Concentration Pathways). The risks of unbalance were considered through human water demand satisfaction but also through compliance with environmental flow requirements, another element not included in the published papers by Fabre et al. and Grouillet et al.

We would wish to stress the fact that given the amount of data processing and the complexity of developing an integrative modelling approach, a single paper could not provide enough details to explain rigorously all the different aspects that were first exposed in the previous papers (Fabre et al., 2015; Grouillet et al., 2015) while exposing this original study that consisted in running our integrated modelling chain to assess the sustainability of planned water uses in the studied river systems under multiple climate change scenarios, and to contribute to

determining the possible causes of unsustainability. On the other hand, it was not possible to write this new paper without providing the reader with minimum information on the studied catchments, the models and data used.

Moreover, we were surprised at the fact that using the same catchments, models and data for validation over the past and future projections would be a problem. As was underlined in Fabre et al. (2015) the calibration and validation of the integrative model over a long past period is essential before using the model for projections; projections of risks of future water stress in different study areas with a different model does not seem to make much sense.

The referee also underlined that some parts of the text were similar between the published papers and the submitted paper.

In the introduction only paragraph 4 (p.9250 line 27 to p.9251 line 12) addressed an issue cited in the introduction of Fabre et al. (2015), which is the need to account for the influence of human water use and management on streamflow.

In the study area section, many similarities can indeed be found between the submitted paper and Fabre et al. (2015). However if one considers it necessary to first develop the model and then apply it for projections of future changes on the same study areas, then the usefulness of writing a different presentation of the study areas seems limited. The referee also underlined that Figure 1, which represents the study areas, was similar to Figure 1 of Fabre et al. (2015). Indeed Figure 1 of the submitted manuscript condenses Figures 1 and 3 of Fabre et al. (2015), showing the location of the main human pressures on water resources and the conceptual representation of the study areas through resource and demand nodes. It seems to us that this figure is essential to the submitted paper, which would be much more difficult to follow without a correct representation of the study areas.

As for similarities in the Methods section, on the 7 pages of methods in the submitted paper, 2 are indeed quite similar to the published paper Fabre et al. (2015), since it seemed to us that a minimum of information on the models used needed to be provided in order to better understand the submitted paper. The Referee underlines that Figure 2 is similar to the figure describing the integrative modeling framework in Fabre et al. (2015). Indeed, since this submitted paper uses the model developed and validated over the past in Fabre et al. (2015) to project future risks of water stress, these figures are bound to be similar. However environmental flows were added and indicators used were different compared to Fabre et al. (2015).

▪ **Referee comment**

A recent paper: J. Fabre et al. (2015), Proc. IAHS, 371, 43–48, creates additional problems in this respect. This open access publication is a conference proceedings but comprises exactly the same information as the present manuscript: It compares future water availability and water demand and develops the same indicators as the present study. It contains almost identical results: figure 3/4/5 of this manuscript (in parts of totally) are

therefore strictly speaking already published. I leave this decision to the editor of HESS, how published conference proceedings with very similar content are evaluated in terms of copyright and redundancy.

Authors' response

We believe that the submitted paper carries much more information than the 6-page conference proceedings paper and has a true added value compared to it. We believe it is a little bit of a stretch to say the paper contains exactly the same information as the present manuscript. The subject of the conference proceedings paper was a basis for discussion on non-stationarity in hydrological modeling. It contained mostly similar results to the submitted paper however the latter contains additional information on environmental flows, an analysis of anthropogenic pressure on water resources, a full analysis of the sustainability of water uses and management as they are planned in the two basins, and a complete discussion of the results. Moreover while the proceedings paper presented projections of water demand satisfaction for two illustrative demand nodes in each catchment, the submitted paper presents and analyses results for all demand nodes (i.e. 6 nodes within the Herault catchment and 8 nodes within the Ebro catchment).

Figure 3 is indeed in the proceedings paper in its same form. Since we believe that not including this figure in the submitted paper may make the interpretation of the projections of water stress more difficult for readers not wishing to refer to the proceedings paper, we propose to cite the proceedings paper in the caption of figure 3.

Figure 4 is partly published in the proceedings paper. However only two demand nodes per study area were presented, whereas figure 4 of the submitted paper presents water demand projections for all studied demand nodes of the Herault and the Ebro basins.

The same can be said regarding figure 5. Moreover the proceedings paper shows results for a slightly different methodology for the estimation of water stress: environmental flows Q_{MIN} were calculated differently in the proceedings paper and the thresholds of agricultural water deficit for calculating the indicator F were different.

▪ **Referee comment**

But also disregarding the conference proceedings, the two published papers in HESS and Journal of Hydrology call for major revision of the present manuscript: The authors must shorten their paper, build upon their own published work and crystallize real new results. This is true for all parts of the present manuscript.

Authors' response

We believe our paper presents novel findings compared to the two published papers. Although it builds on the models described in Fabre et al. (2015) and Grouillet et al. (2015), the methodology consisting of using the integrated model in different combinations of water use and climate scenarios to assess the sustainability of planned water uses is original, and so is the consideration of environmental flows. In Grouillet et al. (2015) water demand projections are given for 9 climate scenarios (18 in the submitted paper), on average between the different climate scenarios (while the range of uncertainty due to the 18 climate scenarios is given in the submitted paper and underlines the importance of considering climate uncertainties in the decision process). Moreover the spatial scale for water demand in the Ebro basin is different between the two papers: while water

demand is summed over each of the 20 sub-basins in Grouillet et al. (2015) it is grouped into demand nodes linked to the main storage dams and supplied by the main irrigation canals.

We propose a number of changes in the manuscript to better underline the novel findings of this paper and condense some parts of the submitted manuscript. These changes are listed at the end of our response and are marked-up in the manuscript at the end of this document.

- **Referee comment**

The introduction needs more structure, should be condensed and subdivided into paragraphs according to relevant topics. Redundancy compared to the published papers must be avoided. At the end a clear research gap and working hypothesis needs to be developed: What is really new in this paper, how does it build upon existing work? As the main topic of the present paper is water scarcity, relevant papers on water scarcity methodologies need to be introduced and later discussed in the context of the present work: The excellent review (Whitepaper by Brown and Matlock, 2011) is one example. More specific examples include the application of the WEAP tool.

Authors' response

We have added some elements at the end of the introduction to specify what is new in the paper and how it builds upon existing work (see list of the changes made in the manuscript and marked-up manuscript at the end of this document).

- **Referee comment**

But also the methodology needs to be shortened, since water availability and demand have been calculated and published before using the same model and the same methods. The water scarcity indices have only been introduced in the conference proceedings, so this could a new topic, the paper could focus on. This only if redundancy with the conference proceedings has been clarified (see above). But why do the authors call their indices "indicators for water demand satisfaction"? They are indices for water scarcity and should be compared to existing indices, e.g. reviewed by Brown and Matlock (2011).

Authors' response

We would like to underline that the submitted paper's originality goes beyond the proposed water scarcity indices. We believe the projections of balance between water demand and availability (including environmental flows) and their associated analysis form the core of this paper. Indeed, if we had first computed water demand in the future (under a baseline trend socio-economic scenario and 9 climate scenarios), future water availability had never been calculated, and the balance between water demand and availability under climate change uncertainties had not been assessed. This was done here under the current climate conditions (1976-2005) and under a range of 18 climate scenarios. Hence, sustainability of the current (2000s) and future (2050 trend scenario) water uses was assessed through an original combination of scenarios. Also it seems to us that the submitted paper would somewhat lack clarity with only references to the published papers and no description of the models used and the areas studied. However we do propose some modifications in the methods section,

which are detailed at the end of our response to Referee 1 and are shown in the marked-up manuscript at the end of this document.

The overall analysis of water demand satisfaction and compliance with environmental flows and level of consumptive use contribute to the topic of water scarcity, however the indices of water demand satisfaction were called so for more precision. The magnitude of the gap between water demand and water availability is a related, descriptive notion, but is not sufficient to characterize water scarcity (see e.g. Jaeger et al., 2013). Hence we propose to keep the name "indicators for water demand satisfaction" in the manuscript.

Reference:

Jaeger, W.K., Plantinga, A.J., Chang, H., Dello, K., Grant, G., Hulse, D., McDonnell, J.J., Lancaster, S., Moradkhani, H., Morzillo, A.T., Mote, P., Nolin, A., Santelmann, M., Wu, J. Toward a formal definition of water scarcity in natural-human systems. *Water Res. Research*. 49, 1-12, 2013.

▪ **Referee comment**

Also in the result section entire paragraphs need to be removed, e.g. 4.1.2 on water demand scenarios, which has been published before. Again the problem with the published conference proceedings needs to be solved, because as stated above, the majority of the results are contained therein.

Authors' response

We believe removing entire paragraphs such as 4.1.2 on water demand scenarios would make the rest of the results quite difficult to follow. In the changes proposed, we tried to be more clear about the fact that water demand projections were already presented in Grouillet et al. (2015) (see p.10 line 324 and p.13 line 414 of the marked-up manuscript), although as state earlier the spatial scale was not the same and more climate scenarios were added, and about the added value of the presented results compared to the paper from the IUGG conference proceedings (see p.4 line 121 of the markdp-up manuscript).

▪ **Referee comment**

A more detailed review is only meaningful, if redundancy is removed and a fundamentally updated version is submitted.

Authors' response

We hope that this updated version of the paper, in which we tried to clarify the relations between our different papers, will be considered for review by Referee 1.

Changes made in the manuscript based on comments from Referee 1

- **Changes made in the Introduction:**

-p.4, line 107 of the marked-up manuscript:

We added some detail about how the paper builds on existing work and about the originality of the submitted paper:

“The purpose of the present study is thus to assess the sustainability of planned water uses in complex mesoscale river basins under multiple climate change scenarios, and to determine the possible causes of unsustainability. *This paper builds on existing work regarding the integrative modeling of the balance between water demand and availability. The development and calibration/validation of the modeling framework used in this paper is exposed in a previously published paper by Fabre et al. (2015a) The present paper also builds on Grouillet et al. (2015) using the same models and water use scenarios to project water demand changes by 2050 under multiple climate change scenarios.*

This paper addresses the need for assessments of the sustainability of water use under both climatic and anthropogenic changes at the river basin scale, considering all water uses including environmental requirements, and accounting for climate change uncertainty. We propose an assessment grounded in real-world water management issues, with water management scenarios built in collaboration with local water agencies. Furthermore we present an analysis through indicators that relate to management goals and present the implications of climate uncertainty for our results, furthering the significance of our study for water management. While a previous conference proceedings paper (Fabre et al., 2015b) describes the basics of the method, the present paper contains additional and valuable information on environmental flows, an original analysis of anthropogenic pressure on water resources, a full analysis of the sustainability of water uses and management as they are planned in the two basins, and a complete discussion of the results. Moreover while the proceedings paper only presented projections of water demand satisfaction for two illustrative demand nodes in each catchment, this paper presents and analyses results for all demand nodes of the studied basins.”

- **Changes made in the Study area section:**

-p.4 line 130 of the marked-up manuscript:

We added “presented in Fabre et al. (2015a)” in the sentence

“This study was conducted in two Mediterranean water management units with contrasting geographical characteristics and water uses, *presented in Fabre et al. (2015a)*” to clarify that the same study areas were used in our previous publications.

-p.5 line 144 of the marked-up manuscript:

We deleted the paragraph describing the hydroclimatic context of the Herault and the Ebro basins to condense the section and avoid redundancy.

-p.6 line 180 of the marked-up manuscript:

We changed “A conceptual representation of water availability and demand was *set up* in each basin”

to

"The conceptual representation of water availability and demand *presented in Fabre et al. (2015a)* was used in each basin".

- **Changes made in the Method section:**

-p.7 line 206 of the marked-up manuscript:

We added the following sentence to begin the Methods section:

"Water availability and demand were modeled following the methods presented in Fabre et al. (2015a) and Grouillet et al. (2015)."

-p.7 line 209 of the marked-up manuscript:

We deleted the description of the hydrological model GR4j. The following sentences were deleted:

"The hydrological model relies on precipitation (P) and potential evapotranspiration (ET0) inputs. A snow module based on mean basin temperature (T) (Ruelland et al., 2011, 2014) was activated in the sub basins with a snowmelt regime. GR4j relies on four parameters, and the snow module adds three more parameters."

-p.7 line 214 of the marked-up manuscript:

We added the reference to Fabre et al. (2015a) for the calibration and validation of the model:

"The model was calibrated over the period 1981-2009 and validated over the period 1971-1980 (Fabre et al., 2015a)."

-p.7 line 229 of the marked-up manuscript:

We changed the sentence "More details on the data used and the modelling of water demands can be found in Grouillet et al. (2015) and Fabre et al. (2015a)"
to

"The data and the models used for the modelling of human water demands can be found in Grouillet et al. (2015) and Fabre et al. (2015a)."

-p.8 line 268 of the marked-up manuscript:

The text "Water availability and demand were compared at each water demand node. An order of priority for water uses was considered, as defined in figure 2."
Was changed to

"Water availability and demand were compared at each water demand node, following the method described in Fabre et al. (2015a) but adding environmental flows QMIN as the water demand to be satisfied in the first order of priority. The order of priority for water uses is shown in figure 2."

-p.9 line 290 of the marked-up manuscript:

We added the following sentence at the beginning of section 3.2.1 (Climate scenarios):

“The climate scenarios used are presented succinctly in Fabre et al. (2015b).”

-p.10 line 324 of the marked-up manuscript:

More details on how the water use scenarios presented here build on previous work by Grouillet et al. (2015) were added.

“Current water uses and the trend scenarios used in this study are presented in Grouillet et al. (2015). However, while simulations of water demand changes by 2015 were initially computed for 6 sub-basins of the Herault basin and 20 sub-basins of the Ebro basin, they were aggregated in the present study at the scale of the main demand nodes (6 nodes in the Herault basin and 8 nodes in the Ebro basin, see Fig. 4), which made it possible to analyze the balance between water availability and demand.”

-p.10 of the marked-up manuscript:

Table 2 presenting details on the water use scenarios was deleted to avoid redundancy with Grouillet et al. (2015).

- **Changes made in the Results section:**

-p.13 line 414 of the marked-up manuscript:

We added the following paragraph:

“Simulations of water demand changes by 2050 were initially computed in Grouillet et al. (2015) under the trend water use scenarios and 9 climate change scenarios, for 6 sub-basins in the Herault basin and 20 sub-basins in the Ebro basin. Here water demand projections are presented per demand node (which differ from the 20 sub-basins of the Ebro in Grouillet et al. (2015)) and for 18 climate change scenarios, showing the dispersion between results for different climate scenarios, adding to the information on average changes presented originally. Thus the results presented here show the sensitivity of water demand projections to contrasted climate projections.”

Answer to comments from Referee 2

On "Sustainability of water uses in managed hydrosystems: human- and climate-induced changes for the mid-21st century" by Fabre et al.

▪ Referee comment

The paper aims at characterizing the sustainability of water management rules for two Mediterranean basins under the context of global change. This manuscript is well written and well organized and I have only few recommendations before publication.

The results presented here, which focus on the future, complement previous published works on the general modelling framework and its former application under past conditions (Fabre et al., 2015; Grouillet et al., 2015).

Authors' response

We would like to thank the referee for reviewing the submission and for his interest in the topic, as well as for his attentive review of our submitted paper.

▪ Referee comment

P 9252: 18 projections are not enough to consider that they form a "wide" range of possible climate scenarios".

Authors' response and changes made in the manuscript

Agreed. We replaced "a wide range of possible climate scenarios" with "a range of possible climate scenarios" (p. 4 line 104 and p.9 line 300 of the marked-up manuscript).

▪ Referee comment

P 9254: the Florensac transfer is not displayed on the map (Fig. 1).

Authors' response and changes made in the manuscript

The Florensac transfer is indicated on the map in Figure 1 by the arrow at the South of the Herault basin pointing towards "to coastal towns". The indication "Florensac transfer (to coastal towns)" was added for more clarity.

▪ Referee comment

P 9255: "by withdrawals inside" => "by withdrawals inside and outside"

Authors' response and changes made in the manuscript

In fact, the intended meaning is "by withdrawals inside the sub-basin" and no "inside and outside" the sub-basin. However the text refers to water uses (indeed outside or inside the basin) supplied by withdrawals inside the basin. A clarification was added in the sentence (page 6 line 188 of the marked-up manuscript):

"In the Herault basin the surface flow at the outlet of each sub-basin was considered to represent water availability for all water uses (*inside or outside the basin*) supplied by withdrawals inside the sub-basin."

▪ **Referee comment**

P 9257: it is not clear on which time step the analyses (in particular the comparisons to the thresholds derived from monthly discharges) were carried out (daily, 10-day, monthly).

Authors' response and changes in the manuscript

The analyses were carried out at a 10-day time step for water demand satisfaction, including the environmental flow Q_{MIN} . "At a 10-day time step" was added at page 9257 line 5 (page 7 line 232 of marked-up manuscript). Influenced streamflow simulated at a 10-day time step was then averaged at a monthly time scale and monthly influenced streamflow was compared to Q_{OBJ} at a monthly time step (as is explained in section 332, page 12 line 393 of the marked-up manuscript)

▪ **Referee comment**

P 9259: ETO is given by the Penman-Monteith formula under current conditions for the Herault basin. How are ETO values obtained under climate projections since other climate data than temperature are required?

Authors' response and changes made in the manuscript

The following two sentences were added in section 3.2.1 to clarify this point (see page 10 line 316 of the marked-up manuscript).

"ETO was then calculated in each climate change scenario, using the FAO Penman-Monteith formula in the Herault basin and the Hargreaves empirical equation in the Ebro basin. The climate data other than temperature that are required in the Penman-Monteith formula (wind speed, net radiation, e.g.) were considered unchanged in the climate scenarios: the values from SAFRAN over 1976-2005 were used in all climate scenarios for 2036-2065."

▪ **Referee comment**

P 9261: how are changes distributed within the two basins? In section 4.1.2, one can find that the increase in irrigated areas (65% and 90%) varies from one sub-basin to another. This is not really consistent with Table 2 (80%).

Authors' response and changes made in the manuscript

The changes applied to the main drivers of water demand between the current and the trend water use scenarios were distributed spatially between the demand nodes.

To clarify this point the following sentence was added in section 3.2.2 (page 10 line 333 of the marked-up manuscript): "The changes applied to the main drivers of water demand between the current and the trend water use scenarios were distributed spatially between the demand nodes. "

However, in order to answer to the review of Referee 1, table 2 was deleted from the manuscript.

▪ **Referee comment**

P 9261: do Q_{min} and Q_{obj} remain unchanged under climate change scenarios?

Authors' response and changes made in the manuscript

Yes Q_{MIN} and Q_{OBJ} remain unchanged under climate change scenarios, since they are considered to be fixed water management criterions, which local stakeholders have not, to date, planned to adapt to future changes in streamflow. The following sentence was added (p.11 line 363 of the marked-up manuscript):

“Water demand for human water uses was calculated for current water uses and for future water uses, both under past and future climate conditions for irrigation water demand. The thresholds Q_{MIN} and Q_{OBJ} for environmental water demand were kept unchanged in all scenarios.”

▪ **Referee comment**

P 9264: $pojected = > projected$

Authors' response and changes made in the manuscript

Agreed. This has been corrected.

▪ **Referee comment**

P 9264: could you identify the upstream / downstream sections in the graphs?

Authors' response and changes made in the manuscript

The outlet of the Herault and the Ebro basins were identified in the graphs for more clarity and easier identification of the upstream/downstream sections.

▪ **Referee comment**

P 9264: is there any explanation to the decrease in AWD for some sub basins of the Ebro River? (decrease in ET_0 ?)

Authors' response

In some climate change scenario spring precipitation is projected to increase. Associated with a low or negligible decrease in summer precipitation and in the scenarios with a lower temperature (hence ET_0) increase, this could explain the decrease in AWD for some sub basins of the Ebro River.

▪ **Referee comment**

P 9265: could you add and comment the changes in total stored water volume in the reservoirs on the graphs?

Authors' response

Unfortunately we are not sure we have understood the question correctly. Does the Referee wish for us to add a figure with changes in the stored volumes in the reservoirs in both basins?

▪ **Referee comment**

P 9268: it is not clear for me on which time step the analyses were carried out regarding the environmental flows.

Authors' response and changes made in the manuscript

The analyses regarding environmental flows Q_{OBJ} presented on page 9268 were carried out at a monthly time step. This is indicated in the methods sections (p.12 line 393 of the marked-up manuscript). The sentence was slightly modified for more clarity: "Finally, *simulated* influenced monthly streamflow was compared for each combination of scenarios to the monthly environmental flows Q_{OBJ} described in section 3.1.1 and the frequency of non-compliance with these monthly environmental flows was calculated".

Also in the results section (p.9268 of the discussion paper, page 16 line 535 of the marked-up manuscript) the following sentence was modified:

From "Figure 7 shows that monthly environmental flows Q_{OBJ} are reached more than eight years out of ten in all sub-basins of the Herault and the Ebro basins (...)"

To "Figure 7 compares simulated influenced streamflow with environmental flows Q_{OBJ} at a monthly time step. Monthly environmental flows Q_{OBJ} are reached more than eight years out of ten in all sub-basins of the Herault and the Ebro basins (...)".

▪ **Referee comment**

Table 1: Martin et al. is missing

Table 2: "et" should be deleted

Table 3: 2050 = > 2050s

Authors' response and changes made in the manuscript

Agreed. Modifications were made accordingly.

▪ **Referee comment**

Figure 2: only "Reservoir level" is on the graph. I suggest adding "Transfer". At which time step, return flows are computed? What does dashed arrow mean? One arrow is missing: we do not know where "return flows" flow.

Authors' response and changes made in the manuscript

Return flows and consumptive use are computed at a 10-day time step. This was added in Figure 2 for more clarity. Also, an arrow showing return flows contribute to influenced streamflow was added.

Finally, the dashed arrow was meant to show that the modeling chain was applied from upstream to downstream until the outlet. However since it seemed unclear we changed it to a full arrow.

- **Referee comment**

Figure 5: it is difficult to identify points related to "2000s water uses Reference climate". I suspect that polygons and curves overlap.

Authors' response and changes made in the manuscript

Agreed. The figure was slightly modified for more clarity. In the original figure in some cases in the "2000s water uses Reference climate" situation there was no deficit, a red dot in the middle of the radar charts was added to show this. In the cases where "2000s water uses Reference climate" and "2050s water uses Reference climate" overlap, we tried to make the dotted line more visible.

- **Referee comment**

Figure 7: There are more gauging stations in the two basins than the number of sites displayed. Why do the authors consider this selection of basins?

Authors' response and changes made in the manuscript

The following sentence was added in section 3.1.1. to clarify this point (p. 8 line 244 of the marked-up manuscript):

" Q_{OBJ} values were considered in the Herault basin at the outlet of each of the defined sub-basins where the local water agency had defined an objective flow (i.e. at the outlets of the Ldeve, Saint Laurent, Gignac and Agde areas). In the Ebro basin they were considered at the outlet of the defined sub-basins not corresponding to the direct outlet of a dam (for which reserved environmental flows are integrated in the dam management rules)."

Sustainability of water uses in managed hydrosystems: human- and climate-induced changes for the mid-21st century

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Abstract. This paper assesses the sustainability of planned water uses in mesoscale river basins under multiple climate change scenarios, and contributes to determining the possible causes of unsustainability. We propose an assessment grounded in real-world water management issues, with water management scenarios built in collaboration with local water agencies. Furthermore we present an analysis through indicators that relate to management goals and present the implications of climate uncertainty for our results, furthering the significance of our study for water management. A modeling framework integrating hydro-climatic and human dynamics and accounting for interactions between resource and demand was ~~developed and~~ applied in two basins of different scales and with contrasting water uses: the Herault (2 500 km², France) and the Ebro (85 000 km², Spain) basins. Natural streamflow was evaluated using a conceptual hydrological model. A demand-driven reservoir management model was designed to account for streamflow regulations from the main dams. Human water demand was estimated from time series of demographic, socio-economic and climatic data. Environmental flows were accounted for by defining streamflow thresholds under which withdrawals were strictly limited. Finally indicators comparing water availability to demand at strategic resource and demand nodes were computed. This framework was applied under different combinations of climatic and water use scenarios for the mid-21st to differentiate the impacts of climate- and human-induced changes on streamflow and water balance. Results showed that objective monthly environmental flows would be guaranteed in current climate conditions in both basins, yet in several areas this could imply limiting human water uses more than once every five years. The impact of the tested climate projections on both water availability and demand could question the water allocations and environmental requirements currently planned for the coming decades. Water shortages for human use could become more frequent and intense, and the pressure on water resources and aquatic ecosystems could intensify. The causes of unsustainability vary across sub-basins and scenarios, and in most areas results are highly dependent on the climate change scenario.

25 1 Introduction

Water security was defined by the Global Water Partnership (GWP, 2000) by the following: “Water security at any level from the household to the global means that every person has access to enough safe water at affordable cost to lead a clean, healthy and productive life, while ensuring that the natural environment is protected and enhanced”. This definition comprises many different concepts, which many authors have tried to define and grasp over the years (Cook and Bakker, 2012). One of the concepts included in the idea of water security is sustainability. A sustainable use of water resources implies being able to satisfy current and future human water demands while preserving functional water-dependent ecosystems (Gleick, 2000). Thus it implies the ability of users to find a long-term balance between the availability and the use of water resources, a challenge at the heart of integrated water management strategies (Vörösmarty et al., 2012). An imbalance between availability and demand can express itself through the incapacity of water supply to meet demand (be it because of insufficient water availability or excessive water demand), and/or through pressures on water-dependent ecosystems due to excessive water consumption by human use. The European Water Framework Directive (WFD) (European Commission, 2000) requires European river basins to reach a sustainable balance between human water use and ecosystem health.

In this setting water sharing plans, when not already enforced, are currently being designed in many river basins. These plans are often focused on the periods compatible with WFD requirements, i.e. the 2015, 2021 or 2027 horizons. However it is widely recognized that mid-latitude areas could experience increased water stress along the 21st century, due to climate and socio-economic changes (Heinrichs et al., 2012; Arnell and Lloyd-Hughes, 2014; Milano et al., 2013b). These projections should encourage decision makers and water managers to look further in time and perhaps lengthen their planning horizons (Hallegatte, 2009). Moreover as underlined by Ludwig et al. (2014) the main difference between Integrated Water Resources Management as prescribed in the WFD and climate change adaptation is the focus on current and historic issues of IWRM, compared to the future focus of adaptation.

In this context, projections of water availability and demand at the river basin scale under scenarios of climate and water use changes are essential to bring a long-term perspective to water sharing plans. To date, studies focusing on climate impacts on water management are mostly focused on projections of water resource availability (Schwank et al., 2014; Bär et al., 2015; Nkomozepe and Chung, 2014; Palazzoli et al., 2015, e.g.). However achieving a sustainable use of water resources depends on hydro-climatic factors (defining the volume of resource) but also on anthropogenic factors, such as water demand and water management infrastructures (e.g. storage and transportation capacity), determining the availability of water resources (Griffin et al., 2013; Menzel and Matovelle, 2010, e.g.). Also, climate change could have considerable impacts on irrigation requirements (Döll, 2002; Woznicki et al., 2015), which should be accounted for in prospective water balance assessments. Some studies have focused only on water demand (Grouillet et al., 2015, e.g.), on fulfilling

environmental flow requirements (Donley et al., 2012, e.g.), or on the tradeoffs between environmental flow requirements and one type of demand (Kirby et al., 2014, e.g.). Wanders and Wada (2015) considered human influence in projections of future drought at a global scale; however they did not consider possible future changes in water use. A number of studies at the river basin scale assessed the impacts of hydrological changes on the capacity to satisfy current demands (López-Moreno et al., 2014; Pulido-Velazquez et al., 2011, e.g.), or future planned demands without considering the possible impact of climate change on agricultural water demand (Milano et al., 2013a, e.g.).

Studies that address the issue of water demand satisfaction at the river basin scale are scarce, even more so studies that account for consumptive use and the influence of human water use on stream-flow (one example being the work of Beck and Bernauer, 2011). Indeed water sustainability must be assessed through the satisfaction of human water needs, the level of pressure on resources, and the respect of environmental instream uses. This implies accounting for and distinguishing water demand (i.e. the amount of water that users would withdraw without restrictions), actual withdrawals, and consumptive use, notably in complex river basins with numerous upstream-downstream relations, reservoirs and water transfers. In a number of existing papers integrating water uses, water management and water availability (Nam et al., 2015; Shamir et al., 2015, e.g.), the systems under study were elementary management units, such as individual reservoirs or an aquifer. To our knowledge fewer studies can be found addressing water balance projections in complex, mesoscale river basins, with numerous spatial and temporal interactions between water uses and water availability (Collet et al., 2013, e.g.).

Integrated modeling of water balance at the basin scale is an extremely complex task which necessarily comprises many biases and uncertainties. Questions have been raised on the confidence that can be placed into projections of hydro-climatic changes (Kundzewicz and Stakhiv, 2010; Wilby, 2010). However if projections of change cannot be considered as predictions and used directly to decide on water allocations or infrastructure dimensioning, models can be used to understand the system under study and to determine the possible causes of change (Letcher et al., 2007; Pielke, 2009, e.g.). In this way, Blöschl and Montanari (2010) recommended the use of “simple” models that will help analyze the system, rather than complex models that may never be complete enough to model the system with perfect accuracy. As stressed by Smit and Wandel (2006), “climate conditions and system dynamics that could be problematic are rarely known a priori”. Modeling studies can help point out potential problems and discriminate anthropogenic and climatic impacts. While Kirby et al. (2014) found that river flows were more sensitive to the range of climate change projections than to the range of diversion reallocation scenarios considered, other studies found that anthropogenic drivers could have more impact than climatic drivers (Beck and Bernauer, 2011; Reynard et al., 2014; Vörösmarty et al., 2000, e.g.).

Uncertainties regarding anthropogenic climate change have been largely discussed in the literature. While some authors issued recommendations on how to improve modeling to better serve

decision making (Milly et al., 2008, e.g.) others have stressed the importance of considering climate
100 uncertainties in the decision process, and finding adaptation solutions despite this uncertainty (Hal-
legatte, 2009; Patt et al., 2005; Wilby, 2010, e.g.). Dessai and Hulme (2004) recommended testing
the sensitivity of systems to changing probabilities in climate to guide adaptation. Following the
framework of robust decision making (Dessai and Hulme, 2007; Dessai et al., 2009; Wilby and Des-
sai, 2010), we propose an approach covering a ~~wide~~ range of possible climate scenarios, given by a
105 selection of global climate models. As underlined by Räisänen (2007), inter-model comparison of
climate change projections may be the most pertinent currently available estimate of uncertainty.

The purpose of the present study is thus to assess the sustainability of planned water uses in com-
plex mesoscale river basins under multiple climate change scenarios ~~using a conceptual modelling~~
~~framework~~, and to determine the possible causes of unsustainability. This paper builds on existing
110 work regarding the integrative modeling of the balance between water demand and availability. The
development and calibration/validation of the modeling framework used in this paper is exposed in a
previously published paper by Fabre et al. (2015a). The present paper also builds on Grouillet et al. (2015),
using the same models and water use scenarios to project water demand changes by 2050 under
multiple climate change scenarios.

115 This paper addresses the need for assessments of the sustainability of water use under both climatic
and anthropogenic changes at the river basin scale, considering all water uses including environmental
requirements, and accounting for climate change uncertainty. We propose an assessment grounded
in real-world water management issues, with water management scenarios built in collaboration
with local water agencies. Furthermore we present an analysis through indicators that relate to man-
120 agement goals and present the implications of climate uncertainty for our results, furthering the
significance of our study for water management. While a previous conference proceedings paper
(Fabre et al., 2015b) describes the basics of the method, the present paper contains additional and
valuable information on environmental flows, an original analysis of anthropogenic pressure on
water resources, a full analysis of the sustainability of water uses and management as they are
125 planned in the two basins, and a complete discussion of the results. Moreover while the proceedings
paper only presented projections of water demand satisfaction for two illustrative demand nodes in
each catchment, this paper presents and analyses results for all demand nodes of the studied basins.

2 Study areas

2.1 Two water management units with contrasting water uses

130 This study was conducted in two Mediterranean water management units with contrasting geograph-
ical characteristics and water uses, presented in Fabre et al. (2015a). The Hérault basin (2 500 km²),
located in the South of France (Fig. 1a), has been part of the territory managed by the Rhône-
Méditerranée Corse water agency since 1964, and the Syndicat Mixte du Bassin du Fleuve Hérault

(SMBFH) was created in the 2000s to ensure more local management and in response to issues
135 that are specific to the Hérault basin, including water availability (SMBFH, 2005). The Ebro basin
(85 000 km²), located in the North of Spain (Fig. 1b), is managed by the Confederación Hidrográfica
del Ebro (CHE), which was created in 1926 with a strong emphasis on resource and infrastructure
development but now ensures a wider role in water management, in line with Integrated Water Re-
sources Management and planning. These two basins already have water sharing issues and could be
140 vulnerable to climate change (Bielsa and Cazcarro, 2015; Collet et al., 2013; Milano et al., 2013a;
Vargas-Amelin and Pindado, 2014). Strategies to adapt to future climate change have been designed
in both basins (AERMC, 2014; García-Vera, 2013). However these strategies are lacking projections
of the impacts of climate change and sustainability of planned water uses.

~~The Hérault and the Ebro basins differ in their geographical characteristics. The Hérault River
145 flows 150 km from Mont Aigoual (1 565 m a.m.s.l.) in the north, through a crystalline system of low
permeability in the upstream part, a karstic system in the middle part, and an alluvial valley in the
downstream part, into the Mediterranean Sea at the town of Agde. The Ebro River flows 910 km
along a north-west to south-east axis from Fontibre in the Cantabrian Range (1 027 m a.m.s.l.),
to the town of Tortosa where it forms a large delta. It is bordered by the Pyrenean range (up to
150 3 383 m a.m.s.l.) in the north, the Iberian range in the south and the Catalan coastal range in the
east. The Hérault basin is characterized by a Mediterranean climate influenced by the Cévennes
mountain range, with mild wet winters and hot dry summers. Temperature and precipitation follow
a north-to-south gradient in the basin, ranging from under 8 to over 15 and from over 1 600 mm yr⁻¹
to less than 600 mm yr⁻¹. Climatic conditions in the Ebro basin are complex due to the contrasting
155 influences of the Atlantic Ocean and the Mediterranean Sea, and of the three mountain ranges,
particularly the Pyrenees (Vicente-Serrano and López-Moreno, 2006). Annual temperatures and precipitation
range from 8 in the Pyrenees to 17 in the lower Ebro valley and from over 2 000 mm yr⁻¹ in the
western Pyrenees to less than 400 mm yr⁻¹ in the semi-arid central Ebro valley. Mean annual
streamflow was 36 m³ s⁻¹ (14 L s⁻¹ km⁻²) in the Hérault and 330 m³ s⁻¹ (4 L s⁻¹ km⁻²) in the
160 Ebro between 1971 and 2009.~~

Figure 1 shows the main anthropogenic pressures on water resources in the Hérault and the Ebro
basins. The upstream part of the Hérault river basin is characterized by low population density and
sparse agricultural areas while the downstream part has a high concentration of urban and agricul-
tural areas (Fig. 1a). The Florensac transfer, which supplies urban water to coastal areas located
165 outside the basin, accounted for one third of total water demand in 2009. Water demand is highly
seasonal, with irrigation demand (mostly for vineyards) and urban demand (increased because of
tourism) both peaking between July and August. Of the five dams in the basin with a total storage
capacity of 8% of total runoff (Fabre et al., 2014), the main one is the Salagou dam 102 hm³), built
in 1968 to supply water for irrigation but currently mostly used for recreational activities on the
170 reservoir lake. The main irrigated areas are concentrated around the Gignac canal which distributes

water from the Herault River to a perimeter of nearly 3 000 ha of irrigable land. The Ebro is a complex and highly regulated hydrosystem with a total of 234 dams, currently amounting to a storage capacity of 60% of total runoff (Fabre et al., 2014). Irrigated areas, covering nearly 700 000 ha in 2009, are concentrated in the semi-arid Ebro valley and are supplied by a network of canals linked to large storage dams, most of which collect water from the Pyrenean Mountains. The population density is mostly very low (under 10 inhab. km⁻²) except in a few urbanized areas such as Zaragoza or Pamplona. Urban water demand and water demand for industrial use amounted to comparable volumes in 2009.

2.2 Conceptual representation of water availability and water demand

~~A-The~~ conceptual representation of water availability and demand ~~was set up~~ presented in Fabre et al. (2015a) was used in each basin: water uses were grouped in water demand nodes each linked to one or more water availability nodes. Water availability nodes were represented either by the surface flow at the outlet of a sub-basin, or by the volumes stored in the main dams. Thus each basin was divided into sub-basins, accounting for the water supply to one or more demand nodes. The conceptual mapping of both hydrosystems accounted for climatic gradients and water use contrasts (for more details see Collet et al. (2014) and Fabre et al. (2015a)). The Herault basin was divided into six sub-basins and the Ebro into 20 (Fig. 1).

In the Herault basin the surface flow at the outlet of each sub-basin was considered to represent water availability for all water uses (inside or outside the basin) supplied by withdrawals inside the sub-basin (Fig. 1a). The southern section of the Herault basin (Agde) has both the highest urban withdrawals and a high level of agricultural water demand. The Gignac canal and its irrigated areas were isolated in the Herault at Gignac sub-basin. Water demand is low and mostly agricultural in the Laroque sub-basin, and minimal in the upstream sub-basins of the Saint-Laurent and Lodeve.

In the Ebro basin the links between reservoirs and irrigation systems were accounted for and eight main demand nodes, corresponding to eight main irrigation systems, were defined (Fig. 1b). In cases where the irrigation systems were directly linked to a storage dam, water availability was considered to be the volume stored in the reservoir. In other cases such as the Ebro valley, surface flow is regulated by dams upstream from the water uses, and water availability was considered to be the surface flow at the outlet of the sub-basin in which water is extracted. Note that apart from the eight main demand nodes presented here, a demand node was defined in each of the 20 sub-basins of the Ebro, grouping the water uses not connected to the large irrigation systems. In this paper we will present the balance between water demand and availability only for the eight main demand nodes.

3 Method

3.1 Integrative modeling of the balance between water availability and demand

205 3.1.1 Modeling water availability and demand

Water availability and demand were modeled following the methods presented in Fabre et al. (2015a) and Grouillet et al. (2015). Natural streamflow was assessed in the six sub-basins in the Herault and the 20 sub-basins in the Ebro using GR4j (Perrin et al., 2003), a conceptual hydrological model run at a daily time step and calibrated/validated at a 10-day time step. The ~~hydrological model relies on precipitation (P) and potential evapotranspiration (E_{T0}) inputs. A snow module based on mean basin temperature (T) (Ruelland et al., 2011, 2014) was activated in the sub-basins with a snowmelt regime. GR4j relies on four parameters, and the snow module adds three more parameters. The model was~~ model was calibrated over the period 1981–2009 and validated over the period 1971–1980 (Fabre et al., 2015a). The hydro-climatic data used in the two basins are described in Fabre et al. (2015a). To assess natural runoff in each sub-basin, the model was calibrated only against runoff data that were considered to be natural, i.e. not influenced by withdrawals or dam management (see Fabre et al., 2015a).

At each demand node, water demand was defined for human water uses (human water demand) and for environmental requirements (environmental water demand). Three types of human water demand were considered: urban water demand (UWD), agricultural water demand (AWD), and other water demands (OWD). Human water demand was defined as the amount of water that users would withdraw without restrictions, i.e. the withdrawals that would enable users to have access to optimal amounts of water considering the efficiency of supply networks and irrigation techniques. UWD referred to water demand for domestic use and for commercial and industrial uses connected to municipal networks. AWD was defined as water demand for irrigation use. Considered negligible in the Herault basin, OWD referred to water demand for industries not connected to municipal networks in the Ebro basin. Water demand for human use was calculated according to anthropogenic drivers (e.g. population and irrigated area dynamics) and climatic drivers (only for agricultural water demand). ~~More details on the data used and the modelling of~~ The data and the models used for the modeling of human water demands can be found in Grouillet et al. (2015) and Fabre et al. (2015a).

Two types of environmental water demand were considered in this study. The first type, called Q_{MIN} , was defined as the streamflow (at a 10-day time step) under which withdrawals for human water use are no longer allowed. This type of minimum flow can also be enforced downstream from a dam or a pumping site, for example, to guarantee availability for other water uses downstream and a minimum flow for the aquatic environment. A second type of environmental flows was considered, in line with planning and water allocations objectives: in water sharing plans, the total volume of water allocated to the different users can be limited to guarantee a minimum monthly average flow,

called objective flow or Q_{OBJ} in this study. This monthly minimum flow is not enforced as such but is used as a planning objective. In the Herault basin for example, water allocations are adjusted to guarantee the respect of this flow at least eight years out of ten.

Q_{MIN} values were defined downstream from storage dams and at specific locations (such as a $30 \text{ m}^3 \text{ s}^{-1}$ constraint for the Ebro at Zaragoza and a $100 \text{ m}^3 \text{ s}^{-1}$ constraint for the Ebro at Tortosa, see CHE, 2013), and threshold values were set at the outlet of each sub-basin, under which withdrawals were forbidden. Q_{OBJ} values were considered in the Herault basin at the outlet of each of the defined sub-basins where the local water agency had defined an objective flow (i.e. at the outlets of the Lodeve, Saint Laurent, Gignac and Agde areas). In the Ebro basin they were considered at the outlet of the defined sub-basins not corresponding to the direct outlet of a dam (for which reserved environmental flows are integrated in the dam management rules). The method used to define these thresholds differed between the two basins, according to the local management rules. In the Herault basin, Q_{MIN} and Q_{OBJ} values were defined by local authorities based on variations around Q_{MNA5} , the minimum monthly flow not exceeded one year out of five in past measurements. Thus in the present study the influenced streamflow as simulated by the model in each sub-basin over the period 1981–2009 (see Fabre et al., 2015a) was used to calculate Q_{MNA5} and, accordingly, Q_{MIN} and Q_{OBJ} . For example, the minimum flow defined by local authorities for the Herault at the gauging station of Gignac is 70% of the Q_{MNA5} value observed at this station. Therefore Q_{MIN} was then defined as 70% of the the Q_{MNA5} as simulated by the model at the gauging station of Gignac over the period 1981–2009. In the Ebro basin Q_{MIN} (and Q_{OBJ} , considered equal to Q_{MIN}) were defined at the outlet of each sub-basin as 10% of the mean annual natural streamflow (simulated as described in Fabre et al., 2015a) over the period 1981–2009 (or 5% of mean annual flow if it exceeded $80 \text{ m}^3 \text{ s}^{-1}$).

A demand-driven dam management model adapted from Fujihara et al. (2008) presented in Fabre et al. (2015a) was run to simulate streamflow regulation and storage operations of each dam (the Salagou dam in the Herault basin and 11 major dams in the Ebro basin). The model computes the water balance of the reservoirs at each 10-day time step, accounting for water demand, entering streamflow, evaporation, and the initial reservoir level. Considering minimum and target reservoir levels, it calculates the reservoir level, the volume of water released in associated canals (if applicable) and in the river downstream from the dam during each 10-day time step.

3.1.2 Comparing water availability and demand and simulating influenced streamflow

Water availability and demand were compared at each water demand node. An-, following the method described in Fabre et al. (2015a) but adding environmental flows Q_{MIN} as the water demand to be satisfied in the first order of priority. The order of priority for water uses ~~was considered, as defined-is shown~~ in figure 2. If water availability was equal to or higher than water demand, then water withdrawals were equal to water demand for all types of human water demand. If water availability was lower than water demand, then restrictions were applied to limit withdrawals for human

275 uses. Restrictions were first applied to AWD, then OWD, then UWD. No restrictions were imposed on industrial and urban demand before agricultural withdrawal restrictions reached 100% of demand. Water shortage was calculated through the difference between water demand and effective water withdrawal. Only a part of the water withdrawn was considered to be actually used (consumptive use), the remaining part was considered to return to the sub-basin outlet as return flow (see Fabre et al., 2015a). Thus the modeling chain simulated:

- 280
- natural water resources and their availability considering water management rules and infrastructures;
 - the ability to satisfy water demands throughout the basin;
 - the influenced streamflow resulting for hydro-climatic conditions and anthropogenic pressures (water withdrawals, return flows and dam management).

285 The modeling chain was calibrated over the period 1981–2009 and validated over the period 1971–1980 at a 10-day time step, and simulated water supply capacity and influenced streamflow efficiently in both basins (Fabre et al., 2015a).

3.2 Climate and water use scenarios for the mid-21st century

3.2.1 Climate scenarios

290 [The climate scenarios used are presented succinctly in Fabre et al. \(2015b\).](#) Climate scenarios covered a reference period (1976–2005, considered to be representative of current climatic variability) and a future period centered on 2050 (2036–2065). For each basin daily climate forcings over the period 1976 to 2005 were extracted from the 8×8 km grids presented in Fabre et al. (2015a). For the Herault basin, climatic data came from the SAFRAN meteorological analysis system (Vidal et al., 295 2010) and (E_{T0}) was calculated using the FAO Penman-Monteith formula (Allen et al., 1998). For the Ebro basin, daily temperature and precipitation measurements from 264 and 818 stations, respectively, were interpolated on an 8×8 km grid (Dezetter et al., 2014; Fabre et al., 2015a). The Hargreaves empirical equation (Hargreaves and Samani, 1985) was used to calculate E_{T0} at a daily time step.

300 In order to cover a ~~wide~~ range of possible climate projections and thus limit over-reliance on a limited number of climate projections (Wilby and Harris, 2006), eighteen future climate scenarios were built based on the outputs from nine Global Climate Models (see Table 1) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) . Using a large set of GCMs is indeed recommended since the dispersion between climate projections stems mainly from the climate models 305 (Arnell et al., 2004; Dessai and Hulme, 2007). The mid-21st century (2036–2065) was chosen for projections through a compromise between local projections of water uses (generally for 2030) and

the necessity to use climate projections in which a signal of climate change could be distinguished from climatic variability.

All simulations of climate change were based on the historical Representative Concentration Pathway (RCP) over the reference period (1976–2005) and the RCPs 4.5 and 8.5 over the future period (2036–2065). The outputs from the nine GCMS were extracted from the IPCC Data Distribution Center. Climate change scenarios were then generated using a change factor method (Déqué, 2007; Milano et al., 2013b; Ruelland et al., 2012, e.g.). For each GCM grid cell, the monthly variations obtained between the reference and future climatic simulations were applied to the observed series of T and P (over the reference period 1971–2005) of the cells of the 8×8 km grids whose center was included within the said GCM grid cell. E_{T0} was then calculated in each climate change scenario, using the FAO Penman-Monteith formula in the Hérault basin and the Hargreaves empirical equation in the Ebro basin. The climate data other than temperature that are required in the Penman-Monteith formula (wind speed, net radiation, e.g.) were considered unchanged in the climate scenarios: the values from SAFRAN over 1976–2005 were used in all climate scenarios for 2036–2065.

3.2.2 Water use scenarios

Water uses were considered through two scenarios in each basin: current water uses and a trend scenario for 2050. Current water uses were defined with the population, irrigated areas, network efficiency, touristic activity, and unit allocations of the 2000s. Current water uses and the trend scenarios used in this study are presented in Grouillet et al. (2015). However, while simulations of water demand changes by 2050 were initially computed for 6 sub-basins of the Hérault basin and 20 sub-basins of the Ebro basin, they were aggregated in the present study at the scale of the main demand nodes (6 nodes in the Hérault basin and 8 nodes in the Ebro basin, see Fig. 4), which made it possible to analyze the balance between water availability and demand.

As part of planning for the respect of the European Water Framework Directive, local agencies make projections of changes in water uses by 2027. The trend scenario was built based on these projections (e.g. for irrigated areas and irrigation efficiency) and the continuation of the trends in these projections (e.g. for population growth) until 2050. The changes applied to the main drivers of water demand between the current and the trend water use scenarios ~~are presented in table 2.~~ were distributed spatially between the demand nodes. Population projections were based on the median scenarios of the national statistic institutes (INSEE in France, INE in Spain). Unit allocations for urban water demand were taken from a study of water uses in the region for the Hérault and from projections by the CHE in the Ebro. In the Hérault basin, Rinaudo (2011) suggested a 12% decrease in domestic unit consumption between the 2000s and 2050, linked with forecasted behavioral changes and improved control of water consumption by household appliances. However projections also suggest an increased connection rate of small industries, parks and gardens and commercial water uses to potable water networks, inducing a total increase of urban unit allocation by 21%.

The efficiency of the potable water network was considered to vary in the Hérault according to local objectives in line with a national policy to reduce losses, and remained constant in the Ebro, where networks are considered already efficient. A prospective study was led in the Hérault basin within the water sharing plan, in which an inventory of local irrigation projects was made (regardless of available resources). These projections were used in the trend scenario. In the Ebro basin irrigated areas were considered to reach their maximum extent defined by the CHE (CHE, 2013). Changes in population (permanent and touristic) and unit urban water consumption were applied uniformly to all demand nodes, whereas changes in network and irrigation efficiency, irrigated areas and industrial activity were different for each demand node. More details on the trend water use scenarios for 2050 can be found in Grouillet et al. (2015).

3.3 Analysis of the relative impact of climate and water use scenarios

3.3.1 Combinations of climate and water use scenarios

The modeling framework was applied under four combinations of climate and water use scenarios to differentiate the impacts of climatic and anthropogenic changes on water supply capacity. These combinations and their corresponding objectives are presented in table 3-2.

Natural streamflow in the reference climate was simulated by running the hydrological model with climate input data from 1976 to 2005. For the simulation of natural streamflow over the period 2036–2065, the hydrological model was run with climate input data from each of the 18 climate scenarios described in section 3.2.1. The parameters obtained by calibration over 1981–2009 were kept identical in all simulations.

Water demand for human water uses was calculated at each demand node for current water uses and for future water uses, both under past and future climate conditions for irrigation water demand. The thresholds Q_{MIN} and Q_{OBJ} for environmental water demand were kept unchanged in all scenarios.

The dam management model was run with the hydro-climatic and water demand inputs corresponding to each combination of scenarios. Future water use scenarios also include changes in dam management such as the doubling of the Yesa dam's storage capacity, a project currently under way in the Ebro basin. Thus target reservoir levels were changed accordingly in combinations regarding the trend water use scenario (Future uses under past climate and Future uses under future climate). Target and minimum levels remained unchanged for the other dams.

3.3.2 Indicators of water demand satisfaction and anthropogenic pressure on water resources

375 As detailed in section 3.1.2, water shortage was calculated at each demand node and for each type of demand, at a 10-day time step. The satisfaction of urban and agricultural water demand was then characterized by three indicators:

- F : frequency of years with at least one significant deficit at a 10-day time step ($>5\%$ of UWD or AWD);
- 380 - D_{10} : average deficit at a 10-day time step;
- D_{AN} : average annual deficit.

These indicators inform us on the frequency and magnitude of water shortages. D_{10} was calculated by averaging the non-null deficits (i.e. water shortage as a percentage of water demand) computed at a 10-day time step over the whole period. Water shortages were summed for each year and the annual deficit was defined as the percentage of total annual demand that could not be satisfied by available 385 resources. D_{AN} was then calculated by averaging the non-null annual deficits over the whole period. The three indicators were computed separately for urban water demand (UWD) and agricultural water demand (AWD).

For each combination of scenarios the level of anthropogenic pressure on water resources was 390 calculated: the difference between natural and influenced streamflow was calculated at the outlet of each basin at a 10-day time step, and averaged over the 30-year period. The level of anthropogenic pressure was expressed as a percentage of natural streamflow. ~~Finally,-~~

Finally, simulated influenced monthly streamflow was compared for each combination of scenarios to the monthly environmental flows Q_{OBJ} described in section 3.1.1 and the frequency of 395 non-compliance with these monthly environmental flows was calculated.

4 Results

4.1 Hydro-climatic and water demand changes

4.1.1 Projections of hydro-climatic changes for the mid-21st century

Figure 3 shows the changes in the temperature, precipitation and natural discharge projected by the 400 nine GCMs and two RCPs for the period 2036–2065 in comparison to the 1976–2005 reference period in the Hérault and the Ebro basins. Temperature projections show a clear increasing trend, particularly marked in the summer (up to $+4.8^{\circ}\text{C}$ in the Hérault basin and $+4.6^{\circ}\text{C}$ in the Ebro basin). Precipitation projections are more uncertain and differ among the 18 scenarios. Annual precipitation

changes range from -13% to $+7\%$ in the Hérault and from -15% to $+5\%$ in the Ebro basin. Nevertheless, spring and summer precipitation are projected to decrease or slightly increase in both basins; in the already dry months of June, July and August all scenarios project a decrease in precipitation.

These climatic scenarios result in changes in simulated natural discharge: while scenarios diverge in fall, winter and spring, all 18 scenarios result in a decrease in summer low flows, slightly more marked in the Hérault (-14% to -57%) than in the Ebro (-4% to -36%) basin. In the Ebro basin discharge changes at the beginning of spring (April) are uncertain, with a possible increase in discharge due to increased and earlier snowmelt, while all scenarios lead to a decrease in spring discharge in the Hérault basin.

4.1.2 Water demand changes under water use and climate scenarios

Simulations of water demand changes by 2050 were initially computed in Grouillet et al. (2015) under the trend water use scenarios and 9 climate change scenarios, for 6 sub-basins in the Hérault basin and 20 sub-basins in the Ebro basin. Here water demand projections are presented per demand node (which differ from the 20 sub-basins of the Ebro in Grouillet et al. (2015)) and for 18 climate change scenarios, showing the dispersion between results for different climate scenarios, adding to the information on average changes presented originally. Thus the results presented here show the sensitivity of water demand projections to contrasted climate projections.

In the Hérault basin projections of water demand for the mid-21st century are contrasted between the upstream and downstream sections (see Fig. 4a). Although demand is expected to increase in some upstream sections such as Laroque and Lodeve, projected agricultural demand remains low relatively to the downstream sections of Gignac and Agde. Depending on the water use scenario considered, the highest AWD is found in the downstream sections of Gignac or Agde. In the Gignac section the increase in efficiency in the water use trend scenario leads AWD to decrease by 50% despite a 65% increase in irrigated areas, whereas AWD in the Agde section doubles in the trend scenario because of a 90% increase in irrigated areas. In both sections the impact of projected climate change on AWD is comparable to the impact of projected anthropogenic changes (in the most pessimistic climate change scenarios). Note the UWD increase ($+57\%$ or 14.8 hm^3 , of which 10.4 hm^3 are linked to an increase in demands outside the basin) in the Agde section, which concentrates 83% of the basin's UWD in the water use trend scenario. In the upstream sections the impacts of projected climate and anthropogenic changes on agricultural water demand are of the same order of magnitude. In the Saint Laurent and Salagou sections, the water use trend scenario causes a slight decrease in AWD (-15%); however changing climate conditions have a dominant impact and cause an increase in AWD (up to $+40\%$ and $+57\%$ in the Saint Laurent and Salagou sections respectively). UWD is projected to increase in the upstream sections, from $+11\%$ in the Laroque section to $+53\%$ in the Salagou section.

AWD is projected to increase in all sections of the Ebro basin and in all scenarios, except in the
440 Bardenas, Alto Aragon and Ebro Valley irrigated areas where some of the climate change scenarios
lead to a decrease in AWD with current water uses. In the water use trend scenario, irrigated areas
are projected to increase in all basins, particularly in the Segre and Lower Ebro areas. In these areas
the impact of the trend scenario is stronger than the impact of some scenarios of climate change
(see Fig. 4b). In the Bardenas, Aragon y Catalunya, Jalon and Guadalupe areas climate change is
445 projected to have as much or more impact on AWD than the changes in water use in the trend
scenario. The uncertainty on the impact of climate change on AWD is largest in the Aragon and
Catalunya, Segre, Jalon and Guadalupe areas; it is lowest in the Lower Ebro area. Although AWD
stays dominant in all scenarios, UWD and OWD are also projected to increase in all areas in the
trend scenario. The highest UWD increases are found in the Aragon and Catalunya (+30%), Segre
450 (+45%) and Lower Ebro (+50%) areas. OWD is projected to double or more in all sections except
the Segre and Lower Ebro (from +100% in Aragon and Catalunya to +185% in the Ebro Valley).

4.2 Water demand satisfaction under climate and water use scenarios

4.2.1 Water demand satisfaction in the Hérault basin

Considering current water uses in the reference climate variability, water shortages appear less than
455 once every five years in all sections of the Hérault basin except in the Gignac and Agde areas, where
agricultural water shortage occurs two years out of five (Fig. 5a). In the Saint Laurent and Lodeve
sections the average restriction on agricultural water demand at a 10-day time step reaches nearly
100%, while restrictions are less severe in the other sections. The annual deficit is highest in Saint-
Laurent and Agde, nearing 20% of agricultural water demand.

460 The trend water use scenario in a reference climate only impacts the satisfaction of AWD in the
Agde area. Despite a significant decrease in AWD in the Gignac area, the frequency of withdrawal re-
strictions is not projected to decrease, due to the high UWD increase in the Agde area. Indeed UWD
was considered of first priority over AWD and no upstream priority was given to AWD in Gignac
over UWD in Agde. Thus if streamflow was insufficient to meet water demand in the downstream
465 sub-basin, agricultural withdrawals upstream were limited.

Considering current water use in climate change scenarios, water demand and availability become
out of balance in all sections of the Hérault basin. However results are highly dependent on the
climate scenario, particularly regarding the frequency of water shortages: depending on the climate
scenario, the frequency of agricultural water shortages in the Gignac area reaches three to eight years
470 out of ten. Despite some possible high increases in the frequency of water shortages, the average
annual deficit are not be affected by climate change except in the Gignac area, where the annual
agricultural water deficit reaches 30% under the most pessimistic climate change scenarios.

Finally, results for planned water uses under climate change scenarios show that projected climate change has a higher impact than the water use trend scenario in all sections of the Herault. In the sections of Gignac and Agde, the water use trend scenario amplifies the impact of the different climate change scenarios.

4.2.2 Water demand satisfaction in the Ebro basin

In the combination of current water uses and reference climate variability, results show that the Bardenas, Ebro Valley and right bank systems (Jalon and Guadalope) are out of balance, with agricultural water shortages every year and annual deficits of 30% in the Ebro Valley and Bardenas, and 60% and 70% in the Jalon and Guadalope areas respectively (see figure 5b). Also, shortages at a 10-day time step are higher in the right bank systems. Urban water shortages also appear frequently in these areas.

Combined with current water uses, climate change scenarios induce an increase in the frequency of shortages in the Alto Aragon and Lower Ebro areas for AWD, and in the Bardenas, Ebro valley and right bank systems for UWD. Projected climate change also increases the magnitude of annual deficits except in the Ebro Valley and Lower Ebro. The impacts are most uncertain in the Alto Aragon and Lower Ebro areas. Note that water demand satisfaction in the Segre is not be impacted by climate change if no changes in water uses occur. It is also hardly impacted in the Aragon and Catalunya area.

The water use trend scenario under reference climate variability results in a significant improvement of the balance between water demand and availability in the Bardenas system, for both urban and agricultural water uses. The increase of the Yesa dam's storage capacity is projected to lead to a decrease in the frequency of agricultural water shortages, from every year to three years out of ten. In the already out of balance systems of Guadalope, Jalon, and the Ebro Valley, and in the balanced systems of Segre and Aragon and Catalunya the water use scenario has little to no impact on water demand satisfaction. Finally the increase in AWD in the Alto Aragon area and the increase in all types of water demand in the Lower Ebro in the trend scenario induces an increase in the frequency of AWD shortage in Alto Aragon and causes AWD and UWD shortages to appear in the Lower Ebro.

The combination of the water use trend scenario and climate change scenarios lead to significant water shortages in the entire Ebro basin, with marked differences between the areas. The benefits of the dam enlargement in the Bardenas area are partly offset by climate change in some of the scenarios. Thus the range climate change scenarios tested in this study makes the efficiency of this adaptation strategy quite uncertain. In the Ebro valley and the right bank systems, projected climate change causes an increase in the magnitude of water shortages and an increase in the frequency of urban water shortages. However in these areas the main causes of imbalance seem to reside in the current conditions, water use and climate changes only causing a slight deterioration in already imbalanced systems. In the Lower Ebro and Segre areas the combination of projected water use and

climate changes lead to frequent agricultural water shortages in both areas (every year in the Lower Ebro, eight years out of ten in the Segre) and to urban water shortages in the Lower Ebro.

4.3 Anthropogenic pressure on water resources

In the Hérault basin simulated anthropogenic pressure on water resources remains low at an annual time step: it increases from 2% to 3% between the current water use and the trend water use scenario, and it reaches 2 to 3% under climate change scenarios and 3 to 4% under a combination of water use trend and climate scenarios. In the combination of current water uses and reference climate, anthropogenic pressures on water resources at the outlet of the Hérault basin reach 20% of natural streamflow at the end of July (Fig. 6a). Anthropogenic pressure increases and reaches 27% of natural streamflow at the same period under the water use trend scenario. Under climate change scenarios consumptive use is projected to increase slightly earlier in the year, with an earlier and more marked peak than in the reference climate. This peak reaches 25% to 45 % (depending on the climate change scenario) with climate change only, and 30% to 50% with the water use trend scenario under climate change.

Figure 6b shows the high impact of storage on streamflow in the Ebro basin: the anthropogenic impact is highest in spring and fall, and decreases in summer when water withdrawals are at their highest. This can be due to withdrawals being made mostly in the reservoirs, and to the operation of the Mequinenza, Ribaroja and Flix dams which aims at securing a flow of $100 \text{ m}^3 \text{ s}^{-1}$ for the Ebro delta. This environmental flow constraint also explains the decrease of anthropogenic impact under climate change scenarios: although natural streamflow decreases in the climate change scenarios, the outflow from the dams was kept at a minimum of $100 \text{ m}^3 \text{ s}^{-1}$, thus leaving a larger percentage of natural flow at the outlet. Anthropogenic pressure on water resources reaches 38% of annual flow under current conditions and increases to 45% of annual natural streamflow under the water use trend scenario. Climate change scenarios result in an increase in anthropogenic pressure, ranging from 36% to 44% with current water uses and from 43% to 52% when combined with the water use trend scenario.

Figure 7 shows ~~that monthly~~ the results of the comparison of simulated influenced streamflow with environmental flows Q_{OBJ} at a monthly time step. Monthly environmental flows Q_{OBJ} ~~is-are~~ reached more than eight years out of ten in all sub-basins of the Hérault and Ebro basins, under current water uses and reference climate variability. However the water use trend scenario causes an increase in the frequency of unsatisfactory years (when influenced streamflow is inferior to environmental objectives) at the outlet of the Ebro basin. Conversely, it improves the respect of environmental flows in the Gignac (Fig. 7a) and Bardenas (Fig. 7b) areas. Climate change scenarios lead to a non-compliance with monthly environmental flows in the Lodeve, Saint-Laurent and Gignac areas of the Hérault basin and in all areas except the Cinca and the Segre sub-basins in the Ebro basin. Finally,

the combination of the trend water use scenario and climate change scenarios is projected to have a
545 high impact on the compliance with environmental flows in the Ebro at Tortosa.

5 Discussion and conclusion

5.1 Significance for water management

The purpose of this study was to assess the sustainability of planned water uses under an ensemble
of climate change scenarios using a conceptual modeling framework, and to determine the possi-
550 ble causes of unsustainability. The sustainability of water uses was appraised through the risk of
imbalance between water availability and demand over the long term (several decades), i.e. the pos-
sibility to satisfy demands for human water use while keeping withdrawals and consumptive use at
environmentally sustainable levels. The sustainability of planned water uses was assessed by simu-
555 lating water demand satisfaction and the pressures of water uses on resources considering climate
variability over 30-year periods, in water use and climate scenarios. Results showed that objective
monthly environmental flows would be guaranteed in current climate conditions in both basins. Yet
in several areas this could imply limiting human water uses more than once every five years, which
implies a need to adapt water uses to lower water availability, or «doing better with what we have»
as suggested by Molle et al. (2010). Moreover the impact of the tested climate projections on both
560 water availability and demand could question the water allocations and environmental constraints
currently planned for the coming decades. Indeed, under climate change and water use scenarios
water shortages for human use could become more frequent and intense, and the pressure on water
resources and aquatic ecosystems could intensify.

In some areas the plans to increase water use, rather than the decrease in availability under climate
565 change scenarios, should cause an imbalance between water use and availability: in four areas of the
Ebro basin (Alto Aragon, Aragon and Catalunya, Segre and Lower Ebro), current water uses could
be sustainable under climate change scenarios. In these areas if water uses change according to local
plans, water demands should be satisfied in current climate conditions. Yet a risk of water stress could
appear over a longer term, under a changing climate. However note that it may be harder by then to
570 reduce, than to curb its increase from now on. In other areas water stress should be induced mainly by
climate change, notably in the Herault basin. Our results showed that the fixed environmental flows
could frequently be unsatisfied, even with also frequent limitations of water withdrawals. Facing
decreasing natural low flows, the question arises whether regulatory minimum flows can be kept at
their current level. Then again, increased consumptive use as shown by simulations under climate
575 change scenarios could further impact ecosystems already perturbed by warmer temperatures, lower
flows, and quickly changing conditions.

The comparison of the Herault and Ebro basins shows that the regulated systems on the left bank
of the Ebro could be only slightly impacted by climate change, up to a certain level in agricultural

water demand, whereas systems with limited streamflow regulation such as the Hérault basin should
580 be directly affected by any decrease in summer low flows. Although anthropogenic pressures on
resources were shown to be much higher in the Ebro than in the Hérault basin, some of the main
water uses could remain in balance with water availability. However in the Ebro basin only the large,
regulated demand nodes were studied; water stress within each area may be quite heterogeneous, in
the same way as the different areas of the Hérault basin. Nevertheless both scales of study remain
585 pertinent, since they each match a scale of water management and planning.

In most areas, results were highly dependent on the climate change scenario. Although this may
induce some difficulties in the analysis of results, the breadth of uncertainty in future climates must
be considered, and characterizing the range of possible climate change scenarios is essential to limit
the risk of over-reliance on one uncertain projection and thus the risk of maladaptation (Pielke, 2001;
590 Wilby, 2010). Also, the sensitivity to climate uncertainties was shown to vary between the demand
nodes. For example in the Hérault basin, the areas of Laroque, Saint-Laurent and Lodeve, which have
comparable frequencies of water shortage in reference conditions, exhibited different sensitivities to
climate uncertainties (see Fig. 5).

5.2 Contributions of the integrated modeling framework

595 The integrated modeling framework enabled us to account for many interactions within the two
studied hydrosystems. Upstream-downstream interactions were considered through the simulation
of water withdrawals, return flows and consumptive use. Interactions between water uses were also
accounted for: while water demand in the Ebro is mostly agricultural and thus water shortages are
mostly caused by a hydro-climatic deficit, in the Hérault basin agricultural water withdrawals can
600 be limited because of the priority given to UWD. In this way the increase in irrigation efficiency in
the Gignac area should not lead to an improvement of AWD satisfaction if it occurs concurrently
with the increase in UWD of the Agde area, as suggested in the trend water use scenario. Finally
by differentiating the impacts of climate change from those of socio-economic and demographic
trends, the modeling framework helped assess the cause of the hydrosystems' vulnerability to water
605 stress, which, as underlined by Blöschl and Montanari (2010), is an essential value of climate change
impact studies. The identification of the drivers of water stress in basins facing rapid climatic and
anthropogenic changes is also at the heart of the challenges put forward in the Panta Rhei hydrolog-
ical scientific decade of the IAHS (International Association of Hydrological Sciences) (Montanari
et al., 2014).

610 The indicators used in this study to characterize the balance between availability and demand
were sensitive to the dynamics of anthropogenic pressures, and should help anticipate undesirable
situations, as recommended by Juwana et al. (2012). They enabled us to assess the frequency and
magnitude of deficits, and thus helped to qualify the vulnerability of the studied hydrosystems to
water stress. The impacts of future changes will indeed be different in areas experiencing more

615 frequent years of shortage of the same magnitudes (see the upstream areas of the Herault basin),
than in areas exposed to increased annual deficits (such as the Gignac and Agde areas of the Herault
basin or the Alto Aragon area of the Ebro basin) or to shortage events with an increased deficit (such
as the Gignac area).

5.3 Limitations and uncertainties

620 Although efforts were made to account for uncertainty in future water stress by using a wide range
of climate scenarios, the full range of uncertainties was far from being completely covered in this
study. Different downscaling techniques, hydrological models (Jiang et al., 2007; Jones et al., 2006,
e.g.), or water use scenarios (Purkey et al., 2008; Reynard et al., 2014; Shamir et al., 2015, e.g.)
could be used, for example, to cover a wider range of uncertainty. Note that only one water use
625 scenario was compared to many climate change scenarios. However the trend water use scenario
should be seen here not as a projection for water managers of what water uses could be at the 2050
horizon, but rather as a quantification (with the expected modeling uncertainties) of water demand
associated with the demographic and socio-economic trends that local managers included in their
planning documents for the mid-term. Thus the trend water use scenario should be considered as a
630 reference state on which to base the design of adaptation measures.

This prospective study was based on debatable assumptions regarding the stationarity of hydrolog-
ical processes and of water management, which may be seen as partly unrealistic. Notably, keeping
the parameters of the hydrological model obtained by calibration over 1981–2009 in all simulations
raises the question of hydrological non-stationarity. The robustness of conceptual hydrological mod-
635 els under changing climatic and anthropogenic drivers is an essential question for impact studies.
According to published research, it seems in the range of climate change studied here, hydrological
model parameters could be transposable (Coron et al., 2012; Vaze et al., 2010). Moreover, climate
projections at the 2050 horizon only accounted for mean monthly changes, due to the downscal-
ing method. Also, note that the water use scenarios were built with constant anthropogenic drivers
640 over 30 years, while simulations over the past 40 years (Fabre et al., 2015a) showed that the non-
stationarity of anthropogenic forcings was a key element to be considered in hydrological modeling.
However one could argue that since the sequence of wet and dry years from the reference period
was kept in climate projections, it might not make more sense to consider varying population and
irrigated areas, considering that the climate variability over the 30-year period is unpredictable. Thus
645 to account for the variability of anthropogenic pressures in future scenarios, it would seem more per-
tinent to use a large range of stationary water use scenarios and to confront them to different climate
scenarios over multi-decadal periods.

Finally, some authors have questioned the use of indicators to assess and predict water stress
(Molle and Mollinga, 2003, e.g.), arguing that indicators tend to aggregate reality and even out
650 spatial and temporal heterogeneities. Although the authors concede that indicators calculated at a

local level and resulting from a complete study may give accurate information, they argue that the added value of using indicators is unclear. In the present study we used indicators to facilitate the comparison of different scenarios: rather than the absolute values of the indicators in each scenario, it is the changes in their values between different scenarios that counts the most. Nevertheless the question remains of the use of these indicators to represent the vulnerability of hydrosystems to water stress. The indicators used in this paper could in fact be considered as harm indicators, quantifying changes in the frequency and magnitude of water shortage for human use. They do not completely grasp the notion of vulnerability, which, according to Hinkel, cannot be measured. Complementary studies using a bottom-up approach, focusing on social vulnerability and adaptive capacity (Bhave et al., 2014; Burton et al., 2002; Farley et al., 2011; Wilby and Dessai, 2010, e.g.) would be needed to assess the vulnerability of these two river basins to water stress. Indeed different systems may not react in the same way to similar water shortage frequency of intensities. In the Laroque area of the Herault basin, for example, summer low flows are sensitive to climatic variability, with no storage capacity to lessen the pressure of summer withdrawals. Furthermore, aquatic ecosystems in this area are fragile and of high value, therefore environmental flows are of particular interest. However, the local agriculture and thus economic activity is highly dependent on irrigation, and frequent limitations of water withdrawals may question this activity.

5.4 Prospects

Applying this integrated ~~modelling~~ modeling framework in different combinations of climate and water use scenarios helped to answer the question of the sustainability of water uses under climate- and human-induced changes, and to determine the causes of water shortage risks. This study enables us to approach possible adaptation options to improve the sustainability of water uses for each study area. In the Herault basin, water managers will have to address the satisfaction of UWD, while accounting for interactions between water uses and between upstream and downstream. For instance this study showed that the efforts regarding irrigation efficiency in Gignac would not necessarily induce an increase in the satisfaction of local agricultural demand because of the priority given to the satisfaction of urban water demand further downstream. In the Ebro adaptation will most likely relate to agricultural water demand. Modifying dam management could have an impact on the balance between demand and availability, however caution is needed while considering long term investments, which may not be effective over the long term in non-stationary climate conditions (Hallegatte, 2009). This was well illustrated in this study by the case of the Yesa dam in the Bardenas area of the Ebro basin, where the benefits of the dam enlargement could be partly offset by climate change.

The next step of this work, currently underway, is thus to assess the sensitivity of future changes in water demand satisfaction to variations in the water use scenarios, and to propose scenarios of

sustainable changes in water uses, both effective in reducing the gap between water demand and availability and robust to climate uncertainties.

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Table 1. Selected GCMs from the IPCC Data Distribution Center: model name, modeling center, atmospheric resolution and main reference. Source: IPCC (2013)

| Model name | Modeling Center (Country) | Atmospheric resolution | Reference |
|-------------------|---|-------------------------------|---|
| CanESM2 | Canadian Centre for Climate Modelling and Analysis (Canada) | 1.875°×1.875° | von Salzen et al. (2013) |
| CNRM-CM5 | <i>Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique</i> (France) | 1.4°×1.4° | Voldoire et al. (2013) |
| CSIRO-MK3.6.0 | Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence (Australia) | 1.875°×1.875° | Rotstayn et al. (2012) |
| GFDL-ESM2G | NOAA Geophysical Fluid Dynamics Laboratory (USA) | 2.5°×2° | Dunne et al. (2012) |
| HADGEM2-CC | Met Office Hadley Centre (UK) | 1.875°×1.25° | Collins et al. (2011); Martin et al. (2011) |
| HADGEM2-ES | Met Office Hadley Centre (UK) | 1.875°×1.25° | Collins et al. (2011); Martin et al. (2011) |
| IPSL-CM5A-MR | <i>Institut Pierre-Simon Laplace</i> (France) | 1.25°×1.25° | Dufresne et al. (2013) |
| MIROC5 | Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (Japan) | 1.40625°×1.40625° | Watanabe et al. (2010) |
| MPIM | Max Planck Institute for Meteorology (Germany) | 1.8°×1.875° | Stevens et al. (2013) |

Main drivers of water demand at the scale of the Herault et and Ebro-basins in the current and the trend water use scenarios. NA : Non Applicable.

| | 2000s | 2050s | Trend | 2000s | 2050s | Trend | UWD | Permanent population |
|---|---------|---------|-------|---------|---------|-------|---------------------------------------|----------------------|
| (inhab.) | 350 417 | 440 651 | +39% | 468 675 | 554 241 | +18% | Touristic activity | +74% |
| | NA | NA | NA | NA | NA | NA | Transfers (inhab. outside the basins) | +18% |
| (m ³ inhab. ⁻¹ yr ⁻¹) | 971 | 117 | +21% | 1091 | 111 | +4% | Network efficiency (%) | +5% |
| | NA | NA | NA | NA | NA | NA | NA | +0% |
| | NA | NA | NA | NA | NA | NA | AWD | +95% |
| (ha) | 4 754 | 8 502 | +80% | 658 500 | 961 400 | +46% | Network and irrigation efficiency (%) | +22% |
| | NA | NA | NA | NA | NA | NA | AWD | +9% |

Table 2. Four combinations of climate and water use scenarios applied in the Herault and the Ebro basins.

| Combination | Water uses | Climate | Aim of the assessment |
|-----------------------------------|-----------------------|-----------|--|
| Current uses under past climate | 2000s | 1976–2005 | Sustainability of current water uses under reference climate variability |
| Current uses under future climate | 2000s | 2036–2065 | Sustainability of current water uses under climate change |
| Future uses under past climate | 2050 2050s | 1976–2005 | Sustainability of planned water uses under reference climate variability |
| Future uses under future climate | 2050 2050s | 2036–2065 | Sustainability of planned water uses under climate change |

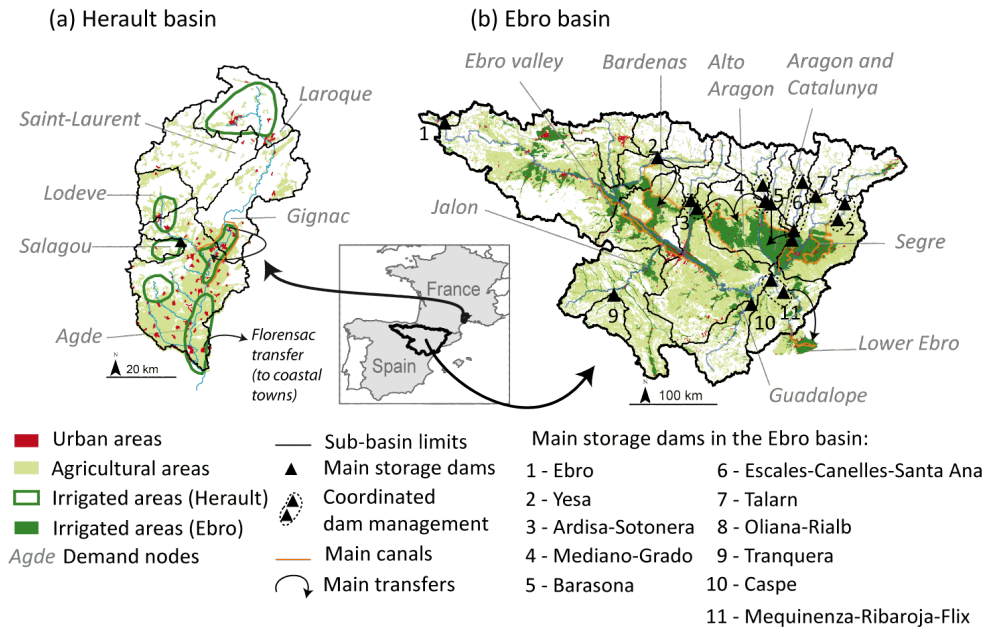


Figure 1. Location, main water uses and water management characteristics of (a) the Herault and (b) the Ebro basins. In the Herault basin, 6 sub-basins matching 6 demand nodes were defined. In the Ebro basin, 20 sub-basins were selected for the simulation of water resources and 8 demand nodes matching the main irrigation systems were defined. [Modified from Fabre et al. \(2015a\).](#)

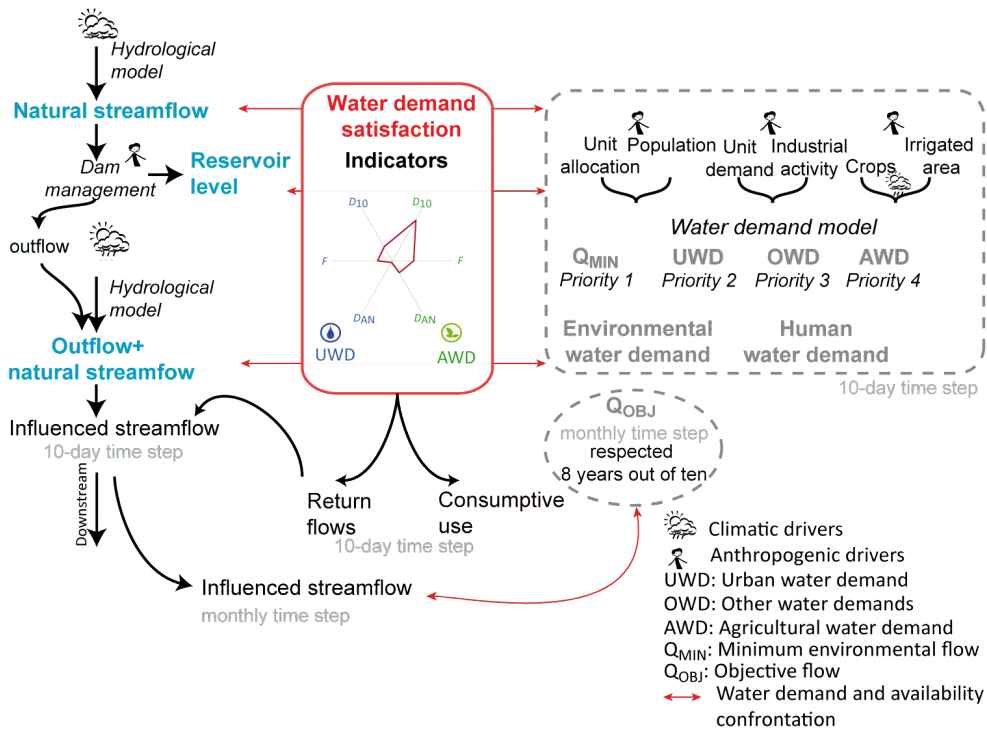


Figure 2. Integrative modelling framework applied at each resource and demand node of the Hérault and the Ebro basins. Water demand and natural streamflow were simulated based on climatic and anthropogenic drivers. Anthropogenic influence on streamflow was assessed through the simulation of demand-driven dam management and consumptive use. Water demand satisfaction was assessed by comparing demand to availability.

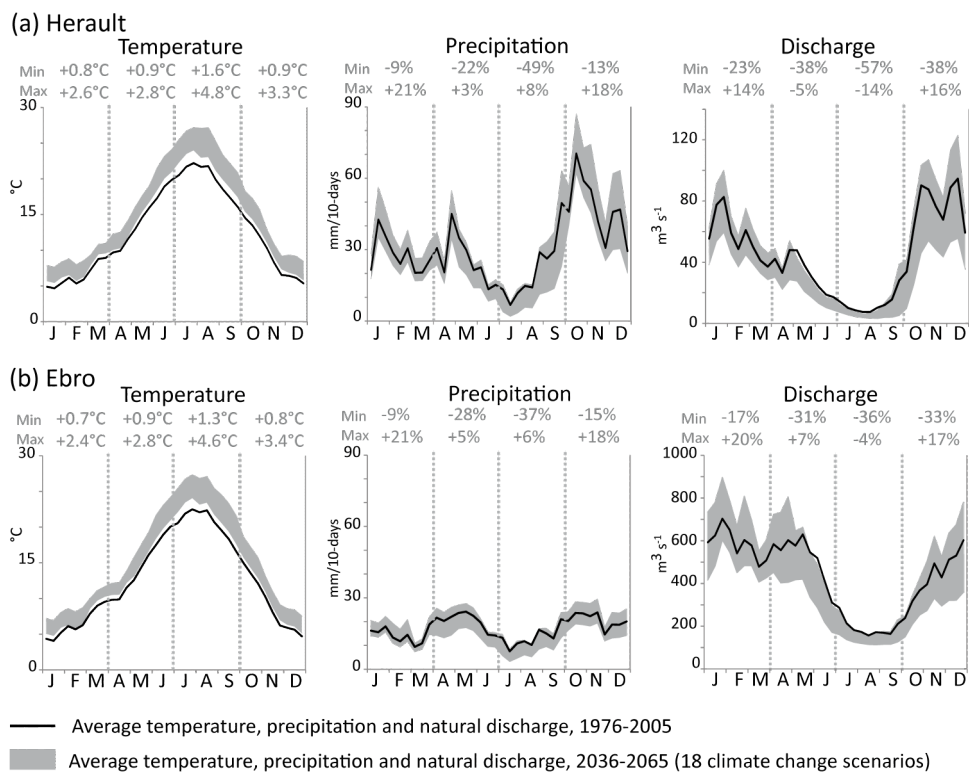


Figure 3. Average temperature, precipitation and natural discharge over the reference period 1976–2005 and under 18 climate change scenarios at the 2050 horizon in (a) the Herault and (b) the Ebro basins. Natural discharge is simulated with the hydrological model over the reference and future period. [Modified from Fabre et al. \(2015b\)](#).

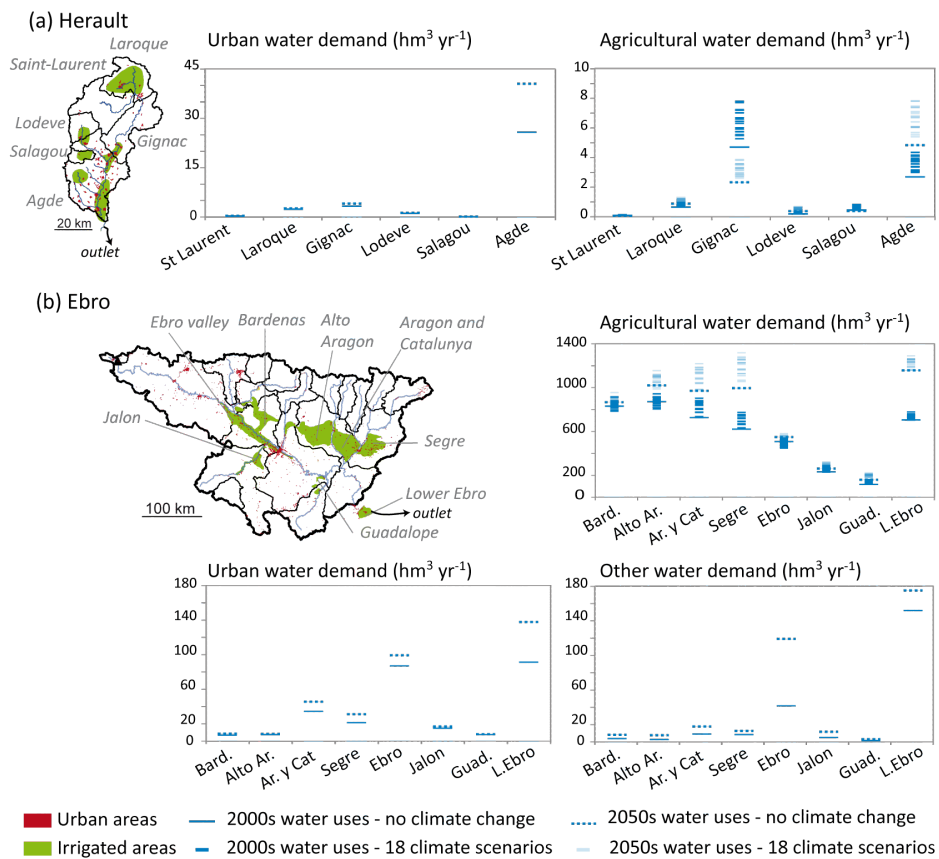


Figure 4. Water demands for human activities in (a) the Herault and (b) the Ebro basins under four combinations of water use and climate scenarios.

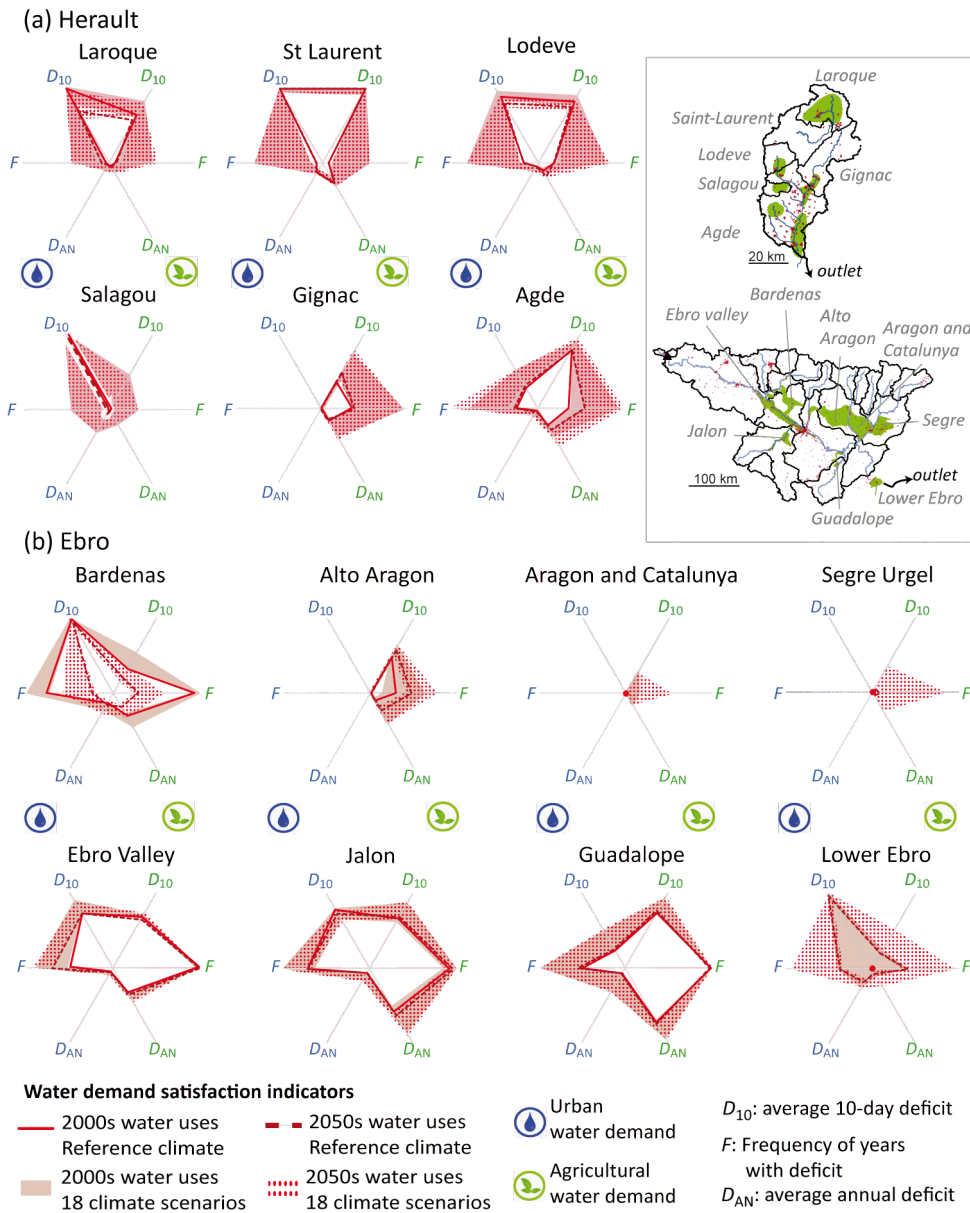


Figure 5. Water demand satisfaction indicators for urban and agricultural water demands in (a) the Hérault basin and (b) the Ebro basin under four combinations of water use and climate scenarios. Each radar chart presents the results for one demand node. For all three indicators values range from 0 (no deficit) to 1 (maximum frequency or intensity of deficit).

Anthropogenic pressures on water resources (percentage of natural streamflow)

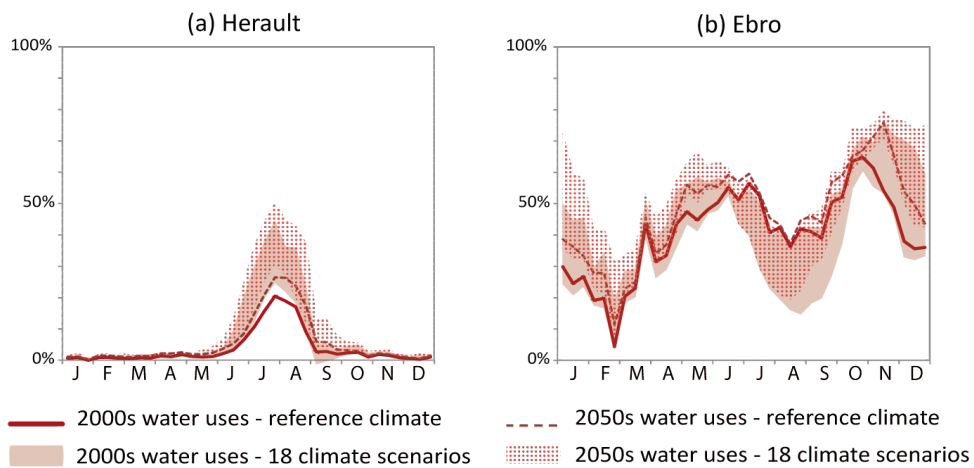


Figure 6. Anthropogenic pressures on water resources under four combinations of climate and water use scenarios in (a) the Herault basin and (b) the Ebro basin. Anthropogenic pressure is computed through the difference between natural and influenced streamflow at the outlet of each basin, expressed as a percentage of natural streamflow.

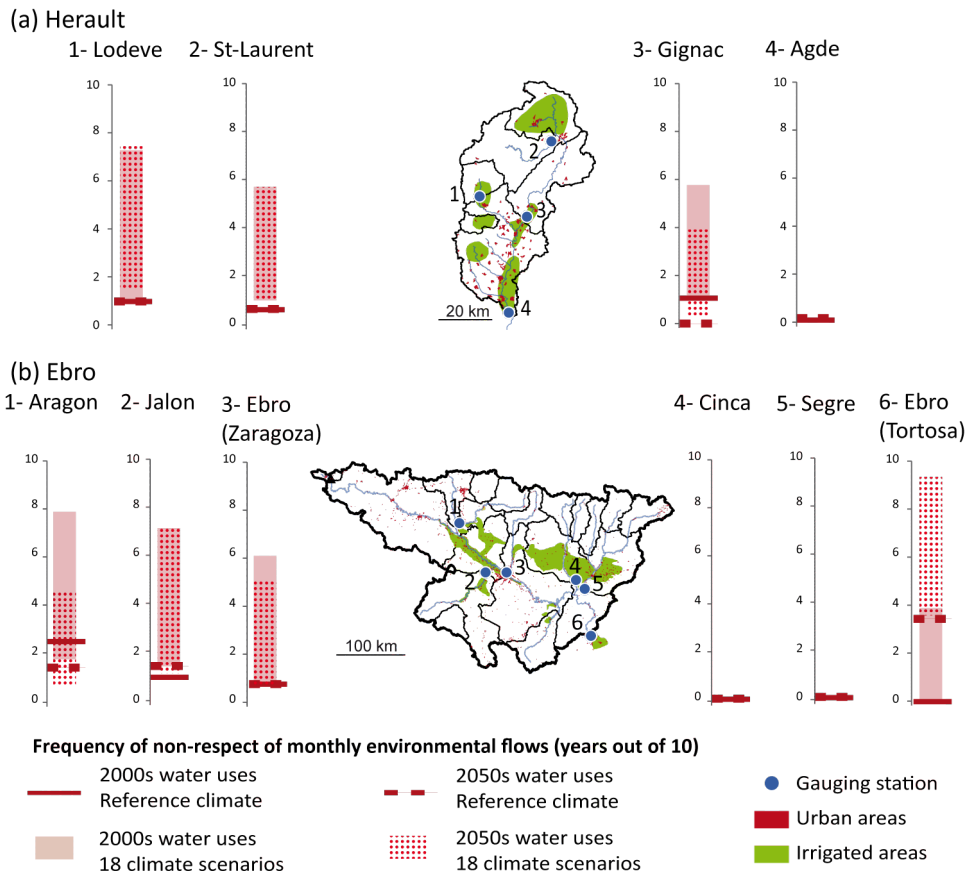


Figure 7. Frequency of years (out of ten) with monthly influenced streamflow inferior to the objective monthly environmental flow Q_{OBJ} in (a) the Hérault basin and (b) the Ebro basin. Frequencies are considered acceptable under two years out of 10.