Water supply sustainability and adaptation strategies under anthropogenic and climatic changes of a meso-scale Mediterranean catchment
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Published in:
Science of the Total Environment

DOI:
10.1016/j.scitotenv.2015.07.093

Publication date:
2015

Document Version
Peer reviewed version

Link to publication in Heriot-Watt University Research Portal

Citation for published version (APA):
Abstract: Assessing water supply sustainability is crucial to meet stakeholders’ needs, notably in the Mediterranean. This region has been identified as a climate change hot spot, and as a region where water demand is continuously increasing due to population growth and the expansion of irrigated areas. The Hérault River catchment (2,500 km², France) is a typical example and a negative trend in discharge has been observed since the 1960s. In this context, local stakeholders need to evaluate possible future changes in water allocation capacity in the catchment, using climate change, dam management and water use scenarios. A modelling framework that was already calibrated and validated on this catchment over the last 50 years was used to assess whether water resources could meet water demands at the 2030 horizon for the domestic, agricultural and environmental sectors. Water supply sustainability was evaluated at the sub-basin scale according to priority allocations using a water supply capacity index, frequency of unsatisfactory years as well as the reliability, resilience and sustainability metrics. Water use projections were based on the evolution of population, per-unit water demand, irrigated areas, water supply network efficiency, as well as on the evaluation of a biological flow. Climate projections were based on an increase in temperature up to 2°C and a decrease in daily precipitation by 20%. Adaptation strategies considered reducing per-unit water demand for the domestic sector and the importation of water volume for the agricultural sector. The dissociated effects of water use and climatic constraints on water supply sustainability were evaluated. Results showed that the downstream portions would be the more impacted as they are the most exploited ones. In the domestic sector, sustainability indicators would be more degraded by climate change scenarios than water use constraints. In the agricultural sector the negative impact of water use scenarios would be stronger. The environmental sector would be hardly satisfied especially in summer with low resilience levels. The adaptation strategies considered in this study would not be sufficient to cope with both anthropogenic and climate changes. Other strategies were discussed based on known examples in the Mediterranean context.

Key words: climate variability; integrated modelling; prospective scenarios; River Hérault; sustainability indicators; water uses
1. INTRODUCTION

1.1. Integrated approach on water supply assessment for future impact studies

The conclusions of the fifth IPCC report AR5 show that since AR4 the awareness of human influence on global warming since the mid-20th century has grown. This influence being now considered as “extremely likely” (IPCC, 2013). Moreover even if greenhouse gas emissions are stopped now the impacts of past and present emissions, on the water cycle among others, will continue in the next centuries. This highlights the urgent need to evaluate the possible impacts of climate change on water resources management and to investigate how policy-makers and the general public may mitigate and adapt to these changes. The Mediterranean is one of the most vulnerable regions to climate change (Giorgi, 2006) as in the second half of the 20th century streamflows decreased by half in many basins (García-Ruiz et al., 2011) while water demand doubled (Blinda and Thivet, 2009). Subsequently the water stress index that was already high to very high in various basins of this region could increase in the future under the constraint of climate and anthropogenic changes (Milano et al., 2013b).

Integrative water management approaches have been developed to allow the analysis of climate change impacts, as well as the co-evolution of water uses related to these changes in the past, present and future periods (see e.g. Yates et al., 2005; Quilbé and Rousseau, 2007; Sun et al., 2008; Bhadwal et al., 2013). These approaches have been used to explain and represent the combined dynamics of climate, hydrosystems and anthroposystems and help the decision-makers to evaluate the sustainability of their water management systems. Arnold (2013) underlined the difficulties in developing such approaches that gather together data from diverse disciplines, especially on meso-scale catchments (considered here for catchments from 1 000 to 10 000 km²). At this scale, water stakeholders need to identify the limits of water supply capacity that could arise on their territory. Moreover the temporal scale of integrative approaches should be representative of the hydro-climatic variability as well as the evolution of anthropogenic constraints on time periods long enough so that the modelling chain can be tested for its robustness and used for future impact studies. One of the main constraints at this spatial scale relies on the generally poor available datasets for water withdrawal and socio-economic series over several decades (Hannah et al., 2011; Grouillet et al., 2015).
In this context, Collet et al. (2013b) presented an integrative water management approach developed on a meso-scale catchment in the French Mediterranean. This modelling framework was applied at a semi-distributed scale over a long period of time, based on the compromise between (i) the aim of evaluating the long-term evolution of water supply capacity and (ii) the availability of hydro-climatic and socio-economic data series with an appropriate time step. This study was part of a wider project on this catchment that aims at evaluating possible future changes in water supply capacity and sustainability under climatic and anthropogenic constraints. It was thus developed in order to be used in a prospective impact study.

1.2. Context for building future complex scenarios

Future impact studies imply building complex future scenarios that rely on the variation of numerous variables such as population, per-unit water demand, crop types, water network delivery efficiency, temperature, precipitations, etc. Water use scenarios should take into account policy constraints related to climate change at various decision-making levels. At the European Union scale, the Water Framework Directive advocates that water bodies attain a good ecological status by 2015. At the French scale, the December 2006 law on water and aquatic environments transcribes these European objectives to the national scale. In parallel, the August 2009 law allows the implementation of measures decided at the Grenelle Environmental Summit through a national climate change adaptation plan. This plan was defined in 2011 and sets a quantified target of reducing the water withdrawals by 20% by 2020. At the basin scale, the authority for water management in southeast of France is SDAGE RMC (Schéma Directeur d’Aménagement et de Gestion des Eaux du bassin Rhône-Méditerranée et Corse). For the period 2011-2015, one of the main objectives of SDAGE RMC is the return to a quantitative equilibrium between water resources and demands, by improving water resource sharing and the anticipation of the future. Meso-scale basins presenting quantitative water management troubles, such as the Hérault River catchment, were identified and a Water Development and Management Plan was developed for each of them to define concrete decisions that would allow the basin, French and European water management objectives to be reached.
Using a wide range of General Circulation Models (GCMs) outputs is generally recommended to estimate a set of possible futures in impact studies, as well as the probability of occurrence of these future scenarios (Wilby, 2010). With this approach, uncertainty of climate models outputs should be characterised and sensitivity and performance of impact models should be evaluated. However as reported by Ludwig et al. (2014) the use of these simulations add numerous uncertainties in future water availability estimation, related to the GCMs model structure that generates large biases in simulation, especially precipitation. Moreover, great uncertainty remains around regional projections in the Mediterranean basin (e.g. Palatella et al., 2011). This can lead to a multiplication of results and of result ranges, which make them more complex to interpret and used by decision-makers. Moreover the physical and chemical constraints implied in rainfall formation processes occur at a spatial scale largely smaller than GCM resolution (Planton et al., 2005). It makes GCM local estimation of precipitation unreliable, especially in regions where precipitation events occur sparsely and can vary greatly in intensity in a very short time. This study does not seek to estimate a wide range of possible futures in water management but rather to give thought to the impact of climate change on water management. Another approach will then be adopted in this study to evaluate the impact of gradual temperature rise and precipitation fall on water management sustainability.

1.3. Choice of indicators to assess water supply sustainability

Defining sustainability depends on the system and/or the resources that need to be sustained. Although the debate is not closed, sustainability always considers the future (Loucks, 1997), and according to the Brundtland Commission (WCED, 1987) it includes “the ability of future generations to meet their needs”. A number of existing indicators can be used to evaluate water supply sustainability. Some approaches use sets of various indicators answering a local management issue, which can lead to a multiplicity of indices, up to several dozen, to analyse and interpret (see e.g. Ioris et al., 2008; Geng et al., 2014). Other approaches use indicators that integrate different natural resources management concepts. Sullivan et al. (2003) defined a water poverty index that assesses the impact of the lack of water on human communities, and which accounts for, among others, available water resources, access to these resources, and the ability of the population to manage their resources. Another index is
the water stress index, defined as the ratio of annual total withdrawals to annual available water resources (Menzel and Matovelle, 2010). The water demand satisfaction rate is also used (e.g. Rosenzweig et al., 2004; Sun et al., 2008; Milano et al., 2013b). This index indicates whether water demand has been satisfied, and has the advantage of being easily understood by both scientists and stakeholders. To facilitate dialogue between researchers and managers and answer their needs in planning future water management, Collet et al. (2013b) also made a frequency analysis of the water supply capacity index. It allowed the managers to know whether the management planning was satisfactory according to the numbers of unsatisfactory years during a mean 5-year period.

However this enlightened within these unsatisfactory years neither the frequency of unsatisfactory time-steps, the capacity of the management system to recover after an unsatisfactory period, nor the quantitative missing water volume. That is to say, how severe and frequent were the unsatisfactory periods during the unsatisfactory years. Loucks (1997) suggested a framework that allows evaluating the sustainability of a system and its management measuring reliability, resilience and vulnerability, based on a subjective point of view defining when the system is unsatisfactory. While the definition of reliability is commonly accepted as the amount of time that a system is in a satisfactory state, definitions of resilience and vulnerability are more debated. After a review of the literature, Hill Clarvis et al. (2014) defined resilience as “a measure of the amount of perturbation a linked social-ecological system can withstand and still maintain the same structure and functions”. In parallel, according to the review of Plummer et al. (2012) “vulnerability in the context of water resources refers to the susceptibility of a system to damage as a function of exposure to external forces”. Based on these definitions, the reliability, resilience and vulnerability metrics as suggested by Loucks (1997) could be used and adjusted to our water management system issues.

1.4. Scope of the paper

After defining water management sustainability metrics, this paper has two main objectives. First it aims at evaluating the possible evolution of water supply sustainability of a meso-scale Mediterranean catchment based on complex hydro-climatic and anthropogenic scenarios. Second it aims at discussing the capacity for human adaptation to climate change on this territory. This work was developed on the
Hérault River catchment thanks to the expertise shared by local water managers. It is thus also destined to be a discussion tool with water stakeholders about the issues raised on this basin, as well as a methodological example that could be transposed on other meso-scale catchments.

2. STUDY AREA

The Hérault catchment is located in the southern France and drains an area of approximately 2,500 km² (Fig. 1). The river rises in the Mont Aigoual in the Cévennes Mountains at 1,565 m a.m.s.l. and its outlet to the Mediterranean Sea is in Agde. The catchment has a population of over 170,000, with the main towns located in the downstream part. The population has doubled since the late 1970s, mainly due to urban development and tourism.

The climate is typically Mediterranean, with dry, hot summers (June, July, August) and wet, mild winters (December, January, February). Precipitation is almost zero in summer and peaks in spring (March, April, May) and autumn (September, October, November). The temperature is highest in summer and lowest in winter. As described by Collet et al. (2014), the upstream part of the catchment contributes the greatest precipitation and has the lowest temperatures while the downstream part has the least precipitation and the highest temperatures.

Surface and groundwater reserves in the upstream and the middle parts of the watershed are not heavily exploited. The Salagou dam (102 hm³) is the largest dam in the catchment and has been in operation since 1968. It is used to generate power and to support runoff during low flows. Salagou Lake serves as a reservoir for irrigation and as a site for water sports. Water withdrawals mainly supply the domestic and agricultural sectors. A total of 75% of the domestic withdrawals are extracted from the alluvial plain in the downstream part of the watershed. Florensac (Fig. 1) supplies water to towns located outside the Hérault catchment, and represents more than 50% of water withdrawn for domestic purpose. A total of 94% of the agricultural water withdrawals exploit surface resources, mainly located in the downstream part of the watershed, to supply water to around 4,500 ha of irrigated land (less than 5% of the utilised agriculture area, see Fig. 1). The biggest irrigation network, the Gignac canal, diverts water from the River Hérault at S¹-Guilhem (Fig. 1). It supplies irrigation water to the Gignac and the Agde portions. The main crops grown upstream in the Hérault catchment
are onion, olive, apple and walnuts. Vineyards and wheat are the dominant crops downstream. Water resources and supplies of this catchment are managed by SMBFH (Syndicat Mixte du Bassin du Fleuve Hérault), Conseil Général de l’Hérault and Conseil Général du Gard.

3. MATERIAL AND METHODS

3.1. Integrated modelling chain

The integrated modelling approach used in this study (Fig. 2) to assess water resources sustainability is based on work by Collet et al. (2013b) which was successfully calibrated and validated for the 1961–2010 period at a 10-day time step. This method was applied over the 2030 horizon (2021–2040) in six portions of the Hérault catchment (Fig. 1). This delineation was previously shown to be suitable for studies of water resources management over a long time period in this catchment (Collet et al., 2014). It accounts for the different hydro-climatic processes within the catchment as well as for the main water demand sites and river discharge regulations by the main storage dam (see Fig. 1). Two main water demand sectors, domestic and agricultural, were identified in the Hérault catchment.

As described by Collet et al. (2013b), water resources were first simulated at a daily time step using a lumped hydrological model for each basin portion and a dam management model, with hydro-climatic and storage-dam data. The GR4J conceptual rainfall-runoff model (Perrin et al., 2003) was
run to simulate water availability. A dam management model was designed to simulate variations in water release from the Salagou storage dam. Water releases (a turbined flow and water releases for flooding management) were constrained by the dam level. Domestic and agricultural water demands were then assessed at a 10-day time step using climatic, withdrawal and irrigated area data as well as soil and crop characteristics. Annual domestic water demand (DWD) was calculated as the product of per capita DWD and the population, for each portion of the catchment. To give a seasonal variability to these series, they were disaggregated to a monthly time-step based on the monthly pattern observed in 2007, the only year with a complete observed monthly series. These series were finally disaggregated evenly to a 10-day time step within each month by simply dividing the monthly values by three. An irrigation management model based on the FAO CropWat model (Allen et al., 1998) was developed to estimate agricultural water demand (AWD). A fraction of water withdrawn (70% for DWD, 15% for AWD) was considered to return to the hydrographic network. Domestic water demand has a higher water supply priority level than agricultural water demand as stipulated in a memorandum dated the 3rd of August 2010 by the French Ministry of Ecology, Energy, Sustainable Development and the Sea (MEEDDM, Ministère de l’Écologie, de l’Energie, du Développement Durable et de la Mer).

Moreover an environmental water demand (EWD), which was not identified in the retrospective period, was taken into account at the 2030 horizon. Indeed, article 1 of the Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 requires that a framework that “prevents further deterioration and protects and enhances the status of aquatic ecosystems […]” is to be established. Article 8 of this Directive also points out that at the latest in 2015, the Member States of the European Union “shall ensure the establishment of programmes for the monitoring of water status […]”, and that “for surface waters such programmes shall cover the volume and level or rate of flow to the extent relevant for ecological […] status […]”. SMBFH, the authority responsible for water management in the Hérault catchment, has already planned to ensure a minimum flow in the catchment’s rivers, for the good ecological status of the hydrographic network (see the classification of ecological status in Annex V of the Directive). In this work the lowest water supply priority was attributed to EWD. This choice illustrates an anthropocentric viewpoint of water management, which
has been observed for the last centuries and might tend to go on in the next decades.

A water supply capacity index (WSCI), whose calculation was based on a water demand satisfaction rate (Milano et al., 2013a), was computed at a 10-day time step. This index assesses the ability of water resources to supply the estimated optimal water demand. It is based on the ratio of water resources availability (WRA) to water demand (WD) (equation (1)).

\[
WSCI = \frac{WRA}{WD} \times 100
\]  

The water supply capacity index was calculated in each portion of the basin and for each type of water demand, taking into account the priority level of each. Sustainability indicators (see section 3.2.) were then calculated for unsatisfactory years, i.e. when at least one time step presented a WSCI below a high satisfactory rate. As stated by Collet et al. (2013b), domestic water demand is more exacting than agricultural water demand since a 97% WSCI is required for satisfaction, while agricultural water demand is highly satisfied from a 75% WSCI. The same satisfactory rate as the DWD one was used for environmental water demand. These ranges are based on recommendations made by SMBFH.

![Fig. 2 General principles of the integrated modelling chain.](image)

3.2. Sustainability indicators
To evaluate water sustainability, four metrics were chosen: the frequency of unsatisfactory years, reliability, resiliency and vulnerability. They were evaluated in each portion of the catchment and for each type of water demand. The former was presented by Collet et al. (2013b). The three latter have already been used in the literature, and recently presented by Hoque et al. (2014) and Asefa et al. (2014). They were calculated for each unsatisfactory year and then mean inter-annual values were computed at the 2030 horizon.

Frequency of Unsatisfactory Years (FUY, equation (2)) was evaluated in year/5 years to meet with water managers’ attempts. Indeed, in the memorandum dated the 3rd of August 2010, MEEDDM stated that water withdrawals should be able to supply water demand for domestic and irrigation purposes, four out of five years, without any restrictions, and respecting the environmental objectives of the European Water Framework Directive. If the frequency of unsatisfactory years is more than 1 year in 5 years then the water management system is thus not sustainable and should be modified. This indicator value varies from 0 to 5.

\[
FUY = \frac{5}{Y} \sum_{y=1}^{Y} UY(y)
\]

with: \( Y \) the total number of years in the time period; \( UY(y) \) the number of unsatisfactory years, i.e. presenting at least one time step with a WSCI below a high satisfaction rate. 

Reliability (REL, equation (3), Hoque et al., 2014) measures the frequency of success of the system. Its value varies from 0 to 1.

\[
REL = 1 - \frac{\sum_{j=1}^{M} d(j)}{T}
\]

with: \( M \) the number of unsatisfactory periods; \( d(j) \) the length of the \( j^{th} \) unsatisfactory period; \( T \) the total length of the time period.

Resiliency (RES, equation (4), Hoque et al., 2014) evaluates how quickly on average a system recovers to a satisfactory state. Its value also varies from 0 to 1.
Vulnerability (VUL, equation (5), Asefa et al., 2014) estimates how severe the unsatisfactory state is. This indicator gives a quantitative evaluation of the unsatisfactory state as it reveals the maximum difference between the complete satisfaction of estimated water demand and the actual water supply capacity in a year.

\[
RES = \frac{M}{\sum_{j=1}^{M} d(j)}
\]

(4)

\[
VUL = \max \left\{ \sum_{j \in d(j)} C(j) - X(j) \right\}
\]

(5)

with: \( C \) the water supply objective (hm\(^3\)/unsatisfactory period); \( X(j) \) the actual system performance during \( j^{th} \) unsatisfactory period (hm\(^3\)/unsatisfactory period).

3.3. Water use and climate scenarios

3.3.1. Water use scenarios

Various water use scenarios were analyzed in this study at the 2030 horizon (2021–2040), compared to the reference period (1991–2010). First, Conseil Général de l’Hérault has been considering managing the Salagou dam water releases to insure a minimum water level in the reservoir (Conseil Général de l’Hérault, 2010). Although this dam is used to deliver hydropower, water for irrigation as well as to support low-flows, its main purpose nowadays is economic: it is one of the most visited tourist attractions of the region in summer, above all for water sports. In order to keep water sport infrastructures functional, a minimum water level in the reservoir, at 136 m a.m.s.l., should be maintained. This constraint is established by managing the turbined flow depending on the period of the year and the water level of the reservoir (see Table 1). These rules allowed the reservoir to fill up from October to December, to remain steady from January to March and to keep a high water level from April to May. An instream flow release (0.08 m\(^3\)/s) was also added to ensure a minimum discharge in the river downstream. Moreover, withdrawals for irrigation were projected to increase for both concerned cities: Bosc-Lacoste (+20%) and Octon (+60%).
Second, domestic water demand projections (Fig. 3c) relied on demographic variations projected by INSEE (Institut National de la Statistique et des Etudes Economiques) from 2021 to 2040 (Fig. 3a) and on per capita water demand tendencies evaluated in partnership with SMBFH (Fig. 3b). The central INSEE scenario was chosen in this study. It is available at the French department scale. The Hérault catchment lies in the Gard (for the Laroque portion) and the Hérault (for the Saint-Laurent, Gignac, Lodève, Salagou and Agde portions) departments. At the 2030 horizon, this region would have the highest population growth in France (+0.8%/year, that is to say twice the national average), resulting from a high inter-regional migration but compensated by the ageing of the baby-boom generation (Audric, 2010). Compared to 2010, these scenarios project in 2040 an increase in population of 25% and 24% in the Gard and Hérault departments respectively. For per capita water demand projections, observed trends (a decrease over 2000–2010 from 120 to 110 m³/inhabitant/year) were extended in the future, leading to a threshold corresponding to the mean value over 1961–1990 (90 m³/inhabitant/year). This period was chosen as it presented steady per capita water demands, before their increase in the 1990s. The resulting domestic water demand scenario would involve an increase of 14% on average from 1991–2010 to 2021–2040 over the whole catchment (Fig. 3c).

Third, agricultural water demand scenarios were built in partnership with SMBFH, resulting from agricultural forecasting at the 2030 horizon negotiated by the Water Development and
Management Plan (Schéma d’Aménagement et de Gestion des Eaux - SAGE) Agriculture Committee of the Hérault catchment. These scenarios were based on the evolution of distribution network efficiency and irrigated areas for each portion of the basin. The distribution network efficiency is planned to reach 85% in all the portions except for the Gignac portion. Improvement works have already been in progress for a few years, especially in the Gignac canal network, where the efficiency should reach 75%. Regarding irrigated areas, an increase of 25% is planned in all the portions. This decision reflects the 2013 reform of the European common agricultural policy that offers financial support to help the installation of new irrigation systems for vineyards. Additional irrigated areas (+1,500 ha) should be developed in the Agde portion for vineyards, resulting in tripling irrigated areas in this portion. These trends would involve an increase in agricultural water demand of 7% in the Laroque portion, up to 124% in the Agde portion.

Finally, consequently to the European Directive Framework constraints, SDAGE RMC, the River Basin Management Plan for water management in the southeastern part of France (see Fig. 1), proposed a framework to define the biological flow. This flow represents the minimum value to insure a sustainable aquatic life in rivers. Based on these requirements, environmental water demand was estimated by SMBFH in 2012 at the outlet of each portion of the catchment (see Table 2).

Table 2 to be inserted here

3.3.2. Climate scenarios

To develop a didactic demonstration that brings scientists and managers to a reflection on adaptation strategies for water management, we chose to use climate scenarios where only precipitation and temperature vary, leading to warmer and drier climatic conditions. This kind of approach was already used in the literature (see e.g. Sultan et al., 2013). Climate scenarios were based on variations of temperature and precipitations compared to daily observations over the 1991–2010 period (Tab. 3). Twelve 30-year climate scenarios were thus calculated, applying these biases on each daily value of observation series. Variation ranges for temperature and precipitations were based on projections presented in the last IPCC report for southern Europe (IPCC, 2013). For precipitation, only scenarios
with decreasing trends were considered to orientate the discussion towards a degradation of water management conditions.

*Table 3 to be inserted here*

The modelling chain was fed by daily series of precipitation and Potential Evapotranspiration (PET). PET was estimated using the Food and Agricultural Organization (FAO) Penman-Monteith formula (Allen et al., 1998), which is mainly constrained by temperature. Although the FAO Penman-Monteith formula estimates the reference evapotranspiration (ET0), PET was being used as approximation of ET0 in this study, as recommended by Allen et al. (1998), as it is adapted to the hydrological model, the dam management model as well as the agricultural water demand estimation. Biases induced by the chosen PET formula were thus limited as a single formula was used in the whole modelling framework.

3.3.3. Water use efforts tested

After evaluating the impact of water use and climate scenarios on water supply sustainability, some adaptation strategies were considered for the Hérault catchment. These strategies were built aiming at reaching the same sustainability level as observed in the reference period (1991–2010), that is to say the same indicators (FUY, REL, RES and VUL) values. The following adaptation scenarios were tested according to SMBFH: First, for domestic water demand, household savings were considered. The maximum per-unit water demand value that would allow domestic water demand to be satisfied was evaluated over 2021–2040 over the whole catchment. This scenario reveals a strong willingness of coastal towns in Southern France to reduce domestic water consumption in their call to population for water savings. Second, for agricultural water demand, water importation was considered to satisfy irrigation needs. The needed minimum water volume to be imported was thus calculated on each portion of the basin that incurred unsatisfactory agricultural water supply. This scenario illustrates an on-going project, the Aqua Domitia project, which has been deriving water from the Rhône River to Southern France and which is planned to reach the Spanish border. Lastly for environmental water...
demand no adaptation strategy was tested, but the effect of strategies for the other demands, which have higher water supply priority, on its sustainability, was evaluated. The issue was to estimate to what extent satisfying high-priority demands would help improving a low-priority demand supply.

3.4. Result analysis process

Results were first analysed regarding effects of water use scenarios only on water supply sustainability. In this first step, the observed climate over the reference period (1991–2010) fed the modelling chain, as well as water use scenarios at the 2030 horizon (2021–2040). Then, effects of climatic scenarios only were studied. In this second step, the twelve climatic scenarios fed the modelling chain, as well as observed water use over the 1991–2010 period. As environmental demand was not considered over the reference period, only the domestic and agricultural sectors were analysed in this step. Lastly, combined effects of water use projections at the 2030 horizon and climate scenarios were estimated. This step-by-step approach allowed a clear understanding of dissociated impacts on water supply sustainability of water use evolution on the one hand, and of climate change on the other hand. All these results were presented for each sustainability indicator, for each type of water demand and on each portion of the Hérault catchment.

After this analysis, adaptation strategies were tested for each future step. Based on the water use efforts planned to be done by local water managers, the required amount of water savings and water importation were calculated on each portion of the basin incurring water supply difficulties. The aim was to go back to the sustainability metrics values calculated in the reference period. The effect of these strategies on water supply sustainability of environmental water demand was finally discussed.

4. RESULTS
Fig. 4 Evolution of water supply capacity for the domestic, agricultural and environmental water demands, on each portion and for each scenario. (a) Mean frequency of unsatisfactory years. (b) Mean reliability for unsatisfactory years. (c) Mean resiliency for unsatisfactory years. (d) Mean vulnerability for unsatisfactory years. For the CO and UAC steps: minimum, maximum and median values are shown.
4.1. Efficiency of the modelling chain

The modelling chain built by Collet et al. (2013b) was already satisfactorily calibrated and validated over the 1961–2010 period for water resource and water demand estimation, as well as for WSCI computation. However, the authors did not use the reliability, resiliency and vulnerability metrics. Hence, values obtained over the reference period (1991–2010) for each portion of the basin and presented in Fig. 4 (columns R) are discussed in this section. Environmental water demand was not identified in the reference period, leading to no result for this demand on this period. Indicators were calculated for both domestic and agricultural demands.

For the domestic sector, water supply shortages appeared only in the Agde portion, with a FUY of 1 year/5 years, a REL of 0.98, a RES of 0.88 and a VUL of 0.79 hm$^3$/year (Fig. 4). These values reflect a fair water management system as unsatisfactory years were not frequent and unsatisfactory periods represented only 2% of the year (with a high reliability) did not last long (with a high resiliency) and were not intense (with a low vulnerability). It means that although there were some water supply shortages, those were not important as they did not last long nor were severe. This is well correlated to water management knowledge of the last decades. For instance two years presenting unsatisfactory sustainability indicator results (not shown here) were actually critical over this period of time: 2005 and 2006, the only years when the Salagou dam was used to support low-flows for the downstream part of the catchment.

For the agricultural sector, water supply shortages appeared in the Gignac and Agde portions (Fig. 4). In Gignac, these satisfaction shortages were not worrying as FUY was under 1 year/5 years with a low vulnerability (0.26 hm$^3$/year), indicating that the system was largely resilient over the reference period. In Agde, FUY was higher (2.25 years/5 years), but the system was satisfied 95% of the time, although it presented a RES of 0.69 and a VUL ten times higher (3.27 hm$^3$/year) than in Gignac. The Agde portion is the most exploited of the catchment and agricultural water demand is not a top-priority, which could explain water supply difficulties. However, although water use tensions appeared in summer, no water restrictions were frequently observed over the reference period. Yet as
mentioned by Collet et al. (2013b), water resources of the Hérault catchment tend to be slightly under-
estimated by the modelling chain, which should lead to too pessimistic water supply capacity
estimations. To limit this kind of bias, results in the future period were analysed compared to those in
the reference period, so that the discussion could focus on the relative impact of water use and climate
change scenarios on the evolution of water supply sustainability.

4.2. Future water supply capacity

4.2.1. Under water use changes only

Figure 4 (columns UO) shows results obtained in the first step of the analytical process. The domestic
water use scenario had an effect in the Salagou and Agde portions. In the Salagou portion, this
scenario slightly deteriorates water supply sustainability compared to the reference period, with a low
FUY (0.25 year/5 years), high REL and RES (0.99 and 0.96 respectively) and a Vul close to zero (10^{-3}
hm^3/year). Compared to observations in the Agde portion in the reference period, this scenario also
deteriorates water supply sustainability, which would reach unacceptable level as FUY would be
above 1 year/5 years (2.25 years/5 years). REL would be similar to observations (0.95) but RES would
decrease strongly (0.69) and Vul would double (1.58 hm^3/year).

The agricultural water use scenario only impacted the Gignac and Agde portions, where water
sustainability results already presented shortages in the reference period. In the Gignac portion, FUY
would increase above 1 year/5 years (1.75 years/5 years), REL would still be high (0.97), RES would
decrease from 1 to 0.83 and Vul would be almost ten times higher (1.8 hm^3/year). In the Agde
portion, FUY would strongly increase to 4 years/5 years, REL and RES would decrease to 0.89 and
0.55 respectively, and Vul would almost triple (8.82 hm^3/year).

As regards to environmental demand, biological flow could not be satisfied over more than 4
years/5 years at all the portion outlets (except at the Salagou outlet where the biological flow is zero).
REL would then be above 0.8 except in Lodève (0.68) where water supply sustainability would be the
lowest. RES would be very low: under 0.5 for all the portions, down to 0.15 in Lodève. Vul would
range from 2.87 hm^3/year in Saint-Laurent to 17.75 hm^3/year in Agde. These values represent 8% of
river discharge at the outlet of each portion for Saint-Laurent and Laroque, 12% for Gignac, 18% for Lodève, and 16% for Agde.

4.2.2. Under climatic changes only

In this section, impacts of climate scenarios only are discussed. First, Figure 5 shows the effects of these twelve climate scenarios on mean annual per-portion discharge (Fig. 5a) and agricultural water demand (AWD) (Fig. 5b). For per-portion discharge at the outlet of each portion of the basin, a decrease in precipitation would have a stronger impact than an increase in temperature. This impact is the lowest at the Laroque portion outlet and the highest at the Agde portion outlet. For no evolution in precipitation, mean annual per-portion discharge would decrease by 1 to 3% for an increase in temperature of 0.5 °C, and by 4 to 12% for an increase in temperature of 2.0 °C. For a 10% decrease in precipitation, per-portion discharge would decrease by 17 to 23% for an increase in temperature of 0.5 °C, and by 20 to 31% for an increase in temperature of 2.0 °C. For a 20% decrease in precipitation, per-portion discharge would decrease by 33 to 41% for an increase in temperature of 0.5 °C, and by 36 to 48% for an increase in temperature of 2.0 °C.

As regards to AWD, climate scenarios would have a small impact in portions that are not heavily exploited while highly irrigated portions could undergo a significant rise in their water demand. In the Saint-Laurent portion, the increase in AWD would range from $10^{-4}$ hm$^3$/year for the +0.5 °C/0% scenario to $2.10^{-3}$ hm$^3$/year for the +2.0 °C/-20% scenario. In the Laroque and Salagou portions, AWD would rise from 0.00 and 0.03 hm$^3$/year respectively for the +0.5 °C/0% scenario to 0.32 and 0.36 hm$^3$/year respectively for the +2.0 °C/-20% scenario. In the Lodève portion, AWD would increase from 0.01 to 0.05 hm$^3$/year. Lastly, in the Gignac and Agde portions, the most irrigated ones, the increase in AWD would range from 0.23 and 0.20 hm$^3$/year respectively for the +0.5 °C/0% scenario to 1.33 and 1.65 hm$^3$/year respectively for the +2.0 °C/-20% scenario.

Figure 4 (columns CO) shows minimum, maximum and median values obtained for each indicator in the second step of the analytical process. For domestic water demand, only the Agde portion would be impacted. FUY would increase from 2 to 3 years/5 years. REL would range around 0.88 and RES from 0.31 to 0.38. VUL could double (1.15 hm$^3$/year) to triple (2.57 hm$^3$/year)
compared to the reference period. These values show that the water supply system in the Agde portion might not be sustainable under the tested climate scenarios, with the same water use level as today.

For agricultural water demand, the Gignac, Lodève and Agde portions would see their water supply sustainability deteriorate under the tested climatic conditions. In the Gignac portion, FUY would increase around 1.75 years/5 years; REL would range around 0.9; RES would fall between 0.38 and 0.78; VUL would mostly double (around 0.64 hm³/year) compared to the reference period. In the Lodève portion, the deterioration would not be significant as FUY would stay below 1 year/5 years (up to 0.25 years/5 years); REL would stand above 0.93; RES would be mostly maximum (but with a minimum value of 0.42); VUL would range between 0 and 0.02 hm³/year. In the Agde portion, FUY would increase from 2.75, slightly more than in the reference period, to 4.25 years/5 years. REL would fall around 0.86 and RES around 0.34. However, VUL would stand at a similar level than in the reference period with values ranging from 4.1 to 4.8 hm³/year.
Fig. 5 Evolution of mean annual simulated values between the reference period (1991–2010) and each climate scenario of (a) discharge (%) at each portion outlet; and (b) agricultural water demand (hm$^3$/year) of each portion.
4.2.3. Under combined scenarios

In this third step, combined effects of water use and climate scenarios were analysed (Fig. 4, columns UAC). For the domestic sector, scenarios impacts can be seen for the Salagou and Agde portions. The Salagou portion would present satisfactory FUY, REL and VUL values similar to those in the UO step. Only RES would fall drastically between 0.25 and 0.63, with the median value at 0.27. It means that for the occasional unsatisfactory years, unsatisfactory states could last 10% of the year and once in an unsatisfactory state, the system could take a long time before going back to a satisfactory state, although it is not alarming because VUL is very low. For the Agde portion all the metrics would significantly deteriorate compared to the reference period. Unsatisfactory years would appear from 2.25 up to 4 years/5 years. Unsatisfactory states would represent a little bit more than 10% of the year (median Rel of 0.88). The water supply system would not be resilient (RES from 0.28 to 0.48), that is to say unsatisfactory states would last long (up to 4 successive 10-day time steps i.e. more than a month). The maximum water volume shortfall would stay at the same level than in the CO scenario: from 1.45 to 2.16 hm$^3$/year.

For the agricultural sector, the Laroque, Gignac, Lodève and Agde portions would present water supply sustainability difficulties. For the Laroque and Lodève portions, that have low agricultural activity, these difficulties would though be negligible: FUY would range below 1 year/5 years respectively; REL and RES would stay mainly at 1; VUL would be low, under 0.1 hm$^3$/year. However, for the Gignac and Agde portions these difficulties would be higher than those of the UO and CO scenarios. FUY could vary from 1.75 to 3 years/5 years in Gignac and from 4.25 to 4.75 years/5 years in Agde. REL would tightly range around 0.9 in Gignac and 0.85 in Agde. RES median values would be 0.44 in Gignac and 0.3 in Agde. VUL would vary from 1.84 to 3.02 hm$^3$/year in Gignac (ten times higher than in the reference period) and 8.53 and 12.32 hm$^3$/year in Agde (up to four times higher than in the reference period). These results call for new water supply systems in both portions for AWD.

For the environmental sector, results are similar to those in the UO step for all the portions. FUY would be above 4 years/5 years. REL would range in the best case around 0.79 for Saint-Laurent
and Laroque, and in the worst case around 0.56 for Lodève, meaning that the minimum environmental streamflow biological flow is not reached from 20% to 40% of the time in a year. These difficulties appear mainly in summer, and last various months as RES would be very low, around 0.32 in Saint-Laurent and 0.14 in Lodève. VUL would range around 3.81 hm$^3$/year in Saint-Laurent, up to 19.36 hm$^3$/year in Agde. These volumes represent 10% of river discharge at the outlet of each portion in Saint-Laurent and Laroque, 14% in Gignac, 22% in Lodève and 18% in Agde.

4.3. Adaptation strategies

Figure 6a shows values of maximum per capita domestic water demand (DWD) that would allow a fair match between water resources and domestic water demand. These values were estimated on the whole territory. Mean per capita DWD was almost 120 m$^3$/inhabitant/year over the 1991–2010 period. Regarding the UO step, per-unit water demand should decrease to 60 m$^3$/inhabitant/year to avoid domestic water supply difficulties. This value corresponds to the per-unit domestic water demand observed in the Saint-Laurent portion over the 1961–1990 period. For the CO step, per capita DWD should fall around 28.5 m$^3$/inhabitant/year (from 45 m$^3$/inhabitant/year to 14 m$^3$/inhabitant/year in the more restrictive scenario). The upper value is equivalent to the per capita DWD observed in the 2000s in the southern rim of the Mediterranean (Morocco, Algeria) (FAO 2014, AQUASTAT database). For the UAC step, the median value of per capita DWD should reach 21.5 m$^3$/inhabitant/year, with the upper boundary at 38 m$^3$/inhabitant/year and the lower boundary at 8 m$^3$/inhabitant/year. The lower boundary value is barely above the observed per capita DWD in Mali and Chad in the 2000s (FAO 2014, AQUASTAT database).

After having improved water supply sustainability for the domestic sector, the adaptation strategy for the agricultural sector was evaluated. Figure 6b shows the maximum water flow that should supply the Gignac and Agde portions so that agricultural water demand would always be satisfied. It represents the capacity sizing of a water distribution network. For the UO step, the Gignac and Agde portions would need a maximum flow of 0.68 and 1.60 hm$^3$/10-day period respectively. The CO step would involve smaller efforts as imported water volumes would range around 0.11 and 0.19
hm³/10-day period for the Gignac and Agde portions respectively. For the UAC step, these values would reach the ones obtained for the UO step and vary tightly around 0.74 and 1.4 hm³/10-day period for Gignac and Agde respectively. These volumes are equivalent to water flows of 0.86 m³/s and 1.62 m³/s for Gignac and Agde respectively.

Fig. 6 Quantification of water use efforts to satisfy water demand for each scenario. (a) Savings in the domestic sector: per-unit value needed to be reached. (b) Supply of the agricultural sector: peak value of imported water volume needed. For the CO and UAC scenarios: minimum, maximum and median values are shown.

Table 4 shows the effect of water use efforts for the domestic and agricultural sectors on water supply sustainability metrics for the environmental sector at the outlet of the Saint-Laurent, Laroque, Gignac, Lodève and Agde portions. The biological flow would not be satisfyingly reached in this case, as FUY would stay above 4.25 years/5 years in all the portions. Rel, Res and Vul would slightly improve but stay at the level or below 0.8 for Rel, between 0.10 and 0.35 for Res and between 2 and 20 hm³/year for Vul.

Table 4 to be inserted here

5. DISCUSSION

5.1. Dissociated effects of water use and climatic constraints
Considering separately a 2030 horizon water use scenario and 12 climate change scenarios allowed their respective impacts on water management sustainability to be evaluated. For domestic water demand (DWD) regarding the water use scenario effects compared to the reference period, water management sustainability could decrease in the Salagou and the Agde portions. Although almost all the indicators would remain at acceptable levels, resiliency would significantly deteriorate in Agde. It means that although this water demand sector has priority, in this portion the water management system would not be efficient anymore under new anthropogenic constraints (mainly an increase in population). For agricultural water demand (AWD), only the portions presenting difficulties in the reference period and having the highest agricultural activity (Gignac and Agde) would be impacted. Here, there would be a with a significant deterioration of resiliency and vulnerability, above all in Agde. This means that in these portions, the agricultural sector which will have an increase in irrigated areas, would not be sustained by the water management system, and there would be significant water shortages. It could also be linked to the fact that this water demand sector has a lower priority level than DWD, although it should be reminded here that 70% of water allocated to DWD returns to the river network.

Regarding the climate change scenarios effects only the Agde portion, already having sustainability lacks in the reference period, would be impacted for DWD. In that case, resiliency would drastically fall in this portion. It means that in this portion after a dry period the water management system would require a long time before it would supply the domestic sector satisfactorily. For AWD, the Gignac and Agde portions as well as the Lodève portion would see their sustainability decrease compared to the reference period, with less satisfactory metrics values than for DWD. This can be seen above all with a strong decrease in resiliency in these three portions. The other indicators would reach same levels as those in the water use scenarios. These results mean that in the Gignac, Lodève and Agde portions the agricultural sector would find long-lasting difficulties in being satisfied during a dry period, although these shortages would not be intense in either amplitude or frequency.

In conclusion, water use scenarios would have a more pronounced impact on the downstream portions for DWD, while climate change scenarios would influence more AWD in the middle part of
the catchment. The Agde portion would still be the more impacted one as it presents the highest population and the highest increase in irrigated areas. In terms of indicator values, water use scenarios would have more effect on vulnerability for the agricultural sector, while climate change scenarios would deteriorate more significantly resiliency for both the domestic and agricultural sectors.

5.2. Feasibility of the adaptation strategies

The adaptation strategies tested in this study were based on those considered today by local managers. For the domestic sector a reduction in water demand was tested, which is consistent with recommendations made by SDAGE RMC. To maintain satisfaction levels observed in the reference period, in the UO step the decrease in per capita DWD would be acceptable as it is slightly below the observed value over France in 2010 (71 m$^3$/inhabitant/year, see Chazot et al., 2012). However, as explained before, in the CO and so the UAC steps, the efforts enabling water demand to match with water resources would not be worth considering as they would ask population to live at a water poverty level. If one of these possible situations would happen, other adaptation strategies should then be considered.

For the agricultural sector, the chosen adaptation strategy was to import water, testing the future Aqua Domitia project, which derives water from the Rhône River to southern France up to the Spanish border. A 2.5 m$^3$/s flow, that is to say 2.2 hm$^3$/10-day period, would be distributed along the French Mediterranean coast. Hence, the Hérault River watershed should be attributed a much lower water flow. This option would be sustainable in the CO step, as for the Gignac and Agde portions, imported flows ranging from 0 to 0.5 hm$^3$/10-day period would be enough to satisfy AWD. However, in the UO and so in the UAC steps, imported water flow values would range around 0.75 hm$^3$/10-day period in the Gignac portion and around 1.5 hm$^3$/10-day period in the Agde portion, hence in total an amount of water equal to the one derived from the Rhône River for the whole Aqua Domitia project. In those cases, this adaptation strategy should be re-examined.

As regards to the environmental water demand, even with drastic water use efforts in the priority sectors, the biological flow would not be reached. Actually sustainability metrics would barely improve with the explored adaptation strategies. Allocating the lowest priority to this water demand
can thus be discussed. We previously showed that EWD having top priority would only slightly decrease the frequency of unsatisfactory years for this water demand, and would imply a strong increase of this indicator for the domestic and agricultural sectors with values above 4 years/5 years (see Collet et al., 2013a). Thus, this water demand seems very restrictive in the Hérault River catchment and would probably be supplied with difficulty in the tested scenarios.

5.3. Considering other water management options

The adaptation strategies tested in this study were quite limited and other water management practices could be considered in a climate change context. The Climate Change Adaptation Program (PACC, Plan d’Adaptation au Changement Climatique) on the SDAGE RMC territory plans on reducing water withdrawals by 20% from now to 2020. In that sense and to reduce agricultural water consumption, this program recommended in 2011 the use of crops that consume less water. Indeed the increase in irrigated areas could have a significant impact in the Hérault river catchment, above all for the wine industry. Agricultural water demand could thus significantly decrease if vineyards were not irrigated, using grape varieties that would not need irrigation and would be adapted to the Mediterranean climate. However, such a measure would not easily be accepted nowadays, as Battaglini et al. (2009) showed that 60% of the French winegrowers would show reluctance to modify their variety of vine. Another solution for increasing resilience and sustainability in vineyard crops is the implementation of a large scale recycled water irrigation system (Lereboullet et al., 2013). This method has been developed in McLaren Vale, in South Australia where a Mediterranean climate is observed, which makes this region more adaptive faced with climate change. Actually, seawater desalination and wastewater reuse are widespread alternative solutions over the Mediterranean basin (Boyé, 2008). These solutions allow the preservation of natural water resources and use low water volumes for local exploitations. On the north rim of the Mediterranean, Spain is the first country using seawater desalination to supply coastal cities with freshwater as well as irrigation needs (Boyé, 2008).

If water savings are not enough, it is also envisaged in the PACC that, as a last resort, new water storage projects could be created for irrigation. This kind of local solution has already been developed in the upstream portions of the Hérault River catchment through hillside storage reservoirs.
These small reservoirs enable the irrigation of local crops that are not easily accessible by existing irrigation networks. These reservoirs also tend to limit floods and could be easily used as extreme rainfall events should intensify in the Cévennes Mountains in the future (Quintana-Seguí et al., 2011). Moreover in mountainous areas, evaporation in reservoirs is low as temperature is lower than in the downstream areas and their size is generally limited (this kind of reservoir generally contains up to a few thousand m$^3$).

Karst aquifers, that mainly constitute the middle part of the catchment, are little exploited as they are not well known up to now. The structure and functioning of these reservoirs are generally complex, leading to difficulties in defining aquifer recharge, storage capacity or high productivity areas (Bakalowicz, 2005). However, some karst aquifers of the Hérault catchment are known for their storage potential (such as the Vis River resurgence and the Buèges River spring), but the fragility of the environment in these areas makes their exploitation difficult and could generate conflicts (Bakalowicz, 2006). Some examples of active management of karst aquifers can be found such as the Lez spring in Southern France, east to the Hérault River catchment, since 1981: water is directly withdrawn in the main drain of the karst aquifer directly linked to the spring. By exploiting water reserves in the karst porosity, this technique allows all over the year withdrawing a higher water volume than the one available in the spring (Maréchal et al., 2013). Models have been developed to study the impact of climate change on the management of this aquifer (see Ladouche et al., 2014). Results, at the 2050 horizon, show that water withdrawals could be increased by up to 20% while keeping an acceptable water level, although recharge could decrease by 30%.

5.4. Limits of the study

Some methodological aspects chosen in this study limit the representativeness of results. First, to allocate water resource to each demand, the Water Supply Capacity Index was calculated taking into account all the available simulated water volume. Thus, high priority water demand can numerically dry up a river at the outlet of a basin portion and so discriminate against the supplying of low priority water demands. That is how the biological flow was unsuccessfully reached. This realistic aspect of water management comes from the fact that water is actually partly withdrawn from groundwater
reservoirs in the Hérault River catchment. Thus, considering the total water resource as superficial at the outlet of each basin portion is not only too restrictive but also unrealistic in terms of water allocation. As already discussed by Collet et al. (2013b), this methodological choice was made because of the scarcity of the piezometric data. It though seemed a fair choice as the main groundwater withdrawals come from the alluvial plain downstream, where the river-groundwater dynamics are closely linked, especially in summer when withdrawals are the highest.

Second, another limit relates to the simulation of the agricultural water demand. FAO model CropWat does not simulate the phenologic stages of crops, which are actually constrained by the crop coefficient value as input data. The possible evolution of crops phenologic stages constrained by climate change was thus not represented on the prospective period. Yet a rise in temperature should lead, among other things, to an earlier maturation of grapes (see i.e. Webb et al., 2011; Hublart et al., 2014), the main crop in the Hérault River catchment. Models that simulate the evolution of crops phenologic stages already exist, such as VineLOGIC (Godwin et al., 2002) for vineyard (see i.e. Webb, 2007), and SARRA-H (Traoré et al., 2011) for all kind of crops (see i.e. Sultan et al., 2013). These models could be used to better simulate a possible temporal shift in crops water needs and thus allow for a more accurate estimation the water demand time variation. Therefore the periods of year when water resources would not be able to satisfy water demand could be better identified.

Third, the modelling chain is not able to take into account a dynamic response in the decision making process for adaptation strategies. That is to say various adaptation strategies were tested over the whole time period but none was introduced or removed within the period, for example after an undesirable state was reached. However, water management is an on-going process that stakeholders and managers frequently revise while the situation changes (i.e. under climate change constraints). A call to improve adaptive and integrated water management approaches is made in the scientific community (see i.e. Giupponi et al., 2013; Montanari et al., 2013), which underlines the difficulties in creating a dialogue between people from different areas of expertise (scientists of different disciplines, policy/decision makers, local experts, stakeholders...) and developing dynamic vulnerability models that include policy measures. Lemieux et al. (2014) presented their approach that implied several dozen people coming from the scientific and stakeholder fields. The adaptation framework they
developed was organized in a 5-year planning cycle, as well as in an on-going annual or biannual monitoring and vulnerability assessment process to continually adjust and choose the more adequate adaptation strategies. It reveals the double dynamics and long-term character of such processes that need to be initiated in the water management community.

Lastly, various sources of uncertainty that can spread in the water management framework should be pointed out in this study. Uncertainty propagation depends on the choices made to build the modelling chain. First, the hydrological and dam management models tended to under-estimate water flows, which could lead to too pessimistic water management sustainability evaluation. Second, the evaluation of agricultural water demand was based on global soil database over the whole catchment, which limits the crop specification from a portion to another. Third, the WSCI was calculated considering only surface water resources, which could have led to an unrealistic water allocation. However, a number of uncertainties were avoided in this study by choosing (i) a step-by-step climate deterioration approach instead of IPCC climate model outputs; (ii) the same PET formula all over the modelling chain; (iii) a comparison of water management sustainability metrics in the future regarding results obtained in the observed period.

6. CONCLUSION AND PROSPECTS
The main purpose of this paper was to discuss water management strategies and adaptation to climate and anthropogenic changes on a Mediterranean catchment at the 2030 horizon. Future complex scenarios were first built, accounting for various dynamics such as population growth, per-unit water demand and irrigated areas evolution, and variation of precipitation and temperature. An integrated modelling chain was used to evaluate the possible impacts of such changes on water management sustainability. Sustainability indicators were defined to quantify unsatisfactory year frequency, reliability, resiliency and vulnerability. This approach allowed a reflection on how the adaptation strategies considered today by local managers could face these changes. It also led to another discussion where other water management strategies were suggested based on known cases in the Mediterranean or similar environments.
The main results showed that, in the Hérault River catchment, both water use and climate scenarios could have significant impacts on the downstream portions, the most exploited ones in the basin. Under observed climate conditions, the water use scenarios could imply a deterioration of water demand supply that could be quite reasonably compensated by a reduction by half of per-unit water demand for the domestic sector and an importation of water for irrigation (between 0.6 and 1.7 m³/s). The biological flow, evaluated to answer the European Directive Framework objectives to ensure a good ecological state of rivers, would difficultly be reached all over the catchment, especially in summer. Compared to the water use scenarios, the climate change scenarios would degrade more all the sustainability indicators, except vulnerability for the agricultural water demand. The corresponding needed per-unit water demand savings would be rather difficult to reach (equivalent to those observed in water-poor countries) but the water imported for irrigation could be more easily considered (0 to 0.6 m³/s). The combination of both types of scenarios could imply very restrictive water use conditions. Local managers could contemplate new adaptation strategies such as wastewater reuse, new water resources exploitation (hillside storage reservoirs, seawater desalination, karstic aquifers) or changes in agricultural practices (crops that are adapted to a drier climate). These solutions have already been considered or in use in other Mediterranean catchments (Simonet, 2011).

The main limits of this study relate to the way the modelling chain was built. First, the calibration of the hydrological and dam management models led to a slight under-estimation of available water resources, that could lead to too pessimistic water supply capacities and thus sustainability indicators. Second, groundwater and surface water were simulated together at the outlet of each basin portion by the hydrological model, allowing no dissociation between the dynamics of both water resources. It led sometimes to the simulation of the complete use of water resources for a water demand, leaving no available water to lower priority demands. This is the main improvement that could be done to the modelling chain to represent water withdrawals in a more realistic way, mainly for the domestic sector. Third, the modelling chain does not allow a dynamic retroaction to account for gradual future changes in the adaptation strategies. Only one set of strategies can be tested at one time over a long
time period. A dynamic integration of adaptive water management strategies would be welcome to simulate how stakeholders could gradually adapt to climatic and anthropogenic changes over time.

Likewise, the approach described in this study offers various contributions to water management sustainability assessment. First, the different models used or developed in the modelling chain are easy to set up for meso-scale catchments, even with a semi-distributed approach, and over long time periods with an appropriate database. Second, this cross-disciplinary method allows adaptation strategies considered by water managers to be tested. Moreover, the chosen sustainability indicators give quantitative results that all stakeholders can use to apprehend and study water management issues on their territory. Third, the semi-distributed approach and the dissociation of water use and climate change scenarios give a better understanding of distributed impacts on a catchment and how each scenario could be locally anticipated.

Many approaches have been developed in the last decades to assess integrative water resources management and set up climate change adaptation strategies in line with stakeholders’ needs (see e.g. Ludwig et al., 2014). But one of the biggest challenges that the research community faces today is integrating the political economy of water management to integrated assessment models (Olmstead, 2013). Taking a step forward in this study would thus be to evaluate the economic aspect of adaptation to both anthropogenic and climate changes. As reminded in the French national climate change adaptation plan, according to economist Nicholas Stern inaction would cost between 5 and 20% of the global gross domestic product, while action would only cost 1 to 2%. This makes clear that climate change adaptation plans could make significant economic savings. Adaptation strategies costs should thus be evaluated, as well as the possible societal impacts, whether positive or negative (infrastructure deterioration, employments gain or loss, etc.). Another aspect of integrative water management is the public implication in the decision-making process. The public can play a key role in the acceptance and the setting up of water management plans and policies (Kolokytha et al., 2002). Participatory management is an effective approach to bring the public and other water stakeholders into the decision-making of water management plans. This method is generally successful, as evidenced by study cases in France and Portugal (Rinaudo et al., 2012) and in Tunisia (Dörfliger and Perrin, 2011).
Acknowledgements This work was carried out as part of the GICC REMedHE project funded by the MEDDE for the period 2012–2015. The authors are grateful to Christophe Vivier, Conseil Général de l’Hérault and Conseil Général du Gard for sharing their knowledge and expertise on the Hérault River catchment. Finally, the anonymous reviewer is thanked for his interest in this work and his useful comments.

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