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Changes in the balance between water uses and availability in two Mediterranean hydrosystems : adaptation to climatic and anthropogenic changes

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THÈSE

Pour obtenir le grade de
Docteur

Délivré par l'**UNIVERSITÉ DE MONTPELLIER**

Préparée au sein de l'école doctorale **SIBAGHE**
Et de l'unité de recherche **HydroSciences Montpellier**

Spécialité: **Eaux continentales et sociétés**

Présentée par **Julie Fabre**

**Changes in the balance between water
uses and availability in two
Mediterranean hydrosystems
–adaptation to climatic and
anthropogenic changes**

Soutenue le 7 décembre 2015 devant le jury composé de

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ABSTRACT

This thesis proposes an original approach to assess multi-decadal changes in the balance between water use and availability in managed river basins. A modeling framework integrating human and hydro-climatic dynamics and accounting for linkages between resource and demand was developed and applied in two basins of different scales and with contrasted water uses: the Hérault (2 500 km², France) and the Ebro (85 000 km², Spain) basins. Natural streamflow was evaluated using a conceptual hydrological model, and a demand-driven reservoir management model was designed to account for streamflow regulations from the main dams. Municipal, industrial and irrigation water demands were estimated from socio-economic and agronomic and climatic drivers. Environmental flows were accounted for by defining streamflow thresholds under which water withdrawals were strictly limited. This framework was successfully calibrated and validated under non-stationary human and hydro-climatic conditions over a past period of 40 years before being applied under four combinations of climatic and water use scenarios to differentiate the impacts of climate- and human-induced changes on streamflow and water balance. Climate simulations from the CMIP5 exercise were used to generate 18 climate scenarios at the 2050 horizon and a trend water use scenario was built based on demographic and local socio-economic trends by the mid-21st century. Indicators comparing water supply to demand were computed. 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. To assess the efficiency of potential adaptation measures under climate change scenarios, the sensitivity of water stress to variations in the main drivers of water demand and dam management was tested. The effectiveness and robustness of individual measures varied between the basins and within each basin. Finally an adaptation scenario combining different measures was tested in both basins, using the integrative modeling framework. This scenario led to encouraging results regarding the decrease of water stress. However, the adaptation strategies were shown to be insufficiently robust to climate change uncertainties. To achieve a sustainable balance between water availability and demand and reduce the vulnerability of water uses to climate change, a complementarity needs to be found between basin-scale studies of the water balance, such as the ones conducted in this thesis, and local assessments of vulnerability and adaptive capacity.

KEYWORDS

Water uses; climate change; impacts; integrated assessment; vulnerability; adaptation, climate uncertainties

RESUME

La thèse propose une approche originale pour évaluer les évolutions à moyen terme des équilibres entre usages et ressources en eau à l'échelle de bassins versants anthropisés. Un cadre de modélisation intégrant les dynamiques hydro-climatiques et des activités humaines ainsi que les liens entre demandes et ressources en eau a été développé et appliqué sur deux bassins d'échelles différentes et aux usages de l'eau contrastés : l'Hérault (2 500 km², France) et l'Ebre (85 000 km², Espagne). Les écoulements naturels ont été simulés avec un modèle hydrologique conceptuel et un modèle de gestion de barrage piloté par les demandes associées et les contraintes de gestion a été implémenté. Les demandes en eau municipale, industrielle et d'irrigation ont été estimées à partir de données socio-economiques, agronomiques et climatiques. Des débits environnementaux seuils, en-dessous desquels les prélèvements sont limités, ont été pris en compte. La chaîne de modélisation a été calée et validée sous les conditions anthropiques et hydro-climatiques non-stationnaires de 40 années passées, avant d'être appliquée sous quatre combinaisons de scénarios de changements climatiques et d'usages de l'eau, permettant ainsi de différencier les impacts climatiques et anthropiques. Des simulations climatiques de l'exercice CMIP5 ont été utilisées pour générer 18 scénarios climatiques à l'horizon 2050, et un scénario tendanciel des usages de l'eau a été proposé sur la base de tendances socio-économiques locales. La disponibilité en eau a été comparée à la demande à travers des indicateurs de fréquence et d'intensité de satisfaction. L'impact des scénarios climatiques sur la disponibilité et la demande en eau pourrait remettre en question les allocations et débits environnementaux envisagés pour les décennies à venir. Les limitations de prélèvements pourraient devenir plus fréquentes, et la pression anthropique sur les milieux aquatiques pourrait s'intensifier. Pour évaluer le potentiel d'adaptation aux changements climatiques, une analyse de sensibilité des indicateurs aux principaux facteurs d'évolution de la demande et de la gestion de barrages a été réalisée. L'efficacité et la robustesse de mesures individuelles varient entre les bassins et selon les nœuds de demande. Un scénario d'adaptation combinant différentes mesures a ensuite été testé. Ce scénario pourrait réduire sensiblement le stress hydrique, cependant sa robustesse vis-à-vis des incertitudes climatiques pourrait être insuffisante. Afin d'atteindre un équilibre durable entre usages et ressources en eau et de réduire la vulnérabilité des usages de l'eau, une complémentarité doit être trouvée entre des études quantitatives à l'échelle de bassins versants, comme celle menée dans cette thèse, et des études locales sur la vulnérabilité socio-économique et les capacités d'adaptation.

MOTS-CLEFS

Usages de l'eau; Changement climatique ; Impacts ; Intégration ; Vulnérabilité ; Adaptation; Incertitude climatique.

Remerciements

En premier lieu je remercie **Denis Ruelland** pour m'avoir permis de mener ce travail de thèse dans des conditions irréprochables, et pour avoir su concilier mon besoin d'indépendance et sa direction attentive des activités du projet, et plus largement de notre équipe de recherche. Toutefois qui dit indépendance ne nie certainement pas le travail d'équipe, car malgré le caractère personnel du doctorat, celui-ci s'effectue nécessairement au sein d'un collectif. Je tiens donc tout particulièrement à remercier **Alain Dezetter** et **Benjamin Grouillet**, avec qui le travail est un véritable plaisir.

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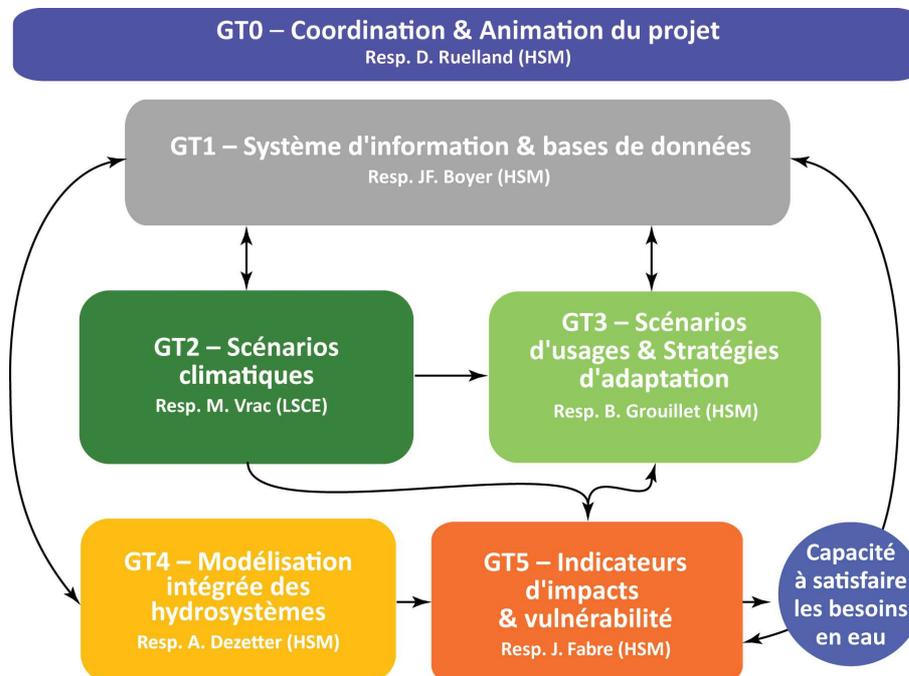
Je remercie toutes les personnes du laboratoire **HydroSciences Montpellier** qui ont fait de ces trois ans une belle expérience scientifique et humaine. En particulier je remercie **Paul Hublart** pour trois ans de collaboration et de cohabitation sympathique et enrichissante. Sans oublier bien sûr deux « anciennes » d'HydroSciences, qui ont ouvert les chantiers de l'étude de l'Ebre et de l'Hérault dans l'équipe, **Marianne Milano** et **Lila Collet**. Je vous remercie toutes les deux d'avoir partagé votre expérience avec moi jusqu'au bout, ce qui a largement facilité le lancement de ce travail de thèse.

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Foreword

This thesis was carried out as part of the GICC-REMedHE¹ project (*Impacts du changement climatique sur la gestion intégrée des Ressources en Eau en Méditerranée: évaluation comparative Hérault-Ebre*) funded by the French Ministry of Ecology, Sustainable Development and Energy for the period 2012–2015. The general objective of the project was to understand the linkages between climatic and anthropogenic pressures and water resources at the river basin scale. It aimed to develop a modeling chain to assess the vulnerability of two Mediterranean basins to climate change.

Four partners were included in the REMedHE project: the HydroSciences Montpellier Laboratory (HSM), the LSCE (*Laboratoire des Sciences du Climat et de l'Environnement*), and the water management agencies from the Hérault and the Ebro basins: the SMBFH (*Syndicat Mixte du Bassin du Fleuve Hérault*) et the CHE (*Confederación Hidrográfica del Ebro*). Five work packages were defined within the project (see below).



Work packages within the REMedHE project.

¹www.remedhe.org

This thesis was focused mainly on the work packages 4 and 5, and built largely on the work package 3. Participation in work package 3 consisted in supervising the collection of data and development of the water demand model. The publications included as appendices to this manuscript reflect the integration of the thesis in the project as a whole. The main chapters of the manuscript are based of the publications below, which were not inserted at the end of the manuscript.

Fabre, J., Ruelland, D., Dezetter, A., Grouillet, B. Simulating past changes in the balance between water demand and availability and assessing their main drivers at the river basin scale. *Hydrol. Earth Syst. Sci.* 19:1263–1285, 2015.

Fabre, J., Ruelland, D., Dezetter, A., Grouillet, B. Sustainability of water uses in managed hydrosystems: human- and climate-induced changes for the mid-21st century. *Hydrol. Earth Syst. Sci. Discuss.* 12:9247–9293, 2015.

Fabre, J., Ruelland, D., Dezetter, A., Grouillet, B. Reducing the gap between water demand and availability under climate and water use changes: assessing the effectiveness and robustness of adaptation. *Proc. SHF Congress*, October 2015, 2015.

Résumé étendu

Equilibres entre usage et disponibilité en eau sur deux hydrosystèmes méditerranéens – adaptation aux changements climatiques et anthropiques²

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²Eu égard au caractère international de la thèse et du projet GICC REMedHE dans lequel elle s'inscrit ainsi que les valorisations auxquelles elle a donné lieu dans les publications internationales, le manuscrit est rédigé en langue anglaise. Le lecteur trouvera ici un résumé étendu en français.

1. Introduction

1.1. Contexte et objectifs

Les évolutions climatiques et anthropiques récentes et à venir dans la région méditerranéenne posent la question de l'équilibre entre usages et ressources en eau. La gestion de cet équilibre, qui dépend de l'évolution conjuguée de l'état quantitatif des ressources en eau et de leurs usages anthropiques et environnementaux, s'effectue à l'échelle de bassins versants, dans des hydrosystèmes fortement anthropisés. Or les initiatives engagées aujourd'hui dans la gestion de l'eau en termes d'adaptation au changement climatique reposent sur une connaissance limitée de la vulnérabilité des hydrosystèmes à ces changements. L'évaluation de cette vulnérabilité se heurte en effet à de nombreux verrous méthodologiques, liés à la nécessaire intégration de processus physiques et humains, ainsi qu'à la représentation de leurs interactions dans l'espace et dans le temps.

Les objectifs de ce travail de thèse s'articulent autour de trois points :

- **comprendre** les interactions entre usages et ressources en eau au sein d'hydrosystèmes anthropisés, en tenant compte des dynamiques spatio-temporelles de variables physiques et socio-économiques ;
- **étudier** la vulnérabilité de ces hydrosystèmes face aux évolutions climatiques et anthropiques à travers des indicateurs liés aux objectifs de gestion et de planification ;
- **analyser** l'influence d'un large spectre de futurs possibles sur la vulnérabilité et les stratégies d'adaptation envisagées.

1.2. Une comparaison de deux bassins méditerranéens

Une chaîne de modélisation a été développée et appliquée sur deux hydrosystèmes contrastés : l'Ebre (Espagne) et l'Hérault (France). Les bassins de l'Ebre et de l'Hérault diffèrent par leurs caractéristiques physiques et anthropiques. Le bassin du fleuve Hérault s'étend sur 2 500 km², avec un climat méditerranéen à influence cévenole. Majoritairement agricoles dans les années 1960, les usages de l'eau ont évolué rapidement face à la croissance démographique et au développement du tourisme. Près d'un tiers de la demande en eau est aujourd'hui associé à l'alimentation en eau potable de communes touristiques hors du bassin. Les conditions climatiques sur le bassin de l'Ebre (85 000 km²) sont complexes du fait des influences contrastées de l'océan Atlantique et de la mer Méditerranée, ainsi que des différentes chaînes montagneuses, principalement les Pyrénées au nord du bassin. Les régimes hydrologiques varient de nival à méditerranéen, en passant par pluvial océanique. Les usages de l'eau sont principalement liés à l'irrigation, secteur qui représentait 92% des prélèvements en eau dans le bassin en 2007. Les principaux secteurs irrigués se situent dans la vallée semi-aride de l'Ebre et sont alimentés en eau par de nombreux barrages (264 en 2007) qui assurent le stockage des écoulements de type pluvio-nival, provenant des Pyrénées et des monts Cantabriques.

2. Modélisation des évolutions passées des équilibres entre ressources et demandes en eau

2.1. Schématisation du fonctionnement demandes/ressources

Des unités homogènes de ressource et de demande en eau (qui constituent des nœuds de ressource et de demande) ont été déterminées. Du point de vue de la ressource, il s'agissait particulièrement d'isoler les zones les plus contributives aux écoulements et de déterminer les barrages-réservoirs stratégiques pour la satisfaction des demandes en eau. Les hétérogénéités géographiques ont également été prises en compte, notamment les contrastes climatiques ou d'occupation du sol.

2.2. Une approche intégrative de modélisation

La plus-value méthodologique de ce travail se concentre sur l'intégration et la conceptualisation des liens ressources-demandes et amont-aval, et sur l'analyse des équilibres ressources-demandes avec des indicateurs pertinents et parlants pour les gestionnaires. Il s'agit de traduire des priorités et règles de gestion en modèles et de privilégier l'étude de l'interaction entre les composantes du système, ainsi que la reconstruction de la dynamique des variables de forçage. Une chaîne de modélisation intégratrice a été développée et appliquée dans un premier temps sur une période rétrospective de quatre décennies (1971–2009), avec pour objectif de caler/valider les différents modules au pas de temps décennaire, et de représenter et comprendre les dynamiques passées des équilibres entre ressources et demandes en eau au sein des hydrosystèmes étudiés.

La chaîne de modélisation comporte trois composantes (cf. Figure 1):

- la simulation des écoulements naturels et des dynamiques de stockage : un modèle hydrologique conceptuel journalier (GR4j) agrégé au pas de temps décennaire a été utilisé pour simuler les écoulements naturels à partir des forçages climatiques, pour chaque unité hydrologique déterminée lors de la schématisation des bassins. Afin de représenter les écoulements de type nival sur l'Ebre, un module neige a été intégré au modèle hydrologique. Pour simuler les écoulements naturels, non-influencés par les prélèvements (principalement agricoles), le calage du modèle a été effectué uniquement sur les décades pour lesquelles la demande d'irrigation simulée est négligeable. Les dynamiques de stockage/restitution ont été prises en compte à travers l'implémentation d'un modèle de gestion de barrage piloté principalement par les besoins d'irrigation et les contraintes de gestion, et appliqué aux principaux ouvrages des deux bassins.
- la représentation dynamique des demandes en eau : les demandes en eau ont été simulées au pas de temps décennaire par nœud de demande pour les trois secteurs principaux d'usages : la demande municipale liée à la population permanente et touristique (MWD), la demande industrielle et énergétique (OWD), et la demande agricole liée à l'irrigation (IWD). La demande en eau municipale a été estimée à partir de données de population et de demande unitaire, et la demande en eau d'irrigation a été simulée à partir de données sur les sols, les types de cultures, les pratiques agricoles (surfaces irriguées, efficacité hydraulique) et les conditions climatiques.

- l'évaluation des équilibres usages-ressources en eau et les indicateurs de vulnérabilité : l'évolution des équilibres entre usages et ressources a été évaluée par la confrontation des ressources disponibles et des demandes en eau en chaque nœud des schémas fonctionnels des hydrosystèmes. Des indicateurs représentant la capacité de satisfaction des demandes en eau et la viabilité sur le long terme des activités humaines dépendantes de la ressource en eau ont été proposés.

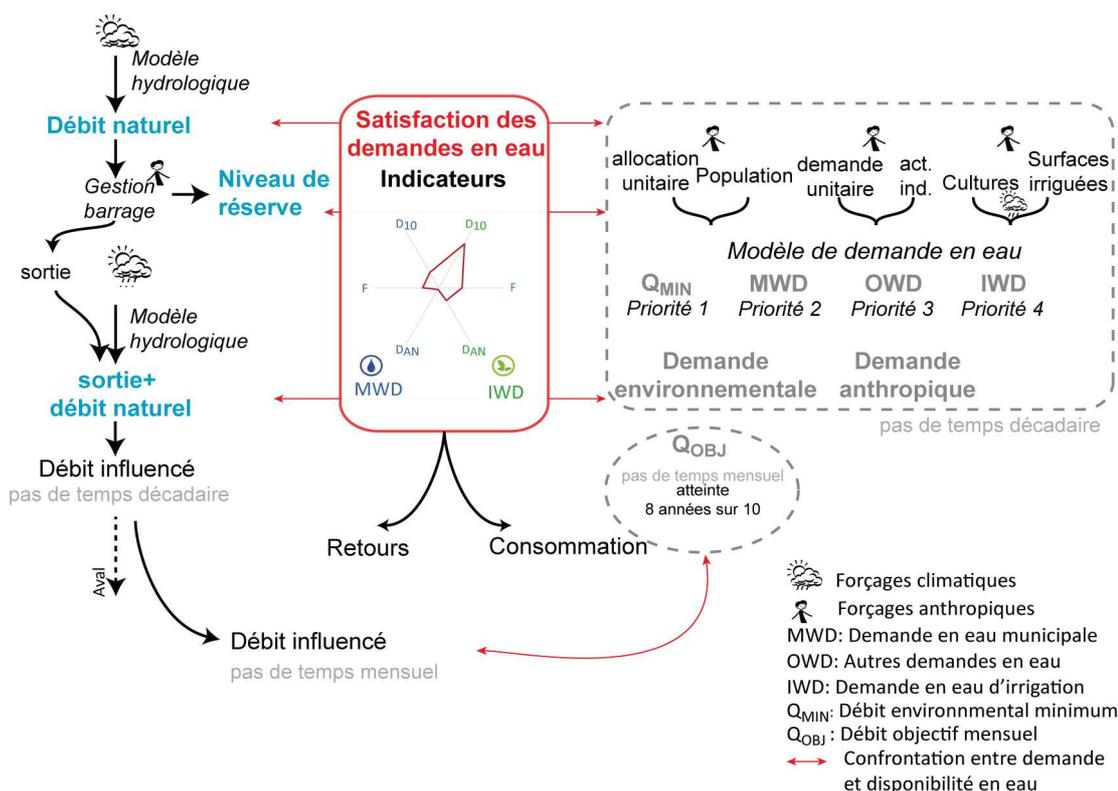


Figure 1. Chaîne de modélisation intégrative développée et appliquée sur les bassins versants de l'Hérault et de l'Ebre au pas de temps décadaire. Les demandes en eau et les débits naturels ont été simulés à partir de contraintes climatiques et anthropiques. La pression anthropique sur les écoulements a été évaluée en simulant la gestion des barrages-reservoirs et la consommation nette.

2.3. Calage et validation de la chaîne et analyse des évolutions passées

2.3.1. Calage de la chaîne de modélisation et analyse de l'évolution passée des débits

La saisonnalité et les variations interannuelles des débits influencés et des niveaux de réserve des barrages sont reproduits de manière satisfaisante pour la plupart des points de mesure de débit et des barrages. Les critères utilisés pour le calage des débits naturels ont été recalculés pour comparer les débits influencés simulés et les débits observés, en ajoutant le critère de Nash-Sutcliffe sur les débits d'étiage. La comparaison des évolutions de débits naturels et influencés a permis de comparer l'impact relatif des facteurs climatiques et anthropiques dans la baisse des débits observée dans les deux bassins (–40% environ entre 1971–1980 et 1981–2009 à l'exutoire des deux bassins). Les pressions anthropiques expliqueraient 3% et 20% de la baisse de débits observée après 1980 sur l'Hérault et l'Ebre respectivement (Figure 2).

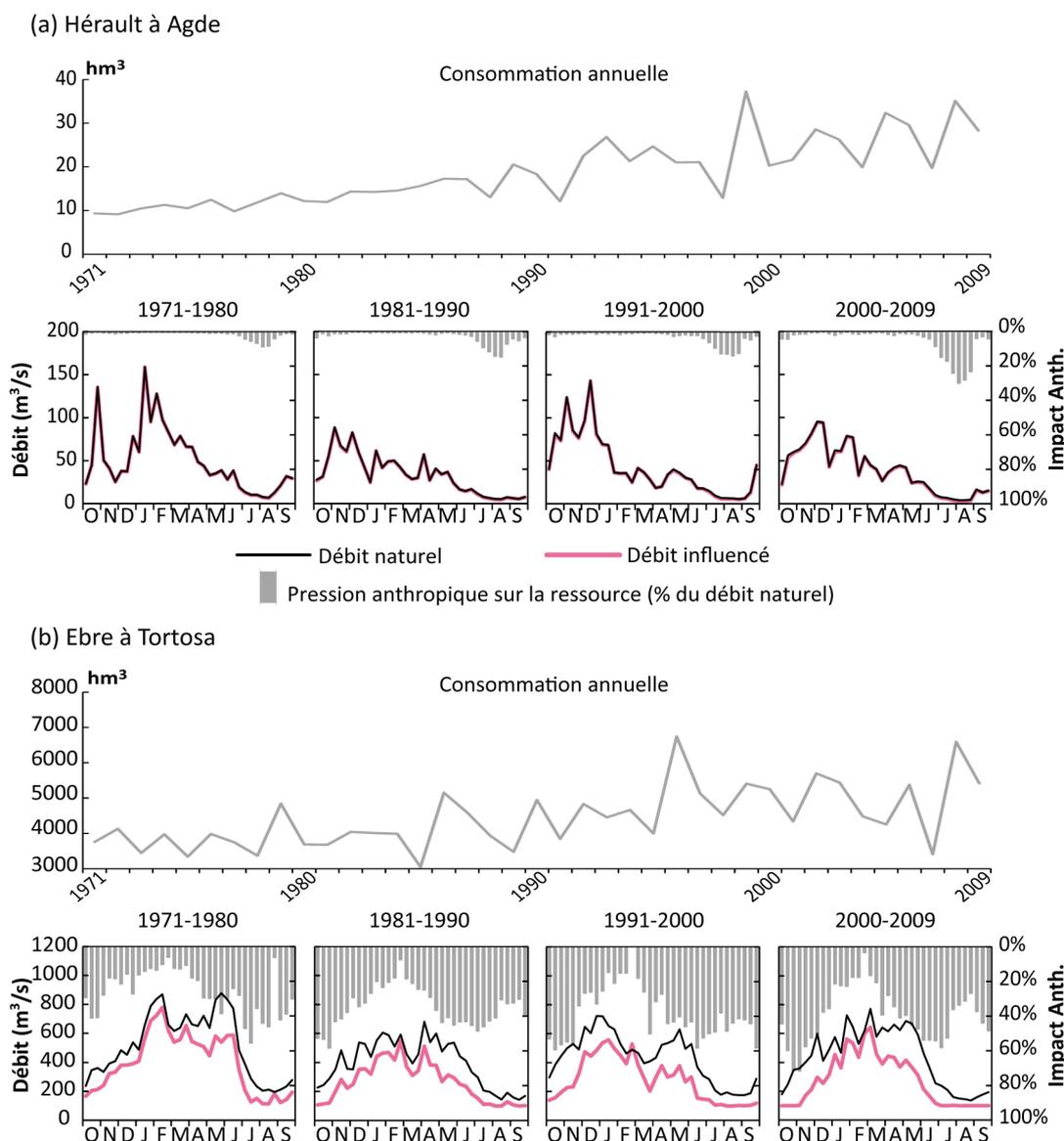


Figure 2. Comparaison des débits simulés naturels et influencés: pression anthropique (par le stockage et la consommation nette) dans les bassins versants (a) de l'Hérault et (b) de l'Ebre.

2.3.2. Reconstruction de l'évolution passée de la satisfaction des demandes en eau

Dans le bassin versant de l'Hérault les besoins d'irrigation de la vigne présentent une tendance à l'augmentation et une forte variabilité interannuelle. La satisfaction de cette demande apparaît sensible à la variabilité hydro-climatique, néanmoins les améliorations d'efficacité de l'irrigation dans le secteur de Gignac dans les années 2000 ont contribué à limiter les déficits. Un déséquilibre quantitatif apparaît dans la basse vallée de l'Hérault dans les années 2000, du fait de l'augmentation des demandes municipales et d'irrigation combinée à la baisse des débits naturels. Dans le bassin versant de l'Ebre les secteurs de la rive droite, en fort déséquilibre quantitatif durant toute la période étudiée, diffèrent de la rive gauche de l'Ebre, qui bénéficie de la régulation des écoulements pyrénéens et cantabriques. Dans certains secteurs de la rive gauche, la demande en eau d'irrigation a largement augmenté (du fait principalement de l'expansion des surfaces irriguées), dépassant la capacité de stockage et donc la ressource disponible.

Malgré une forte sensibilité de certains secteurs clé du bassin de l'Hérault à la variabilité hydro-climatique, les déséquilibres entre usages et disponibilité de l'eau apparaissent plus marqués dans le bassin de l'Ebre, du fait de conditions climatiques plus déficitaires et d'une forte pression agricole sur les ressources en eau. Néanmoins sur l'Ebre un certain nombre de secteurs irrigués, qui concentrent 60% des demandes en eau liées aux grands systèmes d'irrigation, apparaissent à l'équilibre. La demande en eau d'irrigation du secteur de Gignac représente, quant à elle, 70% de la demande d'irrigation totale du bassin de l'Hérault en moyenne entre 1971 et 2009.

3. Projections des évolutions d'équilibres entre ressources et demandes en eau à l'horizon 2050

3.1. Construction des scénarios de disponibilité et de demandes en eau et combinaisons testées

La chaîne de modélisation a été appliquée sous quatre combinaisons de scénarios climatiques et d'usages de l'eau, afin de différencier les impacts climatiques et anthropiques sur la capacité à satisfaire les demandes en eau et le niveau de pression anthropique sur les ressources et les milieux :

- un scénario de référence : combinant les usages de référence (années 2000) et un climat de référence (1976–2005), il vise à étudier la durabilité des usages actuels sous un climat de référence ;
- un scénario de changement climatique seul : combinant les usages de référence et 18 scénarios de changement climatique à l'horizon 2050 (2036–2065), il vise à étudier la durabilité des usages actuels sous changement climatique ;
- un scénario de changement d'usages seul : combinant un scénario tendanciel d'usages de l'eau à l'horizon 2050 et le climat de référence, il vise à étudier la durabilité des usages planifiés sous un climat de référence ;
- un scénario de changement d'usages et de climat : combinant le scénario tendanciel d'usages de l'eau et chacun des 18 scénarios de changement climatique, il vise à étudier la durabilité des usages planifiés sous changement climatique.

Des simulations climatiques du dernier exercice global de simulations CMIP5 ont été utilisées pour générer 18 scénarios climatiques à l'horizon 2050, et un scénario tendanciel des usages de l'eau a été proposé sur la base de tendances démographiques et socio-économiques locales. Des débits environnementaux seuils, en-dessous desquels les prélèvements sont strictement limités, ont également été pris en compte. Des indicateurs caractérisant la fréquence et l'intensité des déficits entre demande et disponibilité en eau ont été calculés pour chaque combinaison de scénarios.

3.2. Analyse des équilibres entre ressources et demandes en eau à l'horizon 2050

Trois indicateurs caractérisant la satisfaction des demandes en eau ont été proposés et calculés, pour la demande en eau municipale (MWD) et la demande en eau d'irrigation (IWD), dans chaque combinaison de scénarios :

- F : la fréquence d'années avec au moins une décade déficitaire (i.e. une limitation de prélèvements de plus de 5 % de la demande) ;
- D_{10} : déficit moyen au pas de temps décadaire ;
- D_{AN} : déficit annuel moyen.

Pour chaque combinaison de scénarios le niveau de pression anthropique sur les ressources en eau a également été évalué en calculant la différence entre les débits naturels et influencés (exprimée en pourcentage du débit naturel) à l'exutoire des deux bassins versants. Le calcul a été effectué au pas de temps décadaire, puis la moyenne interannuelle de la pression au pas de temps décadaire a été calculée sur les périodes de 30 ans.

3.3. Projections à l'horizon 2050 et analyse des résultats

3.3.1. Projections hydro-climatiques et de demandes en eau

Les résultats des projections climatiques montrent une tendance claire à l'augmentation des températures, particulièrement marquée en été (jusqu'à +4.8 °C sur l'Hérault et +4.6 °C sur l'Ebre). Les projections de précipitations sont plus incertaines et diffèrent entre les 18 scénarios considérés. Cependant dans les deux bassins l'ensemble des modèles convergent vers une baisse des précipitations de printemps et d'été. Les changements climatiques simulés ont pour conséquence des évolutions dans les débits naturels simulés : alors que les scénarios divergent pour l'automne, l'hiver et le printemps, ils convergent vers une baisse des débits d'été allant de 15 à 55 % sur l'Hérault et de 5 à 35 % sur l'Ebre.

Les projections de demandes en eau sur le bassin de l'Hérault sont contrastées entre les zones amont et aval. Malgré une hausse de la demande d'irrigation dans certaines zones amont, celle-ci resterait faible comparativement aux zones aval de la vallée de l'Hérault. L'amélioration de l'efficacité de l'irrigation dans le secteur de Gignac permettrait une baisse de 50 % de cette demande malgré une augmentation de 65 % des surfaces irriguées dans le scénario tendanciel. En revanche une augmentation de 90 % des surfaces irriguées dans la basse vallée de l'Hérault mènerait à un doublement de la demande d'irrigation. Les changements climatiques (menant à une hausse de la demande d'irrigation) et les changements d'usages projetés pourraient avoir un impact comparable sur la demande en eau.

La demande en eau d'irrigation devrait augmenter pour tous les nœuds de demande du bassin de l'Ebre et dans tous les scénarios, sauf dans les systèmes de Bardenas, Alto Aragon et la Vallée de l'Ebre où certains scénarios de changements climatiques pourraient induire une baisse de la demande en eau, à surfaces irriguées constantes. Dans les systèmes où le scénario tendanciel prévoit une forte hausse des surfaces irriguées (comme le Segre et le Delta de l'Ebre), les changements anthropiques pourraient avoir davantage d'impact sur l'évolution des demandes en eau que les changements climatiques.

3.3.2. Evolution de la satisfaction des demandes en eau

Dans les conditions de référence, les débits mensuels objectifs pourraient être respectés dans les deux bassins, impliquant néanmoins des restrictions fréquentes sur les prélèvements dans plusieurs nœuds de demande. De plus, face aux projections hydro-climatiques et de demandes en eau la durabilité des usages est mise en question sur les deux bassins. Les restrictions sur les prélèvements pourraient en effet devenir plus fréquentes et plus intenses (Fig. 3), et la pression sur les milieux aquatiques devrait s'intensifier.

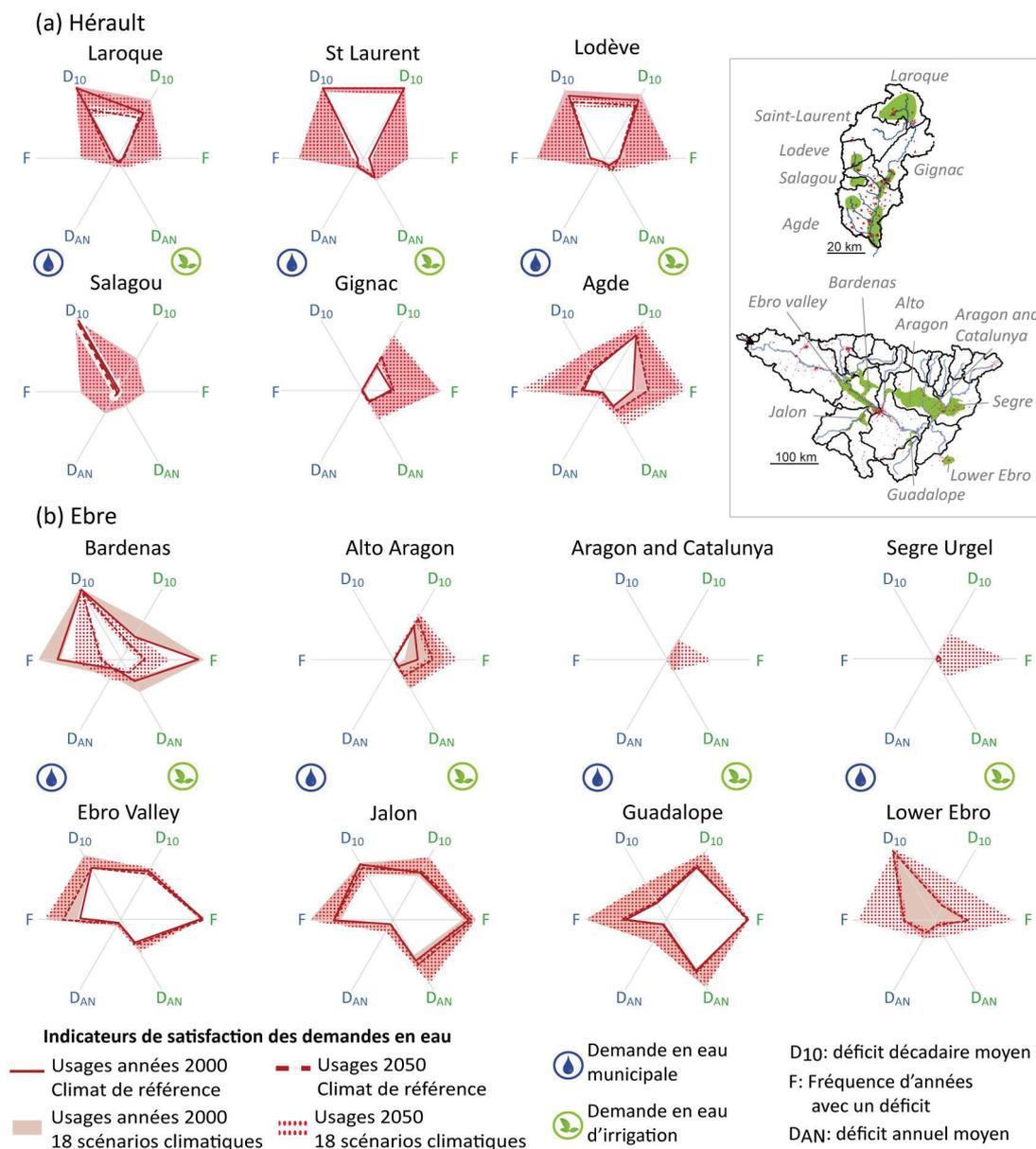


Figure 3. Indicateurs de satisfaction des demandes en eau municipales et d'irrigation dans (a) le bassin de l'Hérault et (b) le bassin de l'Ebre sous quatre combinaisons de scénarios climatiques et d'usages de l'eau.

Dans certains secteurs, les évolutions d'usages pourraient être la principale cause de l'apparition de déséquilibres quantitatifs. Par exemple, dans quatre grands systèmes irrigués du bassin de l'Ebre, les usages actuels pourraient être durables sous des conditions de changements climatiques, néanmoins en combinant le scénario tendanciel d'usages de l'eau avec les projections de changements climatiques, d'importants déséquilibres quantitatifs apparaîtraient.

3.3.3. Pression anthropique sur les ressources en eau

Dans les deux bassins versants, la pression anthropique simulée sur les écoulements pourrait s'accroître, passant respectivement de 2 % (38 %) des ressources annuelles dans le scénario de référence à 3 % (45 %) dans le scénario tendanciel sur le bassin de l'Hérault (et de l'Ebre). Elle pourrait s'élever respectivement à 2 à 3 % (36 à 44 %) des ressources annuelles sous changements climatiques uniquement, et à 3 à 4 % (43 à 52 %) sous changements climatiques et d'usages de l'eau sur l'Hérault et l'Ebre. Au pas de temps décennal, la consommation nette sur le bassin de l'Hérault s'élève à 20 % des ressources décennales à la fin du mois de juillet dans le scénario de référence. Elle s'élèverait à 27 % sous changements d'usages uniquement, et à 25 à 45 % sous changements climatiques uniquement. Sous changements climatiques et d'usages de l'eau, le pic de consommation nette pourrait s'élever, en moyenne, à 30 à 50 % des ressources naturelles au pas de temps décennal.

4. Efficacité et robustesse de mesures d'adaptation

4.1. Analyse de sensibilité : efficacité et robustesse de mesures individuelles

Pour évaluer les mesures d'adaptation sous changement climatique, une analyse de sensibilité des indicateurs aux principaux facteurs d'évolution de la demande et aux règles de gestion des barrages a été préalablement réalisée. L'efficacité est définie comme la baisse moyenne (pour les 18 scénarios climatiques) de fréquence de déficit induite par la mesure d'adaptation. La robustesse de la mesure d'adaptation à l'incertitude climatique est évaluée à travers le nombre de scénarios climatiques sous lesquels la mesure d'adaptation induit une baisse de la fréquence des déficits.

L'efficacité et la robustesse de mesures individuelles restent limitées dans la plupart des cas, et varient entre les bassins et selon les différents nœuds de demande. Les résultats diffèrent pratiquement au cas par cas. L'efficacité et la robustesse de l'adaptation dépendent fortement des caractéristiques des zones considérées : usages dominants, capacité de stockage, etc. Les usages et les ressources étant plus connectés et interdépendants dans le bassin de l'Ebre (avec de nombreux transferts et un niveau élevé d'exploitation de la ressource), les mesures appliquées de manière uniforme sur l'ensemble du bassin pourraient avoir des conséquences inattendues du fait des relations amont-aval.

4.2. Efficacité et robustesse de deux scénarios d'adaptation

Des scénarios d'adaptation combinant les mesures d'adaptation les plus sensibles ont été construits à titre d'exemple et testés avec l'ensemble de la chaîne de modélisation. Ils incluent notamment un plafonnement des surfaces irriguées dans les deux bassins, une stagnation de la population desservie par le transfert d'eau hors du bassin de l'Hérault, une baisse de 30 % de la demande unitaire municipale, et une baisse de 20 % des débits seuils environnementaux.

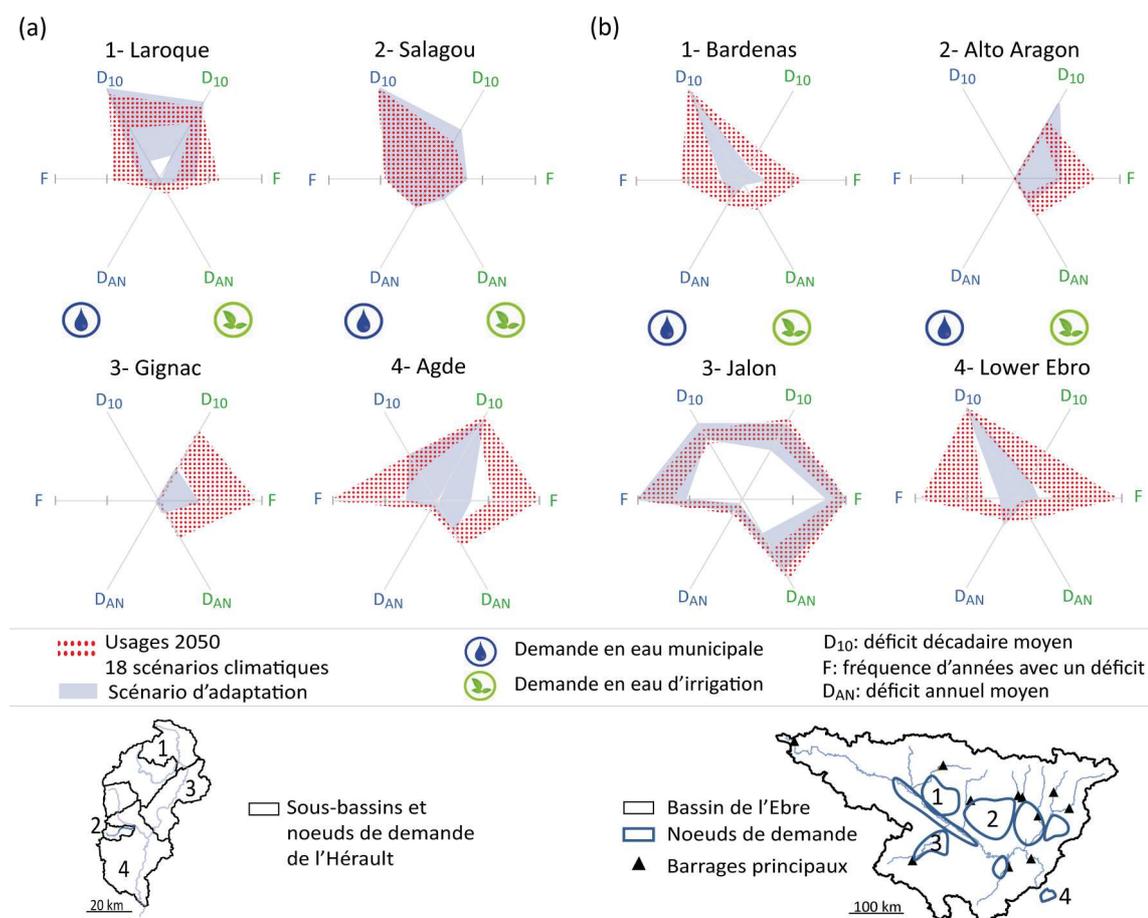


Figure 4. Indicateurs de satisfaction des demandes en eau sous scénarios de changement climatique combinés avec le scénario tendanciel d'usages de l'eau et le scénario d'adaptation pour quatre noeuds de demande des bassins (a) de l'Hérault et (b) de l'Ebre.

Ces scénarios pourraient réduire sensiblement le stress hydrique par rapport aux scénarios tendanciels (Fig. 4). En plus d'une réduction de la fréquence et de l'intensité des limitations de prélèvements, les scénarios d'adaptation mènent à une baisse de la consommation nette (et donc de la pression anthropique sur les milieux) en pourcentage des ressources naturelles, malgré la baisse des débits seuils environnementaux. Néanmoins, leur robustesse semble insuffisante au regard des incertitudes liées aux projections de changement climatique testées.

5. Limites et recommandations

Du fait du manque de données d'observation et de verrous méthodologiques, un certain nombre de limites peuvent être mises en avant quant au le calage et à la validation de la chaîne de modélisation. Les simulations de débits naturels étaient contraintes par le manque de données de mesure des débits naturels et/ou de prélèvements, qui auraient rendu possible une meilleure reconstitution des débits naturels. De plus, les simulations de demande en eau n'ont pu être correctement validées du fait du manque de données d'observation. Enfin l'estimation des retours au milieu par le modèle est sujette à de larges incertitudes. L'utilisation de modèles dans des conditions non-stationnaires est aussi source d'incertitudes dans les simulations des équilibres entre disponibilité et usages de l'eau. Ces incertitudes peuvent provenir de défauts dans le calage du modèle (dus à des problèmes d'équifinalité par exemple) ou d'un « sur-calage » du modèle (obtention de paramètres correspondant à un optimum mathématique mais ne reflétant pas nécessairement les processus hydrologiques), et de la qualité des données en entrée des modèles. De plus, la non-stationnarité des usages de l'eau et des pratiques de gestion sont des éléments indispensables à prendre en compte dans des simulations sur le long terme.

Malgré un effort d'intégration de facteurs physiques et humains dans la chaîne de modélisation, on peut citer d'autres facteurs déterminants des équilibres entre disponibilité et usages de l'eau non-inclus dans les simulations. Les débits naturels ont été simulés à partir de données climatiques, cependant d'autres facteurs tels que des modifications dans le couvert végétal ou dans l'utilisation du sol peuvent affecter la relation pluie-débit. De plus, les ressources en eau souterraines et les relations eaux de surface – eaux souterraines n'ont pas été explicitement prises en compte. Un certain nombre de facteurs physiques et humains non-inclus dans la chaîne de modélisation pourrait influencer sur les évolutions des demandes en eau. On peut citer notamment les processus phénologiques et les pratiques d'irrigation pour le modèle de demande d'irrigation, et les déterminants socio-économiques de la demande en eau unitaire pour le modèle de demande municipale. A visée intégrative, l'approche présentée dans cette thèse ne peut être considérée comme une étude holistique des équilibres quantitatifs. Ainsi, les rétroactions entre les composantes humaines et physiques des hydrosystèmes n'ont pas été prises en compte.

Enfin, la nécessité de baser les stratégies d'adaptation sur une compréhension approfondie de la vulnérabilité des usages de l'eau au changement climatique a été soulignée à plusieurs reprises dans le manuscrit. Bien que cette thèse ait contribué à identifier certains éléments de vulnérabilité des usages de l'eau au changement climatique (notamment la vulnérabilité physique), des études complémentaires seraient nécessaires pour compléter cette évaluation. Des approches ascendantes concentrées sur la vulnérabilité socio-économique et les capacités d'adaptation, mettant l'accent sur les caractéristiques locales, pourraient mettre en avant des éléments essentiels à l'atteinte d'un équilibre durable entre ressources et demandes en eau et à la réduction de la vulnérabilité des usages de l'eau au changement climatique.

6. Perspectives

Etant donnée l'étendue des questions liées à l'atteinte d'un équilibre durable entre disponibilité et demandes en eau, les perspectives de cette étude sont nombreuses. Au vu des limites citées précédemment, des améliorations peuvent être proposées pour la modélisation des équilibres quantitatifs sous des conditions de changements climatiques et anthropiques, et pour une meilleure compréhension de la vulnérabilité des usages de l'eau au changement climatique.

En ce qui concerne la modélisation des équilibres quantitatifs, la méthodologie de simulation des ressources en eau naturelles en l'absence de données sur les prélèvements devrait être approfondie. La méthode utilisée dans cette thèse pourrait être testée en calant des modèles hydrologiques dans des bassins naturels, et en supprimant de manière incrémentale des données des séries observées afin d'évaluer l'impact sur la qualité des simulations. Par ailleurs, davantage de déterminants (physiques et anthropiques) des évolutions de ressources et demandes en eau (comme la phénologie ou les changements d'occupation du sol) pourraient être inclus dans les modélisations.

Afin d'améliorer l'évaluation de la vulnérabilité des usages de l'eau au changement climatique, certains résultats intermédiaires de la chaîne de modélisation pourraient être exploités. De plus, une combinaison de l'évaluation quantitative des équilibres entre ressources et demandes en eau avec d'autres disciplines telles que des sciences sociales et économiques pourrait améliorer la compréhension et la connaissance des capacités d'adaptation locales.

Les perspectives de recherche citées ci-dessus pourraient contribuer à accroître l'utilité des recherches pour la prise de décision sur l'adaptation au changement climatique dans le domaine de la gestion quantitative de l'eau. Au-delà de l'efficacité et de la robustesse de l'adaptation, d'autres questions peuvent se poser. Peut-on concevoir des "voies" d'adaptation avec différentes options, afin de faire face à des évolutions climatiques incertaines ? Comment se préparer à d'éventuels changements imprévus, soudains ? Pourrait-on imaginer des indicateurs avec des seuils d'alerte qui déclencheraient un changement dans les pratiques de gestion de l'eau ? Si des modèles socio-hydrologiques holistiques étaient développés, des simulations des évolutions des hydrosystèmes pourraient être effectuées sur des périodes continues (de 2015 à 2100, par exemple), en intégrant les adaptations spontanées et planifiées et leurs impacts sur les équilibres quantitatifs. Un large ensemble de simulations pourrait intégrer différents niveaux de réchauffement et différents changements de régime des pluies, mais aussi différentes vitesses de changement (progressif ou soudain) et des évolutions contrastées de la variabilité climatique. Une autre alternative pourrait être d'"imaginer un monde sans modèles climatiques" (Wilby, 2011), mettant en avant la nécessité d'une compréhension approfondie de la réponse complexe des hydrosystèmes anthropisés face aux stress climatiques. De telles démarches se concentreraient sur des solutions flexibles et réversibles, améliorant la capacité d'adaptation des systèmes quel que soit le futur climatique.

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General introduction

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1. Facing climatic and anthropogenic changes and reaching a sustainable balance between water availability and demand

1.1. Sustainable water management in influenced river basins

In recent decades, climatic and anthropogenic pressures on water resources have increased in many regions of the world. According to projections of climate and socio-economic changes, mid-latitude areas could experience increased water stress in the course of the 21st century (Arnell, 2004; Heinrichs et al., 2012). In this context water security and quantitative water management are becoming a key issue throughout the world (Vörösmarty et al., 2000, 2012).

Water security was defined by the Global Water Partnership (GWP, 2000) as 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. According to Turner et al. (2003), “sustainable science builds towards an understanding of the human-environment condition with the dual objectives of meeting the needs of society while sustaining the life support systems of the planet”. Hence 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).

The question of sustainable water use is also central to the European Framework Water Directive (WFD) (EC, 2000), which promotes «the sustainable use of water based on the long-term protection of available water resources », and national and local water policies. The WFD calls for water management at the scale of hydrological entities (i.e. river basins), and for an integrative management accounting for the intricate connections between human and environmental issues.

Gallopín et al. (2001) defined socio-ecological systems (SESs) as the pertinent scale of analysis for sustainable development. An SES is a system that includes societal (human) and ecological (biophysical) subsystems in mutual interaction. In the case of water management sustainability, the concept of SESs can be illustrated by the notion of hydrosystems. A hydrosystem can be defined as a system made of water and the associated aquatic environments within a delimited geographical entity. In a river basin or catchment area, water resources are the surface and groundwater of the basin, but also the soil water available for evapotranspiration by cultivated and non-cultivated vegetation.

A hydrosystem also fully incorporates the different water uses and the influence that these uses may have on water resources, including storage and supply facilities. Water uses include all human activities that depend on the water resources in the area (or uses located inside the area and dependent on imported water resources), but also stream-flow or groundwater recharge requirements for instream environmental uses. Thus an imbalance between water 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.

1.2. River basins facing rapid changes in water availability and demand

The water balance of a hydrosystem depends on its water resources, the associated water uses and anthropogenic pressure on the resources, and on the water needs of the aquatic and humid ecosystems. Mediterranean hydrosystems appear to be particularly vulnerable to climatic and anthropogenic changes, which started in the past decades and should continue throughout the 21st century. Water demand has doubled since the 1950s in the Mediterranean region, and projections of demographic changes and irrigated area increase suggest that this increasing trend could last at least up to 2050 (Blinda and Thivet, 2009; Menzel and Matovelle, 2010; Milano et al., 2012). Furthermore, observed climate variability already shows signs of warming and drying (Ludwig et al., 2011; Milano et al., 2012).

Climate projections for the mid-21st century are rather convergent in this region, showing a pronounced warming (+2 to 3 °C) accompanied by a decrease in annual precipitation (Giorgi, 2006; Giorgi and Lionello, 2008). These climatic changes could impact water resources and demand. The increase in evapotranspiration (linked to the increase in temperature) and decrease in precipitation could lead to a significant decrease in runoff (García-Ruiz et al., 2011; Milano et al., 2012, 2013b) and changes in hydrological regimes. Increasing temperatures could also impact snow melt processes and thus modify hydrological regimes dominated or influenced by snow melt (García-Ruiz et al., 2011). Finally, the increase in evapotranspiration in warmer and drier conditions could induce a significant increase in irrigation water needs (Alcamo et al., 2007; Fischer et al., 2007). Thus the conjunction of a water demand increase and a water resource decrease in the Mediterranean region is concerning, and many authors have pointed out the risk of excessive pressures on resources and water use conflicts (Arnell, 2004; Alcamo et al., 2007; Iglesias et al., 2007; Barceló and Sabater, 2010; Heinrichs et al., 2012).

At the same time aquatic ecosystems are receiving growing attention, notably through environmental regulations and water sharing plans. The WFD, aiming for a good environmental status of European water bodies by 2015, reinforces the protection of aquatic ecosystems and sets out the framework to ensure « the sufficient supply of good quality surface water and groundwater as needed for sustainable, balanced and equitable water use ». It 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 constraints, i.e. the 2015, 2021 or 2027 horizons. However it is widely recognized that mid-latitude areas could experience increased water stress throughout the 21st century, due to climate and socio-economic changes (Heinrichs et al., 2012; Milano et al., 2013b; Arnell and Lloyd-Hughes, 2014). 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 (IWRM³) as prescribed by the WFD and climate change adaptation is the focus on current and historic issues of IWRM, compared to the future focus of adaptation.

Recent and expected climatic and anthropogenic changes raise the question of the balance between water resources and water uses over the long term (Lehner et al., 2006; López-Moreno et al., 2011). Can water resources at the river basin scale meet demands for human activities, while maintaining healthy ecosystems today and in the future? Recent studies at different scales in the Mediterranean region (Milano et al., 2012, 2013b) have shown that future climatic and anthropogenic changes could have a significant impact water demand satisfaction.

1.3. Adaptation strategies in response to climate change vulnerability

Strategies are thus required to adapt water management to future climate and socio-economic changes (Ragab and Prudhomme, 2002; Wilby et al., 2006; Hallegatte, 2009; Iglesias et al., 2011; Quevauviller, 2011). Such strategies aim at maintaining a balance between water demand and availability, i.e. being able to supply enough water to satisfy demand while limiting anthropogenic pressure on water resources to sustainable levels. Therefore they need to be based on a thorough understanding of each region's exposure and sensitivity to climatic and anthropogenic pressures. Vulnerability to climate change is not only a consequence of a system's exposure to climatic variations but may be due to a combination of bio-physical impacts of climate change and of anthropogenic pressures (Farley et al., 2011; March et al., 2012; Reynard et al., 2014). Understanding vulnerability of river basins to climate change thus requires a quantitative assessment of water demand and availability, and an appropriate representation of the interactions between water uses and resources (including storage and regulation facilities).

Adaptation strategies are emerging at different scales. At the continental or regional scale (Europe, Mediterranean region), these strategies aim at establishing a framework for adaptation in the water sector, and at setting up a favorable context for measures to be taken locally, in line with specific impacts and vulnerability (Plan Bleu, 2011). The Mediterranean Strategy for Sustainable Development (MSSD) (PNUE PAM, 2005) advocates a sustainable use of water resources and water savings through demand management. The MSSD promotes « no-regret » measures (that yield benefits even in the absence of climate change) aimed at reducing the gap between water demand and resources in the Mediterranean region. The European WFD (EC, 2000) lays down the objectives and principles for Integrated Water Resources Management in Europe. Within the context of the WFD, the European Commission requires Member States to account for climate change in their water management plans and programs of measures (EC, 2009). A European strategy for adaptation to climate change was adopted in April 2013 (EC, 2013).

³IWRM is defined by the Global Water Partnership (GWP) as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP, 2003).

Several countries have adopted national plans to adapt to climate change including measures regarding water management, of which France (MEDDTL, 2011) and Spain (MEARM, 2007). One of the key priorities of the French strategy is to reduce water withdrawals by 20% by 2020. Resource substitution (i.e. building small dams or setting up water transfers) is considered acceptable if water savings prove to be insufficient to reduce the water deficit. The Spanish strategy is turned towards modeling and knowledge development to assess water management plans under scenarios of climate change. Finally, some river basin management agencies are also engaging in adaptation strategies for water management under climate change (AERMC, 2014a, e.g.).

2. Integrative approaches to simulate water shortage risks at the river basin scale

2.1. Adaptation strategies tend to be based on limited knowledge of river basins' vulnerability

The strategies and plans of adaptation to climate change that were mentioned above are often based on limited knowledge of the region, country, river basin or territory's vulnerability to climate change. The assessment of this vulnerability is put off by a number of methodological challenges, linked to the necessary integration of human and physical processes. Vulnerability to climate change is “the degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change” (IPCC, 2007). The potential exposure of the systems to changes in climate variables is provided by projections of climate change. The impacts of climate change on variables of interest such as runoff can then be assessed using impact models. Impact studies provide information on the bio-physical characteristics of a system. Generally, separate studies cover social vulnerability to climate change. They tend to be based on an analysis of past events to understand the characteristics of the territory that make it vulnerable to climate variability (Dessai and Hulme, 2004).

2.2. Both physical and human drivers need to be taken into account

To address the question of vulnerability and adaptation to climate change in highly influenced hydrosystems, it is necessary to combine biophysical and human features (Turner et al., 2003). The vulnerability of a system is not only due to its exposure to climatic hazards, but to a combination of biophysical climate change impacts and of human activities (Farley et al., 2011; March et al., 2012; Plummer et al., 2012). A given area could be highly exposed to climate change impacts such as changes in streamflow regimes or water availability and nevertheless not be vulnerable, if human activities do not highly depend on water resources. Moreover a system could be more impacted by anthropogenic pressures than by climatic pressures (Griffin et al., 2013); human activities can amplify climate change impacts or reduce them (Patwardhan et al., 2009).

A thorough understanding of the balance and linkages between water availability and demand is an essential prerequisite for sound adaptation strategies in terms of quantitative water management. Grasping these linkages requires taking into account physical and human processes (Griffin et al., 2013), and their distribution in space and over

time. Hence integrative approaches are necessary to combine human (socio-economic, demographic, land use) and physical (climatic, hydrological, phenology and soil) dynamics. These approaches should also represent changes in water management (water allocations, dam and canal management, efficiency improvements, etc.). In this way it is essential to move beyond the sectoral dimension of research and combine different fields related to hydrology (geography, agronomy, etc.) in order to integrate the drivers of water balance and vulnerability to climatic and anthropogenic changes.

Analyzing long past periods comprising significant water use and climate variability is essential to understand the drivers (anthropogenic or climatic) leading to water stress. How have the hydro-climatic and water use characteristics of the system changed in the past? Has it already been through a water shortage crisis? The ability to represent past changes is an essential first step before building future scenarios integrating physical and human dimensions and aimed at assessing future changes and necessary adaptations.

2.3. Managing uncertainties

Finally, the assessment of the variations in water availability and associated demand in space and over time involves substantial uncertainties. These may stem from the data (quality and/or interpretation), the models (bias, parameter calibration, limited validation, etc.), or the scenarios of future anthropogenic and climatic trends. The success of climate change adaptation is in great part determined by the management of uncertainties. How can we address the wide range of possible futures linked to climatic and anthropogenic changes and deliver useful messages for water management regarding climate change vulnerability and adaptation? This question calls for collaboration with local stakeholders and cannot be addressed solely through a research perspective.

3. General framework and objectives

Recent and future climatic and anthropogenic changes raise the issue of balancing water availability and demand over the long term in river basins facing rapid climatic and anthropogenic changes. This chapter showed the usefulness of assessing the balance between water availability and demand over multi-decadal time periods, to better understand water stress risks and inform decisions to adapt to future climate changes. It also stressed the importance of considering the impacts of both anthropogenic and climatic changes, and of understanding past changes before looking into the future. Finally, the need to account for uncertainties in projections of future changes and their implications for adaptation strategies was underlined. In this context, the general objectives of this thesis were to assess the balance between water availability and demand over multi-decadal time periods, to better understand water stress risks and inform decisions to adapt to future climatic changes. The following chapter proposes an overview of published literature on the balance between water availability and demand under anthropogenic and climatic changes, based on which it defines the specific research objectives of this thesis and presents the research design and the outline for the manuscript.

Chapter 1.

Literature overview and research objectives

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1. Introduction

This chapter proposes an overview of published literature on the balance between water availability and demand under anthropogenic and climatic changes. Following a review of the contributions and limitations of existing approaches to represent the dynamics of water availability and demand in space and over time, the links between research and decision support for climate change adaptation are considered. The third part of the chapter offers an analysis of possible improvements to better assess the balance between water availability and demand and to better address water management issues. Finally, considering this analysis, the research objectives of this thesis are presented.

2. Contributions and limitations of existing approaches to represent the dynamics of water availability and demand in space and over time

2.1. A need for studies at the river basin scale

Many authors have underlined the need for integrative assessments of the impacts of climate change on the balance between water demand and availability (Füssel and Klein, 2006; Ludwig et al., 2011, e.g.), and an increasing number of studies that deal with this issue can be found in the literature. Studies at the global scale (Arnell, 1999; Alcamo et al., 2003, 2007; Arnell et al., 2011, e.g.) combined socioeconomic and hydro-climatic data from global databases, and identified the regions most susceptible to experience water stress, defined here as an imbalance between water demand and availability, i.e. when water demand is greater than water supply. These studies usually use global databases at a grid-scale (generally $0.5^\circ \times 0.5^\circ$). Water resources are simulated with climatic data inputs, and are compared to water demands. The latter are assessed using population and irrigated areas, and in some cases climatic data (Alcamo et al., 2003, e.g.).

These global studies serve the essential purpose of raising important water management issues and of pointing out the areas most vulnerable to climatic and anthropogenic changes. However water management decisions are more often made at the river basin scale. Water resources at this scale are generally highly influenced by human activities and the assessment of imbalance between water demand and availability implies a thorough analysis of the dynamics of water resources and uses in space and over time.

2.2. A growing but still limited integration of physical and human drivers at the river basin scale

In this mindset, recent studies comparing water demand and availability were conducted at the river basin scale, with the aim of optimizing water allocation in given conditions (Letcher et al., 2004; Welsh et al., 2012, e.g.), or for the design of water management plans (Beck and Bernauer, 2011; Pulido-Velazquez et al., 2011; Varela-Ortega et al., 2011; Shamir et al., 2015, e.g.). Some of these studies at the river basin scale used integrative modeling tools developed to inform decision making, aimed at different types of users (from researchers to water managers). These Decision Support Systems (DSSs) generally

aim to optimize water allocations in known, stationary conditions. The REALM model (Perera et al., 2003), for example, optimizes water allocations for different demand nodes of a given area considering economic costs. Water allocation models tend to be used to assist decision making on issues such as water rights or matching demand with sufficient supply sources, rather than to simulate and represent linkages between water availability and demand and their long-term changes. To our knowledge these models have not been used to simulate past or future dynamics (in space and/or over time) of water demand and availability. Water availability and demand are more often used as input data in these allocation models.

Other existing tools include one or more water resource simulation models, in addition to the allocation model. This is the case, for instance, of MIKE Basin (Doulgeris et al., 2012), a DSS which uses a GIS interface. It is based on a river network model in which the river systems are represented by a network consisting of branches and nodes. This tool enables its users to simulate surface flows and their interactions with groundwater. It also includes a reservoir management model and accounts for allocation priorities between different water users.

Integrated modeling tools that simulate water resources dynamics over time according to climatic drivers are also used in some cases to support multi-decadal planning, notably under climate change scenarios. In this way Pulido-Velazquez et al. (2011) used AQUATOOL (Andreu et al., 1996) in a sub-basin of the Jucar river basin (Spain) to assess the impacts of climate change on surface and groundwater use. Water resources were simulated at a monthly time step and water demand dynamics were not simulated, rather past data on water withdrawals was used as input in the model. Consequently the impacts of climate change on irrigation water demand were not quantified, nor were the impacts of changes in human activities assessed. Only simple scenarios of increase or decrease in total water demands were considered. The WEAP (Water Evaluation and Planning) model (Sieber and Purkey, 2007) allows users to simulate water resources and demand based on anthropogenic and climatic drivers at the river basin scale (Purkey et al., 2008; Varela-Ortega et al., 2011, e.g.). It also includes a dam management model. The WEAP model has been widely used to assess the water balance of water supply capacity throughout different regions of the world. In this way Swiech et al. (2012) simulated the water balance of an irrigation district linked to reservoir in reference climate conditions. Mehta et al. (2013) simulated the water supply capacity of an irrigation district in California under different scenarios of climate and land use changes and accounted for anthropogenic and climatic drivers of the water balance.

Other studies aimed at informing water management and adaptation under climate change were carried out without using specific decision support systems. These studies rarely fully incorporate anthropogenic and climatic drivers. They generally focus on simulating water resources (i.e. surface streamflow and/or groundwater levels) under varying climatic conditions (Jiang et al., 2007; Rasilla et al., 2013; Schwank et al., 2014, e.g.). In some cases, water uses are dealt with by looking at population changes, without quantifying the corresponding water demand (i.e. the volumes associated). In this way Griffin et al. (2013) simulated the impacts of different climate change scenarios on water resources and used the Falkenmark Water Stress Indicator (Falkenmark et al., 1989) to assess water stress under each scenario, considering demographic trends. This indicator

compares available resources to population and does not account for water demand per-capita, which can vary greatly. Thus the impacts of anthropogenic and climatic drivers on water demand were not accounted for. In other cases, water demand is accounted for but data from historical series or estimates by local water managers are used, rather than simulations based on anthropogenic and climatic drivers (Pulido-Velazquez et al., 2011; López-Moreno et al., 2014, e.g.). This limits the possibility of analyzing the drivers of the variations of demand in space and over time, even when sufficient data on withdrawals are available to account for this variability.

Koutroulis et al. (2013) assessed the balance between water availability and demand in Crete under climate change and water demand scenarios. The water demand scenarios were built based on local past and predicted trends of infrastructure building and investments, water conservations measures, etc. However these scenarios did not consider the impacts of climate change on irrigation water demand and consequently did not account for the associated variability of water demand. López-Moreno et al. (2014) assessed the impacts of climate change and land use on runoff upstream from a large storage dam in the Pyrenees. The authors then simulated the dam operations and the projected balance between water availability in the reservoir and agricultural water demand linked to it. However the water demand considered in this study was based on past data and was considered constant in the future scenarios.

By using physically based, distributed hydrological models, some studies considered the dynamics of actual evapotranspiration (of non-irrigated and/or irrigated land cover) to assess their impacts on runoff (Boithias et al., 2014; Kiptala et al., 2014). They often concentrated on natural physical processes and rarely incorporated the impact of blue water use, i.e. water extracted from streams, groundwater or reservoirs, one exception being the work by Kiptala et al. (2014). However in this study the water balance model was calibrated over one year and validated over two years, thus the efficiency of the model to represent long-term dynamics could not be established. This type of research also rarely accounts for the influence of water management on its availability (i.e. storage facilities, dam management, transfers). Thus it does not lead to a complete understanding of the water supply capacity of a system and the sustainability of its water uses.

In this mindset, linkages between water demands and water resources should also be accounted for. Notably, few studies have actually simulated natural streamflow separately from influenced streamflow and accounted for consumptive use. 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 some cases, hydrological models are calibrated on observed (i.e. influenced) streamflow data, and the simulated streamflow is compared to water demand to assess water stress (Collet et al., 2013, e.g.). This method introduces a bias in simulations and probably leads to overestimating water stress, since the amount of water considered available for use has already been decreased by that same use.

Finally, a complex issue is the representation of the interactions between groundwater and surface water, i.e. the use of groundwater resources and the influence that their management could have on streamflow, and the partition of return flows from network losses and inefficient irrigation techniques between evaporation, groundwater recharge and return to surface flow.

2.3. Accounting for dynamics of the water balance in space and over time

Studies that do not fully incorporate anthropogenic and climatic drivers of water availability and demand may not completely grasp the ways in which river basins could be affected by future anthropogenic and climatic changes. In some studies however water demand is simulated based on anthropogenic and climatic drivers, and is compared to water availability based on climatic variability and water management rules (Purkey et al., 2008; Varela-Ortega et al., 2011; Collet et al., 2013; Milano et al., 2013a, e.g.). Nevertheless the research found in the literature often takes a static view of the water balance, accounting for average conditions over several years (Milano et al., 2013a, e.g.) or characteristic situations such as particularly dry or wet years (Varela-Ortega et al., 2011; Boithias et al., 2014, e.g.). Water allocation studies often follow an operational, short- to mid-term approach, and tend to consider a static picture of water uses and resources. Conversely water management plans often require a long-term perspective (Welsh et al., 2012).

Krol et al. (2006) simulated water resources and demand in Northeast Brazil over a 20-year past period and a 100-year future period. The authors underlined the importance of representing hydrosystem dynamics over long time periods. This is essential for models being used in a context of anthropogenic and climatic changes. To our knowledge, few studies have achieved this so far (Collet et al., 2013, e.g.). Before looking into complex future changes, we need to be able to represent long-term variations, which implies accounting for the variability of anthropogenic and climatic drivers.

The balance between water availability and demand also has a highly heterogeneous spatial distribution within river basins, and water stress assessments can vary depending on the spatial scale (Boithias et al., 2014). Thus, it is essential to properly account for the main heterogeneities in water demand and availability. In a number of existing papers integrating water uses, water management and water availability, the systems under study were elementary management units such as individual reservoirs or an aquifer (Nam et al., 2015; Shamir et al., 2015, e.g.). 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; Milano et al., 2013a, e.g.).

3. Linking research and decision support

3.1. Models for research and decision support tools

Oxley et al. (2004) described two types of models: research models ("originating in the problem-driven empirical or theoretical domain") and policy models ("originating in the value-driven perceptual domain"). According to the authors research models tend to be as complex as necessary, with the goal of representing processes as accurately as possible. The scale and level of complexity are determined by the processes being studied. Policy models (still according to Oxley et al. 2004) are developed with the aim to address practical policy issues. The issues at stake determine the spatial and temporal scales used and, together with data availability and time and cost constraints, the degree of complexity of the models. Policy models are developed to help explore the impacts of different policies and usually use robust and extensively tested methods. User-friendliness is also important an important value of these models.

Integrative approaches developed to date and that are based on decision support systems resemble Oxley's definition of policy models and aim at addressing water management issues. The simplification of the models for the sake of user-friendliness may limit their usefulness for exploring scientific questions. Notably Letcher et al. (2007) pointed out the importance of accounting for and assessing the uncertainties and sensitivity of the models used within integrative modeling chains. In a context of research regarding water management issues, a compromise must be found between the two extremes of the research and policy models.

3.2. Projections of water shortage risk

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 (Nkomozepe and Chung 2014; Schwank et al. 2014; Bär et al. 2015; 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 (Menzel and Matovelle, 2010; Griffin et al., 2013, e.g.). Also, climate change could have considerable impacts on irrigation requirements (Döll, 2002; Woznicki et al., 2015, e.g.), 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 trade-offs 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 (Pulido-Velazquez et al., 2011; López-Moreno et al., 2014, e.g.), or future planned demands without considering the possible impact of climate change on agricultural water demand (Milano et al., 2013a, e.g.).

3.3. A need for relevant indicators to address vulnerability and inform adaptation decisions

Analyzing the vulnerability of hydrosystems to climatic and anthropogenic changes also often implies using indicators to evaluate and communicate its potential points of failure. Indicators can be used regarding the state of a system, its evolution, or its sensitivity to a given pressure. They can represent a pressure and/or its impacts on the system, the state of the system, or its response to the impact, following the Driver-Pressure-State-Impact-Response (DPSIR) framework for analyzing environmental problems (EEA, 1999). Sullivan and Meigh (2005) defined indicators as “a statistical concept, providing an indirect way of measuring a given quantity or state, and allowing for comparison over time”. Therefore indicators should be dynamic and account for changes in the system being studied. In a review of indicator-based water sustainability assessments, Juwana et al. (2012) defined important criteria to evaluate the pertinence of indicators. In addition to being integrative, they should be sensitive to spatial and temporal dynamics in anthropogenic pressures, and should help anticipate undesirable situations and/or carry out projections. Finally, threshold values should be set to define undesirable situations in the studied hydrosystems.

Varela-Ortega et al. (2011) proposed indicators specific to the case study of the aquifer « Western La Mancha » in the south of Spain, related to water management in the region. These indicators (e.g. aquifer recharge, decrease in agricultural water demand) provided a useful assessment of the efficiency of local policies. However they were not designed to address the question of the water balance under anthropogenic and climatic changes and are quite context-specific. The « Climate Vulnerability Index » defined by Sullivan and Meigh (2005) combines a range of different drivers of vulnerability to climatic variability, regarding water resources, access to the resources, water uses, the environment, etc. The indicators used for each driver of vulnerability depend on the context of the study area and on available data. Thus the authors present a framework to assess vulnerability, with a few examples of indicators for each driver of vulnerability. They provide little information on possible threshold values to characterize the state of the systems studied.

Some integrative studies at the river basin scale included the use of indicators based on simulations of water resources and demand. In this way Pulido-Velazquez et al. (2011) used indicators of water demand satisfaction, supply reliability, and pressure of water use on the environment to assess the impacts of climate change and adaptive strategies on a conjunctive-use system. This approach concentrated on an average situation, thus providing a static and incomplete view of the system’s vulnerability. Asefa et al. (2014) included statistical components in their analysis, such as resilience and the return period of undesirable events, thus better matching water management criteria. In both cases, indicators were averaged over reference or future time periods. They did not provide information on past dynamics of water stress. Collet et al. (2013) computed an indicator of water supply capacity (i.e. the ratio between water availability and water demand) at a 10-day time step over a past period of 50 years. This indicator enabled the authors to assess the frequency with which water shortages appeared over multi-decadal time periods, and to analyze the dynamics of water demand satisfaction in space and over time.

4. Improvements identified to better address research and management issues

4.1. Methodological improvements for assessments of the balance between water availability and demand at the river basin scale

The overview of published literature enabled to define three areas for improvement in the assessment of the balance between water availability and demand under anthropogenic and climatic changes in highly influenced river basins.

4.1.1. Analyzing past dynamics of the water balance

Few studies included a retrospective, dynamic analysis of the balance between water availability and demand over long time periods. This omission limits the capacity of these approaches to examine and understand the drivers of water stress and past adaptations in hydrosystems facing hydro-climatic and anthropogenic changes. The essential historical reconstruction of the water balance and links between resource and demand makes methodological developments necessary to simulate the variability of water demands, and their influence on streamflow (withdrawals, storage and release, etc.).

4.1.2. Conceptual representation of water availability and demand

In most of the papers found in the literature integrating water uses, water management and water availability, the systems under study were elementary management units such as individual reservoirs or an aquifer. Yet water management plans often cover meso-scale to large-scale basins encompassing many sub-basins with contrasting characteristics, several aquifers, and possibly several dams and water transfers. Representing geographical heterogeneities, spatial dynamics and water management practices in river basins implies a thorough analysis of local water management characteristics and issues. Moreover, correctly conceptualizing complex, highly influenced river basins involves an intensive collection and treatment of hydro-climatic and socio-economic data and other existing information (water management plans, gray literature).

One of the challenges of simulating the balance between water availability and demand is to find an appropriate scale to aggregate water demand into homogeneous demand nodes, and to match these demand nodes with water supply nodes. The storage facilities that contribute the most to demand satisfaction and that are the most impacting on streamflow must be determined, as well as the water transfers between sub-basins and from the river basin to water uses outside the basin. The mapping of water availability and demand nodes also depends on the available data. Time series of several decades of streamflow and/or groundwater level data are needed to calibrate and validate simulations, as well as reservoir levels and water demand data. Simulations of water availability and demand are preferably carried out at the same time step, thus adding a constraint on data availability and processing.

4.1.3. Addressing the complexity of water resources management: water withdrawals, storage and release, consumptive use, return flows

To be able to adapt effectively to future climatic and anthropogenic changes, it is essential to understand the links and interactions between the different drivers leading to water shortage or excessive pressure on water resources. The review of the literature underlined a lack of integration of anthropogenic and climatic drivers in most modeling studies dealing with the balance between water demand and availability in river basins, i.e. at the scale of water management plans. River basins need to be considered as hydrosystems (i.e. systems made of water and the associated aquatic environments within a delimited geographical entity) that fully incorporate the different water uses and the influence that these uses may have on water resources, including storage and supply facilities.

Also, it was shown that representing the influence of anthropogenic water use on water resources is a difficult yet essential task. Perry (2007) defined water use as “any deliberate application of water to a specified purpose”. As stated by the author, this term “does not distinguish between uses that remove the water from further use (evaporation, transpiration, flows to sinks) and uses that have little quantitative impacts on water availability (navigation, hydropower, most domestic uses)”. Anthropogenic water use can influence water availability in different ways.

First, a distinction should be made between water resources and water availability. Water resources can be considered as the total amount of water contained, for a given period of time, in water bodies, aquifers, and the atmosphere. Resources are classically divided into green water, i.e. precipitation and soil water which is used by non-irrigated vegetation, and blue water, i.e. water flows and stocks in water bodies which can be extracted for human use. However only part of the blue water is available for human use. Indeed water availability depends on infrastructures and water management: storage facilities, transportation capacities, instream use or groundwater recharge regulatory requirements, etc. Thus all these elements need to be accounted for in simulations of the water balance to determine the water supply capacity of a hydrosystem.

Second, water use can influence streamflow or groundwater recharge through withdrawals, consumptive use and return flows. Water demand is the amount of water required for a particular use. Here water demand is considered to be 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. Water withdrawals are the amounts of water abstracted from water bodies, considering water availability, management practices and regulatory constraints. Water withdrawals are not necessarily equal to water demands. Water extracted from water bodies is not consumed entirely, and part of it returns to the environment through return flows. The consumptive use, or net consumption, depends on the type of water use (a large part of municipal water returns to the environment in the form of treated wastewater, while the water delivered to irrigated crops is consumed through evapotranspiration) and the efficiency of water supply networks. Water losses from supply networks can either return to the environment (through subsurface flow or groundwater recharge) or be consumed through evapotranspiration.

This complexity of water resources management needs to be accounted for in research quantifying water flows in a given area. This involves a number of methodological developments to simulate natural streamflow (especially when observed streamflow data is mostly influenced), water demand, storage and release operations, water withdrawals and the actual consumptive use.

4.2. Improvements to better address water management issues

4.2.1. Using the models to understand the main drivers of change

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 represent 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 reallocation scenarios considered, other studies found that anthropogenic drivers could have more impact than climatic drivers (Vörösmarty et al., 2000; Beck and Bernauer, 2011; Reynard et al., 2014, e.g.).

4.2.2. Providing relevant projections of water shortage risks and testing measures aimed at reducing the gap between water demand and availability

The review of the literature showed that studies on climate impacts on water management are mostly focused on projections of water resources. To better address water management issues, research is needed on the implications of climate and water use changes on quantitative water management as a whole. This implies providing projections of the balance between water demand and availability, including changes in water demand caused by water use and climate changes, and changes in water availability caused not only by climate changes but also by changes in water resources management (storage capacity, rules for dam management, etc.).

Analyzing the results of simulations under water use and climate change scenarios is also a challenge to better address water management issues in river basins facing climatic and anthropogenic changes. Indicators should be built in collaboration with the local stakeholders (e.g. river basin agencies) to grasp and represent the real-world management issues. This co-construction can help find threshold values of indicators used by water managers to make decisions.

4.2.3. Addressing the implications of climate change uncertainties for water management

Facing warmer and drier conditions is a recurrent problem for water management under climate change. Yet, uncertainties are also a key element to take into account while designing adaptation strategies. They are usually analyzed at the end of impact or vulnerability studies to underline the limits of the results, but their implications for water management are hardly considered. Walker et al. (2003) distinguished two types of uncertainties: epistemic uncertainties stemming from an incomplete understanding of the studied systems, and uncertainties linked to natural variability (i.e. the chaotic or unpredictable character of the studied systems). One could add uncertainties related to scenario building: different scenarios constitute varied plausible futures, the range of which expands with the number of variables taken into account.

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 uncertainties in the decision process, and finding adaptation solutions despite this uncertainty (Patt et al., 2005; Hallegatte, 2009; Wilby, 2010, e.g.). Adapting to climate change not only implies adjusting systems to different hydroclimatic conditions, but also anticipating an uncertain future (Dessai and Hulme, 2007; Plan Bleu, 2011). 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 Dessai, 2010), assessments of future changes in the water balance should cover a wide range of possible climate scenarios, given by a selection of global climate models. As underlined by Räisänen (2007), inter-model comparison of climate change projections may be the most pertinent estimate of uncertainty currently available.

5. Research objectives

In section 4, a number of topics were identified to better address research and management issues regarding quantitative water management in areas facing rapid anthropogenic and climatic changes. In light of this analysis, the objectives of this thesis are the following:

- **represent** linkages between water resource and demand in influenced hydrosystems and account for the multi-decadal dynamics of climatic and anthropogenic drivers (in space and over time);
- **assess** the sustainability of water uses under projected climatic and anthropogenic changes;
- **explore** options to reduce the gap between water demand and availability in an uncertain future.

Considering the scale of most water management decisions, this study was logically undertaken at the river basin scale. Two study areas, which are presented in the following chapter, were chosen in the Mediterranean region, an area particularly affected by climatic and anthropogenic changes. The chapters 3, 4 and 5 then focus on each of the research objectives cited above. The development of an integrated modeling chain over a multi-decadal past period is presented in Chapter 3; Chapter 4 exposes an assessment of the sustainability of water uses under projected climatic and anthropogenic changes; finally, options to reduce the gap between water demand and availability and adaptation scenarios are assessed in Chapter 5. The contributions and limitations of this study are discussed in Chapter 6.

Chapter 2.

The Herault and the Ebro basins

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1. Introduction

The need to better understand and represent linkages between resources and demand and to account for the variability of anthropogenic and climatic drivers is particularly pronounced in the Mediterranean region, which faces significant climatic variability, rapid population growth and economic development, and increasing competition between different water uses (Milano et al., 2012, 2013b). Water supply capacity is essential in the Mediterranean region, which has been identified as one of the most vulnerable regions to water crisis (Alcamo et al., 2007). As a result of climate change, water resources could decrease by 30 to 50% by the 2050 horizon. Combined with increasing water demand, this could lead Mediterranean catchments of Spain and of the southern and eastern rims to face severe water stress (Milano et al., 2013b).

The research carried out in this thesis focused on two river basins of different scales, presented in this chapter: the Herault, a meso-scale basin (2 500 km²) in France, and the Ebro, a large-scale basin (85 000 km²) in Spain. After briefly introducing the geographical context, the hydroclimatic and socio-economic datasets gathered for the thesis are described, followed by the hydroclimatic context in both basins. Finally water uses and water management issues faced in the Herault and the Ebro basins are presented.

2. Geographical context

The Herault and the Ebro catchments differ in their geographical characteristics. The Herault basin is located in the South of France (Fig. 2.1a). It is bordered in the north by the Cevennes Mountains. The Herault River flows 150 km from Mont Aigoual (1 565 m a.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 basin is located in the north of Spain (Fig. 2.1b). The Ebro River flows 910 km in a north-west to south-east direction from Fontibre in the Cantabrian Range (1 027 m a.s.l.), to the town of Tortosa where it forms a large delta. It is bordered by the Pyrenean range (up to 3 383 m a.s.l.) in the north, the Iberian range in the south and the Catalan coastal range in the east.

3. Hydroclimatic and socio-economic datasets

Daily climate forcings for the Herault basin over the period 1969 to 2009 were extracted from the SAFRAN meteorological analysis system (Vidal et al., 2010), an 8 × 8 km grid provided by *Météo France* and validated over France by Quintana-Segui et al. (2008). Potential evapotranspiration (ET_o) 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 using the inverse distance weighted method. Lapse rates of −6.65 °C/1000 m and of −4.16 °C/1 000 m (for the Pyrenean and Cantabrian range, respectively) were applied over 1 000 m a.s.l. for the interpolation of T_{MAX} and T_{MIN}, based on observations from

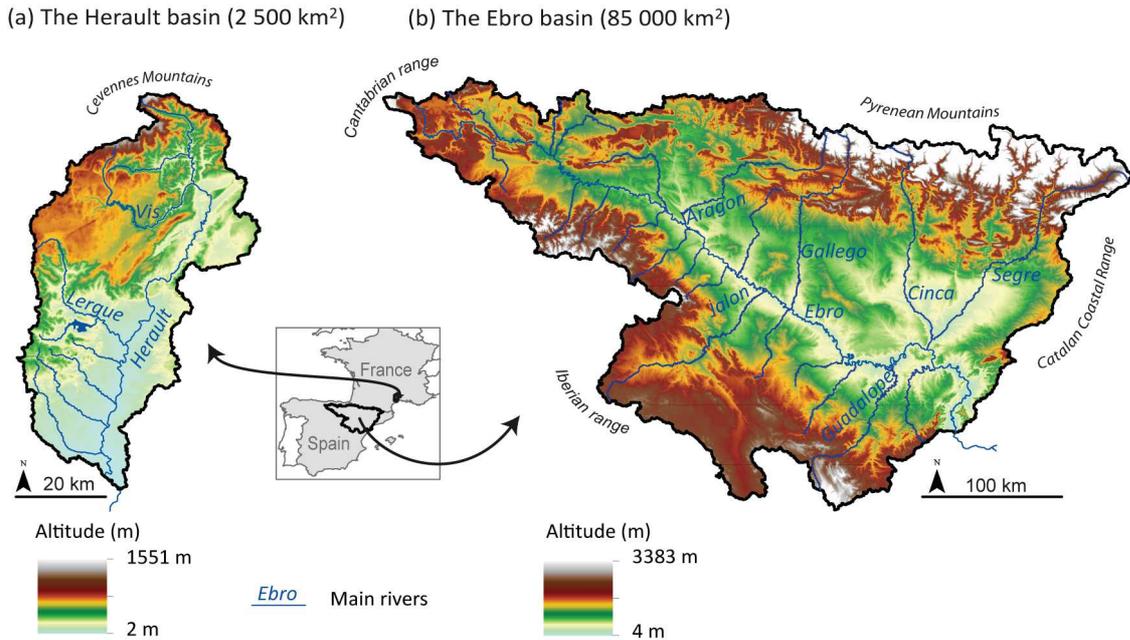


Figure 2.1. Location, topography and main rivers of (a) the Herault basin and (b) the Ebro basin.

the 1969–2009 period (Dezetter et al., 2014, see Appendix B). Since additional data (e.g. wind and humidity) were too scarce to calculate Penman-Monteith ET_0 at the scale of the Ebro basin from 1969 to 2009, the Hargreaves empirical equation (Hargreaves and Samani, 1985) was used to calculate ET_0 at a daily time step. The calibration proposed by Martínez-Cob and Tejero-Juste (2004) in the Ebro valley was applied to the whole basin using equation (2.1).

$$ET_0 = \omega \times (0.0864Ra/\lambda) \times (T_{MAX} - T_{MIN})^{0.5} \times (T_{MEAN} + 17.8) \quad (2..1)$$

where $\omega = 0.0023$ in windy areas, $\omega = 0.0020$ otherwise, Ra = extraterrestrial radiation, λ = latent heat flux, T_{MAX} = maximum daily temperature, T_{MIN} = minimum daily temperature, T_{MEAN} = mean daily temperature.

Windy areas in the Ebro basin were defined by García-Vera and Martínez-Cob (2004) based on available wind speed data. If a common formula in both basins were to be used, considering data availability it would have been based only on temperature (Oudin et al., 2005, e.g.) and not necessarily adapted to agronomic studies. Moreover, simulations of water demand and dam management led to more realistic results with the Hargreaves formula than with the Oudin formula. Thus the most accurate formula applicable in each basin was used, rather than a common formula for both basins.

Daily streamflow data were extracted from the French Ministry of Ecology and Sustainable Development's database *Banque Hydro* (MEDDE, 2010) for the Herault basin and from the *Anuario de aforos* of the Center of studies and experiments on hydraulic systems (CEDEX, 2012) for the Ebro basin. Reservoir levels and outflow data were provided by the General Council of the Herault administrative region (*Conseil Général de l'Hérault*) and by the CEDEX.

The availability of climatic and streamflow data determined the time depth of the analysis of past conditions in the Hérault and the Ebro basins, the objective being a multi-decadal period common to the two basins so as to include significant hydro-climatic and water use variability. According to these criteria, the period 1971–2009 was selected.

Population data were provided by national statistics institutes (INSEE for France and INE for Spain), and information concerning irrigated areas and crop dynamics was extracted from agricultural censuses. The efficiency of water supply networks and of irrigation systems and data relating to unit water consumption and industrial activities were provided by the local water management agencies (adapted from CHE, 2013 and SMBFH, 2005).

4. Hydroclimatic context

The Hérault catchment is characterized by a Mediterranean climate influenced by the Cévennes mountain range, with mild wet winters and hot dry summers. The average seasonal temperature in the period 1971–2009 ranged from 6 °C in the winter to 20 °C in the summer; average annual precipitation was 1 100 mm over the basin. Temperature and precipitation follow a north-to-south gradient in the basin: average annual temperatures range from 8 °C in the north to over 15 °C in the south, and average precipitation ranges from over 1 600 mm/y in the north to less than 600 mm/y in the south. Climatic conditions in the Ebro basin are complex due to the contrasting 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 °C in the Pyrenees to 17 °C in the lower Ebro valley and from over 2 000 mm/y in the western Pyrenees to less than 400 mm/y in the semi-arid central Ebro valley.

Mean annual observed streamflow was 36 m³/s (470 mm/y) in the Hérault and 330 m³/s (120 mm/y) in the Ebro between 1971 and 2009. The Hérault and its tributaries have a Mediterranean regime (severe low flows in summer and high flows in fall and winter with potentially severe floods in fall). Hydrological regimes in the Ebro basin vary from nival to Mediterranean (Bejarano et al., 2010). Upstream sub-basins in the Pyrenean and the Cantabrian ranges produced an average of 47% of the Ebro basin's natural runoff between 1971 and 2009.

The period 1971–2009 comprises significant climate variability: statistical breaks in temperature and discharge series were detected in both basins around the year 1980 (Collet et al., 2014; Milano et al., 2013a). Temperature increased by 1 °C in both basins between 1971–1980 and 1981–2009 and discharge decreased by 41% and 37% between 1971–1979 and 1980–2009 at the outlet of the Hérault and the Ebro basins respectively. Although no statistically significant break was detected, annual precipitation decreased by 10% in the Hérault basin and by 12% in the Ebro basin between 1971–1980 and 1981–2009. Seasonal disparities were identified in the precipitation trends: while winter precipitation decreased by approximately 40% between the two periods in both basins, fall precipitation increased by 21% over the Hérault basin and by 12% over the Ebro basin. Figure 2.3 shows the average monthly temperature, precipitation and discharge over 1971–1980 and 1981–2009 in both basins.

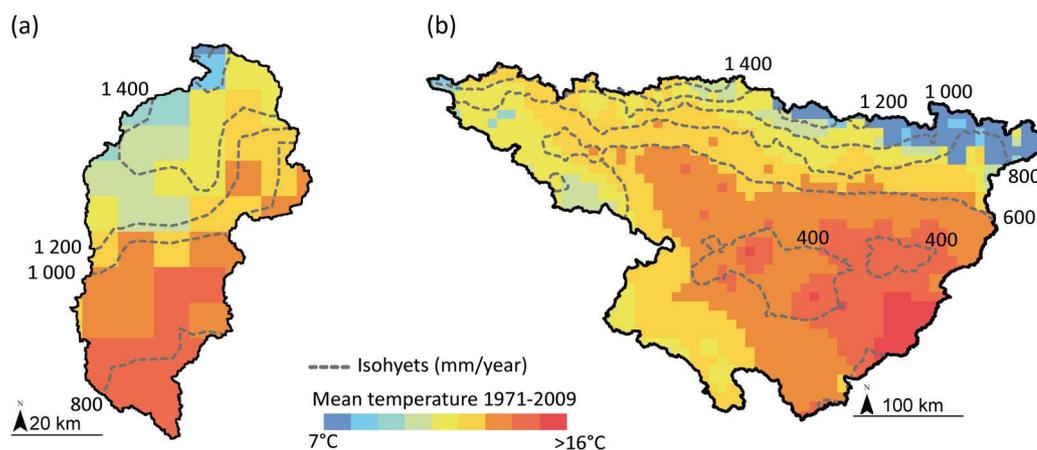


Figure 2.2. Climatic gradients in (a) the Hérault basin and (b) the Ebro basin.

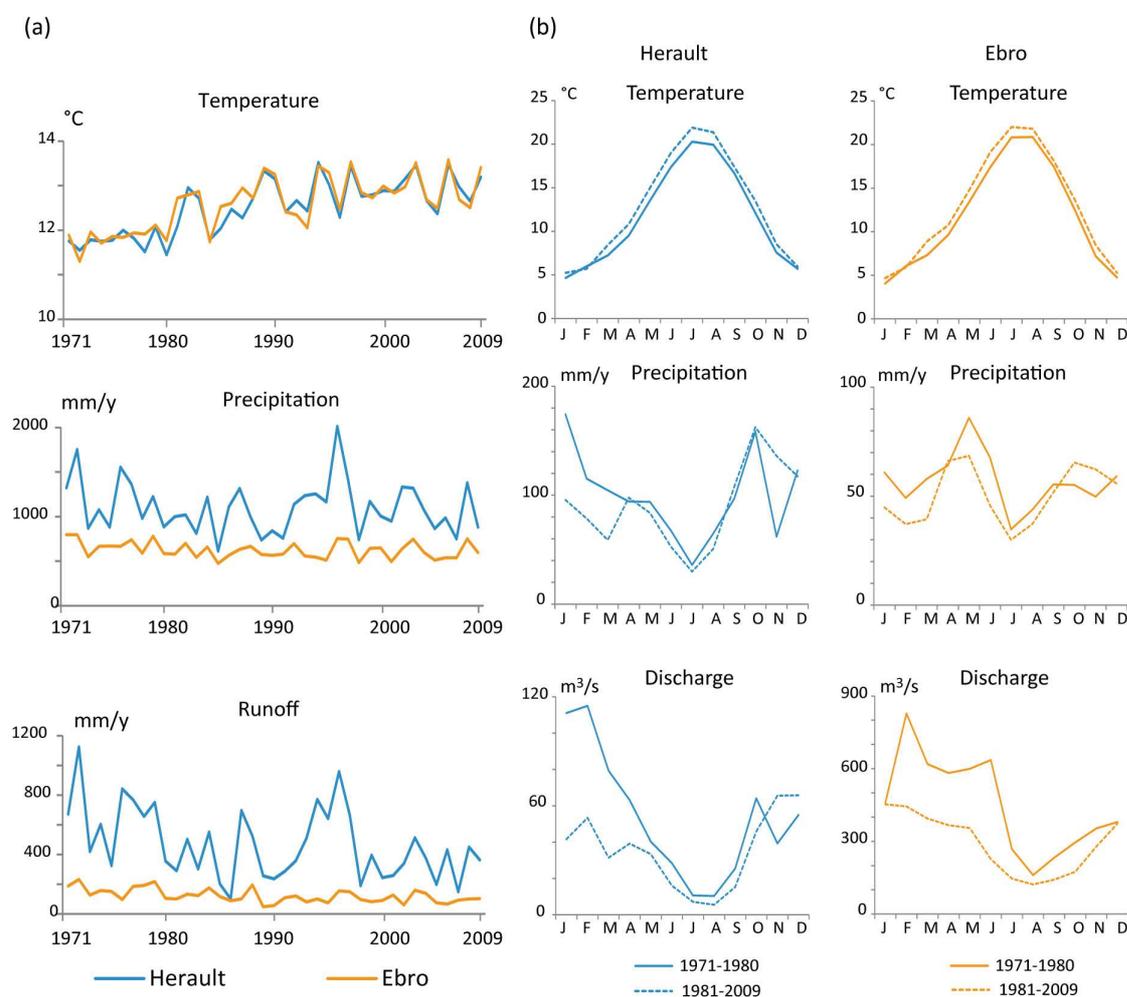


Figure 2.3. Hydroclimatic characteristics of the Hérault and the Ebro basins. (a) Annual temperature, precipitation and runoff variability between 1971 and 2009. (b) Average monthly temperature, precipitation and discharge in the during the periods 1971–1980 and 1981–2009.

5. Water uses and management issues

Figure 2.4 shows the main anthropogenic pressures on water resources in the Hérault and the Ebro basins. In the Hérault basin, the north differs significantly from the south, with low population density and sparse agricultural areas in the north and a high concentration of urban and agricultural areas in the south (Fig. 2.4a). Water demands for irrigation and municipal use inside and outside the basin amount to comparable volumes, i.e. 40 hm³/y for each type of demand on average between 1980 and 2010 (Collet et al., 2014). The Florensac transfer, which supplies potable water to coastal touristic areas located east of the basin, accounted for one third of total water demand in 2009. Water demand is highly seasonal, with irrigation demand (mostly for vineyards) and municipal 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, see Appendix A), 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 lake. The main irrigated areas are concentrated around the Gignac canal which distributes water from the Hérault River to an irrigated perimeter of nearly 3 000 ha. According to local stakeholders, until the 1990s the efficiency of the system barely reached 7% but increased to 20% in the late 2000s.

The Ebro is a complex and highly regulated hydrosystem with a total of 234 dams, amounting to a storage capacity of 60% of total runoff. Irrigated areas 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. In 2007, agricultural water demand amounted to 92% of the total water demand (CHE, 2013). The Ebro basin concentrates 60% of Spain's fruit production and 30% of the country's meat production (CHE, 2013), and agriculture in the basin contributes to a dynamic agro-industrial sector. Together with water demand for the open-air cooling systems of two nuclear power plants, industrial water demand is similar to urban water demand. The population density is mostly very low (under 10 inhab./km²) except in a few urbanized areas such as Zaragoza or Pamplona. Transfers to cities outside the basin have been underway since 1927, the two main ones being urban and industrial water transfers to Bilbao and Tarragona, underway since 1975 and 1989 respectively.

The Hérault basin has been part of the territory managed by the *Agence de l'eau Rhône-Méditerranée Corse* (Rhône Mediterranean Corsica Water Agency) since 1964. The local agency *Syndicat Mixte du Bassin du Fleuve Hérault* (SMBFH) was created in the 2000s to ensure more local management and in response to issues that are specific to the Hérault basin, including water availability (SMBFH, 2005). Studies on the balance between water availability and demand have been launched by local authorities in the Hérault basin and should lead to a water sharing plan for the basin. In contrast, the *Confederación Hidrográfica del Ebro* (CHE) was created in 1926 with the aim of increasing irrigation and water resource management in the Ebro basin, with a strong emphasis on the development of the resource and of infrastructure. The CHE now has a wider role in water management, in line with Integrated Water Resources Management and water sustainability as a whole. Since the 2000s, efforts have been underway to improve network efficiency and increase demand management (Lecina and Playán, 2002; Lecina et al., 2010; Salvador et al., 2011).



Photo 1. Ebro Valley near Zaragoza. (Sept. 2013)



Photo 2. The Ebro basin concentrates 30% of the country's meat production. (Sept. 2013)

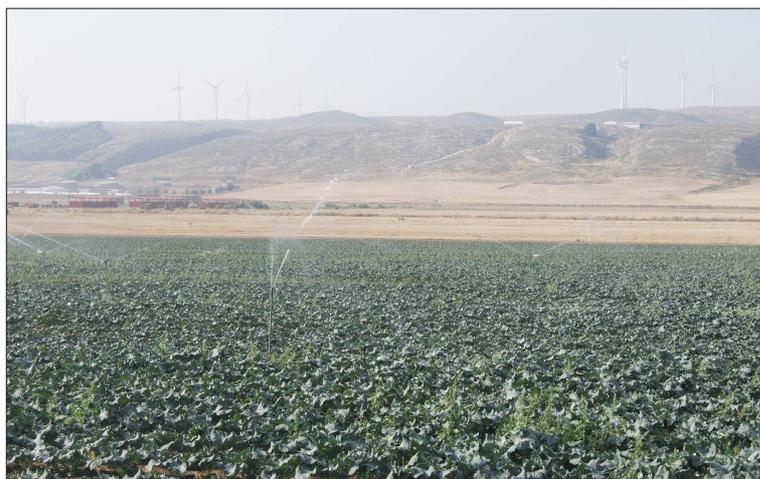


Photo 3. Sprinkler irrigation in the Bardenas area of the Ebro basin. (Sept. 2013)



Photo 4. *El Grado* dam, on the River Cinca. The storage capacity of the Ebro basin amounts to 60% of annual runoff, with more than 250 dams. (Sept. 2013)



Photo 5. The semi-arid Ebro valley concentrates the largest irrigated areas in the basin, supplied by an extensive network of reservoirs and canals. Left: the *Bardenas* canal ($60 \text{ m}^3/\text{s}$). Right: the *Aragon y Catalunya* canal ($36 \text{ m}^3/\text{s}$) is a reversible irrigation canal supplying water from the *Sotonera* or the *Grado* dam, depending on reservoir levels. (Sept. 2013)



Photo 6. Hérault valley upstream from *Valleraugues*. (June 2013)

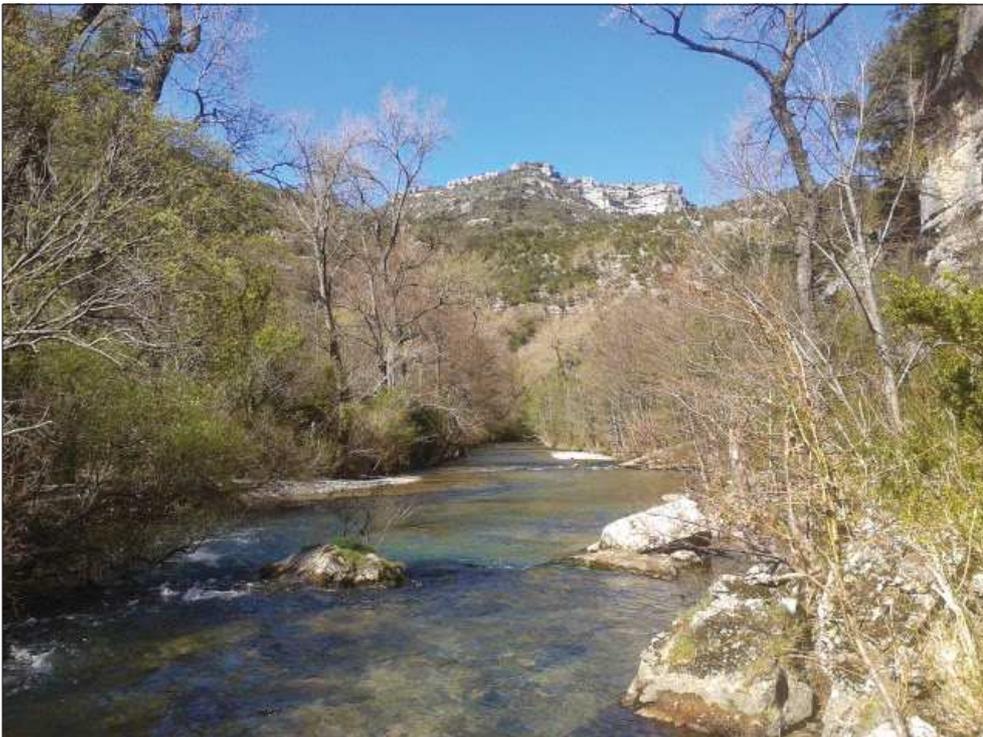


Photo 7. The River Vis, Hérault basin. (April 2015)



Photo 8. Vineyard irrigation in Pouzols. (July 2012)



Photo 2.9. The Gignac Canal going through the town of Aniane illustrates the local territorial dynamics, with growing (indoor and outdoor) municipal water uses in a traditionally agricultural area.

The Hérault and the Ebro basins already face challenges in managing water resources and demand. In both basins, hot dry conditions in summer lead to a peak in irrigation water demand associated with low flows. Since the 1970s, the population has doubled in the Hérault and irrigated areas have increased by 30% in the Ebro. Increasing demand and drier conditions have led to water shortage events in both basins. The EU Water Framework Directive (EC, 2000), which applies to both basins, has also been the source of new requirements through the regulation of environmental flows. A reflection on adaptation to climate change has been engaged in both study areas. The Rhone Mediterranean Corsica Water Agency designed an adaptation plan (AERMC, 2014a), in which balancing water availability and demand under climate change is a central issue. In the Ebro basin several measures to help reduce the basin's vulnerability to expected climate change were included in the Basin Hydrological Plan 2010–2015 (García-Vera, 2013).

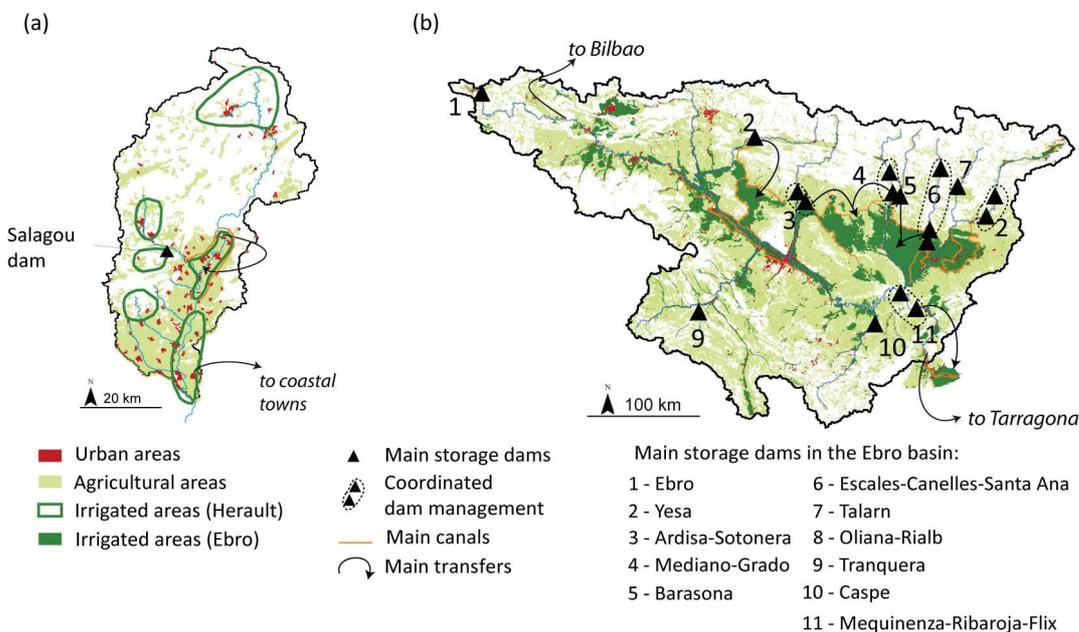


Figure 2.4. Location of the main human pressures on water resources (urban and agricultural areas, main storage dams and water transfers) in (a) the Hérault basin and (b) the Ebro basin.

6. Conclusion: comparing two contrasted basins for methodological and applied purposes

The studies of the Hérault and the Ebro basins will first be compared for methodological purposes. The integrated modeling framework presented in this thesis was developed in two contrasting basins to question the generic nature of integrated models. The modeling chain was developed in different contexts, be it by the type of available data or the basin's characteristics. The Hérault and Ebro hydrosystems differ in their water management stakes and systems. For instance, modeling the Ebro basin implies accounting for both a complex, real-time operations system, and long-term planning considerations. The conceptual representation of this hydrosystem for its modeling was driven mainly by the existence of large irrigation systems and by streamflow regulations by storage dams

and canals. Water resource management in the Hérault basin is less centralized than in the Ebro basin, and withdrawals are more diffuse and water uses more diversified. Some specific management stakes need to be represented in the Hérault hydrosystem, such as the integration of touristic water use and strong environmental requirements.

The comparative analysis of the Hérault and the Ebro basins will focus on results of the assessment of past and future changes in the balance between water availability and demand. The differences or similarities in the drivers of water stress in both basins will be analyzed. Could the differences be due to contrasts in hydro-climatic conditions, levels of equipment and infrastructure development, or to the volume or diversity of water demands? Are the water management systems and storage and regulation capacities of the basin determinant elements in the ability of a hydrosystem to face uncertain climate changes? Are certain water uses more vulnerable than others? Water demand in the Ebro basin is dominantly linked to the irrigation of annual crops, while water demand in the Hérault basin is mostly linked to long term urban and touristic infrastructures and pluriannual crops (mostly vineyards). Will these differences impact the vulnerability and resilience of the studied hydrosystems to climate change?

The results of the work on the Hérault and the Ebro basins will be presented and compared throughout the manuscript. The discussion will strive to bring answers to the questions of model transferability and drivers of vulnerability.

Chapter 3.

Simulating past changes in the balance between water demand and availability¹

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¹This chapter is based on the following paper published in Hydrological Earth Systems Sciences: Fabre, J., Ruelland, D., Dezetter, A., Grouillet, B. Simulating past changes in the balance between water demand and availability and assessing their main drivers at the river basin scale. *Hydrol. Earth Syst. Sci.* 19:1263-1285, 2015.

1. Introduction

The literature review showed the need to better understand the drivers and dynamics of the balance between water uses and availability in river basins, i.e. at the scale of water management plans. Understanding the linkages between the different drivers of water stress in the past is necessary to design efficient adaptation to future climatic and anthropogenic changes. A number of methodological issues were identified in Chapter 1, including the integration of climatic and anthropogenic dynamics, the correct representation of the influence of water use on streamflow, and the need to validate models over a long past period including significant hydro-climatic and water use variability.

Thus this chapter aims to: (i) combine human and hydro-climatic data in an integrative modeling framework to represent water stress and its spatial and temporal dynamics over a past multi-decadal period; and (ii) use this framework and appropriate indicators to analyze past changes in the water balance and assess the sustainability of current water uses.

First the conceptual representation of the water balance and the development of a model to simulate the balance between water availability and demand are presented, as well as the protocol used to calibrate and validate the modeling chain. The results section analyzes the efficiency of the modeling chain and the causes of past changes in observed streamflow. Finally the changes in the balance between water availability and demand over the past 40 years are examined.

2. Method

2.1. Modeling approach used to assess the balance between water demand and availability

2.1.1. Integrative modeling framework

A modeling framework including hydro-climatic and anthropogenic dynamics and accounting for linkages between water resources and water demand at a 10-day time step was designed (Fig. 3.1). Climatic variability affects natural streamflow and water demand (mainly through crop irrigation requirements), while human activities affect water demand through population growth, industrial activity, irrigated areas and the types of irrigated crops, and the efficiency of the water supply networks. Water demand is 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. Anthropogenic drivers of water balance include local water management rules through the operation of dams and canals, which affect water availability. These climatic and anthropogenic drivers were distributed and combined dynamically in space and over time to evaluate changes in water stress.

At each demand node, water demand is compared to water availability (based on streamflow and reservoir levels). If water availability is equal to or higher than water demand, then water withdrawals are equal to water demand for all types of demand. If

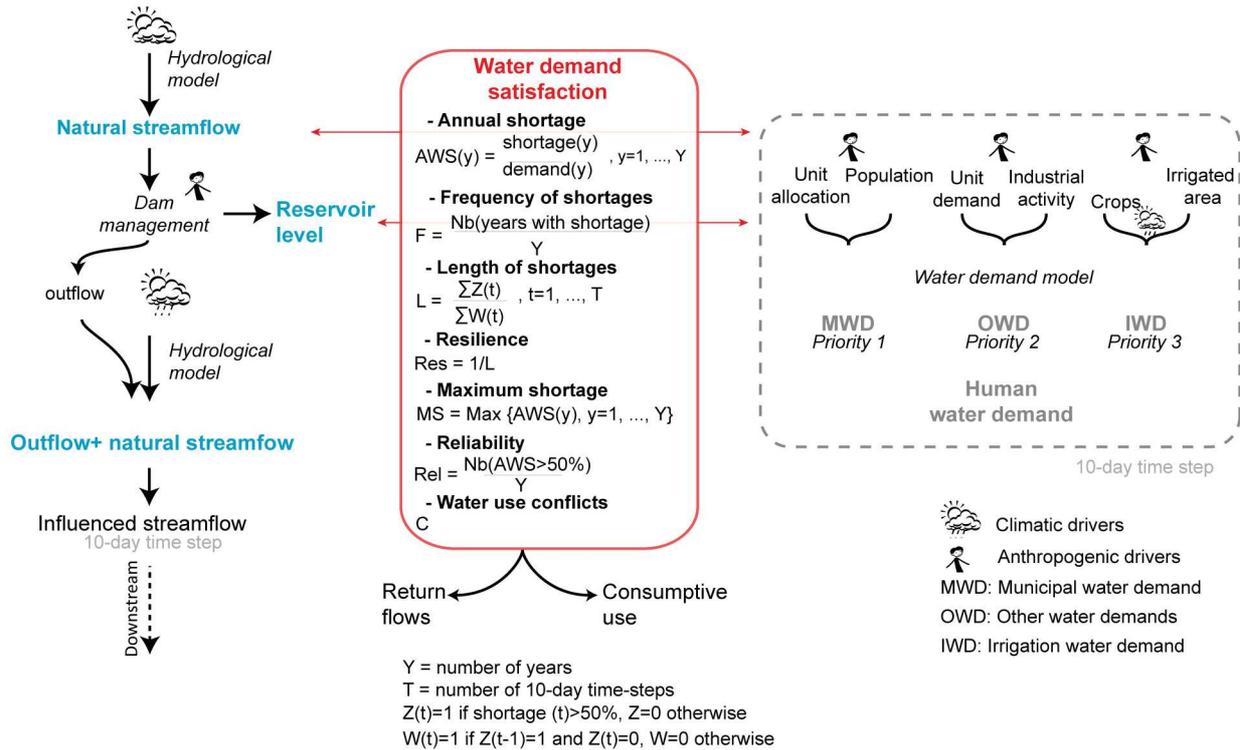


Figure 3.1. General framework for the integrative modeling chain developed and applied to the Herault and the Ebro basins at a 10-day time step over the 1971–2009 period. Water demand and natural streamflow were simulated based on climatic and anthropogenic drivers. Anthropogenic influence on streamflow was assessed through the simulation of demand-driven dam management and consumptive use. Water stress was assessed by comparing demand to availability and characterized through the use of indicators.

water availability is lower than water demand, then restrictions are applied to limit withdrawals. According to the order of priority defined locally, restrictions are first applied to irrigation water demand (IWD), then to industrial and energy water demands (other water demands, OWD), and lastly to municipal water demand (MWD). Water shortage is calculated through the difference between water demand and effective water withdrawal. Only a part of the water withdrawn is actually used, the rest is considered to return to the sub-basin outlet as return flow. The quantification of consumptive use and return flows is explained in section 3.3.2. Natural streamflow is thus modified by dam management, water withdrawals and return flows.

This integrative modeling framework was applied to the 1971–2009 period to capture past variability in climatic and anthropogenic drivers. As described in Chapter 2, this nearly 40-year period includes a wetter and colder decade (1971–1980) and a warmer and drier period (1981–2009). Calibration and validation of the hydrological model was performed over natural streamflow data (see section 3.2.2.), while the simulation of water demand could not be thoroughly validated for lack of data. The simulation of influenced streamflow was validated against observed streamflow data at each resource node (see section 3.3.2.).

2.1.2. Conceptual representation of water demand and water availability nodes

The spatial distribution of water demand and availability was mapped to correctly reproduce the spatial heterogeneity of water shortage in each study area: water stress assessments can vary depending on their spatial or temporal scale (Boithias et al., 2014). Thus it is essential to properly account for the main heterogeneities in water demand and availability. Each basin was divided into sub-basins accounting for the water supply to one or more demand nodes. The Herault basin was divided into six sections and the Ebro into 20 (Fig. 3.2).

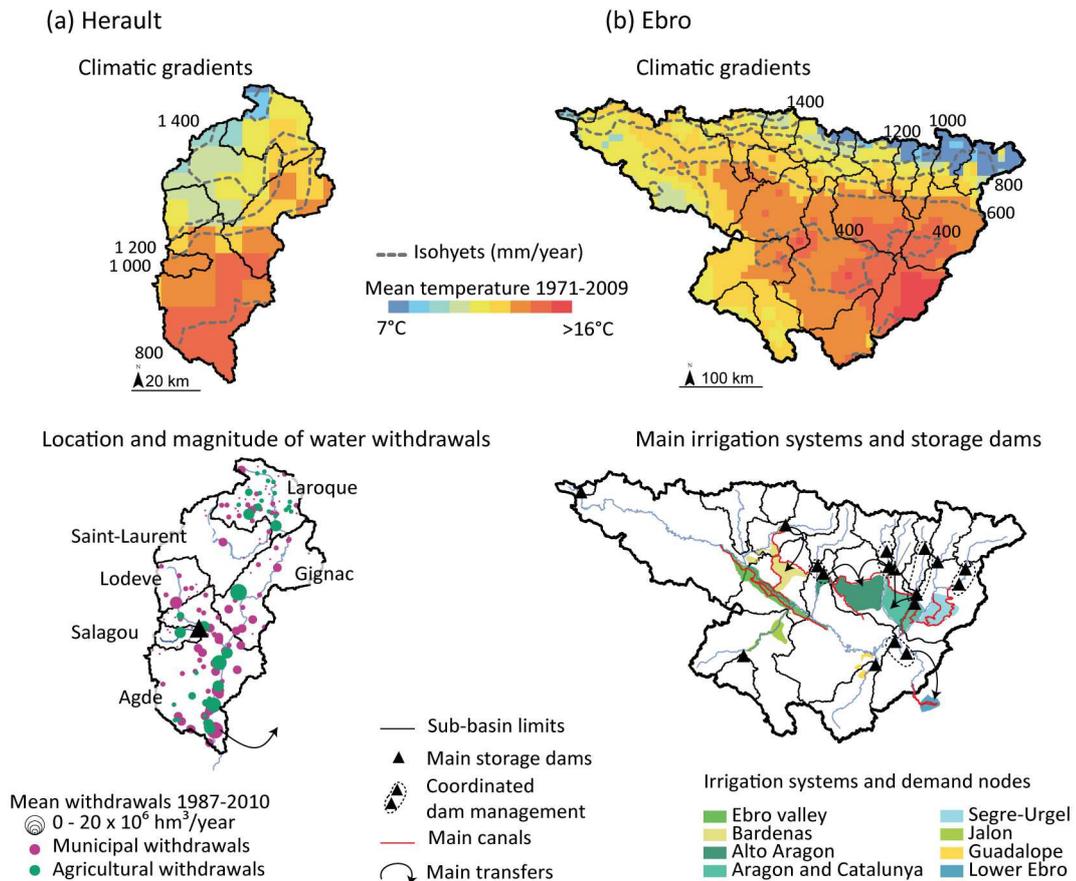


Figure 3.2. Maps of the main physical and human spatial characteristics of the two basins: (a) 6 sections were selected for simulation of water resources and water demand nodes in the Herault basin; (b) 20 sections for simulation of water resources and 8 demand nodes that matched the the main irrigation systems were selected in the Ebro basin.

The map of the Herault hydrosystem (Fig. 3.2a) was based on the work of Collet et al. (2013, 2014). It accounted for the north-south climatic gradient separating the milder wetter upstream catchments from the warmer drier area downstream. Sub-basins were chosen based on their similar water withdrawal characteristics. Water withdrawals are low and mostly agricultural in the Laroque sub-basin, and minimal in the upstream sub-basins of Saint-Laurent and Lodeve. The sub-basin of the Herault at Gignac was delimited to isolate the Gignac canal and its irrigated areas. The southern section of the Herault basin (Agde) has both the highest municipal withdrawals in the basin and a high level of irrigation water demand.

Mapping the Ebro hydrosystem was mainly guided by the existence of extensive irrigation systems managed in association with large storage dams (see black triangles in Figure 3.2b). Seventeen storage dams out of the 234 in the basin were selected and grouped into 11 groups of dams for simulations, representing 77% of the basin's total storage capacity. The Pyrenean catchments influenced by a snow melt hydrological regime were selected to accurately represent the corresponding freshwater availability. The two main right bank systems were also selected, as they are representative of the heterogeneous climatic and hydrological conditions in the Ebro basin.

2.2. Simulation of water demand and natural streamflow

2.2.1. Modeling spatial and temporal variations in water demand

Three types of water demand were considered: (i) Municipal water demand (MWD), including domestic water consumption, irrigation of parks and gardens and commercial water use, (ii) Irrigation water demand (IWD) for crop irrigation and (iii) Other water demands (OWD) linked to industrial processes not connected to municipal networks and to power plant cooling systems. Figure 3.3 shows the conceptual framework used to model water demand. Details concerning the reconstruction of past water demand at the sub-basin scale in the Hérault and the Ebro basins between 1971 and 2009 can be found in Grouillet et al. (2015) (see Appendix C).

The MWD of each municipality was assessed by multiplying a unit water allocation per capita by the population at each 10-day time step. Unit water allocations were calculated from available municipal water withdrawal and population data. These allocations depend on the water abstraction rates of urban activities and on the efficiency of water supply networks, and were assumed to remain stable throughout the study period. Annual variations in population over time were taken into account, as were the seasonal dynamics due to summer tourism in the Hérault basin.

IWD was calculated based on irrigated crops, climate conditions and irrigated areas, using the crop coefficient approach described in Allen et al. (1998). In the case of irrigated vineyards in the Hérault basin, the maximum irrigation requirement (MIR) was considered to be the water required to meet 80% of ETC, in accordance with deficit irrigation techniques. Data on readily available water (RAW) were extracted from the European soil database (EC, 2004) and averaged over each sub-basin.

OWD was not taken into account in the Hérault basin because of the very limited industrial activity. In the Ebro Basin, industrial demand was estimated by the CHE (2013) at the municipality scale by assigning water allocation per employee and per year for each industrial sector. Energy demand in the Ebro basin was assumed to correspond to the volume of water evaporated by the open-air cooling system of the nuclear reactors. Hydropower demand was not accounted for in this study as data for the two study areas were scarce. Moreover, in the Hérault basin, the production of hydropower is limited to a few minor turbines, while in the Ebro basin dams are operated primarily to satisfy agricultural water demand.

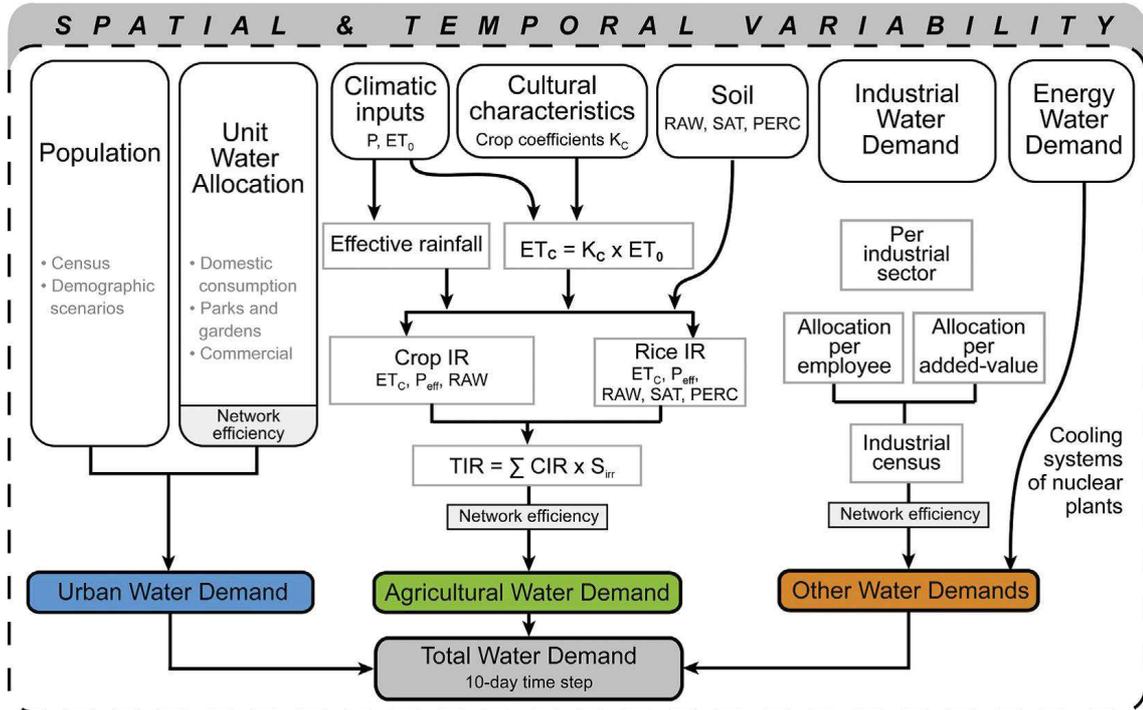


Figure 3.3. Integrative conceptual framework to assess urban, agricultural and other water demands. P: Precipitation, ET_0 : potential evapotranspiration, K_c : crop coefficient, RAW: readily available water, SAT: soil saturation, PERC: soil percolation rate, ET_c : Crop evapotranspiration under standard conditions, P_{eff} : effective rainfall, Crop IR: crop irrigation requirements, Rice IR: rice irrigation requirements, TIR: total irrigation requirements, S_{irr} : irrigated areas. (Grouillet et al., 2015)

2.2.2. Modeling spatial and temporal variations in natural streamflow

Streamflow was modeled in the six sub-basins in the Hérault 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 (see Figure 3.4). The hydrological model relies on precipitation (P) and potential evapotranspiration (ET_0) inputs. It simulates streamflow via a production function (which determines effective precipitation, filling a production reservoir) and a routing function. A snow module based on mean basin temperature (Ruelland et al., 2011, 2014) was added and 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 calibrated using the drier period (1981–2009) and validated using the wetter period (1971–1980). Automatic calibration of the model was performed using a three-step algorithm as described in Dezetter et al. (2014). It combined a random draw of parameter sets and the succession of Rosenbrock and simplex algorithms aimed at minimizing a multi-objective function (*Fagg*) aggregating three goodness-of-fit criteria: the Nash-Sutcliffe efficiency index (NSE), the cumulative volume error (VE) and the mean annual volume error (VEM). NSE values were considered good when they were above 0.65, satisfactory when between 0.5 and 0.65, and poor when they were under 0.5.

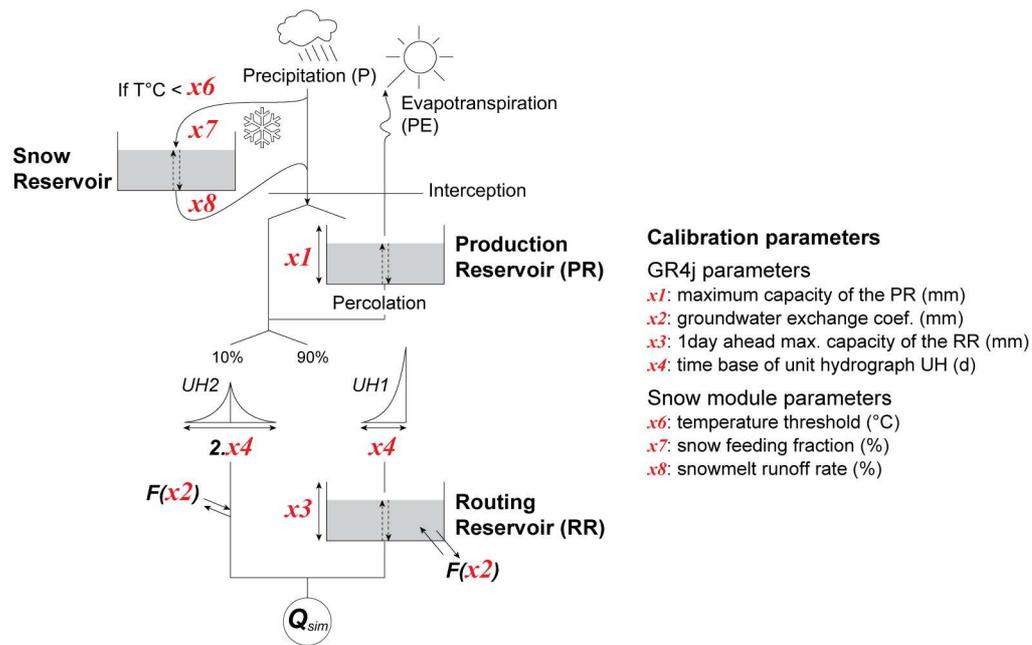


Figure 3.4. Conceptual hydrological model GR4j (Perrin et al., 2003) with an optional snow reservoir (adapted from Ruelland et al., 2014).

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. Withdrawals upstream from the Pyrenean dams were considered to be negligible, so all streamflow data were used for calibration. Data on discharge entering the dams were not directly available, so streamflow upstream from the dams was computed based on a balance between inflows, variations in the reservoir level, outflows, and evaporation. Runoff produced in each downstream sub-basin was computed at a 10-day time step by subtracting the ingoing streamflow from the streamflow at the outlet of the section. However these downstream sections are also strongly influenced by water withdrawals, and natural streamflow could not be calculated based on observed streamflow and water withdrawal data because withdrawal data were not available with the adequate time step and time depth. Thus assumptions had to be made in order to evaluate when streamflow was natural, i.e. not modified by consumptive use.

Since IWD was considered to have the highest consumptive use, it was assumed that when negligible IWD was simulated, then consumptive use was negligible and flows were considered natural. Thus the time steps for which simulated agricultural demand was greater than $0.1 \text{ hm}^3/10\text{-days}$ were not used to calculate the goodness-of-fit criteria. In the downstream sections, the 10-day periods left out of the calibration data correspond to low-flow periods. Consequently, the calibration did not include the effect of withdrawals and consumptive use, which are most relevant under low flow conditions. The simulation of streamflow influenced by reservoir operations and consumptive use was validated against observed data in a later step (see section 3.3.2).

2.3. Comparing resource and demand considering water management rules

2.3.1. Modeling dam management

Accurate simulation of dam management is essential for simulations of water availability in highly equipped hydrosystems. A demand-driven dam management model adapted from Fujihara et al. (2008) was set up and applied to the Salagou dam in the Hérault basin and to 11 major dams or groups of dams in the Ebro basin (see Fig. 3.2). The model outputs were the reservoir level, the volume of water released into associated canals (if applicable) and into the river downstream from the dam during each 10-day time step. In the Ebro basin, reservoirs managed for the supply of irrigation systems are managed with target and minimum levels. In most cases target levels vary throughout the year and the minimum level is fixed and corresponds to a safety reserve or the level of a canal inlet. Water is released to satisfy the demand as long as the reservoir level is above the minimum level. These basic management rules were used to design the dam management model.

As shown in Figure 3.5, the water balance of the reservoir was computed at each 10-day time step, accounting for water demand, entering streamflow, evaporation, and the initial reservoir level. Infiltration was not included in the water balance. Precipitation and evaporation on the reservoirs were computed by averaging the P and ET_0 grid data over the surface of the reservoirs, available through GIS maps. Evaporation was then computed by multiplying ET_0 by a coefficient K_c , recommended by Allen et al. (1998) for open water in a temperate climate. The rules guiding water release from the dams were the following: (i) after adding entering flows ($V_{in} + PR$) and subtracting evaporation from the initial reservoir level, water can be released to satisfy demand and/or minimum flow requirements as long as the reservoir level remains above the defined minimum level R_{min} ; (ii) if the reservoir exceeds the target level R_{tar} , additional water is released from the dam into the river downstream.

Target levels were defined for each 10-day time step according to maximum observed levels over a given time period in which the dam operation rules were similar. Changes in dam operation rules were accounted for throughout the study period. Data on the reservoir level of the Ebro dam, for example, revealed a change in reservoir level variability after 1980, so target levels were defined separately for the periods 1971–1980 and 1981–2009. Minimum levels were provided by the stakeholders in charge of dam operations or, if the information was not available, were defined as the minimum level observed over the studied period. The minimum levels of the reservoirs are kept as a safety reserve for a particular water use (e.g. 100 hm³ in the Ebro dam are kept as a safety water supply to the city of Zaragoza) or to maintain reservoir levels above the elevation of a canal inlet (e.g. elevation of the Aragon and Catalunya canal inlet in the Barasona dam). In the case of the Salagou dam in the Hérault basin, a minimum elevation of 137 m a.s.l. is maintained to enable tourist recreational activities on the lake.

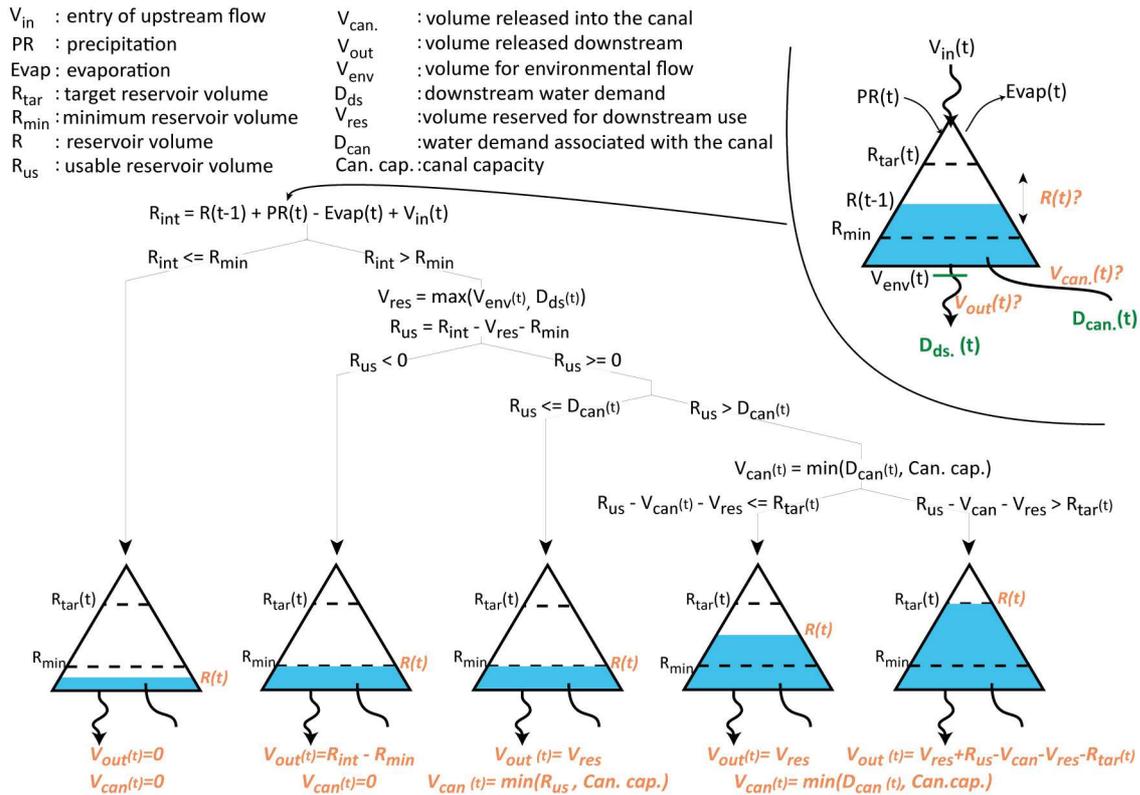


Figure 3.5. Demand driven dam management model. The reservoir level (R) and volumes released downstream (V_{out}) and into the canal (V_{canal} , if applicable) were calculated at a 10-day time step t .

Because dam management rules are driven by the demand associated with each individual dam, simulation of dam operations is highly dependent on the accurate mapping of resources and demand. In the Hérault basin, the Salagou dam supplies water for irrigation in a clearly delimited area (Fig. 2.4a and Fig. 3.2a). In the Ebro basin, dam operation rules are much more complex. Three types of dams can be distinguished according to their type of management:

- Some dams, including the Ebro dam, release water into the river for downstream users. The volume of water released depends on the associated demand and on the runoff produced between the dam and the users (i.e. between the outlet of the Ebro dam and the beginning of the Lodosa canal in the Ebro system).
- In other cases, a canal is directly associated with the dam (e.g. the Bardenas canal and Yesa dam) and transports water from the reservoir to irrigated areas that may be located in a different sub-basin. The volume of water released from the dam depends on the demand associated with the canal and on the capacity of the canal. This type of dam also releases water directly in the river for downstream users or to respect minimum flows.
- Last, the management of two or more dams may be coordinated to supply a particular irrigation system. The dams may be located on the same river and regulate flows from upstream to downstream (e.g. the Escales, Canelles and Santa Ana dams on the Noguera Ribagorçana River or the Mediano and Grado dams on the Cinca River, see Fig. 2.4b), in which case they were simulated as if they were one

large dam located downstream. Two dams located in different sub-basins can also be operated jointly: if the total volume of water demand cannot be met by the first dam, it can be supplemented by the second. This is the case of two systems in the Ebro basin modeled in this study: the Alto Aragon and the Aragon and Catalunya areas (Fig. 2.4b and Fig. 3.2b).

2.3.2. Modeling the influence of water uses on streamflow

At each time step, water withdrawals were evaluated according to water availability, simulated water demand, and the following order of priority: (i) MWD (ii) OWD and (iii) IWD. Return flows were also taken into account. For each type of water demand, a part of the water withdrawn was considered to return to the environment and, *in fine*, to the streamflow at the outlet of the sub-basin in which the water was pumped (see Figure 3.6).

- For MWD, two types of return flows were considered. First, 80% of the volume actually supplied to domestic and more generally urban users was considered to return to the sub-basin outlet as treated effluent. The volume actually supplied was calculated by subtracting losses from the supply network from withdrawals. Second, part of the losses from supply networks was considered to return to the sub-basin outlet.
- For OWD, 80% of withdrawn water was considered to return to the sub-basin outlet.
- For IWD, only part of the losses from supply networks was considered to return to the sub-basin outlet. All the water actually available for crop irrigation was considered to be used by the crops (i.e. consumptive use).

The return flow rate from losses from municipal and irrigation supply networks (α in Figure 3.6) was estimated for the Herault basin as a whole and for each sub-basin of the Ebro basin, to account for soil and geological heterogeneities. Return flow rates were tested from 0 to 1 with a step of 0.1 and were calibrated by optimizing goodness-of-fit criteria including NSE on low flows (July to September included), noted NSE_{LF} , on influenced streamflow. The calculation of these criteria also allowed the whole run of the integrative model to be validated. Therefore, although the hydrological model was not calibrated over low flows (see section 3.2.2), the simulations of influenced streamflow, including over low flows, were validated.

2.3.3. Indicators of balance between water demand and availability

First, anthropogenic and climatic pressures on water resources were assessed. Anthropogenic impacts on streamflow, i.e. consumptive use, were estimated as the difference between simulated natural and modified streamflow. The part of natural streamflow and anthropogenic consumptive use variations in the cause of the observed streamflow decrease (see Chapter 2 section 3) was evaluated by comparing variations in simulated natural and influenced streamflow.

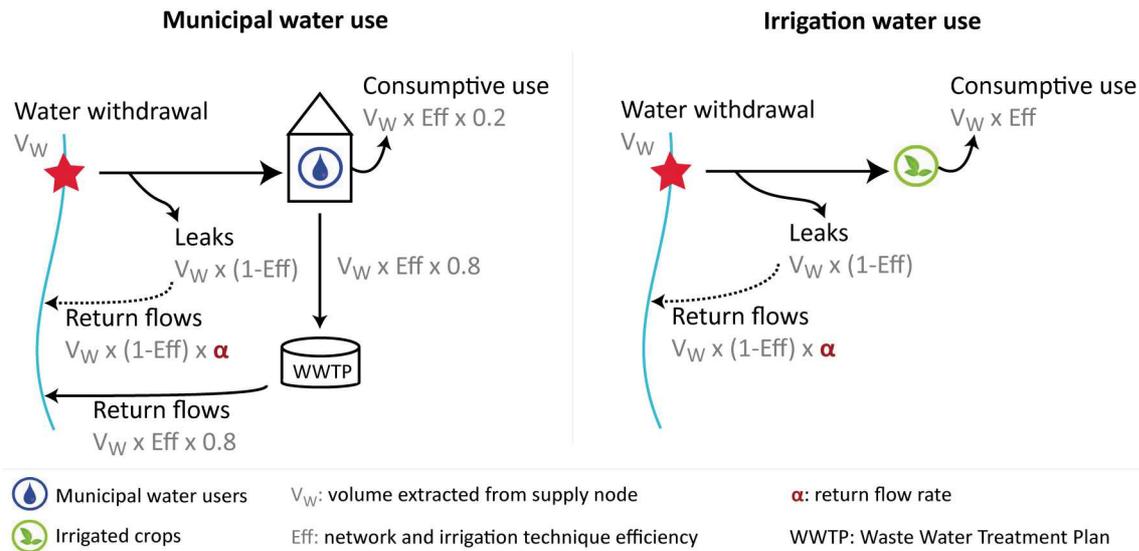


Figure 3.6. Water withdrawals, efficiency, losses, consumptive use and return flows for municipal and irrigation water uses as simulated in the modeling chain. The return flow rates α were estimated for the Hérault basin as a whole and for each sub-basin of the Ebro basin. Return flow rates were tested from 0 to 1 with a step of 0.1 and were calibrated by optimizing goodness-of-fit criteria on influenced streamflow.

Second, water shortages for each type of demand were characterized by the magnitude, frequency, and average length of withdrawal restrictions (see Figure 3.1). These indicators were calculated for each demand node considering hydro-climatic and socio-economic variability between 1971 and 2009. The percentage of water demand that could not be satisfied due to lack of available water was computed for each type of demand at a 10-day time step. According to the local stakeholders, withdrawal restrictions were acceptable as long as they did not exceed 50% of IWD and 5% of MWD. Water shortage analysis concentrated mostly on irrigation water demand since it was last in order of priority (Fig. 3.1). The frequency of withdrawal restrictions (F) was expressed by the number of years out of five including at least one time-step in which restrictions on irrigation water withdrawals exceeded 50% of the demand. The average length of a water shortage (L) was represented by the average number of consecutive time steps with restrictions exceeding 50% of the demand. Years with municipal water shortage exceeding 5% of the demand during at least one 10-day time step were also identified. These years corresponded to critical situations in which withdrawal restrictions also applied to non-agricultural users, pointing to potential water sharing conflicts (C). When restrictions are applied to municipal water withdrawals, this means that all three types of demands face water shortage.

Last, the current sensitivity of the two basins to water stress was evaluated using the calibrated framework: water demand corresponding to the size of the population, the irrigated areas, and industrial activity in the year 2009 was compared to water availability under the prevailing hydro-climatic conditions in the period 1971–2009, using the dam management rules applied in 2009. The climatic conditions of the period 1971–2009 were considered to represent the variability of the present climate. Five indicators (see Figure 3.1) were computed at each demand node to characterize the balance between

water uses and water availability in the Herault and Ebro basins with their current human activities and water management practices, and faced with the climate variability of the recent past. Maximum shortage (MS) was defined as the maximum simulated annual irrigation water shortage rate and reliability (Rel) was considered to be the rate of occurrence of satisfactory years (adapted from Asefa et al., 2014), i.e. years with an annual irrigation water shortage below 50%. Shortage frequency (F) indicates the frequency of occurrence of irrigation water withdrawal restrictions of more than 50% at a 10-day time step, and resilience (Res), computed as the inverse of the average length of withdrawal restrictions, shows how quickly withdrawal restrictions were lifted. Resilience ranges from 0 to 1, a value of 0.5 indicating for example that restrictions were lifted after two time steps on average. The definitions of maximum shortage (the maximum annual shortage over the study period, also called “vulnerability” in the literature), reliability (the frequency of years with overall water supply at least at 50% of demand), and resilience (indicating how quickly the system returns into balance, i.e. the inverse of average length of shortage episodes) were based on the metrics used in the literature to evaluate the performance of water supply systems (Hashimoto et al., 1982; Fowler et al., 2003). The final indicator was the frequency of occurrence of water sharing conflicts (C). As stated above, the years with an occurrence of water sharing conflicts were considered to be the years with urban water shortage exceeding 5% of the demand during at least one 10-day time step. For each indicator, an acceptable range of values was defined according to management criteria in the local basin agencies.

3. Results

3.1. Efficiency of the modeling chain

3.1.1. Simulation of natural streamflow

Calibration and validation results for the simulation of natural streamflow are presented in Table 3.1. The sub-basins of the Ebro in which the snowmelt module was activated are indicated in gray. Overall, the results were satisfactory except for some downstream sections in which discharge was significantly modified and few calibration data were consequently available on natural streamflow. However, the sub-basins where the model performed poorly generally produced only a small proportion of total discharge. In the Herault basin NSE values were over 0.80 and volume error (VE) was negligible over the calibration period in all sub-basins except in the Agde section. In the upstream Saint-Laurent and Laroque sub-basins, NSE values over the validation period were slightly lower (0.79 and 0.72 respectively), and volume errors tended to increase slightly. The lack of observed streamflow in the 1970s in the Gignac, Salagou and Agde sub-basins prevented validation of natural streamflow simulations in these areas.

The simulated natural streamflow in the Ebro basin were in good agreement with observed streamflow in the sub-basins that contribute most to discharge at the outlet, i.e. the Pyrenean sub-basins and the Ebro upstream from the Aragon River (sub-basin 2 in Table 3.1). In these sub-basins, NSE values were above 0.60 and VEM and absolute values of VE were below 18% over the calibration and validation periods, with the exception of the Noguera Ribagorzana sub-basin upstream from the Santa-Ana dam (sub-basin 9). In this sub-basin the three dams (Escales, Canelles and Santa Ana) were simulated as one large

dam in the location of Santa Ana (see section 3.3.1), thus multiplying possible errors in the calculation of the natural discharge at Santa Ana. In sub-basins 13, 14 and 20 (Ebro at Zaragoza, Mequinenza and Tortosa, see Table 3.1) results indicated poor calibration and validation scores. This can be explained by the high level of influence of withdrawals on streamflow, leaving very few data for calibration. The simulation of natural streamflow in these three sub-basins of the semi-arid Ebro valley was thus considered to be unreliable. However, the climatic and topographic conditions of the middle and lower Ebro valley suggest that the contribution of these areas to total discharge is minor. For the rest of the study, the contributions of sub-basins 13, 14 and 20 to the natural discharge of the Ebro River were set to zero.

Table 3.1. Calibration and validation results of the simulation of natural streamflow in the Hérault and the Ebro basins. Optimal values of NSE, VE and VEM are 1, 0 and 0 respectively.

| | | Calibration | | | Validation | | | Simulated annual streamflow (m ³ /s) |
|-------------------------------------------------------------------------------------|-----------------------|-------------|------|-----|------------|------|------|-------------------------------------------------|
| | | NSE | VE | VEM | NSE | VE | VEM | 1971-2009 |
| Hérault | | | | | | | | |
|  | 1.Vis at St-Laurent | 0.88 | 0% | 11% | 0.79 | 19% | 16% | 10 |
| | 2.Hérault at Laroque | 0.80 | 0% | 21% | 0.72 | -15% | 22% | 9 |
| | 3.Hérault at Gignac | 0.83 | 0% | 19% | NA | NA | NA | 8 |
| | 4.Lergue at Lodeve | 0.84 | 0% | 26% | 0.94 | -5% | 9% | 4 |
| | 5.Salagou | 0.95 | 0% | 6% | NA | NA | NA | 1 |
| | 6.Hérault at Agde | 0.34 | 0% | 60% | NA | NA | NA | 11 |
| Ebro | | | | | | | | |
|  | 1.Ebro at Arroyo | 0.83 | 0% | 8% | 0.73 | -13% | 12% | 10 |
| | 2.Ebro at Castejon | 0.76 | 0% | 5% | 0.64 | -10% | 10% | 123 |
| | 3.Arga | 0.82 | 0% | 9% | 0.72 | -11% | 18% | 38 |
| | 4.Irati at Liedena | 0.85 | 0% | 9% | 0.87 | 0% | 7% | 29 |
| | 5.Aragon at Yesa | 0.83 | 0% | 7% | 0.78 | -15% | 15% | 38 |
| | 6.Gallego at Ardisa | 0.73 | 0% | 12% | 0.62 | -2% | 12% | 25 |
| | 7.Cinca at Grado | 0.80 | 0% | 5% | 0.83 | 3% | 4% | 42 |
| | 8.Esera | 0.71 | 0% | 7% | 0.67 | -6% | 7% | 21 |
| | 9.Noguera Ribagorzana | 0.34 | 0% | 10% | 0.57 | -6% | 28% | 20 |
| | 10.Noguera Pallaresa | 0.66 | 0% | 12% | 0.72 | -13% | 14% | 31 |
| | 11.Segre at Oliana | 0.73 | 0% | 11% | 0.72 | -17% | 17% | 26 |
| | 12.Aragon at Caparros | 0.39 | 0% | 20% | 0.16 | -46% | 44% | 6 |
| | 13.Ebro at Zaragoza | 0.13 | 0% | 21% | -1.55 | 25% | 2% | 28 |
| | 14.Ebro at Mequinenza | 0.02 | 0% | 5% | -1.15 | 5% | 0% | 13 |
| | 15.Cinca at Fraga | 0.61 | 0% | 3% | 0.18 | -53% | 18% | 13 |
| | 16.Segre at Seros | 0.30 | -20% | 60% | 0.13 | -24% | 51% | 11 |
| | 17.Piedra | 0.62 | 0% | 9% | 0.16 | -12% | 16% | 3 |
| | 18.Jalon en Grisen | 0.76 | 0% | 24% | -0.91 | -52% | 10% | 4 |
| | 19.Guadalope | 0.71 | 0% | 43% | NA | NA | NA | 2 |
| | 20.Ebro at Tortosa | 0.07 | 0% | 83% | -0.59 | 39% | 124% | 30 |

3.1.2. Simulation of dam management

Figure 3.7 shows the simulated reservoir levels in comparison with observed reservoir levels. Seasonal dam operations were well represented for the majority of dams. Moreover, simulated interannual variations of the reservoir levels were in good agreement with observations (e.g. the Ebro, Sotonera or Tranquera dams). Despite the complexity of their management, the reservoir levels of the Yesa and Grado dams were satisfactorily simulated, with NSE values of 0.68 and 0.56 respectively and mean volume errors of 9% and 8%.

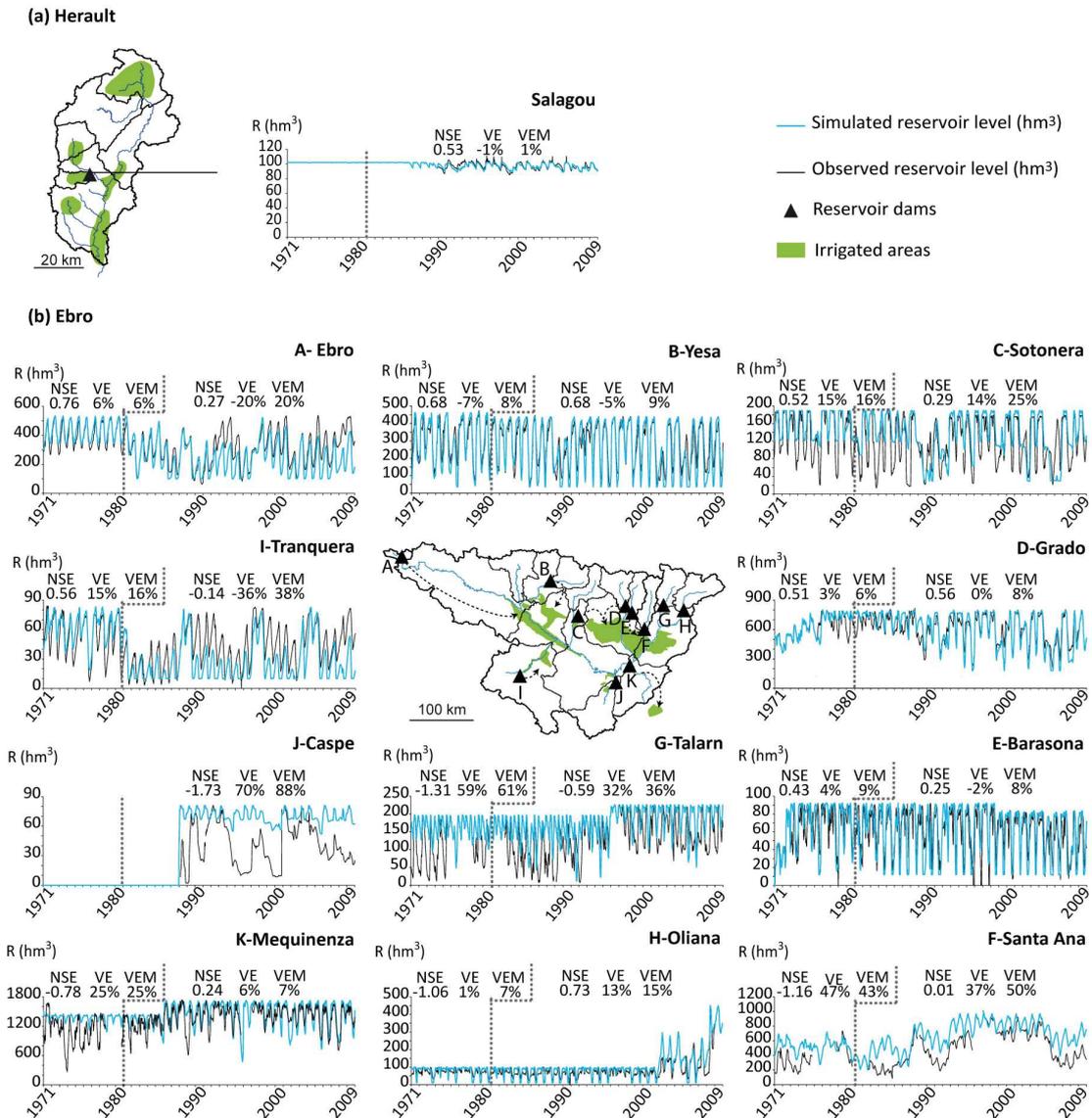


Figure 3.7. Simulated and observed reservoir levels (R) of the main dams in (a) the Herault basin and (b) the Ebro basin. Results for the periods over which simulations of natural streamflow were calibrated (1981–2009) and validated (1971–1980) are marked with a gray dotted line. Optimal values of NSE, VE and VEM are 1, 0 and 0 respectively.

Simulations of the Salagou reservoir level led to scores of 0.53 for NSE and 1% for VEM over the period 1990–2009 (reservoir level data were only available after 1990). As can be seen in figure 3.7a, the reservoir level started showing significant seasonal variations in 1986, which is consistent with the start-up of a hydropower turbine and with increasing water demand for irrigation since the 1990s.

3.1.3. Simulation of influenced streamflow

Influenced streamflow was accurately simulated in the Hérault basin (see Figure 3.8a) with NSE values above 0.80 in all sub-basins for the calibration and validation periods, except at the outlet of the Salagou dam where the outflow was only moderately well simulated by the dam management model. However, the contribution of the Salagou dam to streamflow at the outlet of the basin is very low.

Results at the outlet of the Ebro basin (see Figure 3.8b) showed that the influenced discharge in this complex hydrosystem was well simulated: aggregated simulations at the basin outlet led to NSE and volume error scores of 0.68 and –6% respectively over the calibration period, and of 0.64 and –12% over the validation period. The influenced discharge in the Cinca and Segre systems was poorly reproduced, with NSE values under 0.50 and negative low flow NSE (NSE_{LF} , see section 3.3.2) values over the calibration period. Streamflow in the downstream Segre sub-basin is influenced by outflows from the Santa Ana, Talarn and Oliana dams, which have complex management rules.

The ability to represent observed low flows, which are highly influenced by storage and water withdrawals, is an indicator of the modeling chain's efficiency. Low flows were well simulated at the outlet of the Hérault basin (Hérault at Agde) with NSE_{LF} values of 0.66 and 0.87 over the 1981–2009 and 1971–1980 periods respectively. The low NSE_{LF} values in the Vis at Saint-Laurent and Hérault at Laroque sub-basins over the 1971–1980 period (0.28 and –0.16) respectively, are most likely due to difficulties of the hydrological model to reproduce the functioning of the karstic system in wet periods, as it was calibrated over a drier period. Low flows in some of the Ebro sub-basins were poorly simulated, particularly in the Cinca and Segre sub-basins, where low flows are highly influenced and depend almost exclusively on the outflow from the various storage dams.

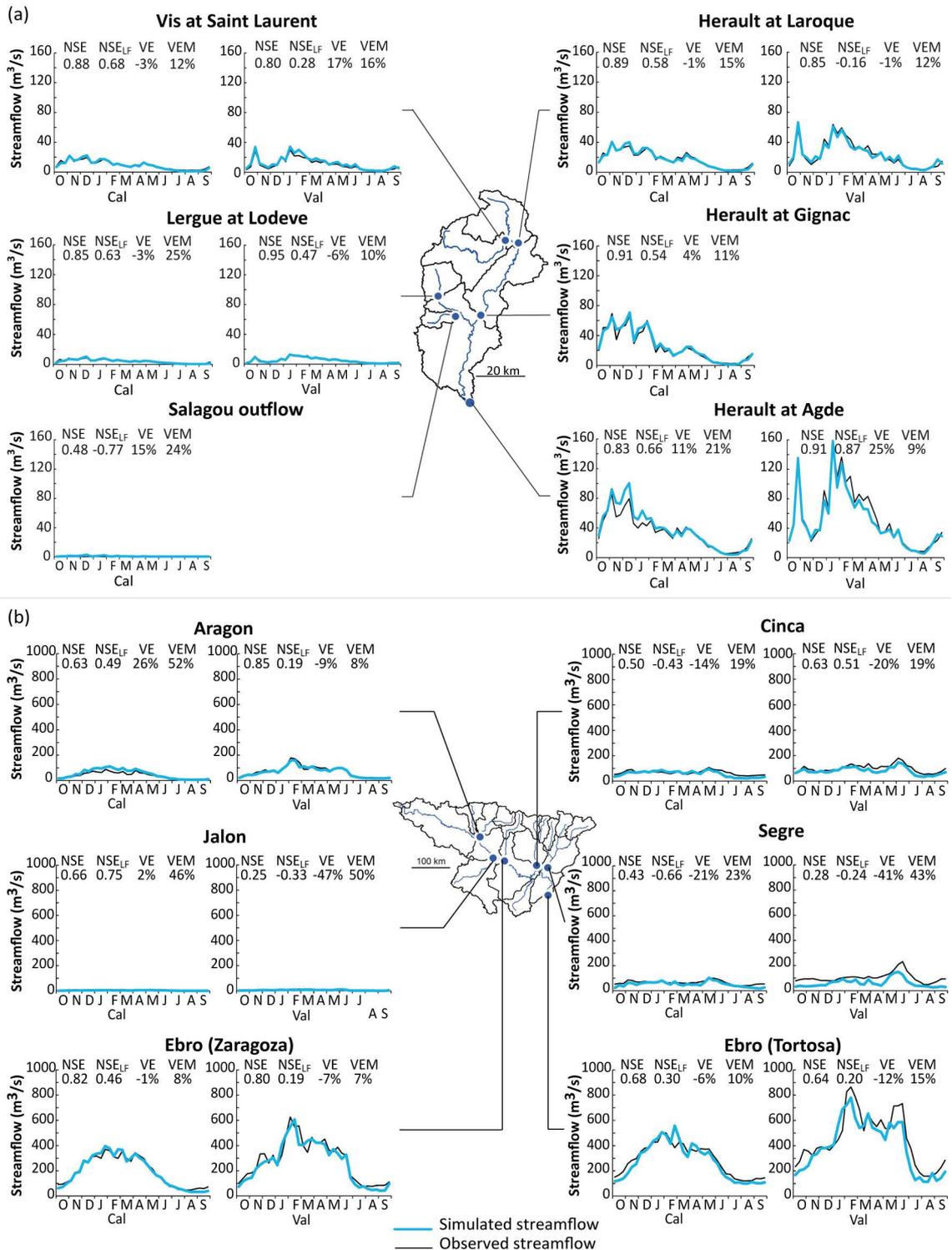


Figure 3.8. Simulation of influenced streamflow in (a) the Herault basin and (b) the Ebro basin from 1971 to 2009: results for the periods over which simulations of natural streamflow were calibrated (Cal: 1981–2009) and validated (Val: 1971–1980). Optimal values of NSE (Nash-Sutcliffe efficiency index), NSE_{LF} (low flow NSE), VE (cumulative volume error), and VEM (mean annual volume error) are 1, 1, 0 and 0 respectively.

3.2. Analysis of the causes of past changes in observed streamflow

3.2.1. Variations in water demand under anthropogenic and climate variability

Total water demand in the Hérault basin doubled between the 1970s (24 hm³/y) and the 2000s (53 hm³/y) mainly because of a significant increase in MWD (from 18 hm³/y in the 1970s to 36 hm³/y in the 2000s over the whole basin), particularly for the Florensac transfer in the Agde section where MWD more than doubled (see Figure 3.10a). Total IWD also increased (from 6 hm³/y to 17 hm³/y between the 1970s and the 2000s) with heterogeneities throughout the basin. In the Laroque upstream section, IWD decreased in the 1990s due to agricultural decline and stabilized in the 2000s. In the other upstream sections, IWD increased significantly, but volumes nevertheless remained very low. The simulated increase in IWD over the Hérault basin is mostly due to warmer and drier conditions from the 1980s on, which led to a threefold increase in IWD in the Gignac area (see Figure 3.10a).

Total demand in the Ebro basin increased from 4 330 hm³/y in the 1970s to 6 820 hm³/y in the 2000s, with the largest increase in the 1970s and the 1980s. As shown in Figure 3.10b, the main increase in IWD occurred in the Bardenas and Alto Aragón irrigation systems (from 400 hm³/y to 880 hm³/y and from 320 hm³/y to 950 hm³/y respectively between the 1970s and the 2000s). In the Ebro valley, Aragón and Catalunya and Segre systems, IWD increased between the 1970s and the 1980s and stabilized (or even slightly decreased in the case of the Ebro valley) after 1990. On the right bank, IWD remained almost unchanged, with a peak in the 1980s in the Jalon sub-basin.

At Agde, the natural streamflow of the Hérault river decreased in the winter, spring and summer (−52%, −30% and −39% respectively) and increased in the fall (+36%). Similar changes were observed in upstream sections, with a bigger decrease in the streamflow in summer at Laroque and Gignac (−47 and −48% respectively). The natural streamflow of the Ebro river at Tortosa also decreased in the winter, spring and summer (−21%, −29% and −23% respectively) and increased slightly (+8%) in the fall. In sub-basins influenced by a snowmelt regime such as the Cinca and Segre catchments, peak flow occurred one month earlier (May instead of June) after 1980, and streamflow decreased in spring and summer.

The changes in natural streamflow simulated in both basins are in agreement with the climatic trends described in section 2.3., i.e. a decrease in winter precipitation and an increase in fall precipitation between 1971–1980 and 1981–2009, associated with a 1 °C increase in annual temperature.

3.2.2. Impact of climatic variability on natural streamflow

Simulated changes in natural streamflow at the outlet of the Hérault and the Ebro basins are illustrated in Figure 3.9. The 1980s and 2000s appear to have been particularly dry compared to the 1970s and the 1990s, mainly in the Hérault basin. In both basins, simulated natural streamflow decreased by approximately 20% between 1971–1980 and 1981–2009.

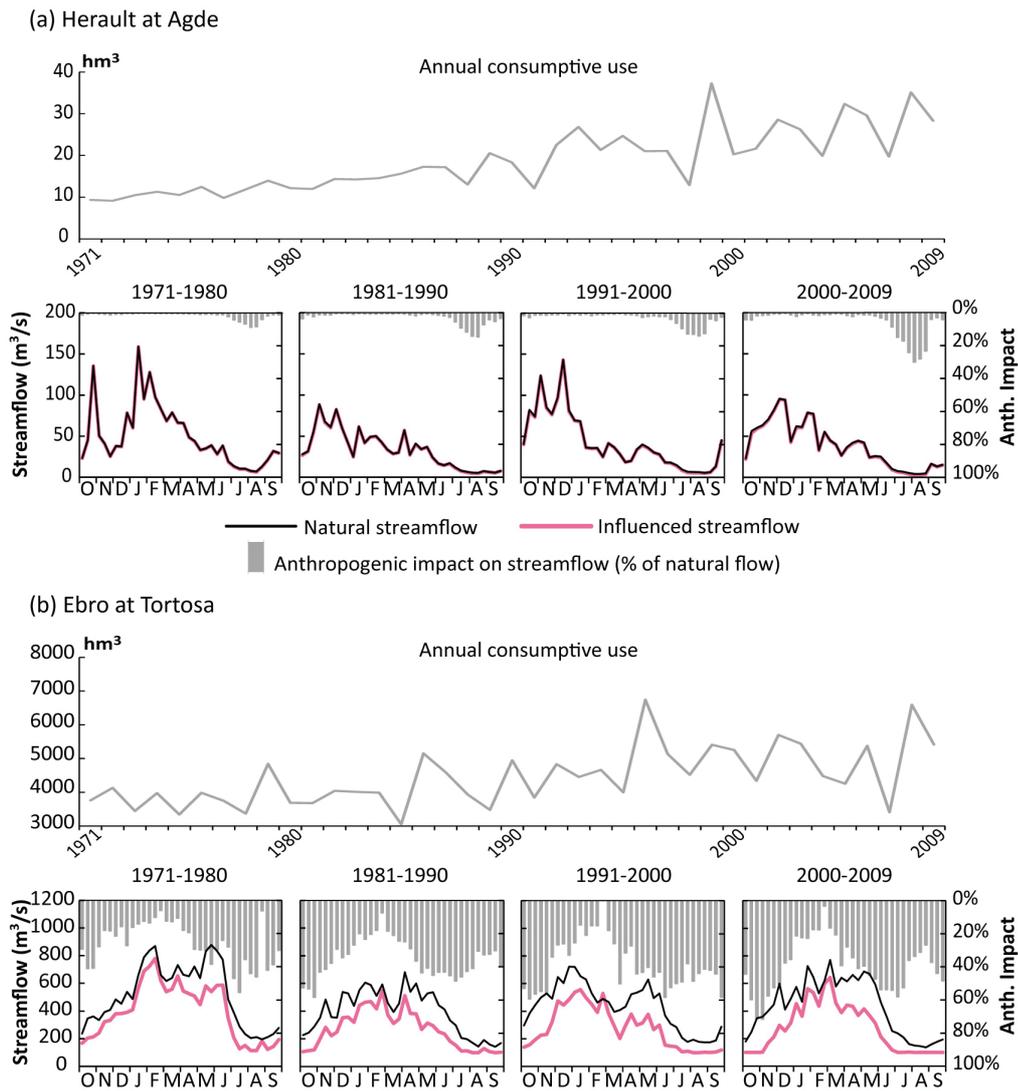


Figure 3.9. Comparison of natural vs. influenced simulated streamflow: anthropogenic impacts (consumptive use and water storage) on (a) the Herault river and on (b) the Ebro river.

3.2.3. Relative impact of anthropogenic and climatic drivers on streamflow

Figure 3.9 also shows that the consumptive use increased between 1971 and 2009 in both basins, in absolute terms and relative to natural streamflow: average annual consumptive use increased from 11 hm³/y (1% of mean annual natural streamflow) in the 1970s to 27 hm³/y (2% of mean annual natural streamflow) in the 2000s in the Herault basin, and from 3 830 hm³/y (24% of mean annual natural streamflow) in the 1970s to 5 000 hm³/y (38% of mean annual natural streamflow) in the 2000s in the Ebro basin. Annual water consumption stabilized in the 2000s in both basins.

In the Herault basin the impact of water use was highest in the summer: it reached 30% of natural flow between mid-July and mid-August in the 2000s (Fig. 3.9a). In the Ebro basin the storage role of reservoirs is clearly visible, with anthropogenic impacts decreasing in July and August, when withdrawals were made from reservoirs (Fig. 3.9b).

Simulating natural and influenced streamflow made it possible to distinguish the impacts of climate and consumptive use variations on streamflow (a decrease in streamflow was observed at the outlet of both basins between 1971–1980 and 1981–2009, see Chapter 2). In the upstream sections of the Herault basin (Saint-Laurent, Laroque and Lodeve, results not shown) the decrease in streamflow between 1971–1980 and 1981–2009 was linked to a natural decrease in streamflow only, whereas in Gignac and Agde, respectively 1% and 3% of the decrease in annual influenced streamflow was linked to an increase in consumptive use. Simulations linked 80% of the decrease in influenced discharge at the outlet of the Ebro basin between 1971–1980 and 1981–2009 to a decrease in natural discharge, and 20% to the increase in consumptive use. These proportions varied throughout the basin: 75–25% in the Aragon sub-basin, 50–50% in the Cinca sub-basin and a decrease in consumptive use in the Segre sub-basin.

3.3. Analysis of the balance between water demand and availability

3.3.1. Simulation of water shortages over the period 1971–2009

Figure 3.10 shows the water shortages simulated between 1971 and 2009 in the Herault and the Ebro basins. Results are only presented for the Gignac and Agde sections of the Herault basin, as they concentrate most of the water uses and simulations did not identify any water shortage in the other sub-basins. Figure 3.10a shows the frequent occurrence of irrigation water shortages in the Gignac area from the 1980s on. Although IWD decreased slightly in the 2000s due to recent efforts to improve the efficiency of the Gignac canal, water shortage events continued to occur three years out of five. In Agde, increasing MWD and IWD continued to be satisfied until the 2000s. Restrictions on irrigation and municipal water withdrawals appeared in 2005, a dry year. These results are consistent with the information provided by local stakeholders on the occurrence of water supply problems in the Herault basin in the past 40 years: the main stakes concerning the supply of irrigation water are concentrated around the Gignac canal, while user conflicts may appear in the downstream area of Agde. The year 2005 was indeed notable for tensions around water resources, with strict regulations concerning the use of water and the release of additional water from the Salagou dam to replenish low flows in the Herault River.

Figure 3.10b shows the results of the simulation of water shortage for the eight main management systems in the Ebro basin. The systems on the right bank are very exposed to water shortage, particularly the Guadalupe sub-basin. Although some irrigation water withdrawal restrictions may have been applied in all areas except the lower Ebro, between 1971 and 2009, only the Ebro valley, Bardenas and Alto Aragon areas faced shortages exceeding 50% of demand. In the case of the Bardenas irrigation system, the increase in water shortage mirrored an increase in water demand. The storage capacity of the Yesa dam is currently being increased by about 600 hm³. In the Alto Aragon system, the Sotonera and Grado dams have been managed together since 1982, which helped improve the balance between water demand and availability despite a significant increase in demand (from 320 hm³/y to 950 hm³/y between the 1970s and the 2000s). However irrigation water shortage periods did occur in the 2000s. The construction of new storage facilities to increase the storage capacity by about 400 hm³ is planned in this area.

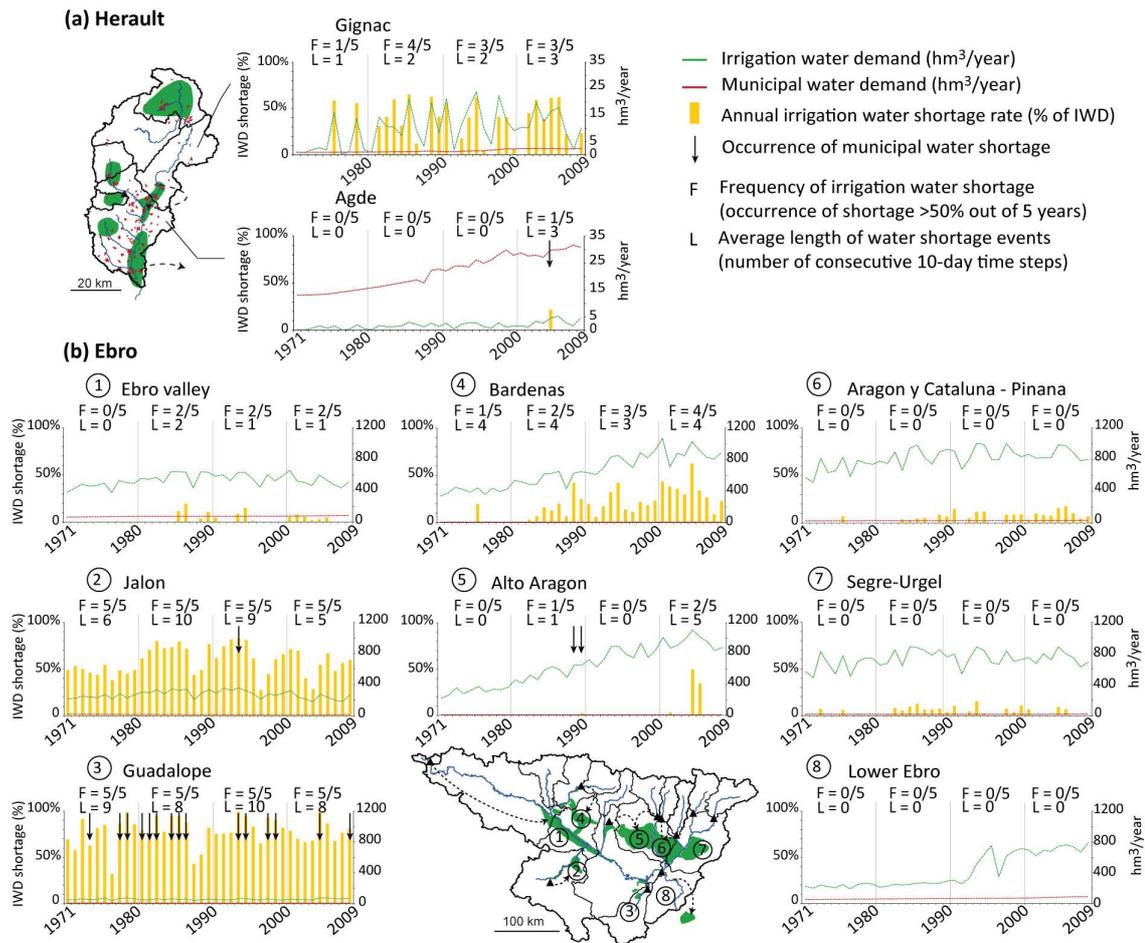


Figure 3.10. Frequency and intensity of irrigation and municipal water shortage in the period 1971–2009 considering the spatial and temporal dynamics of water uses and hydro-climatic conditions (a) in the Herault basin and (b) in the Ebro basin.

3.3.2. Sustainability of current water uses in the hydro-climatic conditions of the recent past (1971–2009)

In the Gignac area of the Herault basin, the impact of the improved efficiency of the canal in the 2000s (see section 2.3) is clear: while IWD reached $13 \text{ hm}^3/\text{y}$ on average and shortages occurred in three years out of five in the 1990s (see Figure 3.10a), IWD would only have been $4 \text{ hm}^3/\text{y}$ with shortages one year out of five on average, with the same irrigated areas and efficiency as today and under the same climate conditions (Fig. 3.11a). However water shortages would have become more frequent and intense with the warmer and drier conditions of the 2000s, owing both to an increase in demand due to increasing evapotranspiration and decreasing precipitation, and to a reduction in available water resources (see Figure 3.9a). Figure 3.12 shows that, on the whole, water use and availability are better balanced in the Herault than in the Ebro hydrosystem. Apart from the Salagou area with a maximum shortage of 70% and resilience of 0.3 and the Agde area with a resilience of 0.3, the indicators remain in an acceptable range in all demand nodes of the Herault basin (see Figure 3.12).

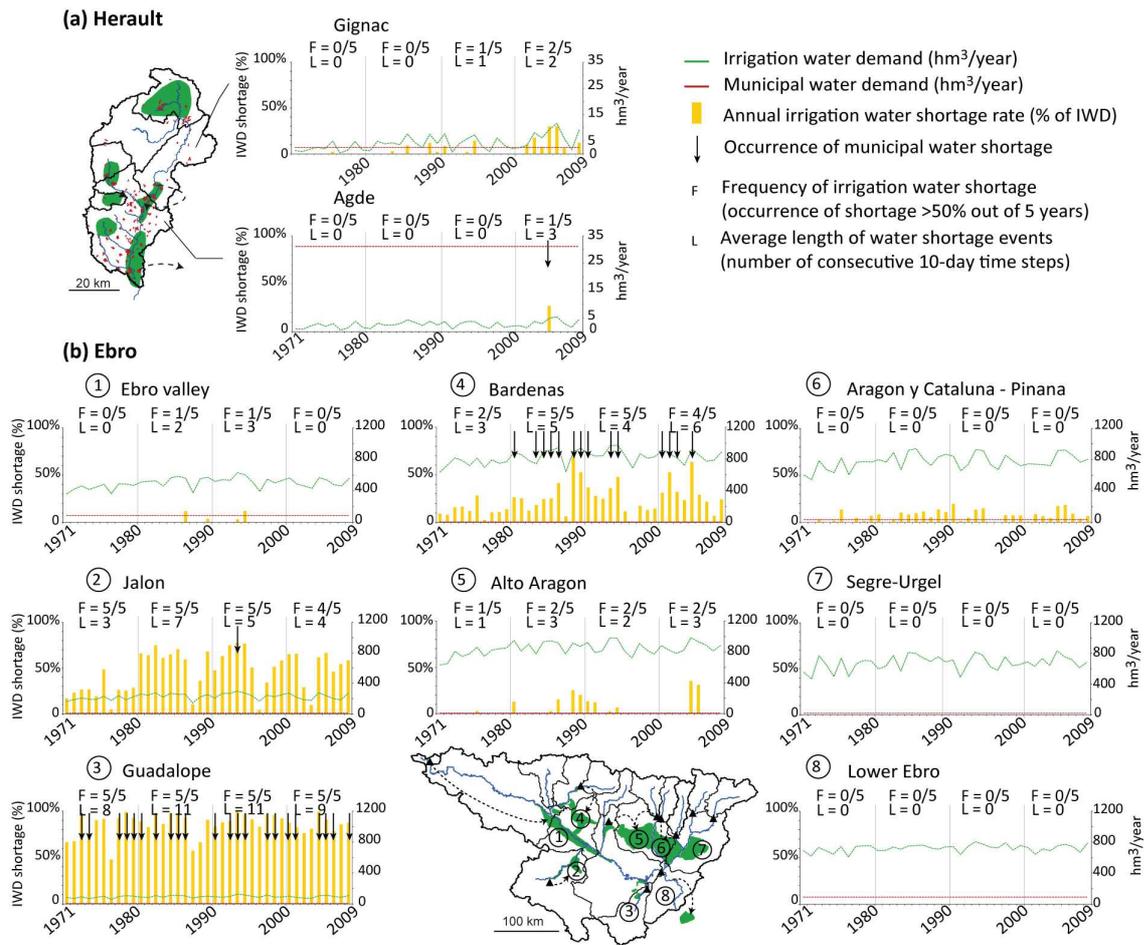


Figure 3.11. Frequency and intensity of irrigation and municipal water shortage under current water uses (2009) and hydro-climatic conditions in the period 1971–2009 (a) in the Hérault basin and (b) in the Ebro basin.

According to the results shown in Figure 3.12, the Aragón and Catalunya, Ebro valley, Segre-Urgel and Lower Ebro sections in the Ebro basin appear to have found a sustainable balance between water use and availability if climatic conditions remain in the range of variability as that observed in the recent past. Comparison of Figure 3.10b and Figure 3.11b shows an improvement in the water balance in the Segre-Urgel irrigation system due to the construction of the Rialb dam in the early 2000s, which was added to the storage capacity of the Oliana dam. The combined operation of the two dams reduces annual irrigation water shortage rates (Fig. 3.11b) compared to the Oliana dam without the additional storage capacity of Rialb (Fig. 3.10b). On the other hand, the expansion of irrigated areas in the Bardenas and Alto Aragón systems appears to have contributed to the increase in water stress revealed in Figure 3.10b. Figure 3.11b shows that the current uses of water in the Bardenas system would not match water availability in the hydro-climatic conditions of the recent past. With its current water use and water management and under unchanged climate variability, in the future, this area could face many long severe shortage events (MS=75% and Res=0.2), even though, generally speaking, the system can still be considered to be reliable since years with a total deficit over 50% occur in our simulations less frequently than once every five years (see Fig. 3.12). Finally, the Jalon and Guadalupe areas appear to be particularly unbalanced (see Fig. 3.12), even though no conflicts between users have arisen in the Jalon (C=0) due to very low IWD.

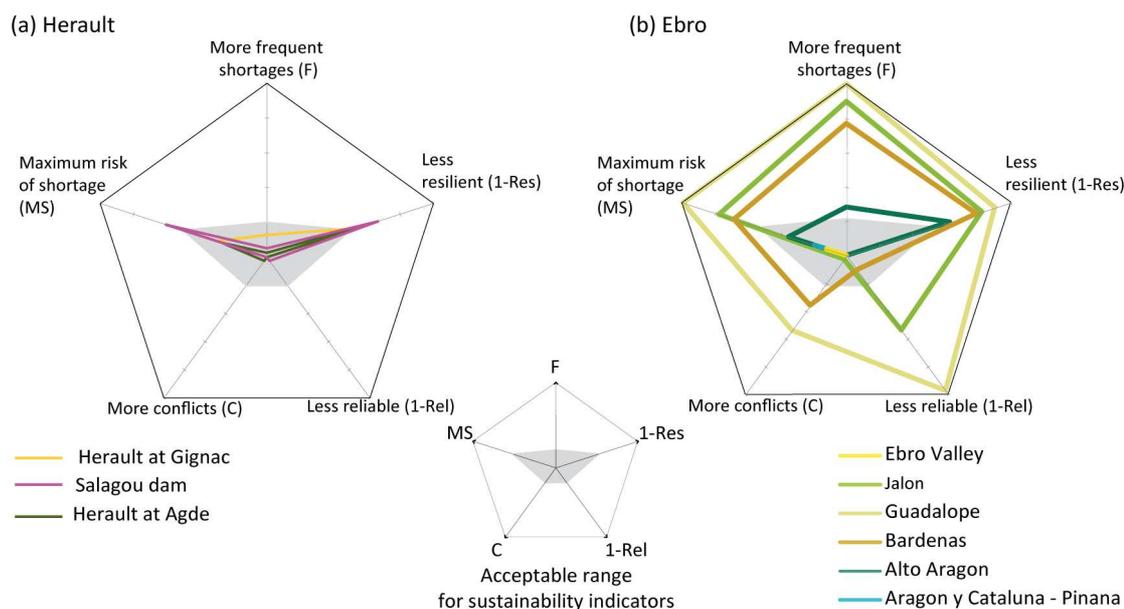


Figure 3.12. Sustainability of current water uses (2009) under the hydro-climatic conditions of the recent past (1971–2009) for (a) the Herault and (b) the Ebro basins: frequency of irrigation water shortage (F) and of water use conflicts (C) in years out of 5 years, resilience (Res), maximum irrigation water shortage (MS), reliability (Rel) at the main demand nodes of each catchment. Only demand nodes with at least one non-null indicator value are represented in the radar charts.

4. Discussion

4.1. An efficient approach to simulate long-term variations in complex hydrosystems, enabling a better understanding of processes leading to water stress

The purpose of this chapter was to: (i) combine socioeconomic and hydro-climatic data in an integrative modeling framework to represent water stress and its spatial and temporal variations over a past multi-decadal period; and (ii) use this framework and appropriate indicators to assess the sustainability of current water uses. The approach presented in this paper enabled better identification of the drivers of water stress in basins facing rapid climatic and anthropogenic changes, which is at the heart of the challenges put forward in the Panta Rhei hydrological scientific decade of IAHS (Montanari et al., 2014). The originality of the approach lies in its ability to integrate different modeling tools (runoff, water demand, dams) and data with many different time and space scales, and provide indicators to assess the sustainability of water uses. The outcome of this chapter is twofold. First, the presented modeling framework was shown to efficiently simulate long-term variations in influenced streamflow, reservoir levels and water stress in complex hydrosystems facing significant water use and climate variability. Second, the simulations enabled us to understand the relative influence of anthropogenic and climatic pressures on water stress, and thus provided knowledge on the processes leading to water stress, which was not available through simple data analysis.

The modeling framework was validated by comparing simulated reservoir levels and influenced streamflow with observed data over a nearly 40-year period. Influenced streamflow was represented by accounting for the significant variability of water use and climate during the period, and by properly simulating anthropogenic pressures on water resources (i.e. water withdrawals, consumptive use and dam management). A combination of socioeconomic and hydro-climatic data based primarily on the mapping of resource and demand nodes enabled us to account for heterogeneities in water use and management practices in the two basins. The main heterogeneities in resource availability were identified by isolating the catchments that contributed most to runoff in the Herault basin and the catchments with a snow melt hydrological regime in the Ebro basin, and by defining the dams most important for the satisfaction of water demands. Also, local water management was taken into account and the demand nodes in our study represent actual management units, a scale at which water allocations are discussed.

To our knowledge other studies did not simulate natural and influenced streamflow at the meso-scale and did not achieve a historical reconstruction of water demand and the influence of water use on streamflow over such a long period. Lanini et al. (2004) designed an integrated model of the Herault socio-hydrosystem, with detailed accounts of hydrogeological processes and decisions on water use. However this model was calibrated and validated over a short period and only covers an area of approximately 100 km² in the Herault valley. Collet et al. (2013) successfully modeled influenced streamflow with simulations of water demand satisfaction and consumptive use; however the hydrological model was calibrated using observed streamflow data, i.e. influenced streamflow. In the Ebro basin, some studies such as López-Moreno et al. (2014) successfully simulated natural streamflow in snowmelt sub-basins, and demand-driven dam management, although with water demand assumed constant from one year to another and therefore an incomplete integration of drivers of water stress. Finally Milano et al. (2013a) proposed a representation of water stress over the whole Ebro basin, accounting for three storage dams and with a simulation of natural streamflow. However the natural streamflow data used for calibration of the hydrological model in this case were based on outputs from another model, and the hydrological model did not account for snow melt's influence on runoff. Moreover water stress was assessed at a monthly time step, and water demand was considered constant over a 20-year period.

Because the indicators used to measure water stress were defined with local stakeholders, they were appropriate for water management issues. These indicators are sensitive to the spatial and temporal dynamics of anthropogenic pressures, and should help anticipate undesirable situations and/or make projections, as recommended by Juwana et al. (2012). Threshold values were set to define undesirable situations in each hydrosystem. The indicators can be seen as a way of interpreting simulation results to characterize the dynamics of the balance between demand and availability over four decades. Including anthropogenic and climatic drivers in a spatially and temporally distributed modeling approach enabled us to correctly simulate changes in water demand satisfaction in the Herault and the Ebro basins: the simulated trends matched the situations described by local managers. Our simulation results made it possible to analyze the impacts of climate variability and variations in water uses and water management practices on the balance between demand and availability.

In the Hérault basin, the irrigation needs of vineyards increased and were subject to great variability (standard deviation reached 60% of the mean water demand over 1971–2009). Municipal water demand also increased significantly, and water use conflicts started to appear in the basin. IWD satisfaction in the Gignac area appears to be sensitive to hydro-climatic variability (the 1970s were wetter whereas the 1980s and the 2000s were warmer and drier). However the improvement in irrigation efficiency in the 2000s succeeded in limiting irrigation water shortages in the Gignac area. In the Agde section, an imbalance between demand and availability emerged in the 2000s because of the combined increase in IWD and MWD and the decrease in natural streamflow. Although MWD also increased in the Ebro basin, it remained very low compared to IWD. The main driver of the decrease in water demand satisfaction in the Ebro was the increase in demand triggered by the expansion of irrigated land, which exceeded the water supply capacity in some areas (under current management and storage capacity).

Although key areas of the Hérault basin were highly sensitive to hydro-climatic variability, the balance between water uses and availability in the Ebro basin appears to be more critical, owing to high agricultural pressure on water resources. All the same, water demand and availability were shown to be in balance in large systems of the Ebro basin such as the Ebro Valley, Aragon and Catalunya, Segre, and Lower Ebro, which concentrate 60% of the water demand from the large irrigation systems in the basin. In comparison, water demand in the Gignac area represented, on average, 70% of total IWD over the Hérault basin over the past 40 years. What is more, the vineyards in the Hérault basin may be more vulnerable to an unreliable water supply than the cereal and fodder crops grown in the Ebro basin, where cropping patterns can be adjusted on a yearly basis to adapt them to the hydro-climatic conditions. The spatial distribution of the integrative approach contributed to identify the most vulnerable areas: the main stakes for maintaining or reaching water balance are concentrated in the Gignac and Agde areas in the Hérault basin, and on the right bank and in the Bardenas and Alto Aragon systems in the Ebro basin.

4.2. Limitations of the integrated modeling framework

The widespread anthropogenic influence on streamflow made calibration and validation of natural streamflow difficult, particularly in the Ebro basin. The challenge was that no water withdrawal data were available at a finer time scale than annual values; consequently reconstructing series of natural streamflow through data analysis would have been impossible. Another way of simulating natural flow would have been to integrate the water withdrawals and return flows in the calibration procedure by simulating natural flows, modifying them with simulated withdrawals (according to simulated demand and availability) and return flows, and applying the performance criteria to the influenced flow (Beck and Bernauer, 2011, e.g.). Although this method could be conceivable in a simple system of, for example, one or two sub-basins with few storage dams, here the calibration on influenced flow would have taken into account the bias in streamflow regulation, withdrawal simulations, etc., thus not guaranteeing the quality of natural streamflow simulations. Since the influence of consumptive use is highest during low flow periods, the hydrological model was mostly calibrated over periods of mid and high flows.

The other components of the modeling chain (the dam management model, the simulation of water demand, and the simulation of influenced streamflow) were validated against observed data, if available. As shown in section 4.1.2, the functioning of some dams was poorly simulated. In the case of the Caspe and Talarn dams, this may be due to the streamflow regulations by other dams located upstream and not included in this study. Furthermore the Talarn dam is mostly operated for hydropower production, which was not included in this study. In the case of the Caspe dam, the irrigated areas actually linked to the dam may have been underestimated. The Sotonera and Grado dams are operated jointly since 1981. The reconstruction of the changes in irrigated areas and their attribution to one dam or the other was a difficult task and a misrepresentation of the links between irrigated areas and each dam might have led, for example, to the Sotonera dam to be under-solicited in our simulations. The same can be said of the jointly operated Barasona and Santa Ana dams. Moreover simulations considered the three dams Escales, Canelles and Santa Ana as one large dam in the location of Santa Ana (see section 3.3.1). This may be an oversimplification of the real-life management of these dams.

The ability to represent observed low flows, which are highly influenced by storage and water withdrawals, is an indicator of the modeling chain's efficiency. Low flows were well simulated at the outlet of the Herault basin. As indicated in section 4.1.3, the poor simulations of low flows in the upstream sub-basins of the Vis at Saint-Laurent and the Herault at Laroque are most likely due to difficulties of the hydrological model to reproduce the functioning of the karstic system. Indeed withdrawals are very scarce in these areas, therefore their influence on streamflow is limited and many natural streamflow data were available for the calibration of the model. The simulated low flows in the Herault at Gignac could be biased because of the upstream natural streamflow simulations and because of a biased simulation of withdrawals from the Gignac canal and their influence on streamflow. Low flows in the Ebro basin were more problematic, particularly in the Cinca and Segre sub-basins, where low flows depend almost exclusively on the outflow from the various storage dams. Streamflow is influenced by the management of the Grado dam (operated jointly with the Sotonera dam) and of the Barasona dam (operated jointly with the Santa Ana dam) at the outlet of the Cinca sub-basin, and by the management of the Santa Ana dam and of the jointly operated Talarn and Oliana dams at the outlet of the Segre basin.

Although the long-term reconstruction of past water demands produced valuable information that was not available using regular data sources, accurate validation of water demand simulations in space and over time was not possible due to the lack of appropriate data on withdrawals. Nonetheless, the orders of magnitude, seasonal distributions, and past dynamics appear to be in agreement with the data that were available as well as with the knowledge of local managers (see Grouillet et al., 2015). For example, in this study an average irrigation water demand of $6\,820\text{ hm}^3/\text{y}$ was simulated in the 2000s, while the CHE (2013) indicated an IWD of $8\,500\text{ hm}^3/\text{y}$.

Another point to consider is the assumption made on groundwater simulation and the groundwater-surface flow links. The hydrological model used in this study does not fully account for groundwater and groundwater-surface flow links. It simulates streamflow coming from both surface and groundwater sources. Other models that properly account for surface-groundwater interactions exist (Pulido-Velazquez et al., 2007, 2012, e.g.).

However, the application of such models at the scale of the Hérault or the Ebro basin is complex, considering the heterogeneity of hydrogeological contexts (e.g. the Hérault basin varies from schist to karstic and alluvial zones), and the availability of piezometric data, too sparse in space and in time to allow acceptable calibration and validation of a more complex hydrological model over the 40-year period. Considering the small contribution of groundwater to water supply in the Ebro basin (4%, see CHE, 2013), this modeling issue probably has a limited impact on the simulation of streamflow. In the Hérault, the sub-basins of the Vis at Saint-Laurent, Hérault at Gignac and Lergue at Lodeve have developed karstic systems, and low flows are comprised almost exclusively of streamflow from karstic springs. Simulations somewhat underestimate low flows of the Vis at Saint-Laurent and the Hérault at Gignac, which could be explained by the inability of the GR4j model to represent the complex karstic system. However the main water withdrawal in these areas is by far the Gignac irrigation canal, which takes water directly from the Hérault River upstream from Gignac. In the downstream sub-basin of the Hérault (the Agde area), most of the water supply comes from the alluvial aquifer a few meters from the river bed. In our simulations, we assumed these withdrawals impacted surface flow directly, since surface and groundwater flows have been shown to be tightly linked in this area (Weng and Dörfliger, 2002).

Simulations of water shortages at a 10-day time step should be interpreted with caution, as no real-time water management adjustments were considered in this modeling framework. Indeed, the order of priority for the supply of water to different uses was fixed in the model, and no restrictions were imposed on industrial and urban demand before agricultural withdrawal restrictions reached 100% of demand. In real life, water use restrictions can be decided on in advance, to limit non-essential urban uses before supplies to irrigators are entirely cut off. Likewise, in the Ebro basin each *Junta de Explotación* can decide on the water volumes allocated to different users at the beginning of the irrigation season, based on the filling level of the associated reservoirs. Thus, if the irrigation season begins with low reservoir levels, withdrawals can be partially restricted throughout the season instead of waiting until the reservoirs are at their minimum level before limiting withdrawals. Sometimes farmers decide on their cropping patterns according to the reservoir level and/or snow cover (Salvador et al., 2011). In systems with no storage capacity like the Gignac canal or the Agde section in the Hérault basin, water shortages may be more irregular. In future studies, anticipated water reallocation should be incorporated in the model to better integrate the human aspects of water management.

Finally, the simulation of MWD, OWD and IWD does not provide a comprehensive view of water uses. Notably the demand for hydropower production was only partly accounted for through reserved flows at the dams used for agricultural water supply. This could be a source of bias in the modeling of influenced streamflow, as the operation of dams for the production of hydropower can have a major impact on the downstream streamflow and hence significantly affect downstream users. Also, despite the increasing attention paid to environmental flows, these flows were not included in this chapter, except for reserved flows at dam outlets in the Ebro basin. However considering the time depth of the study, one could argue that water withdrawals would not have been limited by environmental concerns during the majority of the study period. Environmental flows were taken into account in the following chapters, when assessing the sustainability of the hydrosystems' water balance.

5. Conclusion

This chapter presented the modeling framework developed in this thesis to study and analyze changes in the balance between water availability and demand at the river basin scale. The model was shown to simulate changes in influenced streamflow and the satisfaction of water demands efficiently. It also enabled a better understanding of the causes of past changes in observed streamflow. Despite the limitations mentioned above, the approach described in this chapter was considered to be useful to simulate changes in the balance between water availability and demand under scenarios of climate and water use changes.

Chapter 4.

Sustainability of water uses under human- and climate-induced changes¹

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¹This chapter is based on the following paper published in Hydrological Earth Systems Sciences Discussions: Fabre, J., Ruelland, D., Dezetter, A., Grouillet, B. Sustainability of water uses in managed hydrosystems: human- and climate-induced changes for the mid-21st century. *Hydrol. Earth Syst. Sci. Discuss.* 12:9247-9293, 2015.

1. Introduction

The European Water Framework Directive (WFD) (EC, 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 constraints, i.e. the 2015, 2021 or 2027 horizons and do not generally account for climate change. In this chapter the need for projections of water balance under anthropogenic and climatic changes is addressed.

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 uncertainties in the decision process, and finding adaptation solutions despite this uncertainty (Patt et al., 2005; Hallegatte, 2009; Wilby, 2010). 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 Dessai, 2010), this chapter proposes an approach covering a wide range of possible climate scenarios, given by a 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 this chapter is thus to assess the sustainability of planned water uses in the Hérault and Ebro river basins under multiple climate change scenarios using the conceptual modeling framework developed in Chapter 3, and to determine the possible causes of unsustainability. The assessment is grounded in real-world water management issues, with water management scenarios built in collaboration with local water agencies. Furthermore an analysis through indicators that relate to management goals will be presented, as well as the implications of climate uncertainty for the results.

2. Methods for building scenarios and analyzing their impacts on water use sustainability

2.1. Building climate and water use scenarios at the 2050 horizon

2.1.1. Climate scenarios

Climate scenarios covered a 30-year 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 Chapter 2 (section 2). For the Hérault basin, climatic data came from the SAFRAN meteorological analysis system (Vidal et al., 2010) and potential evapotranspiration (ET_0) 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). The Hargreaves empirical equation (Hargreaves and Samani, 1985) was used to calculate ET_0 at a daily time step.

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 (GCMs) (see Table 4.1) 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 (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.

Table 4.1. 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° | Voltaire 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 |

The GCM runs from CMIP5 were driven by Representative Concentration Pathways (RCPs), which are scenarios of the increase in radiative forcing. The simulations of climate change used in this study were based on the historical RCP over the reference period (1976–2005) and the RCPs 8.5 (a business-as-usual scenario) and 4.5 (a cautiously optimistic scenario) 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; Ruelland et al., 2012; Milano et al., 2013b, 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 1976–2005) of the cells of the 8×8 km grids whose center was included within the said GCM grid cell.

2.1.2. Water use scenarios

Two water use scenarios were considered in each basin: a scenario based on 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.

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 4.2. Population projections were based on the median scenarios of the national statistic institutes (INSEE in France, INE in Spain). Unit allocations for municipal water demand were taken from a study of water uses in the region for the Herault and from projections by the CHE in the Ebro. In the Herault basin, Rinaudo (2011) suggested a 12% decrease in per capita domestic demand 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 unit municipal allocation by 21%. The efficiency of the potable water network was considered to vary in the Herault according to local objectives in line with a national policy to reduce leaks, and remained constant in the Ebro, where networks are considered to be already efficient. A prospective study was led in the Herault 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 municipal water demand 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.

Table 4.2. 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.

| | Herault | | | Ebro | | |
|--------------------------------------------------------------------|---------|---------|-------|---------|---------|-------|
| | 2000s | 2050s | Trend | 2000s | 2050s | Trend |
| MWD Permanent population (inhab.) | 350 417 | 440 651 | +39% | 468 675 | 554 241 | +18% |
| Touristic activity | | | +74% | NA | NA | NA |
| Transfers (inhab. outside the basins) | 186 620 | 234 676 | +38% | | | +27% |
| Unit allocation ($\text{m}^3 \text{inhab.}^{-1} \text{yr}^{-1}$) | 97 | 117 | +21% | 109 | 111 | +4% |
| Network efficiency (%) | 75 | 80 | +5% | NA | NA | +0% |
| OWD Industrial water allocation | NA | NA | NA | NA | NA | +95% |
| IWD Irrigated areas (ha) | 4 754 | 8 502 | +80% | 658 500 | 961 400 | +46% |
| Network and irrigation efficiency (%) | 60 | 75 | +22% | 60 | 65 | +9% |

2.2. Using the integrative model under prospective scenarios

2.2.1. Modeling water demand and availability under prospective scenarios

The integrated model presented in Chapter 3 (see Figure 4.1) was used to simulate the balance between water demand and availability at the 2050 horizon, based on the scenarios of climate and water use changes presented above.

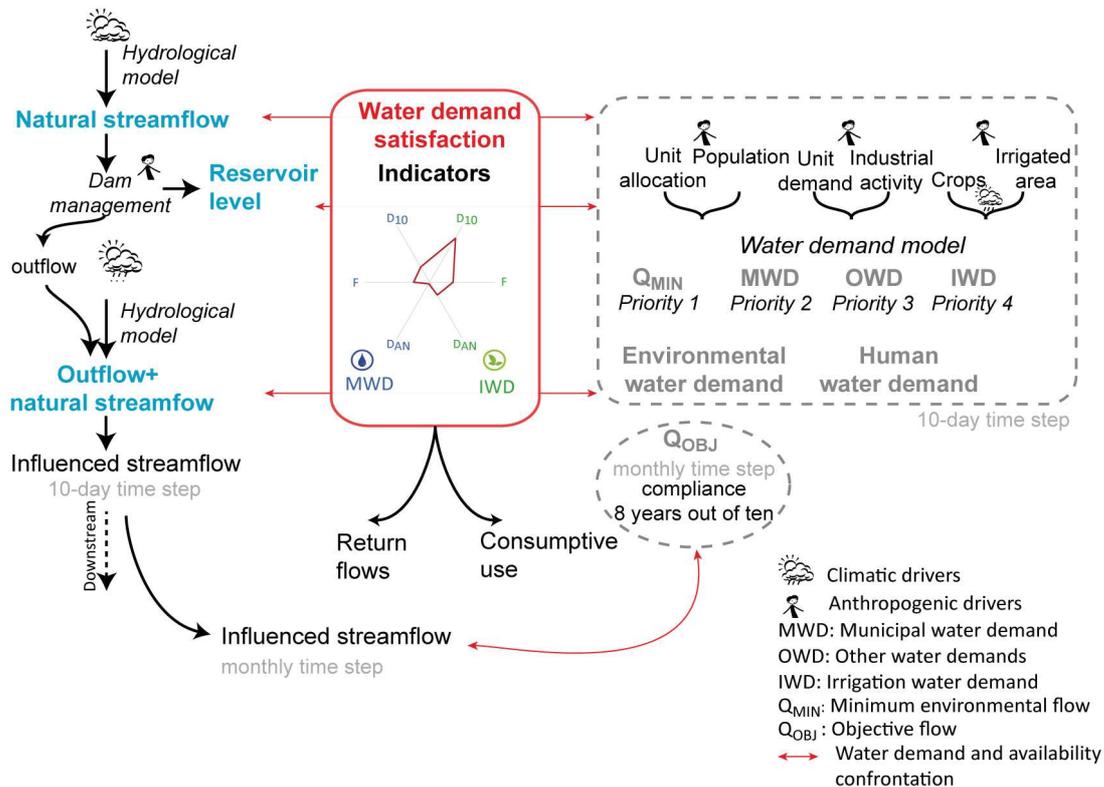


Figure 4.1. Integrative modeling framework applied at each resource and demand node of the Herault and the Ebro basins. Water demand and natural streamflow were simulated based on climatic and anthropogenic drivers. Anthropogenic influence on streamflow was assessed through the simulation of demand-driven dam management and consumptive use. Water demand satisfaction was assessed by comparing demand to availability.

At each demand node, water demand was defined for human water uses (human water demand), as in Chapter 3, and water demand for environmental sustainability (environmental water demand) was added in the prospective scenarios. Two types of environmental water demand were considered in this study. The first type, called Q_{MIN} , was defined as the streamflow 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 comply with this flow requirement at least eight years out of ten.

Q_{MIN} values were defined downstream from storage dams and at specific locations (such as a $30 \text{ m}^3/\text{s}$ constraint for the Ebro at Zaragoza and a $100 \text{ m}^3/\text{s}$ 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. 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 $QMNA5$, 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 1981–2009² (Chapter 3) was used to calculate $QMNA5$ and, accordingly, Q_{MIN} and Q_{OBJ} . For example, the minimum flow defined by local authorities for the Herault at the stream gauge of Gignac is 70% of the $QMNA5$ value observed at this station. Therefore Q_{MIN} was then defined as 70% of the $QMNA5$ as simulated by the model at the stream gauge 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 Chapter 3) over the period 1981–2009 (or 5% of mean annual flow if it exceeded $80 \text{ m}^3/\text{s}$).

2.2.2. Comparing water demand and availability and simulating influenced streamflow

Water availability and demand were compared at each water demand node. An order of priority for water uses was considered, as defined in Figure 4.1. 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 uses. Restrictions were first applied to IWD, then OWD, then MWD. No restrictions were imposed on industrial and municipal 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. Thus the modeling chain simulated:

- 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).

²This period was used to define $QMNA5$ rather than the reference period used for climate scenarios (1976-2005) because it fit more closely with the data available in the Herault basin and used by local authorities to define $QMNA5$.

2.3. Analyzing the relative impact of climate and water use scenarios

2.3.1. Combinations of climate change 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 use sustainability. These combinations and their corresponding objectives are presented in Table 4.3.

Table 4.3. Four combinations of climate and water use scenarios applied in the Hérault 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 | 1976–2005 | Sustainability of planned water uses under reference climate variability |
| Future uses under future climate | 2050 | 2036–2065 | Sustainability of planned water uses under climate change |

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 2.1.1. The parameters obtained by calibration over 1981–2009 were kept identical in all simulations.

The dam management model was run with the hydroclimatic and water demand inputs corresponding to each combination of scenarios. Future water use scenarios also included changes in dam management such as the doubling of the Yesa dam 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.

2.3.2. Indicators of water demand satisfaction

As detailed in section 2.2.2, water shortage was calculated at each demand node and for each type of demand, at a 10-day time step. The satisfaction of municipal and irrigation 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 MWD or IWD³);
- D₁₀: average deficit at a 10-day time step;
- D_{AN}: average annual deficit.

³Note that in Chapter 3 deficits were considered significant for IWD only when they exceeded 50% of demand.

These indicators characterized 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 defined as the percentage of total annual demand that could not be satisfied by available resources. D_{AN} was then calculated by averaging the annual deficits over the whole period. The three indicators were computed separately for municipal water demand (MWD) and irrigation water demand (IWD).

2.3.3. Anthropogenic pressure on water resources

For each combination of scenarios the level of anthropogenic pressure on water resources was 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, influenced monthly streamflow was compared for each combination of scenarios to the monthly environmental flows Q_{OBJ} described in section 2.2.1 and the frequency of non-respect of these monthly environmental flows was calculated.

3. Results

3.1. Hydro-climatic and water demand changes

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

Figure 4.2 shows the changes in the temperature, precipitation and natural discharge projected by the nine GCMs and two RCPs for the period 2036–2065 in comparison to the 1976–2005 reference period in the Herault 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 Herault 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 Herault 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 Herault (-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 snow melt, while all scenarios lead to a decrease in spring discharge in the Herault basin.

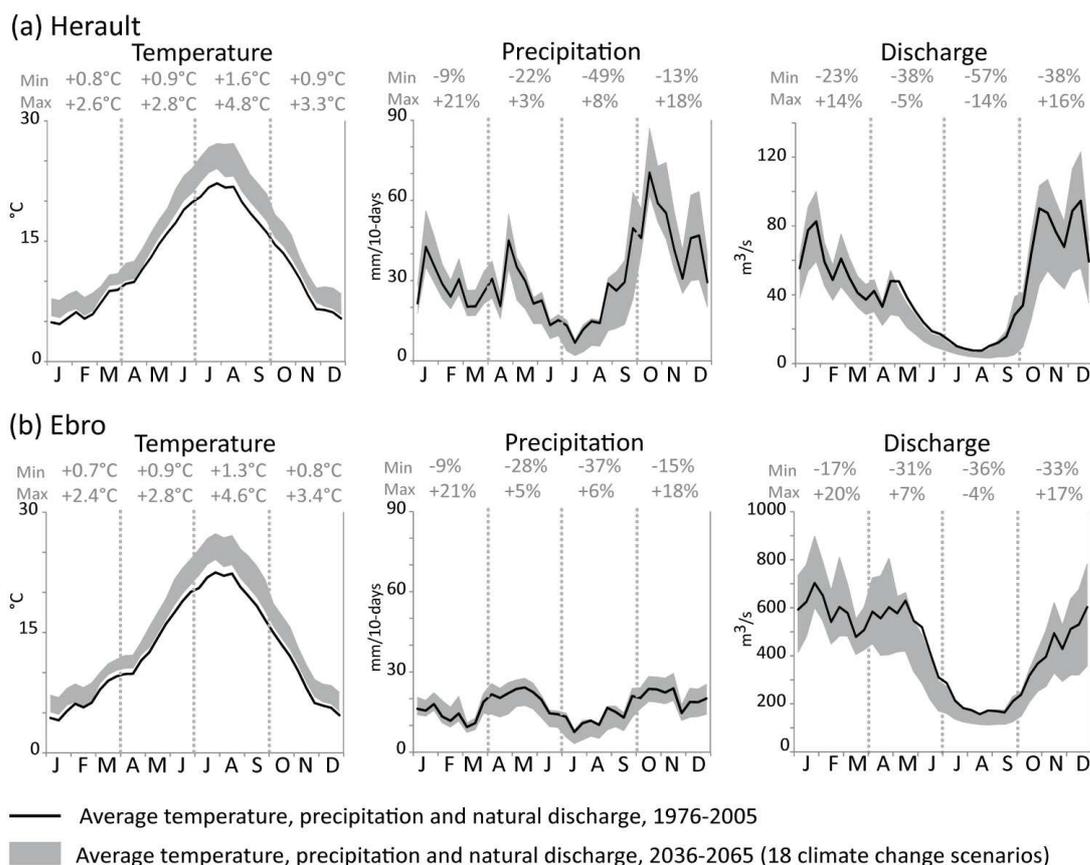


Figure 4.2. Average temperature, precipitation and natural discharge over the reference period 1976–2005 and under 18 climate change scenarios at the 2050 horizon in (a) the Herault and (b) the Ebro basins. Natural discharge is simulated with the hydrological model over the reference and future period.

3.1.2. Water demand changes under water use and climate scenarios

In the Herault basin projections of water demand for the mid-21st century are contrasted between the upstream and downstream sections (see Figure 4.3a). Although demand is expected to increase in some upstream sections such as Laroque and Lodeve, projected irrigation demand remains low relatively to the downstream sections of Gignac and Agde. Depending on the water use scenario considered, the highest IWD 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 IWD to decrease by 50% despite a 65% increase in irrigated areas, whereas IWD 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 IWD is comparable to the impact of projected anthropogenic changes (in the most pessimistic climate change scenarios). Note the MWD increase (+57% or 14.8 hm³, of which 10.4 hm³ are linked to an increase in demands outside the basin) in the Agde section, which concentrates 83% of the basin's MWD in the water use trend scenario. In the upstream sections the impacts of projected climate and anthropogenic changes on irrigation 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 IWD (–15%); however changing climate conditions have a dominant impact and cause an increase in IWD (up to +40% and +57% in the Saint Laurent and Salagou sections respectively). MWD is projected to increase in the upstream sections, from +11% in the Laroque section to +53% in the Salagou section.

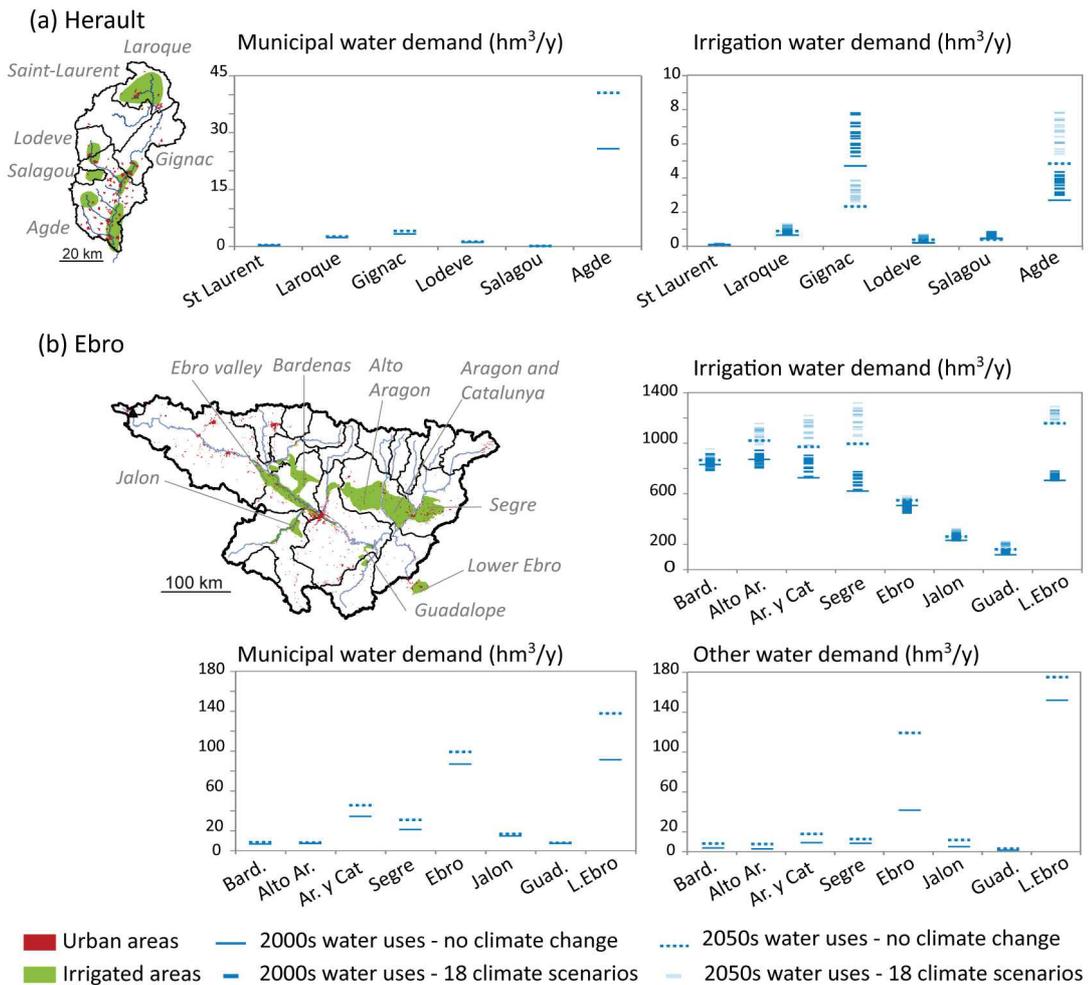


Figure 4.3. Water demands for human activities in (a) the Herault and (b) the Ebro basins under four combinations of water use and climate scenarios.

IWD is projected to increase in all sections of the Ebro basin and in all scenarios, except in the Bardenas, Alto Aragon and Ebro Valley irrigated areas where some of the climate change scenarios lead to a decrease in IWD 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 Figure 4.3b). In the Bardenas, Aragon y Catalunya, Jalon and Guadalope areas climate change is projected to have as much or more impact on IWD than the changes in water use in the trend scenario. The uncertainty on the impact of climate change on IWD is largest in the Aragon and Catalunya, Segre, Jalon and Guadalope areas; it is lower in the Lower Ebro area. Although IWD stays dominant in all scenarios, MWD and OWD are also projected to increase in all areas in the trend scenario. The highest MWD increases are found in the Aragon and Catalunya (+30%), Segre (+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).

3.2. Water demand satisfaction under climate and water use scenarios

Figure 4.4 shows the water demand satisfaction indicators for MWD and IWD, under the four combinations of climate and water use scenarios. Each radar chart presents the results for one demand node. For all indicators values range from 0 (no deficit, at the center of the chart) to 1 (maximum frequency or intensity of deficit, at the outer edges of the chart).

3.2.1. Water demand satisfaction in the Hérault basin

Considering current water uses in the reference climate variability, water shortages appear less than once every five years in all sections of the Hérault basin except in the Gignac and Agde areas, where irrigation water shortage occurs two years out of five (Fig. 4.4a). In the Saint Laurent and Lodeve sections the average restriction on irrigation 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 irrigation water demand.

The trend water use scenario in a reference climate only impacts the satisfaction of IWD in the Agde area. Despite a significant decrease in IWD in the Gignac area, the frequency of withdrawal restrictions is not projected to decrease, due to the high MWD increase in the Agde area. Indeed MWD was considered of first priority over IWD and no upstream priority was given to IWD in Gignac over MWD in Agde. Thus if streamflow was insufficient to meet water demand in the downstream sub-basin, irrigation 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 irrigation water shortages in the Gignac area reaches three to eight years out of ten. Despite some possible high increases in the frequency of water shortages, the average annual deficit is not affected by climate change except in the Gignac area, where the annual irrigation 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 Hérault. In the sections of Gignac and Agde, the water use trend scenario amplifies the impact of the different climate change scenarios.

3.2.2. 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 irrigation 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 4.4b). Also, shortages at a 10-day time step are higher in the right bank systems. Municipal water shortages also appear frequently in these areas.

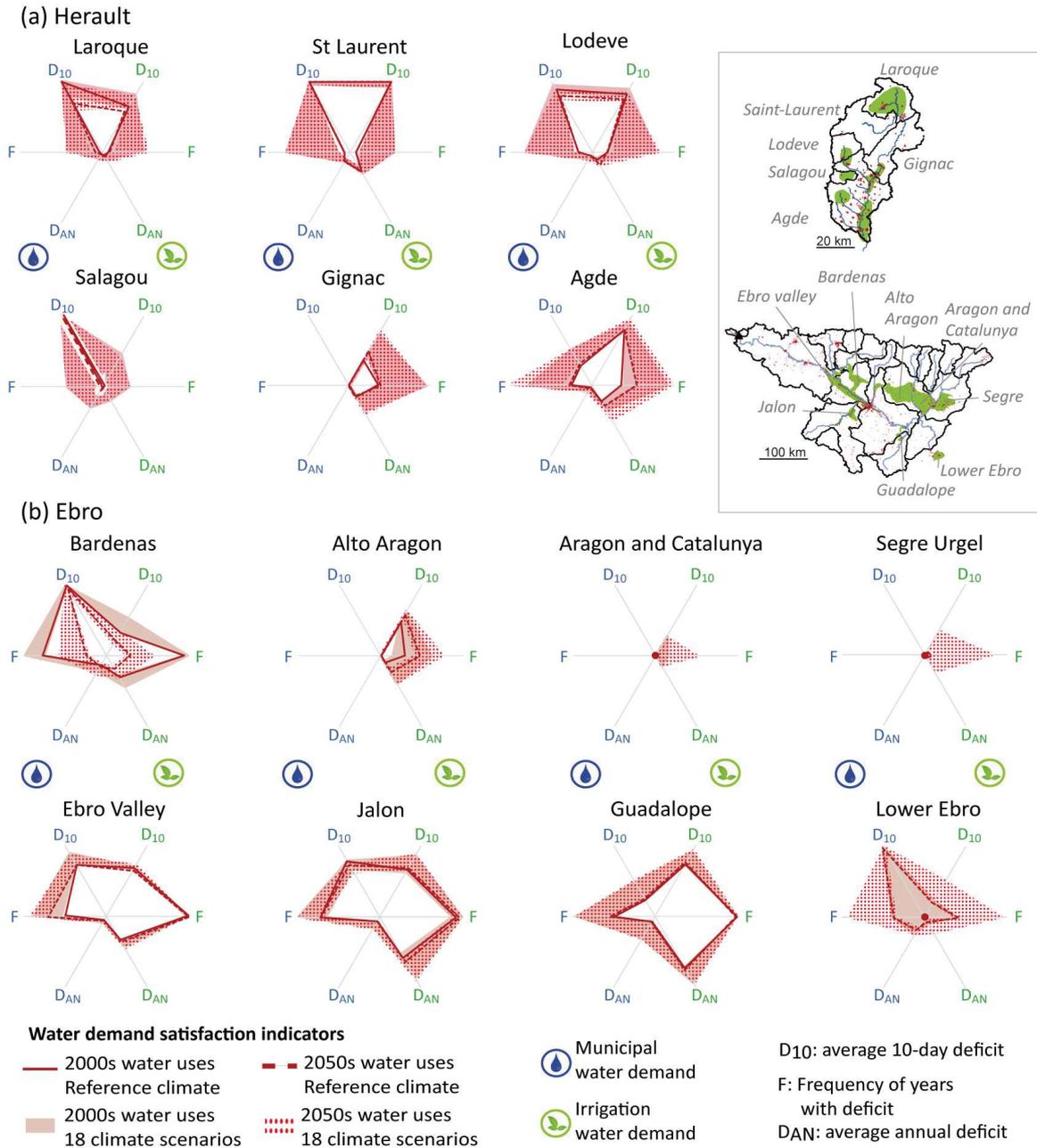


Figure 4.4. Water demand satisfaction indicators for municipal and irrigation water demands in (a) the Herault basin and (b) the Ebro basin under four combinations of water use and climate scenarios. For all three indicators values range from 0 (no deficit) to 1 (maximum frequency or intensity of deficit).

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 IWD, and in the Bardenas, Ebro valley and right bank systems for MWD. 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 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 municipal and irrigation water uses. The increase of the Yesa dam's storage capacity is projected to lead to a decrease in the frequency of irrigation water shortages, from every year to three years out of ten. In the already out of balance systems of Guadalupe, 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 IWD 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 IWD shortage in Alto Aragon and causes IWD and MWD 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 of 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 irrigation water shortages and an increase in the frequency of municipal 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 irrigation water shortages in both areas (every year in the Lower Ebro, eight years out of ten in the Segre) and to municipal water shortages in the Lower Ebro.

3.3. 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. 4.5a). 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 4.5b 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, Ribarroja and Flix dams which aims at securing a flow of 100 m³/s 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 m³/s, 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.

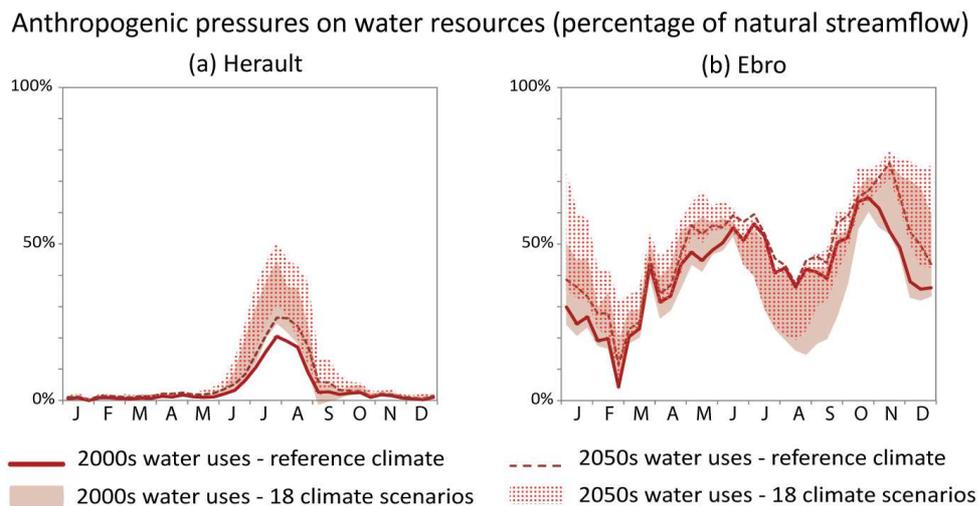


Figure 4.5. Anthropogenic pressures on water resources under four combinations of climate and water use scenarios in (a) the Hérault basin and (b) the Ebro basin. Anthropogenic pressure is computed through the difference between natural and influenced streamflow at the outlet of each basin, expressed as a percentage of natural streamflow.

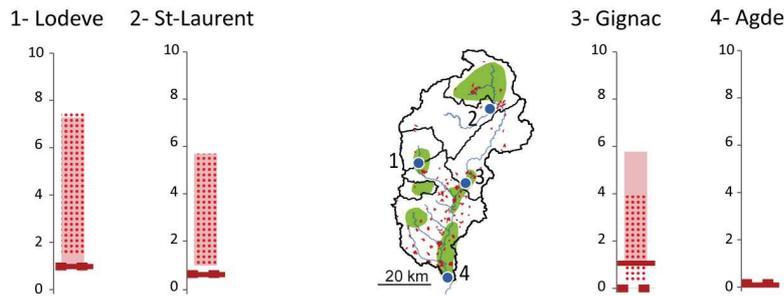
Figure 4.6 shows that monthly environmental flows Q_{OBJ} are reached more than eight years out of ten in all sub-basins of the Hérault and Ebro basins, under current water uses and reference climate variability. However the water use trend scenario causes an increase in the frequency of unsatisfactory 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. 4.6a) and Bardenas (Fig. 4.6b) 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 of the Ebro basins except the Cinca and the Segre sub-basins. Finally, the combination of the trend water use scenario and climate change scenarios is projected to have a high impact on the compliance with environmental flows in the Ebro at Tortosa.

4. Discussion

4.1. Significance for water management

The purpose of this chapter was to assess the sustainability of planned water uses under multiple climate change scenarios using a conceptual modeling framework, and to determine the possible causes of unsustainability. The sustainability of water uses can be appraised through the risk of imbalance between water availability and demand over the long term (several decades), i.e. the possibility to satisfy demands for human water

(a) Herault



(b) Ebro

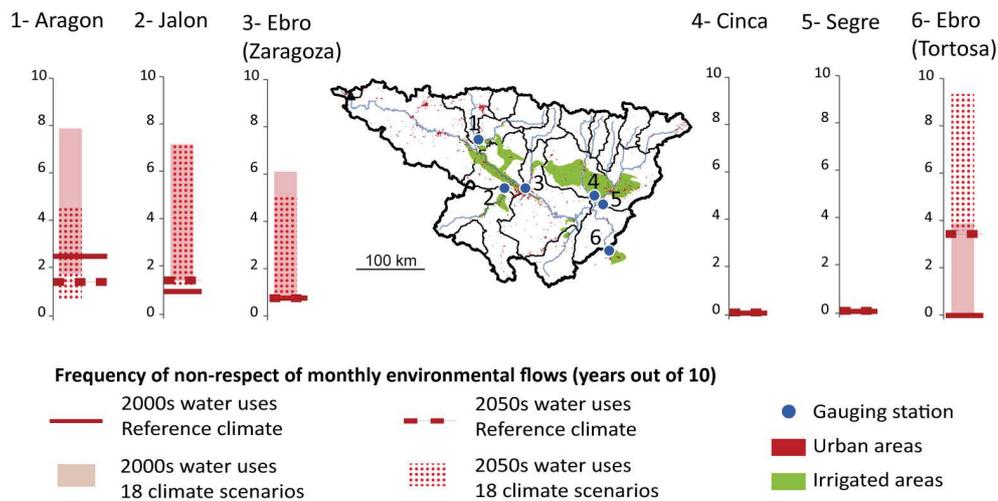


Figure 4.6. Frequency of years (out of ten) with monthly influenced streamflow inferior to the objective monthly environmental flow Q_{OBJ} in (a) the Herault basin and (b) the Ebro basin. Frequencies are considered acceptable under two years out of 10.

use while keeping withdrawals and consumptive use at environmentally sustainable levels. The sustainability of planned water uses was assessed by simulating 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. (2010b). Moreover the impact of the tested climate projections on both 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 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 reduce demand, than to curb its increase from now on. In other areas water stress should be induced mainly by climate change, notably in the Hérault basin. 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 rises whether regulatory minimum flows can be kept at their current level. Then again, increased consumptive use as shown by results under climate change scenarios could further impact ecosystems already perturbed by warmer temperatures, lower flows, and quickly changing conditions.

The comparison of the Hérault 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 irrigation water demand) whereas systems with little streamflow regulation such as the Hérault basin should 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 meaningful, 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 complicate 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; 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.

4.2. Limitations

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. Different downscaling techniques, hydrological models (Jones et al., 2006; Jiang et al., 2007, 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 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. Thus the trend water use scenario should be considered as a reference state on which to base the design of adaptation measures.

This prospective study was based on strong assumptions regarding the stationarity of hydrological 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 models under changing climatic and anthropogenic drivers is an essential question for impact studies (Coron et al., 2012; Vaze et al., 2010). Moreover, climate projections at the 2050 horizon only accounted for mean monthly changes, due to the downscaling method. Also, note that the water use scenarios were built with constant anthropogenic drivers over 30 years, while simulations over the past 40 years 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 to account for the variability of anthropogenic pressures in future scenarios, it would seem more pertinent to use a large range of stationary water use scenarios and to confront them to different climate scenarios over multi-decadal periods.

5. Conclusion

Applying the integrated 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. The impact of the tested climate projections on both 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.

This chapter encourages us to explore possible adaptation options to improve the sustainability of water uses for each study area. In the Hérault basin, water managers will have to address the satisfaction of MWD, while accounting for interactions between water uses and between upstream and downstream areas. For instance this study showed that the efforts regarding irrigation efficiency in Gignac would not necessarily induce an increase in the satisfaction of local irrigation demand because of the priority given to the satisfaction of municipal water demand further downstream. In the Ebro adaptation will most likely relate to irrigation 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, described in Chapter 5, was 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.

Chapter 5.

Effectiveness and robustness of adaptation measures to enhance water use sustainability under climate- and human-induced changes¹

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¹This chapter is based on the following paper published in the proceedings of the symposium "Water Tensions in Europe and in the Mediterranean: water crisis by 2050?" of *Société Hydrotechnique de France* (SHF) held in Paris on October, 8-9 2015 : Fabre, J., Ruelland, D., Dezetter, A., Grouillet, B. Reducing the gap between water demand and availability under climate and water use changes: assessing the effectiveness and robustness of adaptation. *Proc. SHF Congress*, October 2015, 2015.

1. Introduction

Chapter 4 showed that planned water uses in the Hérault and Ebro basins may not be sustainable under climate change scenarios: anthropogenic water demand would be frequently unsatisfied and environmental flow objectives would not be reached. Therefore changes could be made in the local water management plans to adapt to possible climate changes, and reach a sustainable balance between water demand and availability. In case of an imbalance between water demand and availability two types of options can be considered to reduce the deficit: reducing demand or to increasing availability. The adaptation considered in this chapter is an adjustment of local plans, to assess if altering these plans could help achieve a sustainable water balance. Thus each element of the trend scenarios is considered and the impact of variations in these drivers on the water balance is assessed.

For adaptation to be successful and cost-effective, water management policies need to be robust to uncertainty (Olmstead, 2014). The question of uncertainty is addressed by assessing these impacts in 18 climate scenarios and by proposing metrics to account for the robustness of adaptation measures. In this chapter the method used to test the sensitivity of water balance to variations in anthropogenic drivers is presented. The results section shows the assessment of the effectiveness and robustness of each individual adaptation measure, and the effect of one possible combination of adaptation measures for the Hérault and the Ebro basins.

2. Methodological framework to test the sensitivity of water balance to variations in anthropogenic drivers

2.1. Defining drivers of adaptation

2.1.1. Sensitivity to variations in the main drivers of water demand

First, options aimed at curbing the MWD and IWD increases simulated in the trend water use scenario were tested. The drivers of water demand considered in the water demand model were population, per capita municipal demand, tourism and the supply network efficiency for MWD, and irrigated areas and efficiency of irrigation for IWD (see Chapter 3). The sensitivity of water demand satisfaction to variations in each of these drivers was tested. Except for the efficiency of municipal water supply networks and of irrigation, all drivers of water demand are expected to increase in the trend water use scenario. Thus the influence of each driver on water demand was considered one at a time, by reducing its increase projected in the trend water use scenario and comparing the water demand satisfaction results to those in the trend scenario. Each driver was tested individually, leaving all the other drivers at the level of the trend scenario. The projected increase was reduced gradually by steps of 10%: each driver of water demand was tested with a curb in the increase projected in the trend scenario going from 10% to 100% (the latter being equivalent to keeping the driver at its current level).

2.1.2. Sensitivity to variations in environmental flows

In the trend scenario, environmental flows were kept constant. Since natural streamflow is expected to decrease in both basins under climate change scenarios (see Chapter 4), a reduction in minimum environmental flows by steps of 10% was also tested. Environmental flows were reduced up to 100% (which is synonym of removing the environmental requirements). However in the Ebro basin only the environmental flows which values depended on natural streamflow were changed: the thresholds of 30 m³/s at Zaragoza and 100 m³/s at the outlet of the basin were kept constant.

2.1.3. Sensitivity to variations in dam management

Variations in dam management can be tested by varying objective and minimum reservoir levels, water supply priorities associated to the dam, or even the total storage capacity. Here the example of the Salagou dam in the Herault basin is chosen to illustrate the sensitivity of the water balance to variations in dam management.

Currently the turbine flow for the Salagou hydropower plant is 0.5 m³/s (see Chapter 3). This turbine flow is the only outflow from the Salagou dam during the summer. Adjustments in the management of operations of the dam were tested, to ensure low flow replenishment on the Herault River: an increase in the outflow from the Salagou dam during the months of July and August was tested. The outflow was changed by increments of 0.1 m³/s, ranging from 0.5 m³/s to 1.5 m³/s. However, in current conditions the minimum reservoir level strongly limits summer outflow from the dam. Thus increasing summer outflow would necessarily imply a decrease in the minimum reservoir level. For the purpose of the sensitivity tests performed in this chapter, the minimum reservoir level was decreased to 80 hm³ (compared to 89 hm³ in the reference scenario), regardless of the actual feasibility of such a measure.

Note that changes in the management of the Salagou dam could impact the water balance of the area supplied by the dam, and of the downstream areas of Gignac and Agde. Although the Gignac irrigation canal inlet is located upstream from the confluence of the river Herault and the river Lergue (carrying the outflow from the Salagou dam, see Figure 3.2), replenishing low flows in the river Herault could improve the satisfaction of municipal water demand in the Agde area, thus enabling irrigators upstream to increase water withdrawals.

2.2. Assessing the effectiveness and robustness of adaptation measures

2.2.1. Testing the effectiveness and robustness of individual measures

Each individual measure was then evaluated through its impact on the frequency of years with shortage (indicator F, see Chapter 4). Anticipating adaptation to deeply uncertain changes in the climate requires selecting measures that are not only effective (i.e. that reach the goal of balancing water demand and availability) in a given climate change scenario, but that are also robust to climate change uncertainties (i.e. that are effective in many different climate change scenarios). The effectiveness of adaptation was measured by the average decrease in shortage frequency induced by variations in the drivers under the 18 climate change scenarios, and robustness was measured by the number of climate scenarios in which the measure had an impact on shortage frequencies. Variations in the drivers of water demand and adjustments in environmental flows were applied homogeneously and simultaneously to all water demand and availability nodes, thus the impact of each adaptation option is measured throughout the basin.

2.2.2. Combining adaptation measures aimed at reducing the gap between water demand and availability

Finally, a combination of measures aimed at reducing water demand in each basin was proposed, based on the sensitivity tests and on knowledge of local water management. The integrated modeling framework was used to test these new water use scenarios and the indicators presented in Chapter 4 were calculated in each one of the 18 climate change scenarios. The changes in anthropogenic pressures on water resources between the trend scenario and the adaptation scenario were also assessed. Anthropogenic pressures were computed, as in Chapter 4, by comparing influenced and natural streamflow simulated by the model at the outlet of each basin.

3. Results

Although the modeling framework was run over all the sub-basins and demand nodes of the Herault and the Ebro basin, for the sake of concision and clarity results are presented for four representative demand nodes in each basin: the Laroque, Salagou, Gignac and Agde areas in the Herault basin, and the Bardenas, Alto Aragon, Jalon and Lower Ebro areas in the Ebro basin. Results for all demand nodes are shown in Appendices H2 and H3.

3.1. Sensitivity of municipal and irrigation water demand to individual measures

3.1.1. Curbing municipal water demand increase

The impact of tourism limitation on annual MWD is smaller than the impact of limiting population growth in all areas of the Herault basin (see Figure 5.1a). Results also show that MWD is mainly concentrated in the Agde area, therefore the impact of limiting population or tourism growth in this area has a larger impact on the total volume of MWD in the Herault basin. The same can be said of the Lower Ebro area in the Ebro basin, where population is also planned to increase more than in the other areas of the basin.

3.1.2. Curbing irrigation water demand increase

As shown in Figure 5.1 IWD could be significantly reduced in demand nodes where large irrigation increases are planned (Gignac and Agde in the Herault basin and Alto Aragon and Lower Ebro in the Ebro basin). Note that in the Herault basin, reducing irrigated areas could also reduce the uncertainty range between climate scenarios. In the Bardenas area of the Ebro basin, the trend scenario projects an irrigated area increase of only 10%, therefore there is little leeway for adaptation through the control of irrigated areas, without decreasing the current irrigated area.

Large increases in irrigation efficiency (supply network and irrigation techniques) are projected in the trend scenario for the Herault basin, particularly in the Gignac area where efficiency should increase from 22% currently to 70% at the 2050 horizon. This should lead to a threefold reduction in IWD if irrigated areas remain constant (results not shown here).

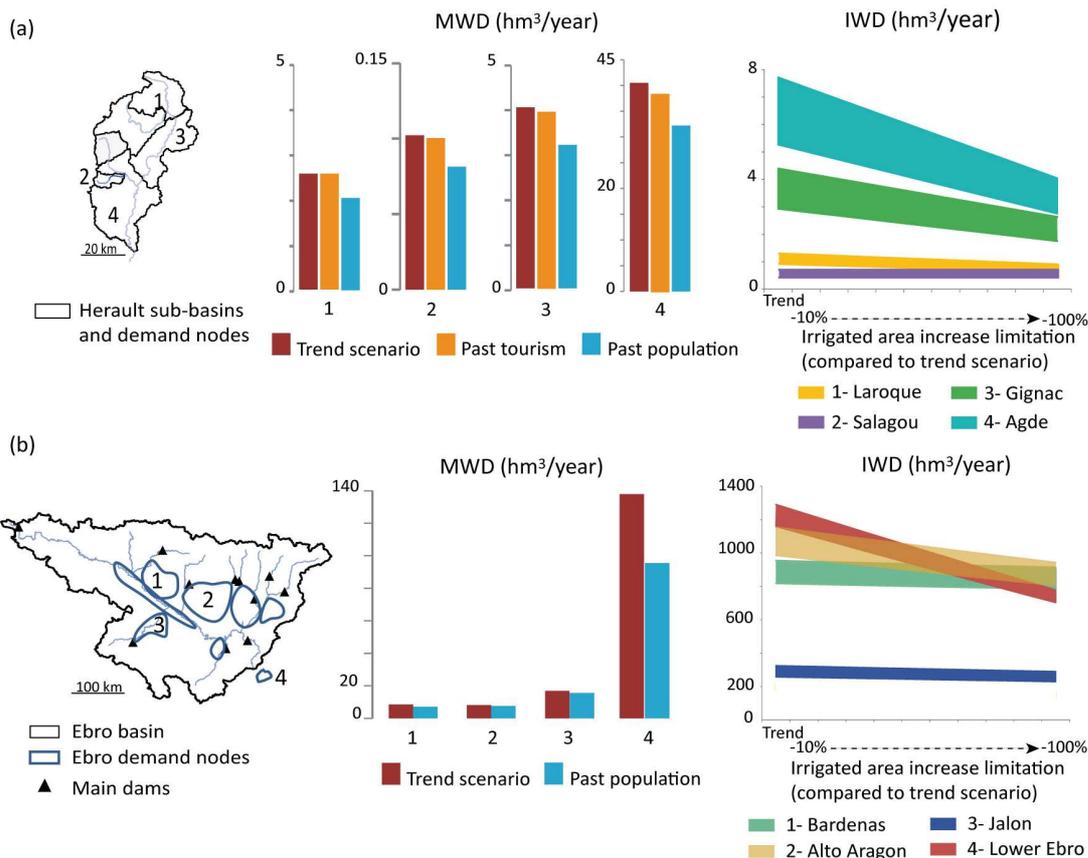


Figure 5.1. Impacts of variations in the main drivers of water demand (permanent and touristic population, irrigated areas) on MWD and IWD in four areas of (a) the Herault basin and (b) the Ebro basin.

3.2. Effectiveness and robustness of individual measures

3.2.1. Curbing municipal and irrigation water demand increase

In the Herault basin the limitation of population and tourism growth could contribute to decreasing the frequency of municipal and irrigation water shortage only in the downstream areas of Gignac and Agde (see Figure 5.2). These adaptation measures have a limited impact in upstream basins (such as the Laroque area). In both Gignac and Agde areas, population growth limitation is more effective than tourism growth limitation. However the effectiveness of these measures is low when considered individually: although limiting population growth is most effective in decreasing municipal water shortage in the Agde area, strictly limiting population growth (i.e. in an unlikely scenario of constant demography) would only lower the average shortage frequency in this area from 0.65 to 0.56.

Figure 5.2 also shows the robustness of each individual adaptation measure: if the frequency of shortage is sensitive to a reduction in a given water demand driver in many different climate change scenarios, then the measure is considered to be robust. For instance, results show that the frequency of water shortage is sensitive to a population growth limitation of 50% in 16 scenarios out of 18, while tourism growth has to be drastically limited before it starts impacting many climate scenarios (see Figure 5.2). Therefore in the Agde and Gignac areas of the Herault basin, population growth limitation is considered more robust to climate uncertainty than tourism growth limitation.

In the Hérault basin, limiting the projected irrigated area increase should mostly impact the satisfaction of IWD in the downstream areas of Gignac and Agde (see Figure 5.2). It could only slightly improve the satisfaction of MWD in the Agde area, due to lower consumptive use from areas upstream. Curbing the irrigated area increase should be as effective in reducing irrigation water shortage as curbing population growth in the Agde area, and slightly less effective in the Gignac area.

In the Ebro basin, population growth limitation is neither effective in the reduction of shortage frequency, nor robust to climate uncertainties (Fig. 5.3). As a result, curbing population growth should have no impact on IWD satisfaction in the Bardenas, Alto Aragón and Jalon areas, and a slight impact in the Lower Ebro area. Conversely, curbing the irrigated area increase might have a significant impact on the frequency of municipal and irrigation water shortage in the Bardenas, Alto Aragón and Lower Ebro areas. However it should not be effective in the Jalon area. This measure should be more robust to climate uncertainties in the Lower Ebro area than in the Bardenas area. Note that, conversely to the Hérault basin, decreasing IWD could improve the satisfaction of MWD in the Ebro basin, even though MWD has a higher supply priority. This can be due to: (i) the reliance on storage dams in the Ebro basin: where water is supplied by dams, a high irrigation demand can cause the reservoir to be emptied earlier in the season, therefore leaving less water for municipal water supply at the end of the season; (ii) a lower consumptive use induced by a lower IWD in upstream areas, therefore leaving more water available for downstream users.

3.2.2. Adjusting environmental flows

Adjusting environmental flows could be the most effective driver to increase water demand satisfaction in the Hérault basin (Fig. 5.2). For instance, decreasing environmental flows by 50% in the Agde area could bring the municipal shortage frequency down to 0.2 on average over the 18 climate scenarios. This measure should induce a decrease in shortage frequencies in all 18 scenarios, therefore it is considered to be robust to climate uncertainties. Decreasing environmental flow is also the only tested measure that could have an impact on water demand satisfaction in upstream areas of the Hérault basin such as the Laroque demand node.

Results for the Ebro basin are more contrasted (see Figure 5.3). In the Lower Ebro, since no variation was applied on the 100 m³/s constraint at the outlet of the basin, shortage for human water demands could increase: with lower environmental flows in the upstream sub-basins, incoming streamflow should be reduced, making the 100 m³/s threshold harder to respect and therefore more restraining for anthropogenic water use. Decreasing environmental flows in the Jalon sub-basin could effectively reduce municipal water shortage frequency, whereas irrigation water shortage frequency should remain unaffected.

3.2.3. Adjusting dam management

Increasing the outflow from the Salagou dam in July and August could significantly reduce municipal and irrigation water shortage frequency in the areas of Gignac and Agde (particularly for MWD in Agde and AWD in Gignac). Results show that the measure's robustness increases with the outflow from the dam, reaching its maximum (for MWD in Agde and IWD in Gignac) for an outflow of $1 \text{ m}^3/\text{s}$. As can be seen in Figure 5.2, this measure has contradictory impacts on water demand satisfaction for water uses on the Salagou lake. If outflows from the lake are only slightly increased, lowering the minimum reservoir level enables water demand to be fully satisfied. However the more the outflow is increased, the more water shortages on the lake are frequent. Irrigation water shortages reach the same frequency, on average, as in the trend scenario (once every five years, i.e. $F=0.2$), when the outflow in July and August is raised to $1 \text{ m}^3/\text{s}$.

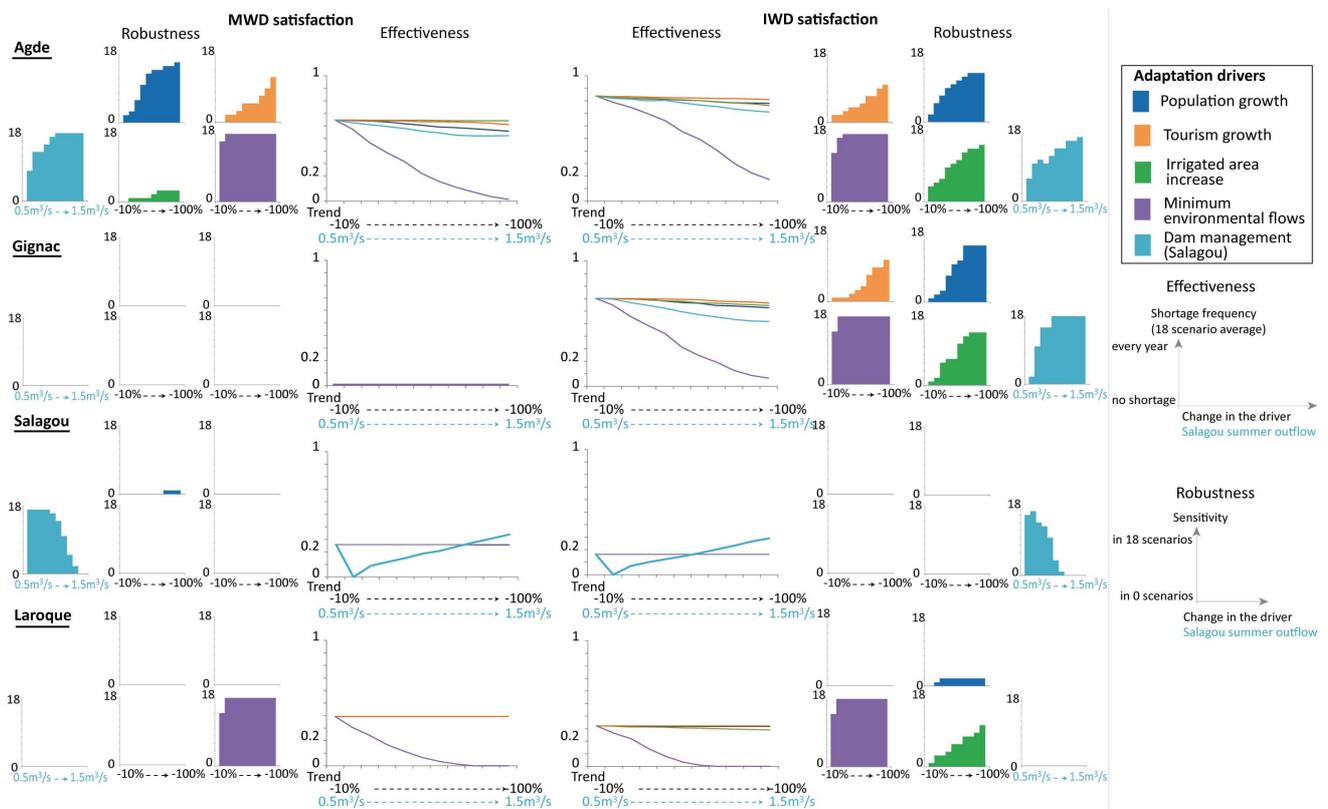


Figure 5.2. Effectiveness and robustness of variations in drivers of water demand in reducing the gap between water demand and availability in four areas of the Hérault basin. Effectiveness is measured by the changes in the water shortage frequency (averaged over the 18 climate scenarios). Robustness is measured by the number of climate scenarios in which the shortage frequency is reduced.

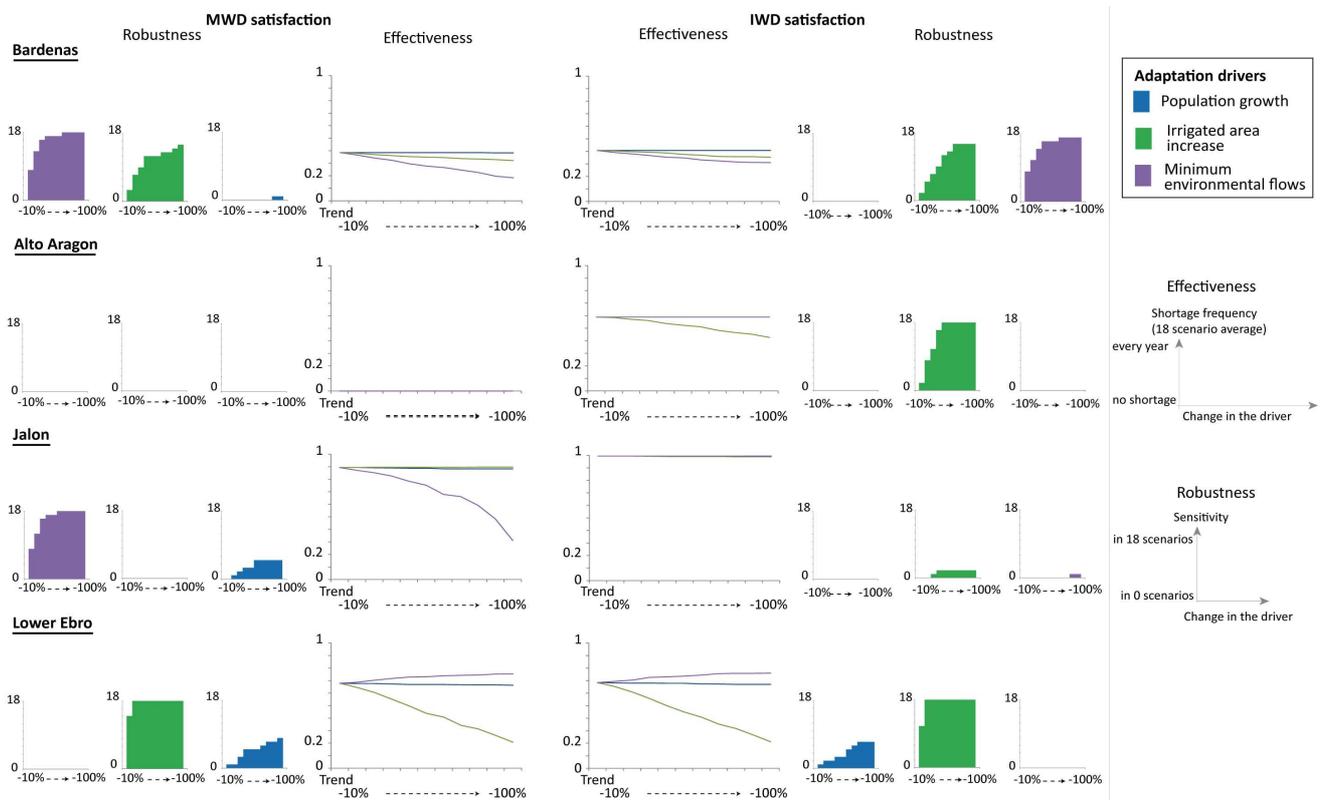


Figure 5.3. Effectiveness and robustness of variations in drivers of water demand in reducing the gap between water demand and availability in four areas of the Ebro basin. Effectiveness is measured by the changes in the water shortage frequency (averaged over the 18 climate scenarios). Robustness is measured by the number of climate scenarios in which the shortage frequency is reduced.

3.3. Effectiveness and robustness of two adaptation scenarios

3.3.1. Adaptation scenarios aimed at reducing the gap between water demand and availability

Sections 3.1 and 3.2 presented the effectiveness of individual adaptation measures, regardless of their realism or feasibility. Although some measures were shown to be more effective and/or robust than others, each individual measure should have a limited impact on water shortage frequency. Therefore different measures must be combined in order to design effective and robust adaptation strategies. Based on the effectiveness and robustness of the individual measures, and on knowledge of local water management issues, an example of adaptation scenarios for the Hérault and the Ebro basins is proposed (see Table 5.1).

Table 5.1. Two examples of adaptation scenarios in the Hérault and the Ebro basin. Percentages are expressed in comparison to the water use trend scenario except for irrigation efficiency.

| | | Hérault | Ebro |
|---------------------|----------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| IWD | Irrigated area Irrigation efficiency | No increase Trend scenario | No increase All surface irrigation converted to sprinkler (50%) and localized (50%) |
| MWD | Population <i>in the basin</i> <i>transfers</i> Unit consumption Efficiency Tourism | Trend scenario No increase –30% Trend scenario No increase | Trend scenario Trend scenario –30% Trend scenario NA |
| OWD | Industrial activity | NA | Trend scenario |
| Environmental flows | QMIN | –20% | 30 m ³ /s at Zaragoza Kept at 100 m ³ /s at Tortosa –20% elsewhere |

Keeping the population supplied by transfers from the Hérault basin constant implies finding a new source of supply for all additional population. The project *Aqua Domitia*, which would convey water from the River Rhone to a currently loosely defined area comprising the south of the Hérault basin, could for example contribute to the supply of additional population. Since natural low flows could decrease between 15 and 60% in the Hérault and between 5 and 35% in the Ebro (see Chapter 4), a 20% decrease in environmental flows is proposed here. Finally, based on the results presented in section 3.2.3, the outflow from the Salagou dam was set to 1 m³/s in July and August, with a minimum reservoir level fixed at 136 m a.s.l. (i.e. 82 hm³).

3.3.2. Impacts on water demand satisfaction

Figure 5.4 shows the range of values for the three water demand satisfaction indicators in the 18 climate change scenarios, for the trend water use scenario and the adaptation scenarios.

Figure 5.4a shows that the adaptation scenario in the Hérault basin could bring municipal water shortage down to an acceptable frequency (less than 2 years out of 10) in all 18 climate scenarios: the adaptation scenario could reduce the vulnerability of municipal water uses to climate change and their sensitivity to climate uncertainty. Irrigation water shortage frequency could also be reduced, however the climate uncertainty should remain large and in some scenarios the shortage frequency could exceed 0.2. Annual deficits could be reduced in both Agde and Gignac areas, and the average 10-day deficit could be reduced in the Gignac area.

In the Ebro basin the adaptation scenario could bring shortage frequency down to an acceptable level in the Bardenas and Lower Ebro areas (see Figure 5.4b). This scenario could also lead to a reduction of annual water deficits and of the sensitivity of annual deficits to climate uncertainty. In the Alto Aragon irrigation system, irrigation water shortage could exceed acceptable frequency only in 2 scenarios out of 18. The results in the Jalon sub-basin are representative of the right bank of the Ebro basin, where the adaptation scenario proposed would have little effect on water shortage.

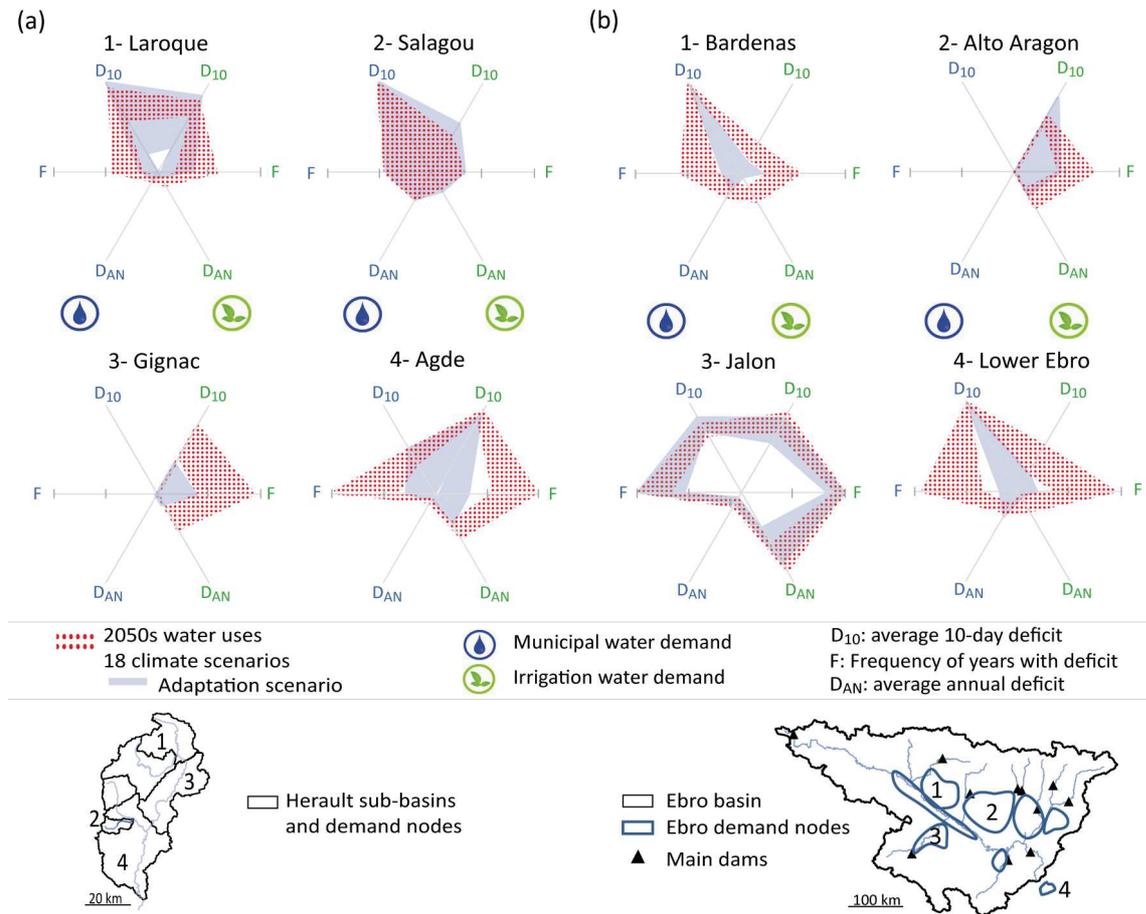


Figure 5.4. Water demand satisfaction indicators for municipal and irrigation water demands under climate change scenarios combined with the trend water use scenario and adaptation scenarios in four areas of (a) the Hérault and (b) the Ebro basin. Indicators values range from 0 (no deficit) to 1 (maximum frequency or intensity of deficit).

3.3.3. Impacts on the level of anthropogenic pressures on water resources

Results in Chapter 4 showed that in the trend water use scenario, under a range of 18 climate change scenarios, anthropogenic pressures on water resources in the Hérault and the Ebro basin could increase compared to the reference scenario. Annual consumptive use could reach 3 to 4% in the Hérault basin and 43 to 52% in the Ebro basin. The adaptation scenarios tested here could contribute to lowering the level of anthropogenic pressures on water resources under climate change scenarios, with annual consumptive use ranging from 1 to 3% in the Hérault basin and from 31 to 40% in the Ebro basin (see Figure 5.5). However the range of uncertainty between the different climate change scenarios could remain large, particularly at an infra-annual time-step: in the Hérault basin consumptive use at the end of July could range from 7 to 45% of natural discharge on average (compared to 31 to 50% with the trend water use scenario), depending on the climate change scenario.

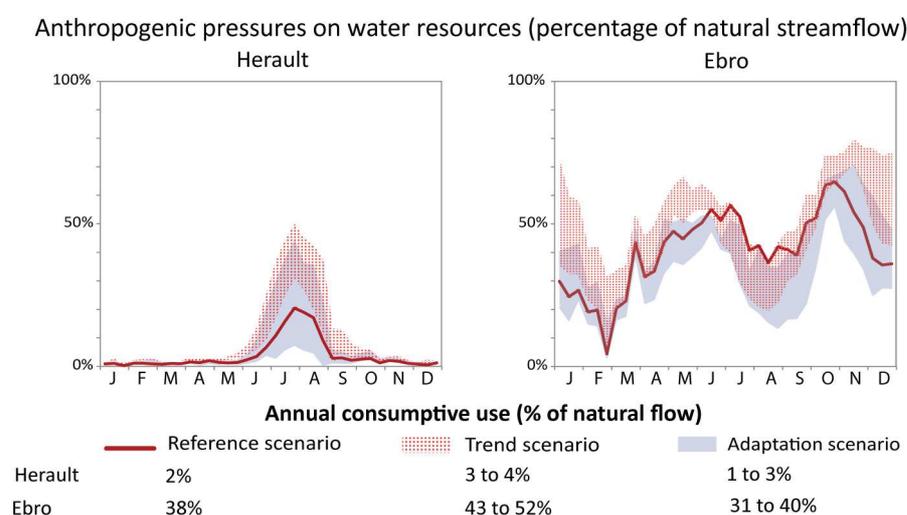


Figure 5.5. Anthropogenic pressure on water resources in the reference scenario and under climate change scenarios combined with the trend water use scenario and adaptation scenarios in the Hérault basin and the Ebro basin. Anthropogenic pressure is computed through the difference between natural and influenced streamflow at the outlet of each basin, expressed as a percentage of natural streamflow.

4. Discussion

4.1. Outcome

The aim of this chapter was to assess options to reduce the gap between water demand and availability under scenarios of water use and climate changes, at the river basin scale. This chapter shows that the integrative modeling framework developed in this thesis could be used for this purpose. An original method was provided to assess the impacts on water balance of changes in the drivers of the water use trend scenario, by simulating their individual impact under 18 climate change scenarios from the CMIP5 exercise, thus covering a wide range of climate uncertainties. The indicators developed in Chapter 4 were used as a measure of success (the management objective was set is to have F less than 0.2, i.e. shortages less frequently than 2 years out of 10).

Objective criteria were used to assess the adaptation options. Notably, a distinction was made between the effectiveness of a given measure (i.e. the decrease in shortage frequency that it could lead to) and its robustness (i.e. if it was effective in a wide range of contrasted climate scenarios). The measure of robustness was made possible by the use of a wide range of climate change projections. Most studies on adaptation to climate change characterized a system's performance using varying metrics or indicators, but using a single hydro-climatic change scenario (Pulido-Velazquez et al., 2011, e.g.) or representative dry/normal years (Varela-Ortega et al., 2011, e.g.). Dessai and Hulme (2007) assessed the robustness of adaptation decisions to climate change uncertainty by performing a local sensitivity analysis on various elements of a hydro-climatic modeling chain, to determine whether the adaptation measures proposed by the local water authorities were sensitive to the different sources of uncertainty in the modeling approach. This differs slightly from the approach presented in this chapter: here robustness is measured by the number of different climate scenarios in which frequency of shortage is reduced by applying the measure. This allows the user to objectively compare different potential drivers of adaptation, in different areas. Results show for instance that even slightly curbing the irrigated area increase in the Lower Ebro area of the Ebro basin could reduce urban and agricultural water shortages in all climate scenarios, whereas this measure could be less robust to climate uncertainty in the Bardenas area.

In most cases individual measures were shown to have little impact on water stress in different areas of the Hérault and the Ebro basin, and no “one size fits all” solution was found. The effectiveness and robustness of adaptation were highly dependent on the basins' characteristics: dominant water uses (municipal or irrigation water demand), storage capacity, etc. In the Ebro basin water uses and resources are more connected than in the Hérault basin. Hence, measures applied uniformly to all sub-basins could have unexpected effects because of upstream-downstream impacts. Indeed the different sub-basins of the Ebro are tightly connected, notably by large water transfers, and because of the high level of consumptive use (i.e. 40% of natural streamflow vs. 3% in the Hérault (see Chapter 3) making different water uses more interdependent.

Finally results showed the need to combine different measures to reduce water stress. The adaptation scenarios presented in the study could be effective but were shown to be insufficiently robust to climate change uncertainties in some areas. The modeling framework also enables the assessment of anthropogenic pressure on water resources, which showed that the adaptation scenarios do not only improve water demand satisfaction, but also reduce the level of pressures on resources. Indeed the adaptation scenarios lead to a decrease not only in demand, but also in consumptive use (by decreasing irrigated areas and unit urban water consumption compared to the trend scenarios). Note that the consumptive use in percentage of natural resources was shown to decrease even with lower environmental requirements.

4.2. Limitations

This chapter showed how the modeling chain presented in Chapter 3 could be used to assess adaptation options based on the trend water use scenarios, which were shown in Chapter 4 to be unsustainable in view of climate change. Since the trend water use scenario was considered as the state of reference for adaptation, the measures

regarding population, tourism and irrigated areas were limited to curbing the planned growth. This methodological choice partly explains the different sensitivity at each demand node: in areas where a large increase in irrigated areas is planned and the current situation is balanced, such as the Lower Ebro, the irrigated area increase could be limited, keeping the system balanced under climate change. Conversely, as explained in section 3.1.2, in the Bardenas area there is little leeway for adaptation through the control of irrigated areas, without decreasing the current irrigated area.

The impact of changes in drivers of water demand and in dam management were compared to the trend water use scenario regardless of the feasibility of such changes, which could in some cases be questioned. For instance the option to curb the population increase compared to the trend scenario can be seen as implausible or unreasonable. However the idea of adapting urban planning and zoning for land use to be compatible with available resources is growing, notably in France. The French national plan for adaptation to climate change (MEDDTL, 2011) and the adaptation plan of the Rhone Mediterranean Corsica water agency (AERMC, 2014a) both call for the adaptation of land use to make it compatible with available resources. Also, limiting the increase in population supplied by the basin could be done by finding new water resources or by capping the volume of water which can be transferred outside of the basin. However these solutions are in fact an augmentation of water supply, bringing about the risk of ever-growing water demand, leading to over-tapping of water resources (Molle, 2008).

The decrease of unit municipal water use seems like a more plausible option, and is largely documented in the literature. Indeed in many developed countries unit water use has already started to decrease (Gleick, 2003; Schleich and Hillenbrand, 2009; Hejazi et al., 2013). Per capita municipal water use varies across countries and regions. While this thesis documented unit water uses of 97 m³/cap/y (or 265 L/cap/day) in the Herault basin and 109 m³/cap/y (or 299 L/cap/day) in the Ebro basin, Schleich and Hillenbrand (2009) reported values of 126 L/cap/day in Germany, 115 L/cap/day in Belgium and 265 L/cap/day in Spain in 2006. Vandecasteele et al. (2014) reported a unit municipal water use of 175 L/cap/day in Germany in 2006. This difference may be due to the fact that water use is not always clearly defined (it could be synonym of water withdrawals, of the water actually used in each household, or the total billed water in a municipality divided by the number of inhabitants, etc.). Gleick (1996) recommended a minimum amount of 50 L/cap/day to meet basic needs for drinking, sanitation, bathing and food preparation. However municipal water use is not only a result of basic water needs, it also includes outdoor domestic use (e.g. for swimming pools and landscaping), outdoor municipal use (landscaping) and industrial and commercial uses connected to the municipal network. According to Hejazi et al. (2014), municipal water use is a function of per-capita income, efficiency, technological improvements, and water prices. Different options have been reviewed for decreasing per capita water use: water pricing, technological upgrading, desert landscaping, restrictions (Hejazi et al., 2014; Panagopoulos, 2014, e.g.). While studies in the literature have simulated possible decreases in unit water use going from 10% to 30% in developed countries (Alcamo et al., 2000; Rinaudo, 2011; Dawadi and Ahmad, 2013; Hejazi et al., 2013), a 30% decrease in unit water use as suggested in the adaption scenarios seems like an ambitious yet feasible option.

The adaptation measure consisting in limiting the irrigated area growth planned in the trend water use scenario aims at limiting the irrigation water demand increase to the supply capacity of the system (considering its water management infrastructures). This measure is more effective in the Ebro basins, where water demand is mostly agricultural and is not limited by other uses. Indeed it is hardly effective in the Agde area of the Herault basin, where a large increase in irrigated areas is planned in the trend water use scenario. In the case of hydrologically independent (upstream, no transfers) agricultural areas (such as the Alto Aragon and Segre areas of the Ebro basin), a limit for the increase in irrigated areas dependent on the system's capacity might be found, in the line of adapting land use to make it compatible with available resources (AERMC, 2014a). An equivalent measure would be to determine the volume allocated to irrigation based on the volume available for supply. Irrigators could then adapt their production systems in order to maximize profit from the available volume (by improving the efficiency of water delivery, by growing more water-efficient crops, etc.). However unintended consequences could derive from this type of policy, such as an increase in irrigated areas and/or in consumptive use despite constant or decreasing water withdrawals (Ward and Pulido-Velazquez, 2008).

In the modeling framework used here, efficiency was defined as the ratio between water actually used (water delivered to municipal users or consumptive use for irrigation users) and water withdrawn from the environment. In the case of irrigation, this definition matches the one of Israelsen (1950), in which Batchelor et al. (2014) argue that the potential for return flows is ignored. Although return flows were considered in the modeling framework, other aspects of efficiency were overlooked. The approach used here does not account for non-productive consumptive use (Perry, 2007; Gleick et al., 2011), e.g. unproductive soil evaporation, yet this type of consumptive use can be non-negligible. Indeed Luquet et al. (2005) showed that unproductive soil evaporation in early stages of cotton development could be reduced by 75 to 85% by shifting from flood to drip irrigation. Also, unintended consequences of efficiency improvements should be considered. For instance, a co-benefit of efficiency improvements can be the improved reliability of a limited supply (Gleick et al., 2011), which might increase water demand from new users attracted by the co-benefits (Lopez-Gunn et al., 2012). Improvements in efficiency can also be accompanied by intensification of the consumptive use of existing water users (Batchelor et al., 2014), an illustration of Jevon's paradox explained by Alcott (2005): technological progress that increases the efficiency with which a resource is used tends to increase (rather than decrease) the rate of consumption of that resource. As for municipal water demand, for which a high percentage of the water withdrawn returns to the environment as treated waste water, Perry (2007) stressed that "it is the location of the diversion and return flows that determines the impact [of efficiency improvements] on total water use and consumption". Indeed an efficiency improvement for a transfer will allow more water to stay inside that basin, whereas an efficiency improvement for municipal uses inside the basin only allows less water to be pumped (thus also reducing the volume of return flows). Nevertheless reducing leakage in supply networks can also be considered as an economic necessity (Rogers, 2014), since pumping and treating water unusefully is also an economic loss.

The measure proposed in the adaptation scenarios to decrease environmental flow requirements by 20% may also be discussed. In the context of rapidly changing environmental conditions (climate, streamflow, water uses, etc.) aquatic ecosystems may require strict conservation measures to enhance their resilience and adaptability. Thus decreasing environmental requirements may appear as an additional threat to ecosystem health. Yet the natural decrease in low flows projected in the 18 climate change scenarios could also be taken into consideration. However the aim of the work presented above is not to make a judgment about such decisions in river basin management, but rather to assess the sensitivity of the balance between water availability and demand to changes in water use and management rules. As mentioned in section 4.1, note that the consumptive use in percentage of natural resources was shown to decrease in the adaptation scenarios, even with lower environmental requirements.

Results showed that modifying management rules for the Salagou dam could improve water demand satisfaction in the Gignac and Agde areas of the Hérault basin. Although this work served as an illustration of how the modeling chain could be used to assess adaptation options for dam management, the adaptation of dam management to fulfill different requirements (water withdrawals, flood management, hydropower production, recreational activities, etc.) constitutes a subject of research in its own right and many studies on the topic can be found in the literature (Yao and Georgakakos, 2001; Raje and Mujumdar, 2010; Gómez et al., 2014, e.g.).

Finally, adaptation measures were applied over the whole basins, without differentiating the demand nodes. Yet some areas may be able to face an increase in water demand, without impacting the balance in other areas. For instance in the Hérault basin, as shown in the adaptation scenario, it may not be necessary to limit the population supplied inside the basin if no additional population is supplied by the Florensac water transfer. In the Ebro basin, some irrigation systems may still be able to face an increase in irrigated areas. For a better insight on the possibilities to improve the balance between water availability and demand at the river basin scale, measures should be tested for each sub-basin or demand node, while assessing their impacts on the whole river basin.

5. Conclusion

This chapter showed the integrative modeling framework developed in this thesis could be used to assess adaptation options to reduce the gap between water demand and availability under scenarios of water use and climate changes. An original method is provided to assess the effectiveness of adaptation measures and their robustness, by simulating the impact of each adaptation measure under 18 climate change scenarios from the CMIP5 exercise, thus covering a wide range of climate uncertainties.

Chapter 6.

Discussion

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1. Introduction

The general objectives of this thesis were to assess the balance between water availability and demand over multi-decadal time periods, to better understand water stress risks and support decisions to adapt to future climatic changes. In this context a special focus was set on the importance of considering the impacts of both anthropogenic and climatic changes, of understanding past changes before looking into the future, and of accounting for uncertainties and their implications for adaptation strategies. Considering the analysis of possible improvements to better assess the balance between water availability and demand and to better address water management issues, the specific objectives of this thesis were to:

- **represent** linkages between water resource and demand in influenced hydrosystems and account for the multi-decadal dynamics of climatic and anthropogenic drivers (in space and over time);
- **assess** the sustainability of water uses under projected climatic and anthropogenic changes;
- **explore** options to reduce the gap between water demand and availability in an uncertain future.

These points were addressed in Chapters 3, 4 and 5 of the manuscript. The study focused on two contrasted Mediterranean river basins, both facing rapid climatic and anthropogenic changes: the Herault basin (2 500 km², France) and the Ebro basin (85 000 km², Spain). First an integrative modeling chain combining hydro-climatic and socio-economic data was developed to simulate the balance between water availability and demand and its spatial and temporal dynamics. The modeling chain was calibrated and validated over a 40-year past period and used to analyze past changes in the water balance. Second, scenarios of water use and climate changes were built for the mid-21st century and the sustainability of planned water uses was assessed with the integrated modeling chain. Finally the effectiveness and robustness of adaptation measures were assessed.

The results of this research are examined in this chapter in light of the research objectives. After an analysis of the advances in the integrated modeling of water stress and the limitations of the work, its significance for water management is discussed. Finally the discussion is opened on vulnerability assessments and their contribution to climate change adaptation.

2. Advances in the integrated modeling of water stress and limitations

2.1. An efficient approach to simulate long-term variations in complex hydrosystems

2.1.1. Integrating climatic and anthropogenic drivers over a long past period

Chapter 3 showed that the modeling chain developed in this thesis efficiently simulated the balance between water availability and demand, over nearly four decades

(1971–2009). As stated in the literature review (Chapter 1), a correct historical reconstruction of streamflow and, more generally, of the water balance, is an essential step prior to using models in prospective studies. According to Krol et al. (2006), “a reasonable dynamic understanding [of the system] is preferred over an excellent static understanding”. Few studies in the literature included a retrospective, dynamic analysis of the balance between water availability and demand over such long time periods. Here the hydrological model was calibrated against 29 years of observed natural streamflow data (1981–2009). This period, warmer and drier than the validation period (1971–1980), comprises relatively drier (the 1980s and the 2000s) and wetter (the 1990s) decades. The validation of simulated influenced streamflow against observed influenced streamflow data over the 1971–2009 period showed the ability of the modeling chain to represent the Hérault and the Ebro systems’ dynamics.

The variations in the balance between water availability and demand were simulated by modeling water resources and their availability, as well as water demand. Thus the influence of both climatic and anthropogenic drivers on the water balance was accounted for. The influence of water management on water availability was accounted for, notably by modeling dam operations or by simulating water transfers considering the transportation capacities in place. In particular, the reconstruction of past changes in water demand taking into account socio-economic but also climatic changes was essential to the modeling chain. Since no water withdrawal data were available at a finer time scale than annual values, reconstructing series of natural streamflow through data analysis would have been impossible. However, note that the reconstruction of past water demand was challenging precisely because of the lack of data.

2.1.2. Accounting for the complexity of water management

The literature review in Chapter 1 also underlined the need to account for the complexity of water management in meso-scale and large-scale hydrosystems, by proposing relevant conceptual representations of water availability and demand and by addressing the complexity of the water balance, including anthropogenic influence on streamflow. The heterogeneities in water use and management practices in the Hérault and the Ebro basins were accounted for by means of the mapping of resource and demand nodes. The representation of these complex hydrosystems involved a large collection of information from databases and other sources such as gray literature (water management plans, technical reports) and collaboration with local stakeholders. As stated by Sivapalan et al. (2012), “an important part of understanding socio-hydrologic processes is to understand which way the water is flowing and why it is so”. This is particularly relevant in cases such as the Ebro basin, where many transfers occur between sub-basins, and some dams in the headwaters are operated based on demand and streamflow hundreds of kilometers downstream (e.g. the Ebro dam). Locating the strategic resource and demand nodes and understanding the management of the multiple (sometimes reversible) canals was only possible through field visits and the review of gray literature.

Anthropogenic influence on streamflow was accounted for by simulating natural streamflow throughout the entire basins, as well as the modifications caused by human water use, i.e. storage and release operations and consumptive use. The quantification of consumptive use brought a useful insight to the analysis of changes in the water

balance. For instance, it made it possible to estimate the part of discharge decrease that was due to anthropogenic pressures. Also, the impacts of efficiency improvements in scenarios of future changes were assessed. Indeed Ward and Pulido-Velazquez (2008) showed that water conservation measures could increase irrigation water use, and that the adoption of more efficient irrigation technologies could reduce return flows and limit aquifer recharge, thus causing a further depletion of water resources. By including consumptive use and return flows, the modeling chain allows to address the complexity of water management and to anticipate such consequences of well-intended measures.

2.1.3. Transferability of the modeling chain

One of the aims of studying two contrasted hydrosystems was to question the transferability of complex, integrated models. The modeling chain was developed in different contexts, be it by the type of available data or the basin's characteristics and water management stakes. The methodology was common to the two basins. In terms of data availability, an additional climatic data processing step was necessary in the Ebro basin (i.e. the selection of temperature and rainfall measurements and the interpolation of the time series on a grid scale), compared to the Hérault basin for which the SAFRAN reanalysis was available. Note that a SAFRAN reanalysis is currently being implemented over the Ebro basin (Quintana-Seguí et al., 2015), however to date only a one-year pilot implementation has been validated.

The method applied to simulate natural streamflow was the same between the two basins. However this approach would not be transferable in certain hydrological regimes such as purely snow or ice melt systems, where the streamflow peak corresponds in time with the summer peak in water demand. In such cases peak flows could not be taken out for calibration. In the case of the Ebro basin, the upstream sub-basins were considered uninfluenced by water use, thus hydrological simulations of the snowmelt regime were calibrated against all available data. Also, in the context of the Hérault and the Ebro basins the study concentrated on the balance between blue water use and availability. However in some regions (probably the most vulnerable ones to climatic and anthropogenic changes) agriculture is mainly rain-fed. Thus impact and vulnerability assessment methods should be designed to study a continuum between green and blue water (Vidal et al., 2009), in order to be applicable in different types of hydrosystems.

As was shown in this thesis the conceptual representation of the main resource and demand nodes is a key step in the modeling of contrasting hydrosystems of different sizes and levels of complexity. In this process data availability strongly constrains the scale and time-depth of the study. For instance, modeling the Ebro basin implied accounting for both a complex, real-time operations system, and long-term planning considerations. The conceptual representation of this hydrosystem for its modeling was driven mainly by the existence of large irrigation systems and by streamflow regulations by storage dams and canals. This was made possible by the availability of long time series of streamflow and reservoir level data. Water resource management in the Hérault basin is less centralized than in the Ebro basin, and withdrawals are more diffuse and water uses more diversified. Some specific management stakes needed to be represented in the Hérault hydrosystem, such as the integration of touristic water use and strong environmental requirements.

2.2. Uncertainties and limits to the use of the modeling chain in prospective studies

2.2.1. Partial calibration and validation of the elements of the modeling chain

Because of data availability and methodological barriers, the calibration and validation of the modeling chain showed some shortcomings. First, the simulation of natural streamflow was constrained by the lack of observations or measurements of natural streamflow, and/or water withdrawals data which would have made a reconstruction of natural streamflow series possible. The method chosen here to simulate natural streamflow (i.e. to calibrate the hydrological model only on the time steps for which net consumption was considered to be negligible) was not found in other studies in the literature. Most often, the natural resource is simulated upstream from water abstractions or reservoirs, in elementary sub-basins (López-Moreno et al., 2014, e.g.). In other cases, a hydrological model was calibrated against streamflow data from an earlier period preceding most water abstractions and/or in areas upstream from abstractions (the parameters obtained then being transferred to the influenced basins). In this way the model SIMPA (Monreal et al., 1999) was calibrated and applied over Spain to assess the country's natural resources for the Spanish White Book on Water (MMA, 2000). The model was calibrated over the period 1940–1995 using only gauging stations uninfluenced by water use.

Considering the hydrological regimes of the Hérault and the Ebro basins, the method proposed in this thesis implied calibrating the GR4j model mostly on high and medium flows, low flows being left out since they are concurrent with a peak in water use. This could evidently be a source of bias in the assessment of natural water resources. In the Hérault basin, low flows originate mostly from karst springs, i.e. the River Vis with its karst resurgence of typically 1.5 to 2 m³/s during summer months, and springs located in the Hérault Valley upstream from Gignac such as the “Cent Fonts” spring with low flows of approximately 350 to 500 L/s (Ladouche et al., 2006). Without data on low flows, the hydrological model could misrepresent the processes linked to these springs, thus its robustness in prospective scenarios could be questioned. In the Ebro basin, the intensive water use left very few data for calibration in the semi-arid sectors of the Ebro Valley, thus the model was not able to simulate streamflow correctly.

Another difficulty in the validation of the modeling chain should be underlined, regarding the water demand model. Indeed as stated in Chapter 3, accurate validation of water demand simulations in space and over time was not possible due to the lack of appropriate data on withdrawals. Water withdrawal data are not available at a finer time step than a monthly one, and water abstractions for irrigation are seldom metered. In the Hérault basin, part of the Rhone-Mediterranean and Corsica Water Agency management area, only annual data (starting in 1987) was available. Moreover these data are related to the taxes paid by water users to the Agency, and may not be representative of the actual water use. The Agency itself warns users of the data to be cautious if applying the data to water resources assessments (AERMIC, 2014b).

Finally, simulations included a calibration of return flows, i.e. a determination of the percentage of water losses that ended up returning to streamflow. This calibration was not linked to any physical reality or measurement, and the return flows obtained may

compensate other biases in the modeling chain (natural streamflow and/or water withdrawal simulations, e.g.). In the Hérault basin all water losses were assumed to return to the outlet of the sub-basin as surface flow at a 10-day time step, an unlikely result in reality. This could be due to the fact that natural low flows might be underestimated (with an inaccurate representation of the functioning of karstic springs notably) or water demand might be overestimated (particularly for vineyard irrigation, which is driven more by quality considerations for wine production than for maximum yields).

2.2.2. Uncertainties in hydrological modeling under non-stationary conditions

Notwithstanding the partial validation of the modeling chain, the use of hydrological models with parameter values calibrated against historical observations to predict responses to climate change may be questioned (Vaze et al., 2010; Coron et al., 2012, e.g.). Uncertainties linked to hydrological models used in non-stationary conditions may stem from miscalibration or overcalibration of the model parameters (Andréassian et al., 2012). Miscalibration can be linked to a failure of the search algorithms to localize the exact mathematical optimum in the climatic conditions of the calibration period. Overcalibrated parameters, on the other hand, may correspond to a perfect mathematical optimum; however they may not be suitable for extrapolation under different conditions. Overcalibration can be linked to an ill-adapted objective function used for calibration, a too short calibration period, or problems in the model structure (Andréassian et al., 2012). Several studies found that hydrological models calibrated against historical data could fail to adapt to non-stationary conditions (Vaze et al., 2010; Coron et al., 2012; Brigode et al., 2013; Lespinas et al., 2014; Ruelland et al., 2015). Efficiency losses were found to be greater for transfers from wetter to drier periods, than the other way around (Vaze et al., 2010; Coron et al., 2012). Moreover, changes in mean precipitation seem to be the main cause for poor parameter transferability.

Another source of uncertainty in hydrological modeling is the quality of the data used for input in the model. In this way, the hydrological model's efficiency may improve with the density of rain gauges in the basin (Andréassian et al., 2001). In the Ebro basin, the eastern sub-basins of the Pyrenees presented a low density of rain gauges, which may be a cause of misvaluation of water resources in this area. Also, the potential evaporation formulation can be a source of uncertainty for hydrological climate change impacts (Kay and Davies, 2008). Conversely to the Penman-Monteith formulation used in the Hérault basin, the Hargreaves formulation only uses temperature to calculate potential evaporation (with an empirical wind factor kept constant in time). Yet physically, evaporative demand is driven by net radiation, vapor pressure, wind speed, and air temperature, all of which have changed in the past decades and could evolve under climate change (Donohue et al., 2010). Several studies have found that evaporative demand has decreased in certain areas of the Earth, notably due to a decrease in wind speed (Donohue et al., 2010; McVicar et al., 2012).

Finally, non-stationary conditions for hydrological modeling also include the non-stationarity of water uses, water management practices, etc. The variability of water demand simulated over the past 40 years and the high level of water use influence on streamflow showed that non-stationarity in anthropogenic drivers was a key element to be considered in hydrological modeling. In this regard simulations were obviously not

perfect due notably to the non-exhaustive consideration of all storage-dams and to our limited knowledge on water withdrawals, which led to an impossible validation of water demand simulations and to a debatable hypothesis concerning the modeling of natural streamflow.

2.3. Shortcomings in the integration of human and physical drivers of water stress

2.3.1. Drivers of changes in water resources

The drivers of changes in water resources (i.e. natural streamflow) taken into account in this study were exclusively climatic. Indeed the rainfall-runoff relationships of all sub-basins were considered unchanged in future scenarios, since the parameters of the hydrological model were kept equal to the values found for the calibration period. However factors other than climatic changes can affect the precipitation-runoff relationship, such as land use or land cover changes. In this respect, Gallart and Llorens (2003) found that the decrease in streamflow observed in the Ebro basin over the past 50 years could be partly explained by an increase in forest cover in the headwaters of the basin. They found that one third of the observed decrease could not be explained by human consumption or by climate, and linked this to an increase in evaporation in the headwaters due to reforestation. In the same way Morán-Tejeda et al. (2012) investigated possible causes for the river discharge decrease observed in the Duero basin (Spain) in the past 50 years. In the absence of significant trends in human consumption or precipitation, they concluded that revegetation had contributed to the observed streamflow decrease. However, in a typically Mediterranean climate such as the one observed in the Herault basin, reforestation could have less impact on water resources. Indeed the effect of forest on runoff is mainly a more efficient use of soil moisture reserve during summer and an increased interception of incidental rainfall. With relatively shallow soils and considering the high intensity of Mediterranean storms, the conditions do not seem conducive to these types of impacts (Cosandey et al., 2005).

Another shortcoming in the integration of drivers of changes in water resources is the lack of simulation of groundwater resources and groundwater-surface flow links. As was discussed in Chapter 3, other models that properly account for surface-groundwater interactions exist (Pulido-Velazquez et al., 2007, 2012, e.g.), however the application of such models at the scale of the Herault or the Ebro basin is complex, considering the heterogeneity of hydrogeological contexts and the availability of piezometric data, too sparse in space and in time to allow acceptable calibration and validation of a more complex hydrogeological model over the 40-year period.

2.3.2. Drivers of changes in water demand

A number of physical and anthropogenic drivers of changes in water demand were not accounted for in this study. For instance, more physical processes could be included in the irrigation water demand model. First, the crop coefficients K_c were considered constant over the years. Yet environmental factors such as the soil water content may affect evapotranspiration. In this way Allen et al. (1998) suggested an adjustment of K_c in water stress conditions. Evapotranspiration can also be reduced in case of excessive

heat, i.e. temperature stress (Woznicki et al., 2015). Additionally, a dual coefficient approach could have separated plant transpiration from soil evaporation, thus enabling a simulation of changes in agricultural practices that could decrease soil evaporation and thus decrease consumptive use without decreasing the crop yield. Second, the effects of variations in atmospheric concentrations of carbon dioxide on crop behavior (Taub, 2010) were not accounted for. Reductions in leaf stomatal conductance with increasing concentrations of atmospheric carbon dioxide could reduce plant transpiration and hence reduce crop water use, moderating the impacts of climate change on agricultural water demand (Bunce, 2004). Finally, increases in temperature can accelerate crop development (Meza et al., 2008, e.g.), inducing changes in crop calendars.

The irrigation water demand model used here was based on a calculation of theoretical water needs to achieve maximum crop yields. However the decision to irrigate and the water volumes applied usually depend on other practical factors. Water turns are typically a widespread management practice for traditional irrigation canals: each user is authorized to abstract water from the canal for a certain number of hours per week. This practice corresponds to flooding irrigation techniques, where the volume of water applied to the field certainly depends on the level of water stress but also on the water turns. Moreover the aim of irrigation is not necessarily to maximize crop yields, with considerations such as economic return of irrigation (Paredes et al., 2014) or crop quality. In this way the irrigation of grapes grown for wine production (as is the case in the Hérault and the Ebro basins) generally aims for regularity of production and quality (Zarrouk et al., 2012; Romero et al., 2013). In particular, deficit irrigation is a wide-spread technique to obtain a higher quality of grapes (Santesteban et al., 2011).

Regarding the municipal water demand model, unit consumption data was used without considering the drivers behind its variations. Nevertheless, as stated in the discussion of Chapter 5, municipal water use can be a function of per-capita income, efficiency, technological improvements, and water prices (Hejazi et al., 2014). Moreover the proportion of outdoor water uses in a municipality, and the corresponding climatic conditions and efficiency, can impact the water consumption per capita. Thus apart from estimating possible decreases in unit consumption in adaptation scenarios, the modeling chain does not allow a quantitative assessment of the efficiency of demand management policies such as water pricing, technological upgrading or xeriscaping in reducing the gap between water availability and demand. Finally, the drivers of change in water demand for industrial and energy production were not explicitly accounted for in this study.

2.3.3. Towards dynamic integrated models simulating interactions between social and biophysical features

Gallopín (2006) stated that “issues related to vulnerability, resilience and adaptive capacity emerge from the dynamic interplay between the social and ecological components of social ecological systems”. In the same way, advocates of socio-hydrology stress that the connections between water and humans need to be studied more deeply, and that the social and physical features of hydrosystems co-evolve and interact in dynamic ways (Sivapalan et al., 2012; Montanari et al., 2014). Mitchell (2005) considers that two interpretations have developed in association with the holistic approach to water resources management: comprehensive (associated to a need to understand all variables and rela-

tionships), and integrative (which emphasizes key or selected variables and relationships, while maintaining a system orientation). In this mindset, the approach presented in this thesis aimed to be integrative but did not reach a comprehensive view of the water balance. It accounted for many links between human and physical components of the systems, but did not include feedbacks between these components. For instance in the Ebro basin a re-negotiation of water allocations and dam operations is carried out before each irrigation season. The basin is divided into 17 *Juntas de Explotación*, i.e. Operations Committees bringing together representatives of the different water users. According to the reservoir levels and the snowpack of the year, a 6-month management plan is proposed for the dams in each of the committees' territories. These dynamic feedbacks between water availability and water management were not accounted for in the modeling chain. Also other criteria determining water use and availability were not included in the modeling chain, such as water quality. In this way, future plans in the Ebro basin include a new water transfer from the Yesa dam to the city of Zaragoza, not because the Ebro River is insufficient in terms of water quantity, but because of increasing levels of pollution.

A holistic approach of the water cycle dynamics over long time periods exceeds the scope of a PhD thesis. It calls for multi-disciplinary collaboration (Sivapalan et al., 2012; Montanari et al., 2014), beyond an eventual juxtaposition of discipline-oriented integrated approaches. However one could ask the question of how much can actually be integrated in a model and do we have to wait to have the perfect model before it can be used? A scenario-based approach using an integrated model can respond to Integrated Water Resources Management challenges (Sav) by assessing the ways in which management decisions that are being considered could affect runoff, and conversely in what way these decisions could be affected by runoff (Sivapalan et al., 2012). This type of approach would not necessarily strive to *predict* the co-evolution of social and hydrological processes, but rather to *project* plausible future changes and to assist decision makers in foreseeing some of the unintended consequences of water policies. It is obvious that hydrosystems will not respond to climatic and anthropogenic changes exactly in the ways projected by integrated models. Climate change impacts will most likely induce adaptations, notably by farmers (Meza et al., 2008; Molle et al., 2010a). Nevertheless crop production systems respond to many biophysical and management related factors; according to Olesen et al. (2011) their interactions make the farming systems' response to climate change too complex of a task to be handled by models alone. The authors argue that a semi-quantitative approach with knowledgeable experts could help to cover many more interacting factors.

3. Significance for water management: changes in the balance between water demand and availability

3.1. A better understanding of the processes leading to water stress

3.1.1. In the past

Integrating climatic and anthropogenic drivers of water stress and simulating the water balance over multi-decadal periods contributed to develop a better understanding of the processes leading to water stress, by analyzing the past and projecting future changes.

Analysis of past data showed a decrease in streamflow in both basins. Also, growing attention is being paid to quantitative management and sustainability. This thesis contributed to an objective understanding of these past changes in water stress, by simulating all the components of the balance between water availability and demand (i.e. natural streamflow, water demand, water withdrawals, dam management, consumptive use and the resulting influenced streamflow) dynamically in space and over time.

First, results showed spatially heterogeneous changes in water stress, with some areas (mostly the downstream areas) experiencing increasing stress, while other areas had a more stable balance. The simulation of theoretical water shortages with current water uses and the climate variability of 1971–2009, compared to the reconstruction of actual water shortages in the same period, showed that in some areas the warmer and drier conditions of recent years affected water demand satisfaction. Conversely in some large irrigation systems of the Ebro basin and in the lower Hérault valley (Agde area) the increase in irrigated areas and population contributed for a larger part in the increase of water shortage frequency. Although the storage capacity of the Ebro basin seemed to enable it to absorb climate variability and a certain increase in demand, the results did not show clear differences in the causes of water shortage between the Hérault and the Ebro basins. Contrasts in the causes of water stress changes were as large between sub-basins of the same river basin as between the two study areas. However one clear difference between the two basins is that the main changes in water demand are concentrated on municipal water use in the Hérault basin and on irrigation water use in the Ebro basin.

Second, simulating natural and influenced streamflow made it possible to propose an explanation for the observed decrease in streamflow (with the limitations cited earlier in section 2 of this chapter). Lespinas et al. (2009) assumed that past trends in the Hérault basin might be partially related to an increase of abstraction. In the same way, Collet et al. (2014) stated that the increase in water withdrawals in the Hérault basin probably contributed to the decrease of low flows in the downstream areas. However they did not propose a quantification of this contribution. While 3% of the decrease in observed discharge at the outlet of the Hérault basin were linked to an increase in consumptive use, the latter was estimated to have been responsible for 20% of the decrease in observed discharge at the outlet of the Ebro basin.

3.1.2. In the future

This thesis not only provided projections of future water stress under scenarios of climatic and water use changes, it separated the influence of climatic and anthropogenic changes on future changes in the balance between water availability and demand. Previous studies in the Hérault and the Ebro basins provided projections of climate change impacts on water resources (Rasilla et al., 2013; Lespinas et al., 2014, e.g.). Few studies have considered the combined impacts of climate and water use changes (Milano et al., 2013a; Collet et al., 2015, e.g.), and only Collet et al. (2015) distinguished the impacts of climate and water use changes on water demand satisfaction in the Hérault basin. This separation of the impacts of climatic and anthropogenic changes contributed to a better understanding of water stress risks in the two basins.

While the water use change scenario hardly impacted water demand satisfaction in the Hérault basin (only slightly increasing agricultural water shortage frequency in the lower Hérault valley), it could lead to increased water stress in the northern (left bank) sub-basins of the Ebro. Yet this is only the case when water use changes are combined with climate change. Thus although projections of water demand satisfaction under combined climatic and anthropogenic changes were pessimistic in both the Hérault and the Ebro basins, the large irrigation systems of the Ebro basin, in their current state, were found to be less sensitive to climate change scenarios than the Hérault basin. Although further analysis would be needed to confirm this analysis, the storage capacity of the Ebro basin might explain this difference.

3.2. Providing projections of water stress and assessing adaptation options

3.2.1. Sustainability of planned water uses

The literature review (Chapter 1) showed a need for research on the implications of climate and water use changes on quantitative water management as a whole. This thesis addressed this need by providing projections of water shortage risks that were relevant for water managers. The projections assessed the sustainability of planned water uses in both basins. Notably the assessment of both water demand satisfaction and anthropogenic pressure on water resources contributed to a more integrated view on water management. Although some of them assessed the capacity of hydrosystems to meet environmental streamflow requirements, most studies assessing future changes water supply capacity did not include an assessment of the pressure on aquatic ecosystems resulting from water use in prospective scenarios (Milano et al., 2013a; Collet et al., 2015, e.g.).

In this way, projections showed that not only could water abstractions be limited more frequently than the management goal, but the impact of water use on streamflow could strongly increase by the mid 21st century. However because of the large storage capacity in the Ebro basin climate and water use changes could result in increased storage in the fall, winter and spring (a higher percentage of natural streamflow being kept in the reservoirs) and a decreased impact on streamflow in the summer (as a percentage of natural streamflow) because of maintained outflows from the dams. This differs greatly from the Hérault basin, in which the anthropogenic pressure on water resources could double (as a percentage of natural streamflow) during the months of June, July and August.

3.2.2. Exploring and assessing adaptation options or changes in the trend scenario

Chapter 5 showed that the modeling chain could also be used to assess adaptation options to reduce the gap between water availability and demand under scenarios of water use and climate changes. The sensitivity of water shortages to each of the anthropogenic drivers considered in the model was tested. This underlines the importance of simulating water demand and water management, as opposed to using observed data or variations of water demand compared to past data (Pulido-Velazquez et al., 2011; López-Moreno et al., 2014).

3.3. Analyzing the changes through the use of indicators and dealing with uncertainties

3.3.1. Contributions and limitations of the indicators

The literature review underlined a need for relevant indicators to address vulnerability and inform adaptation decisions. The indicators used in this study were related to the frequency and intensity of water shortages. Additional indicators and different representations were used for the analysis of past changes (Chapter 3) compared to projections of future changes (Chapters 4 and 5). The chronological representation used in Chapter 3 is informative for stakeholders: it can indicate gradual or sudden changes, the succession of problematic years, etc. However this type of representation did not seem suitable for projections in which the projections of inter-annual climate variability were irrelevant (due notably to the method used to generate climate scenarios). The same can be said regarding the average length of water shortage episodes of the related resilience indicator.

Moreover, multiplying the number of indicators (five different indicators were used to assess the sustainability of current water uses in Chapter 3) can make the interpretation and communication of results difficult. Sustainability science and the use of indicators require a developed collaboration between science and decision-making (Turner et al., 2003; Vogel et al., 2007). Vogel et al. (2007) pointed out the fact that policy makers and managers usually do not receive the information they need. Although the information conveyed by the indicators in Chapter 3 could be relevant for decision-making, their representation was complex and exchanges with water managers were difficult. Adding to the need to convey the range of climate uncertainties in the projections, this led to reducing the number of indicators and expressing the frequency and intensity of water shortages in the radar charts.

Nevertheless some authors have questioned the use of indicators to assess and predict water stress (Molle and Mollinga, 2003; Hinkel, 2011, e.g.), arguing that indicators tend to aggregate reality and even out spatial and temporal heterogeneities. Although Molle and Mollinga (2003) 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, indicators were used 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 thesis 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 (2011), cannot be measured. Other indicators could characterize water stress changes. For instance the filling of reservoirs could indicate if changes in streamflow could cause existing or planned infrastructure to be improperly sized. Also calculating the water stress of irrigated crops could put the water shortages into perspective: what percentage of potential evapotranspiration did the shortage represent?

3.3.2. Dealing with uncertainties

Uncertainties are a key element to take into account while designing adaptation strategies. While continued efforts must be carried out to improve models in order to better serve decision making (Milly et al., 2008; Kundzewicz and Stakhiv, 2010; Sivapalan et al., 2012; Montanari et al., 2014), predictive and modeling uncertainties will not be reduced before decisions on adaptation to future climate change need to be taken (Wilby, 2010). Hence the implications for water management of uncertainties in future changes need to be addressed. This study contributed to doing so by considering a wide range of climate change scenarios and their implications for the sustainability of planned water uses and the assessment of adaptation measures.

The range of future climates was given by using many climate models. In other studies climate change uncertainties were conveyed by building simple scenarios of multiple combinations of incremental increase/decrease in temperature and precipitation (Sultan et al., 2013; Collet et al., 2015). While the scenarios were built for a crop model running from May to September in Sultan et al. (2013), Collet et al. (2015) used the scenarios for multi-decadal integrated simulations of water stress. The changes in temperature and rainfall were thus considered homogeneous through the seasons. Although the uncertainties in climate modeling are deep, considering equal changes throughout the seasons (notably in rainfall) does not necessarily improve the quality of the information delivered to local stakeholders. Using such a method reduces the range of uncertainties by eluding some changes that could be crucial for water management, such as a possible rainfall increase in autumn and winter that could contribute to replenish water resources.

The implications of climate change uncertainties on the evaluation of adaptation measures were assessed in this PhD thesis through the use of the robustness criteria, i.e. the number of climate scenarios in which the system was sensitive to a given adaptation measure. Most studies on adaptation to climate change characterized a system's performance using a single hydro-climatic change scenario (Pulido-Velazquez et al., 2011, e.g.) or representative dry/normal years (Varela-Ortega et al., 2011, e.g.). However in this study only the implications of the uncertainties in climate modeling were accounted for. Yet many other sources of uncertainties (discussed in section 2 of this chapter) could have an impact on simulation results, notably the modeling of natural streamflow, water demand, and dam management.

4. Grounding climate change adaptation in a solid understanding of the vulnerability of water uses

4.1. What is vulnerability and how is it linked to adaptation?

4.1.1. A widely used and debated concept

In everyday vocabulary, vulnerability is a measure of possible future harm (Wolf et al., 2013). Hence it seems reasonable to aim to ground climate change adaptation in a solid understanding of the vulnerability of water uses. Vulnerability and adaptation have become central to research in the field of global change, however the multidisciplinary nature of this field leads to linguistic, paradigmatic, theoretical and methodological tensions (Vogel et al., 2007). Vulnerability, as a theoretical concept linked to sustainability, environmental and climate change sciences, is defined and conceptualized in different ways according to the field of research (Gallopín, 2006; Füssel, 2007; Plummer et al., 2012), and it appears it “has no universally accepted definition” (Downing et al., 2005). In fact according to Timmerman (1981), “vulnerability is a term of such broad use as to be almost useless for careful description at the present, except as a rhetorical indicator of areas of greatest concern.”

The concept of vulnerability was originally used in geography and natural hazards research (Füssel, 2007). In the field of risks and hazards, it is a property of the system exposed to hazard (i.e. a dose-response relationship between the hazard and its adverse effects), and risk is measured by a combination of the hazard and the vulnerability of the system to the hazard (Downing et al., 2005; Füssel and Klein, 2006). For Gallopín (2006) a system may be very vulnerable to a certain perturbation, but may persist without problems if it is not exposed to it. In a social-constructivist framework, social vulnerability is an *a priori* condition determined by socio-economic and political factors (Füssel and Klein, 2006). According to Adger (2006), “vulnerability is the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt”. Going beyond differences between physical and social vulnerability, the IPCC gives a definition of vulnerability specific to climate change: as “the degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change” (Füssel and Klein, 2006; IPCC, 2007). Hence in this case vulnerability is the residual impact of climate change after adaptation measures have been implemented.

Thus many conceptual and semantic ambiguities exist in the theoretical field of vulnerability. Vulnerability can be a starting point or an outcome, it can be expressed in relation to an external stressor or to an undesirable outcome, as an inherent property of a system or contingent upon a specific scenario of external stresses and internal responses, and it can be a static or a dynamic concept (Füssel and Klein, 2006). If exposure is externalized from the concept of vulnerability, then vulnerability is considered to be a property of the system, becoming expressed when the system is exposed to the perturbation; if exposure is included in vulnerability, then vulnerability is a property of the relationship between the system and its environment, rather than a property of the targeted system (Gallopín, 2006). While theoretical definitions of vulnerability remain vague, different operational definitions, i.e. concrete methods for assessing vulnerability, can be found and divided into three types (Wolf et al., 2013): evaluation of harm for projected future evolutions, evaluation of the current capacity to reduce harm, or a combination of the latter.

4.1.2. Linkages with adaptation and other concepts like resilience and robustness

The emergence of vulnerability assessments is linked to the need for adaptation to climate change, since adaptation aims to reduced vulnerability (Smit and Wandel, 2006). Vulnerability assessments aim to identify people and/or places that are most susceptible to harm and to identify actions to reduce vulnerability (Luers, 2005). Hinkel (2011) stated that these assessments had become a political necessity for allocating global resources to the most vulnerable countries, raising awareness of climate change, and monitoring adaptation policies.

A concept often linked to vulnerability and adaptation to climate change is resilience. The resilience of a social-ecological system refers to the magnitude of disturbance that can be absorbed before it changes to a radically different state, as well as the capacity for adaptation to emerging circumstances (Adger, 2006). According to Folke (2006), a vulnerable social-ecological system has lost resilience, and losing resilience implies loss of adaptability. When the resilience of a system is exceeded, it will need to adapt. Anticipative adaptation can also aim to increase the resilience of a system, i.e. to widen its climatic coping range (Plan Bleu, 2011). Walker et al. (2004) defined resilience as the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks. This definition covers a certain type of adaptation. In fact, in this point of view resilience could be understood as the capacity of a system to adapt (to climate change). Beyond a certain level of change, the system might not be able to adapt but will need to be transformed.

Hence the concepts of vulnerability, resilience and adaptation are tightly linked, however the linkages between these concepts are not clearly defined. This is partly due to the fact that climate change vulnerability assessments implicate both social and natural sciences, which may have a very different view on these concepts. In order to better understand the implications of climate change for social-ecological systems and to advance research on the ways to respond to the impacts, Gallopín (2006) stated that “reaching some kind of agreement between social and natural scientists working together on global change on the way the concepts [of vulnerability, resilience and adaptive capacity] are used would represent an important step forward.”

4.1.3. Top-down and bottom-up approaches to vulnerability assessments

According to Downing et al. (2005) vulnerability assessments aim to identify and characterize the manner in which human and natural systems are sensitive to climate. Dessai and Hulme (2004) distinguished physical vulnerability from social vulnerability, and in the same way, top-down approaches from bottom-up approaches to assess vulnerability. Top-down approaches are model- and scenario-based. Climate simulations from global climate models are generally used (after having applied a downscaling technique) as inputs for impact models (hydrological, e.g., in the case of water resources assessments). The impact models can be linked to system models such as water management models or integrated models of the water balance. The modeling chains are then sometimes used to analyze adaptation measures. Top-down approaches correspond to a definition of vulnerability that includes exposure to climate change. Bottom-up approaches are decision-centered (Girard et al., 2015). They focus on social vulnerability and adap-

tive capacity to climate variations, and correspond to a definition of vulnerability that excludes exposure to climate change. Thus bottom-up approaches usually concentrate on past climate variability and the analysis of the system's reaction to past pressures or stresses.

As was underlined by Plummer et al. (2012), water vulnerability assessments need to be holistic. Considering the wide range of social and biophysical features of hydrosystems and the multiple concepts linked to sustainability, climate change vulnerability and adaptation, Turner et al. (2003) identified a number of elements to include in vulnerability analyses: multiple interacting stressors, exposure, sensitivity of the system to the exposure, capacity to cope or respond, and the system's restructuring after the response is taken. This holistic approach to climate change vulnerability and adaptation requires a combination of top-down and bottom-up approaches (Farley et al., 2011; Bhave et al., 2014; Girard et al., 2015). While climate, hydrological and water management models bring crucial information on the possible exposure of the system to harm (with uncertainties increasing along the modeling chain), it is essential to determine locally suitable adaptation options, and the evaluation of adaptation options should involve both qualitative and quantitative approaches (Bhave et al., 2014). The analysis of past changes, although future climate variability may reach beyond what has been observed in the past, can contribute to qualify vulnerability. Moreover the inherent knowledge of stakeholders regarding adaptation and their ability to think unconventionally outside the framework of impact models are of great value for the design of adaptation strategies (Bhave et al., 2013).

4.2. Contribution to the assessment of vulnerability and adaptation

Considering the analysis of the concepts of vulnerability and adaptation presented above, this section will review in what this thesis contributed to the assessment of vulnerability and adaptation to climate change in the Hérault and the Ebro basins. To be more specific, it will consider the vulnerability of water uses to climate change and the adaptation of water management to reduce this vulnerability.

4.2.1. Analyzing past changes in the water balance

Giving historical context and explaining the past variations in water demand satisfaction can help understand the vulnerability of hydrosystems to climatic and anthropogenic changes. In this way the analysis of the water balance over the past four decades carried out in Chapter 3 did not only serve to validate the modeling chain. For instance the analysis of the past changes in water demand satisfaction showed the sensitivity of water demand for vineyard irrigation in the Hérault basin. Conversely, despite large decreases in available water resources, water demands remained fully satisfied in the downstream areas of both basins (the Agde area in the lower Hérault valley and the Lower Ebro irrigation system in the Ebro basin).

Note that the projections of water use sustainability by the mid-21st century show the contribution of top-down, scenario-based modeling approaches in addition to bottom-up approaches considering past vulnerability to climate variability. Areas which seem to be able to cope with climate variability in the past could face different conditions in the future and exhibit unexpected vulnerability. In the projections presented in Chapter 4, this is the case for example of the upstream areas of the Hérault basin and the Lower Ebro Segre areas of the Ebro basin.

4.2.2. Water stress projections and indicators contributing to assess vulnerability

This thesis also contributed to the assessment of the vulnerability of water uses to climate change by providing projections of the balance between water availability and demand, using indicators linked to water management. It identified the manner in which the water balance of the Herault and the Ebro basins could be sensitive to climate change. Exposure to climate change was assessed by providing downscaled climate projections over the basins. The resulting projections of natural streamflow could be considered as an assessment of the exposure to change or of an element of the sensitivity of the system to climate change. Finally projections of water demand satisfaction and compliance with environmental requirements indicated the sensitivity of water uses to changes, or, following the IPCC definition of vulnerability, the degree to which water uses were susceptible to adverse impacts of climate change.

Although Hinkel (2011) argues that vulnerability cannot be measured, studies using various vulnerability indicators to assess the sustainability of water supply systems are found in the literature. In these studies (Fowler et al., 2003; Asefa et al., 2014; Collet et al., 2015), vulnerability is defined by the extent of the failure of supply to meet demand (or the maximum gap between supply and demand over a given period). Other indicators are used to measure the reliability and resilience of the systems, which, according to the theoretical literature on vulnerability, are concepts that could be considered as elements of vulnerability. The indicators used in this thesis to represent the sustainability of water uses by the mid-21st century contributed to assess the vulnerability of water uses. The latter can be considered vulnerable if climate change projections induce an increase in the frequency and/or intensity of water shortages.

4.2.3. The assessment of adaptation options

By assessing the effectiveness and robustness of adaptation measures and scenarios, the question of the coping capacity of the hydrosystems was approached. The sensitivity of the system to adjustments in water management compared to the trend scenarios was considered, thus contributing to assess if water uses were capable of reaching sustainability under climate change scenarios. In this way the research went beyond an impact assessment: according to Füssel and Klein (2006), a distinction can be made between impact assessments, first generation vulnerability assessments, and second generation vulnerability assessments. First generation vulnerability assessments are an extension of impact assessments that evaluate climate impacts in terms of their relevance for society and by the consideration of potential adaptation. Compared to impact assessments, vulnerability assessments tend to include additional factors that increase their relevance for decision-makers, such as a more comprehensive representation of the main stressors (including non-climatic).

4.3. Limitations of the approach to assess vulnerability

This thesis identified some elements of the vulnerability of water uses to climate change, notably physical vulnerability, by simulating the exposure and sensitivity of the water balance to climatic and anthropogenic changes in the Hérault and the Ebro basins. Complementary studies using a bottom-up approach, focusing on social vulnerability and adaptive capacity (Burton et al., 2002; Wilby and Dessai, 2010; Farley et al., 2011; Bhave et al., 2014, e.g.) would be needed to assess the vulnerability of water uses to climate change in these two river basins.

The frequency and intensity of water shortages are not the only elements that can characterize the vulnerability of water uses. The analysis of past changes in the water balance showed intense and frequent shortages over the past 40 years, notably in the Gignac area of the Hérault basin and the right bank sub-basins of the Ebro (Jalon and Guadalupe systems). These deficits could reflect very different situations in terms of yield or economic harm, and could conceal local adaptations to water stress that were not accounted for in the simulations. Notwithstanding the uncertainties in modeling and the possible overestimation of water shortages by the modeling chain, simulations showed particularly intense and frequent shortages on the right bank of the Ebro. A thorough study of these areas would be necessary to identify and characterize possible local adaptations (such as private wells or desalination of brackish water for resource enhancement or adapted agricultural practices such as deficit irrigation) and to understand the economic and social impact of water shortages. The fact that the increase in frequency and intensity of shortages in the Bardenas irrigation system led to a project to double the capacity of the Yesa dam, while shortages seem to have persisted on the right bank during several decades, may be explained by other factors than hydro-climatic conditions.

Over the course of this thesis, certain characteristics of the Hérault basin which could not be identified in water balance simulations were revealed by field visits of the basin. In the upstream areas, very local issues of instream use may arise. Traditional irrigation uses gravity-fed canals which may abstract a large portion of streamflow in the summer (see Photo 6.4 to 6.7). Although this technique implies abundant return flows, it may (locally) disrupt instream environmental uses. Thus a balance between water availability and demand at the scale of the sub-basins could hide local tensions and vulnerabilities. Note that traditional irrigation systems tend to be converted to sprinkler or drip irrigation, and small farm-scale reservoirs may be built to alleviate the pressure on low flows.

Also different systems may not react in the same way to similar water shortage frequencies or intensities. In the Laroque area of the Hérault basin, for example, summer low flows are sensitive to climate 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.



Photo 6.1 and Photo 6.2. The increase in frequency and intensity of shortages in the Bardenas irrigation system led to a project to double the capacity of the Yesa dam, which met a strong opposition by local stakeholders. (Sept. 2013)



Photo 6.3. The Salagou dam (Herauld basin) is a highly touristic site. Modifying management rules to increase outflows in the summer might impact touristic activities. (Jan. 2015, photo D. Ruelland)



Photo 6.4 and Photo 6.5. Traditional irrigation in the Hérault basin uses gravity-fed canals (left) which may abstract a large portion of streamflow. Local agriculture in the upstream areas of the Hérault (right) is highly dependent on irrigation. (June 2013)



Photo 6.6. and Photo 6.7. Traditional irrigation systems tend to be converted to sprinkler or drip irrigation, and small farm-scale reservoirs may be built to alleviate the pressure on low flows. (June 2013)

Regarding the use of modeling and indicators, further exploiting some of the intermediary results of the modeling chain could help characterize the vulnerability of water uses to climate change. For instance, the occurrence of water shortages could be better characterized: do they tend to occur more frequently after a dry winter or during a particularly warm summer? Are they linked to a succession of dry seasons or is summer rainfall the only driver? Better understanding the cause of shortages could help anticipate them. Also, using additional indicators such as the ones cited in section 3.3.1 could participate to the characterization of vulnerability.

Finally, in terms of adaptation options, many other measures could be considered to thoroughly assess the ability of water uses to cope with decreasing water resources. Notably farmers may make many adjustments to adapt to warmer and drier conditions (Meza et al., 2008; Molle et al., 2010a; Woznicki et al., 2015). Considering the need to improve agricultural systems' resilience facing climate variability, Vidal et al. (2009) stated that the distinction between strictly rainfed and strictly irrigated was invalid when considering real-world issues. According to the authors, high and stable water productivities under water-scarce conditions can be achieved through a better management of the "green-to-blue" water continuum.

These complementary analyses of vulnerability need to be led locally, at a finer scale than basin management plans. Thus to achieve a sustainable balance between water availability and demand and reduce the vulnerability of water uses to climate change, a real complementarity needs to be found between basin-scale studies of the water balance, such as the ones conducted in this thesis, and local assessments of vulnerability and adaptation.

General conclusion

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1. Context overview

Recent and future climate and anthropogenic changes raise the issue of balancing water availability and demand over the long term in river basins facing these rapid changes. Strategies are thus required to adapt water management to future climate and socio-economic changes. Such strategies aim at maintaining a balance between water demand and availability, i.e. being able to supply enough water to satisfy demand while limiting anthropogenic pressure on water resources to sustainable levels. Therefore they need to be based on a thorough understanding of each region's exposure and sensitivity to climatic and anthropogenic pressures. The water balance of a hydrosystem depends on its water resources, the associated water uses and anthropogenic pressure on the resources, and on the water needs of aquatic and humid ecosystems.

These elements of context underline the usefulness of assessing the balance between water availability and demand over multi-decadal time periods, to better understand water stress risks and support decisions to adapt to future climate changes. They also stress the importance of considering the impacts of both anthropogenic and climatic changes, and of understanding past changes before looking into the future. Finally, accounting for uncertainties in projections of future changes and their implications for adaptation strategies is an essential point to be considered. In light of the topics identified in the literature to better address research and management issues regarding quantitative water management in areas facing rapid anthropogenic and climatic changes, the objectives of this thesis were to:

- **represent** connections between water resource and demand in influenced hydrosystems while accounting for the multi-decadal dynamics of climatic and anthropogenic drivers;
- **assess** the sustainability of water uses under projected climatic and anthropogenic changes;
- **explore** options to reduce the gap between water demand and availability in an uncertain future.

A modeling chain was developed and applied in two contrasted Mediterranean hydrosystems: the Herault basin (2 500 km², France) and the Ebro basin (85 000 km², Spain). The Herault and the Ebro basins differ in their geographical and water use characteristics. The climate in the Herault basin is typically Mediterranean and influenced by the Cevennes mountain range, with mild wet winters and hot dry summers. The Herault is characterized by competing municipal and irrigation water demands, both highly seasonal with a summer peak in tourism and irrigation demands, associated with a low storage capacity. Climatic conditions in the Ebro basin are complex due to the contrasting influences of the Atlantic Ocean and the Mediterranean Sea, and of the three mountain ranges, particularly the Pyrenees. Hydrological regimes vary from nival to Mediterranean. The Ebro is a complex and highly regulated hydrosystem with a total of 264 dams, amounting to a storage capacity of 60% of total runoff. Irrigated areas 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. In 2007, agricultural water demand amounted to 92% of the total water demand.

2. Summary of conducted research

An integrative modelling framework was developed and applied in both basins. Water demands for human use were simulated according to anthropogenic and climatic drivers and aggregated at each demand node. Natural streamflow was simulated in each sub-basin using the conceptual hydrological model GR4j with a snowmelt module added in the sub-basins with a snowmelt regime. Streamflow regulations and storage were accounted for with a reservoir management model. Water demand satisfaction was assessed by comparing demand to availability at the main water demand nodes. If water availability was lower than water demand, then restrictions were applied to limit withdrawals for human water use. Restrictions were first applied to irrigation water demand (IWD), then to industrial and energy production water demands (other water demands, OWD), then to municipal water demand (MWD). Water shortage was calculated through the difference between water demand and effective water withdrawal, as a percentage of water demand. Only a part of the water withdrawn was considered to be actually used (consumptive use), the rest was considered to return to the sub-basin outlet as return flow.

This modelling chain was calibrated and validated at a 10-day time step over the period 1971–2009 and proved efficient to simulate water supply capacity and influenced streamflow in both basins. Simulated influenced streamflow was in good agreement with observed discharge at the outlet of each studied basin. Comparison of the influenced vs. natural streamflow as simulated by the model allowed the level of anthropogenic pressure on the water resources to be estimated in the Herault and Ebro basins: anthropological consumptive use amounted to 2% of the natural discharge on average over the period 2001–2009 in the Herault basin, while it amounted to 38% over the same period in the Ebro basin.

The modelling chain was then applied under four combinations of climate and water use scenarios to distinguish the impacts of human- and climate-induced changes on water supply capacity at the 2050 horizon. Two water use scenarios were considered: water uses of the 2000s and a trend water use scenario at the 2050 horizon. The trend water use scenario was built based on projections from the local water management agencies and the continuation of recent trends. A reference climate scenario over 1976–2005 and 18 climate change scenarios at the 2050 horizon were considered. A minimum environmental flow was defined downstream from storage dams and at specific locations and threshold values were set at the outlet of each sub-basin, under which withdrawals were not authorized. Three indicators were used to characterize the water supply capacity for the main water demands, i.e. municipal and irrigation: (i) F : frequency of years with at least one deficit greater than 5% of demand at a 10-day time step; (ii) D_{10} : average deficit at a 10-day time step and (iii) D_{AN} : average annual deficit. 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.

Finally, the sensitivity of water stress to variations in the main drivers of water demand was tested to assess the efficiency of potential adaptation measures under climate change scenarios. The effectiveness of adaptation was measured by the average decrease in shortage frequency induced by variations in the drivers under the 18 climate change scenarios, and robustness was measured by the number of climate scenarios in which the measure had an impact. The effectiveness and robustness of individual measures varied between the basins and inside each basin, depending on the demand nodes. An adaptation scenario combining different measures was tested in both basins, using the integrative modeling framework. This scenario led to encouraging results regarding the decrease of water stress. However, the effectiveness of the combined adaptation strategies was shown to be insufficiently robust to climate change uncertainties.

3. Limitations

Because of data availability and methodological barriers, the calibration and validation of the modeling chain showed some shortcomings. The simulation of natural streamflow was constrained by the lack of observations or measurements of natural streamflow and/or water withdrawal data which would have made a reconstruction of natural streamflow possible. Moreover, accurate validation of water demand simulations in space and over time was not possible due to the lack of appropriate data on withdrawals. Finally the return flows estimated by the model are subject to many uncertainties.

Uncertainties in the modeling of the balance between water availability and demand also arise from using models under non-stationary conditions. Uncertainties linked to hydrological models used in non-stationary conditions may stem from miscalibration or overcalibration of the model parameter, and from the quality of the data used for input in the models. Also, non-stationary conditions for hydrological modeling include the non-stationarity of water uses and water management practices.

Although many human and physical features were integrated in the modeling chain, some drivers of changes in water resources and demand were not included in the simulations. The drivers of changes in natural streamflow taking into account in this study were exclusively climatic, however other factors such as land use or land cover changes can affect the rainfall-runoff relationship. Also, groundwater resources and groundwater-surface flow links were hardly accounted for. A number of physical and anthropogenic drivers of changes in water demand were not accounted for, such as phenological processes and agricultural practices for the irrigation water demand model, and socio-economic drivers controlling municipal unit water consumption. Consequently, the approach developed in this thesis aimed to be integrative but did not reach a comprehensive view of the water balance. Notably, it did not account for feedbacks between the human and physical components of the system, and did not simulate the co-evolution of the social and physical components of the hydrosystems.

Finally, a need to ground adaptation strategies in a solid understanding of the vulnerability of water uses to climate change was underlined several times in this manuscript. Although the thesis contributed to identify some elements of the vulnerability of water uses to climate change (notably physical vulnerability), complementary studies would be

needed to complete this assessment. A focus on social vulnerability and adaptive capacity using a bottom-up approach emphasizing local specificities could reveal essential elements for achieving a sustainable balance between water availability and demand and reducing the vulnerability of water uses to climate change.

4. Prospects

Given the extent of the issues behind the goal of a sustainable balance between water availability and demand, the range of prospects for this type of study could be extremely wide. In light of the limitations discussed above, some improvements can be proposed on one hand for the multi-decadal modeling of the water balance under anthropogenic and climatic changes, and on the other hand for a better assessment of the vulnerability of water uses to climate change.

Regarding the modeling of the water balance, further research should be conducted on the methodology used to simulate natural water resources in the absence of water withdrawal data. Also, the integration of human and physical features could be improved by accounting for more drivers of changes in resources and demand, such as land use changes or crop phenology. By showing the necessity to consider human features (water uses, anthropogenic pressure on water resources, e.g.) in the study of the water balance, this thesis was in line with the IAHS (International Association of Hydrological Sciences) scientific decade "Panta Rhei – Everything Flows", which is dedicated to research activities on change in hydrology and society (Montanari et al., 2014).

For an improved assessment of the vulnerability of water uses to climate change, some intermediary results of the modeling chain could be further exploited to improve the understanding of the causes of water shortages. Combining the quantitative assessment of the water balance with other research fields such as social sciences and economy would advance the understanding of adaptive capacity. The results obtained by modeling at the river basin scale could be compared to the information obtained by an analysis of vulnerability at the local scale.

The research prospects mentioned above could contribute to better assist decision making for adaptation to climate change in the field of water resources management. The need to collaborate with local stakeholders was underlined several times throughout the manuscript: to understand water management rules in the basins, to validate simulations of water stress in the past, to choose pertinent indicators, and to build trend water use and adaptation scenarios. An effort to do so was made in the GICC-REMedHE project, notably by including the water management agencies in the project. However some barriers necessarily arise in the collaboration, ranging from different objectives and interests in the research results, to a lack of time or a difficult coordination between the timing of the research project and planning decisions being made by the managers. It seems that a particular emphasis should be put and time should be spent on defining what the "needs" of local stakeholders really are in terms of understanding of the hydrosystems and projections.

Regarding adaptation to climate change, other questions arise beyond effectiveness and robustness of adaptation. What is the optimal timing for adaptation measures? Can we design dynamic adaptive pathways with several options to better deal with climate uncertainties? Are we prepared to face unexpected, sudden changes? Could we imagine warning thresholds that would trigger a shift in water management? If holistic, socio-hydrology models integrating feedbacks between natural and social systems were developed, one could imagine running simulations of changes in hydrosystems from the current period to, for instance, the end of the century, integrating spontaneous and planned adaptations and their impacts on the water balance. Large ensembles of simulations could be run, with different levels of warming or precipitation changes, but also different changes in climate variability, different speeds of climate change (progressive or sudden e.g.). Alternatively, one could “imagine a world without climate models” (Wilby, 2011) emphasizing adaptive water management and a thorough understanding of the complex responses of highly influenced water hydrosystems to climatic pressures, focusing on flexible, reversible solutions that could enhance the system’s adaptive capacity regardless of the future climate.

References

- Adger, W. Vulnerability. *Global Environ. Change*, 16:268–281, 2006.
- AERMC –*Agence de l'eau Rhône Méditerranée Corse*. Plan de bassin d'adaptation au changement climatique dans le domaine de l'eau. bassin rhône-méditerranée., 2014a. URL www.eaurmc.fr. last access: June 2015.
- AERMC –*Agence de l'eau Rhône Méditerranée Corse*. Catalogue des données techniques issues des processus redevances. version mars 2014., 2014b. URL sierm.eaurmc.fr/telechargement/donnees.CAT_prelevement.pdf. last access: September 2015.
- Alcamo, J., Heinrichs, T., and Rösch, T. World water in 2025 –global modeling and scenario analysis for the world commission on water for the 21st century. Technical Report A0002, Center for Environmental Systems Research, University of Kassel, 2000.
- Alcamo, J., Döll, P., Heinrichs, T., Kaspar, F., Lehner, B., Rösch, T., and Siebert, S. Global estimates of water withdrawals and availability under current and future 'business-as-usual' conditions. *Hydrol. Sci. J.*, 48:339–348, 2003.
- Alcamo, J., Flörke, M., and Märker, M. Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrol. Sci. J.*, 52:247–275, 2007.
- Alcott, B. Jevon's paradox. *Ecol. Econ.*, 54:9–21, 2005.
- Allen, R., Pereira, L., Raes, D., and Smith, M. Crop evapotranspiration –guidelines for computing crop water requirements. *FAO Irrigation and drainage paper*, 56, 1998.
- Andréassian, V., Perrin, C., Michel, C., Usart-Sanchez, I., and Lavabre, J. Impact of imperfect rainfall knowledge on the efficiency and the parameters of watershed models. *J. Hydrol.*, 250:206–223, 2001.
- Andréassian, V., Moine, N. L., Perrin, C., Ramos, M., Oudin, L., Mathevet, T., Lerat, J., and Berthet, L. All that glitters is not gold: the case of calibrating hydrological models. *Hydrol. Process.*, 26:2206–2210, 2012.
- Andreu, J., Capilla, J., and Sanchis, E. Aquatool, a generalized decision-support system for water resources planning and operational management. *J. Hydrol*, 177:269–291, 1996.
- Arnell, N. Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Env. Change*, 14:31–52, 2004.

References

- Arnell, N. Climate change and global water resources. *Global Env. Change*, 9:31–49, 1999.
- Arnell, N. and Lloyd-Hughes, B. The global-scale impacts of climate change and agricultural water resources and flooding under new climate and socio-economic scenarios. *Climatic Change*, 122:127–140, 2014.
- Arnell, N., Livermore, M., Kovats, S., Levy, P., Nicholls, R., Parry, M., and Gaffin, S. Climate and socio-economic scenarios for global-scale climate change impacts assessments: characterising the SRES storylines. *Global Env. Change*, 14:3–20, 2004.
- Arnell, N., van Vuuren, D., and Isaac, M. The implications of climate policy for the impacts of climate change on global water resources. *Global Env. Change*, 21:592–603, 2011.
- Asefa, T., Clayton, J., Adams, A., and Anderson, D. Performance evaluation of a water resources system under varying climatic conditions: Reliability, resilience, vulnerability and beyond. *J. Hydrol*, 508:53–65, 2014.
- Barceló, D. and Sabater, S. Water quality assessment under scarcity: prospects and challenges in Mediterranean watersheds. *J. Hydrol.*, 38:1–4, 2010.
- Batchelor, C., Reddy, V., Linstead, C., Dhar, M., Roy, S., and May, R. Do water-saving technologies improve environmental flows? *J. Hydrol.*, 518:140–149, 2014.
- Beck, L. and Bernauer, T. How will combined changes in water demand and climate affect water availability in the Zambezi river basin? *Global Env. Change*, 21:1061–1072, 2011.
- Bejarano, M., Marchamalo, M., de Jalon, D. G., and del Tánago, M. G. Flow regime patterns and their controlling factors in the Ebro basin (Spain). *J. Hydrol.*, 385:323–335, 2010.
- Bhave, A., Mishra, A., and Groot, A. Sub-basin scale characterization of climate change vulnerability, impacts and adaptation in an Indian River basin. *Reg. Env. Change*, 13: 1087–1098, 2013.
- Bhave, A., Mishra, A., and Raghuvanshi, N. A combined bottom-up and top-down approach for assessment of climate change adaptation options. *J. Hydrol*, 518:150–161, 2014.
- Blinda, M. and Thivet, G. Ressources et demandes en eau en Méditerranée: situation et perspectives. *Sécheresse*, 20:9–16, 2009.
- Blöschl, G. and Montanari, A. Climate change impacts – throwing the dice? *Hydrol. Processes*, 24:374–381, 2010.
- Boithias, L., Acuña, V., Vergoñós, L., Ziv, G., Marcé, R., and Sabater, S. Assessment of the water supply:demand ratios in a Mediterranean basin under different global change scenarios and mitigation alternatives. *Sci. Tot. Environ.*, 470–471:567–577, 2014.
- Bär, R., Rouholahnejad, E., Rahman, K., Abbaspour, K., and Lehmann, A. Climate change and agricultural water resources: A vulnerability assessment of the Black Sea catchment. *Env. Sci. Pol.*, 46:57–69, 2015.

References

- Brigode, P., Oudin, L., and Perrin, C. Hydrological model parameter instability: A source of additional uncertainty in estimating the hydrological impacts of climate change? *J. Hydrol.*, 476:410–425, 2013.
- Bunce, J. Carbon dioxide effects on stomatal responses to the environment and water use by crops under field conditions. *Oecologia*, 140:1–10, 2004.
- Burton, I., Huq, S., Lim, B., Pilifosova, O., and Schipper, E. From impacts assessment to adaptation priorities: the shaping of adaptation policy. *Climate Policy*, 2:145–159, 2002.
- CEDEX –*Centro de estudios y experimentacion de obras publicas*. Anuario de aforos, 2012. URL hercules.cedex.es/anoarioaforos/default.asp. last access: February 2014.
- CHE –*Confederación Hidrográfica del Ebro*. Propuesta de proyecto de plan hidrológico de la cuenca del Ebro. Memoria., 2013. URL www.chebro.es. last access: October 2014.
- Collet, L., Ruelland, D., Borrell-Estupina, V., Dezetter, A., and Servat, E. Integrated modeling to assess long-term water supply capacity of a meso-scale Mediterranean catchment. *Sci. Tot. Env.*, 461–462:528–540, 2013.
- Collet, L., Ruelland, D., Borrell-Estupina, V., and Servat, E. Assessing the long-term impact of climatic variability and human activities on the water resources of a meso-scale Mediterranean catchment. *Hydrol. Sci. J.*, 59:1457–1469, 2014.
- Collet, L., Ruelland, D., Borrell-Estupina, V., Dezetter, A., and Servat, E. Water supply sustainability and adaptation strategies under anthropogenic and climatic changes of a meso-scale Mediterranean catchment. *Sci. Tot. Env.*, 536:589–602, 2015.
- Collins, W., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and Woodward, S. Development and evaluation of an earth-system model –HadGEM2. *Geoscientific Model Development*, 4:1051–1075, 2011.
- Cook, C. and Bakker, K. Water security: Debating an emerging paradigm. *Global Env. Change*, 22:94–102, 2012.
- Coron, L., Andréassian, V., Perrin, C., Lerat, J., Vaze, J., Bourqui, M., and Hendrickx, F. Crash testing hydrological models in contrasted climate conditions : an experiment on 216 Australian catchments. *Water Resour. Res.*, 48, 2012. doi: 10.1029/2011WR011721.
- Cosandey, C., Andréassian, V., Martin, C., Didon-Lescot, J., Lavabre, J., Folton, N., Mathys, N., and Richard, D. The hydrological impact of Mediterranean forest: a review of French research. *J. Hydrol.*, 301:235–249, 2005.
- Dawadi, S. and Ahmad, S. Evaluating the impact of demand-side management on water resources under changing climatic conditions and increasing population. *J. Environ. Manage.*, 114:261–275, 2013.

References

- Déqué, M. Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: model results and statistical correction according to observed values. *Global Planet. Change*, 57:16–26, 2007.
- Dessai, S. and Hulme, M. Does climate adaptation policy need probabilities? *Climate Policy*, 4:107–128, 2004.
- Dessai, S. and Hulme, M. Assessing the robustness of adaptation decisions to climate change uncertainties: a case study on water resources management in the East of England. *Global Environ. Change*, 17:59–72, 2007.
- Dessai, S., Hulme, M., Lempert, R., and Pielke, R. Climate prediction : a limit to adaptation? In Adger, N., Lorenzoni, I., and O'Brien, K., editors, *Adapting to climate change: thresholds, values, governance*. Cambridge University Press, 2009.
- Dezetter, A., Fabre, J., Ruelland, D., and Servat, E. Selecting an optimal climatic dataset for integrated modeling of the Ebro hydrosystem. In *Hydrology in a changing world: environmental and human dimensions (Proc. 7th FRIEND Int. Conf., Montpellier, France, 7–10 Oct. 2014)*, volume 363, page 355–360. IAHS Publ., 2014.
- Döll, P. Impact of climate change and variability on irrigation requirements: a global perspective. *Climatic Change*, 54:269–293, 2002.
- Donley, E., Naiman, R., and Marineau, M. Strategic planning for instream flow restoration: a case study of potential climate change impacts in the central Columbia River basin. *Global Change Biol.*, 18:3071–3086, 2012.
- Donohue, R., McVicar, T., and Roderick, M. Assessing the ability of potential evaporation formulations to capture the dynamics in evaporative demand within a changing climate. *J. Hydrol.*, 386:186–197, 2010.
- Doulgeris, C., Georgiou, P., Papadimos, D., and Papamichail, D. Ecosystem approach to water resources management. Using the MIKE 11 modeling system in the Strymonas River and Lake Kerkini. *J. Environ. Manage.*, 94:132–143, 2012.
- Downing, T., Patwardhan, A., Klein, R., Mukhala, A., Stephen, L., Wlnograd, M., and Ziervogel, G. Assessing vulnerability for climate adaptation. *Adaptation policy frameworks for climate change: Developing strategies, policies and measures*, page 67–90, 2005.
- Dufresne, J., Foujols, M., Denvil, S., Caubel, A., Marti, O., Aumont, O., Balkanski, Y., Bekki, S., Bellenger, H., Benshila, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., de Noblet, N., Duvel, J., Ethé, C., Fairhead, L., Fichet, T., Flavoni, S., Friedlingstein, P., Grandpeix, J., Guez, L., Guilyardi, E., Hauglustaine, D., Hourdin, F., Idelkadi, A., Ghattas, J., Joussaume, S., Kageyama, M., Krinner, G., Labetoulle, S., Lahellec, A., Lefebvre, M., Lefevre, F., Levy, C., Li, Z., Lloyd, J., Lott, F., Madec, G., Mancip, M., Marchand, M., Masson, S., Meurdesoif, Y., Mignot, J., Musat, I., Parouty, S., Polcher, J., Rio, C., Schulz, M., Swingedouw, D., Szopa, S., Talandier, C., Terray, P., Viovy, N., and Vuichard, N. Climate change projections using the IPSL-CM5 earth system model: from CMIP3 to CMIP5. *Climate Dynamics*, 40: 2123–2165, 2013.

References

- Dunne, J., John, J., Adcroft, A., Griffies, S., Hallberg, R., Shevliakova, E., Stouffer, R., Cooke, W., Dunne, K., Harrison, M., Krasting, J., S.L. Malysheva, d. P. M., Philipps, P., Sentman, L., Samuels, B., Spelman, M., Winton, M., Wittenberg, A., and Zadeh, N. GFDL's ESM2 global coupled climate-carbon earth system models. part I: physical formulation and baseline simulation characteristics. *J. Climate*, 25:6646–6665, 2012.
- EC–European Commission. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy, 2000.
- EC–European Commission. European Soil Database (distribution version V2.0), 2004.
- EC–European Commission. Common implementation strategy for the Water Framework Directive (2000/60/EC). river basins management in a changing climate. guidance document No. 24., 2009.
- EC–European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee of the Regions: An EU Strategy on adaptation to climate change. COM (2013) 216 final., 2013.
- EEA –European Environment Agency. Environmental indicators: typology and overview. Technical Report 25, European Environment Agency, 1999.
- Fabre, J., Collet, L., Milano, M., Ruelland, D., Dezetter, A., Ardoin-Bardin, S., and Servat, E. Assessing the long-term evolution of water supply capacity: comparison of two Mediterranean catchments. In *Hydrology in a changing world: environmental and human dimensions (Proc. 7th FRIEND Int. Conf., Montpellier, France, 7–10 Oct. 2014)*, volume 363, page 203–208. IAHS Publ., 2014.
- Falkenmark, M., Lundqvist, J., and Widstrand, C. Macro-scale water scarcity requires micro-scale approaches. *Natural Resources Forum*, 13:258–267, 1989.
- Farley, K., Tague, C., and Grant, C. Vulnerability of water supply from the Oregon Cascades to changing climate: Linking science to users and policy. *Global Environ. Change*, 21: 110–122, 2011.
- Fischer, G., Tubiello, F., van Velthuizen, H., and Wiberg, D. Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080. *Technological Forecasting and Social Change*, 74:1083–1107, 2007.
- Folke, C. Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environ. Change*, 16:253–267, 2006.
- Fowler, H., Kilsby, C., and O'Connell, P. Modeling the impacts of climatic change and variability on the reliability, resilience, and vulnerability of a water resource system. *Water Resour. Res.*, 39(8), 2003. doi: 10.1029/2002WR001778.
- Füssel, H. Adaptation planning for climate change: concepts, assessment approaches, and key lessons. *Sustain. Sci.*, 2:265–275, 2007.
- Füssel, H. and Klein, R. Climate change vulnerability assessments: an evolution of conceptual thinking. *Climatic Change*, 75:301–329, 2006.

References

- Fujihara, Y., Tanaka, K., Watanabe, T., Nagano, T., and Kojiri, T. Assessing the impacts of climate change on the water resources of the Seyhan River Basin in Turkey: Use of dynamically downscaled data for hydrologic simulations. *J. Hydrol.*, 353:33–48, 2008.
- Gallart, F. and Llorens, P. Catchment management under environmental change: Impact of land cover change on water resources. *Water Int.*, 28:334–340, 2003.
- Gallopín, G., Funtowicz, S., O'connor, M., and Ravetz, J. Science for the 21st century: from social contract to the scientific core. *Int. Social Science J.*, 168:219–229, 2001.
- Gallopín, G. C. Linkages between vulnerability, resilience, and adaptive capacity. *Global Environ. Change*, 16:293–303, 2006.
- García-Vera, M. The application of hydrological planning as a climate change adaptation tool in the Ebro basin. *Int. J. Water Resour. Dev.*, 29:219–236, 2013.
- García-Vera, M. and Martínez-Cob, A. Revisión de las necesidades hídricas netas de los cultivos de la Cuenca del Ebro. Technical report, Confederación Hidrográfica del Ebro, Zaragoza, 2004.
- García-Ruiz, J., López-Moreno, J., Vicente-Serrano, S., Lasanta-Martínez, T., and Beguería, S. Mediterranean water resources in a global change scenario. *Earth Sci. Rev.*, 105: 121–139, 2011.
- Giorgi, F. Climate change hot-spots. *Geophysical Research Letters*, 33, 2006.
- Giorgi, F. and Lionello, P. Climate change projections for the Mediterranean region. *Global and Planetary Change*, 63:90–104, 2008.
- Girard, C., Pulido-Velazquez, M., Rinaudo, J., Pagé, C., and Caballero, Y. Integrating top-down and bottom-up approaches to design global change adaptation at the river basin scale. *Global Environ. Change*, 34:132–146, 2015.
- Gleick, P. The changing water paradigm. a look at twenty-first century water resources development. *Water In.*, 25:127–138, 2000.
- Gleick, P. Water use. *Annual Review of Environment and Resources*, 28:275–314, 2003. doi: 10.1146/annurev.enerdy.28.040202.122849.
- Gleick, P. Basic water requirements for human activities: meeting basic needs. *Water Int.*, 21:83–92, 1996.
- Gleick, P., Christian-Smith, J., and Cooley, H. Water-use efficiency and productivity: re-thinking the basin approach. *Water Int.*, 36:784–798, 2011.
- Gómez, C., Pérez-BLANCO, C., and Batalla, R. Tradeoffs in river restoration: Flushing flows vs. hydropower generation in the Lower Ebro River, Spain. *J. Hydrol.*, 518:130–139, 2014.
- Griffin, M., Montz, B., and Arrigo, J. Evaluating climate change induced water stress: A case study of the Lower Cape Fear basin, NC. *Applied Geography*, 40:115–128, 2013.

References

- Grouillet, B., Fabre, J., Ruelland, D., and Dezetter, A. Historical reconstruction and 2050 projections of water demand under anthropogenic and climate changes in two contrasted Mediterranean catchments. *J. Hydrol*, 522:684–696, 2015.
- GWP –Global Water Partnership. Towards water security: A framework for action. Technical report, Global Water Partnership, 2000.
- GWP –Global Water Partnership. Integrated water resources management toolbox, version 2. Technical report, Global Water Partnership, 2003.
- Hallegatte, S. Strategies to adapt to an uncertain climate change. *Global Env. Change*, 19:240–247, 2009.
- Hargreaves, G. and Samani, Z. Reference crop evapotranspiration from temperature. *Appl. Eng. Agric.*, 1:96–99, 1985.
- Hashimoto, T., Stedinger, J., and Loucks, D. Reliability, resiliency, and vulnerability criteria for water resources system performance evaluation. *Water Resour. Res.*, 10:14–20, 1982.
- Heinrichs, T., Lehner, B., and Alcamo, J. An integrated analysis of change in water stress in Europe. *Integrated Assess.*, 3:15–29, 2012.
- Hejazi, M., Edmonds, J., Chaturvedi, V., Davies, E., and Eom, J. Scenarios of global municipal water-use demand projections over the 21st century. *Hydrol. Sci. J.*, 58:519–538, 2013.
- Hejazi, M., Edmonds, J., Clarke, L., Kyle, P., Davies, E., Chaturvedi, V., Wise, M., Patel, P., Eom, J., and Calvin, K. Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technological Forecasting and Social Change*, 81:205–226, 2014.
- Hinkel, J. Indicators of vulnerability and adaptive capacity: towards a clarification of the science-policy interface. *Global Environ. Change*, 21:198–208, 2011.
- Iglesias, A., Garrote, L., Diz, A., Schlickenrieder, Martin-Carrasco, F., Flores, F., and Moño, M. Challenges to manage the risk of water scarcity and climate change in the Mediterranean. *Water Resour. Manag.*, 21:775–788, 2007.
- Iglesias, A., Garrote, L., Diz, A., Schlickenrieder, and Martin-Carrasco, F. Re-thinking water policy priorities in the Mediterranean region in view of climate change. *Environ. Sci. Policy*, 14:744–757, 2011.
- IPCC. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 2007.
- IPCC. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 2013.
- Israelsen, O. *Irrigation principles and practices*. John Wiley and Sons Inc, 1950.

References

- Jiang, T., Chen, Y., XU, C., Chen, X., and Singh, V. Comparison of hydrological impacts of climate change simulated by six hydrological models in the Dongjiang Basin, South China. *J. Hydrol.*, 336:316–333, 2007.
- Jones, R., Chiew, F., Boughton, W., and Zhang, L. Estimating the sensitivity of mean annual runoff to climate change using selected hydrological models. *Advances in Water Resour.*, 29:1419–1429, 2006.
- Juwana, I., Muttill, N., and Perera, B. Indicator-based water sustainability assessment – a review. *Sci. Tot. Env.*, 438:357–371, 2012.
- Kay, A. and Davies, H. Calculating potential evaporation from climate model data: A source of uncertainty for hydrological climate change impacts. *J. Hydrol.*, 358:221–239, 2008.
- Kiptala, J., Mul, M., Mohamed, Y., and van der Zaag, P. Modelling stream flow and quantifying blue water using modified STREAM model for a heterogeneous, highly utilized and data-scarce river basin in Africa. *Hydrol. Earth Syst. Sci.*, 18:2287–2303, 2014.
- Kirby, J., Connor, J., Ahmad, M., Gao, L., and Mainuddin, M. Climate change and environmental water reallocation in the Murray-Darling Basin: Impacts of flows, diversions and economic returns to irrigation. *J. Hydrol.*, 518:120–129, 2014.
- Koutroulis, A., Tsanis, I., Daliakopoulos, I., and Jacob, D. Impact of climate change on water resources status: A case study for Crete Island, Greece. *J. Hydrol*, 479:146–158, 2013.
- Krol, M., Jaeger, A., Bronstert, A., and Güntner, A. Integrated modeling of climate, water, soil, agricultural and socio-economic processes: A general introduction of the methodology and some exemplary results from the semi-arid north-east of Brazil. *J. Hydrol*, 328:417–431, 2006.
- Kundzewicz, Z. and Stakhiv, E. Are climate models “ready for prime time” in water resources management applications, or is more research needed? *Hydrol. Sci. J.*, 55: 1085–1089, 2010.
- Ladouche, B., Maréchal, J., Dörfliker, N., and Lachassagne, P. Système karstique des Cent Fonts. simulation de scénarios d'exploitation et de gestion de la ressource. Technical Report BRGM/RP-54865-FR, BRGM, 2006.
- Lanini, S., Courtois, N., Giraud, F., Petit, V., and Rinaudo, J. Socio-hydrosystem modelling for integrated water-resources management –the Hérault catchment case study, southern France. *Environ. Model. Softw.*, 19:1011–1019, 2004.
- Lecina, S. and Playán, E. Mejora del regadío de la Comunidad de Regantes V del Canal de Bardenas. In *Actas del XX Congreso Nacional de Riegos y Drenajes (AERYD)*, Ciudad Real., page 99–101, 2002.
- Lecina, S., Isidoro, D., Playán, E., and Aragües, R. Irrigation modernization and water conservation in Spain: The case of *Riegos del Alto Aragón*. *Agric. Water Manage.*, 97: 1663–1675, 2010.

References

- Lehner, B., Alcamo, J., Heinrichs, T., and Kaspar, F. Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis. *Clim. Change*, 75:273–299, 2006.
- Lespinas, F., Ludwig, W., and Heussner, S. Impact of recent climate change on the hydrology of coastal Mediterranean rivers in Southern France. *Clim. Change*, 2009. doi: 10.1007/s10584-009-9668-1.
- Lespinas, F., Ludwig, W., and Heussner, S. Hydrological and climatic uncertainties associated with modeling the impact of climate change on water resources of small Mediterranean coastal rivers. *J. Hydrol.*, 511:403–422, 2014.
- Letcher, R., Croke, B., and Jakeman, A. Integrated assessment modelling for water resource allocation and management: a generalized conceptual framework. *Environ. Model. Softw.*, 22:733–742, 2007.
- Letcher, R., Jakeman, A., and Croke, B. Model development for integrated assessment of water allocation options. *Water Resour. Res.*, 40(5), 2004. doi: 10.1029/2003WR002933.
- Lopez-Gunn, E., Zorrilla, P., Prieto, F., and Llamas, M. Lost in translation? water efficiency in Spanish agriculture. *Agric. Water Manage.*, 108:83–95, 2012.
- López-Moreno, J., Vicente-Serrano, S., Morán-Tejeda, E., Zabalza, E., Lorenzo-Lacruz, J., and García-Ruiz, J. Impact of climate evolution and land use changes on water yield in the Ebro basin. *Hydrol. Earth Syst. Sci.*, 15:311–322, 2011.
- López-Moreno, J., Zabalza, J., Vicente-Serrano, S., Revuelto, J., Gilaberte, M., Azorin-Molina, C., Morán-Tejeda, E., García-Ruiz, J., and Tague, C. Impact of climate and land use change on water availability and reservoir management: Scenarios in the Upper Aragón River, Spanish Pyrenees. *Sci. Tot. Environ.*, 493:1222–1231, 2014.
- Ludwig, F., van Slobbe, E., and Cofino, W. Climate change adaptation and Integrated Water Resource Management in the water sector. *J. Hydrol.*, 518:235–242, 2014.
- Ludwig, R., Roson, R., Zografos, C., and Kallis, G. Towards an inter-disciplinary research agenda on climate change, water and security in Southern Europe and neighboring countries. *Environ. Sci. Policy*, 14:794–803, 2011.
- Luers, A. The surface of vulnerability: an analytical framework for examining environmental change. *Global Environ. Change*, 518:235–242, 2005.
- Luquet, D., Vidal, A., Smith, M., and Dauzat, J. 'More crop per drop': how to make it acceptable for farmers? *Agric. Water Manage.*, 76:108–119, 2005.
- March, H., Therond, O., and Leenhardt, F. Water futures: Reviewing water-scenario analyses through an original interpretative framework. *Ecol. Econ.*, 82:126–137, 2012.
- Martin, G. M., Bellouin, N., Collins, W., Culverwell, I., Halloran, P., Hardiman, S., Hinton, T., Jones, C., McDonald, R., McLaren, A., O'Connor, F., Roberts, M., Rodriguez, J., Woodward, S., Best, M., Brooks, M., Brown, A., Butchart, N., Dearden, C., Derbyshire, S., Dharssi, I., Doutriaux-Boucher, M., Edwards, J., Falloon, P., Gedney, N., Gray, L.,

References

- Hewitt, H., Hobson, M., Huddleston, M., Hughes, J., Ineson, S., Ingram, W., James, P., Johns, T., Johnson, C., Jones, A., Jones, C., Joshi, M., Keen, A., Liddicoat, S., Lock, A., Maidens, A., Manners, J., Milton, S., Rae, J., Ridley, J., Sellar, A., Senior, C., Totterdell, I., Verhoef, A., Vidale, P., and Wiltshire, A. The HadGEM2 family of Met Office Unified Model climate configurations. *Geoscientific Model Development*, 4:723–757, 2011.
- Martínez-Cob, A. and Tejero-Juste, M. A wind-based qualitative calibration of the Hargreaves ET_0 estimation equation in semiarid regions. *Agric. Water Manage.*, 64: 251–264, 2004.
- McVicar, T., Roderick, M., Donohue, R., Li, L., Niel, T. V., Thomas, A., Grieser, J., Jhajharia, D., Himri, Y., Mahowald, N., Mescherskaya, A., Kruger, A., Rehman, S., and Dinpashoh, Y. Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. *J. Hydrol.*, 416–417:182–205, 2012.
- MEARM –Ministère de l'Environnement et des Affaires Rurales et Maritimes.
- MEDDE –*Ministère de l'Ecologie du Développement Durable et de l'Energie*. Banque Hydro, 2010. URL <http://www.hydro.eaufrance.fr/selection.php>. last access: October 2010.
- MEDDTL –*Ministère de l'Ecologie du Développement Durable du Transport et du Logement*. Plan national d'adaptation de la France aux effets du changement climatique 2011–2015, 2011.
- Mehta, V., Haden, V., Joyce, B., Purkey, D., and Jackson, L. Irrigation demand and supply, given projections of climate and land-use change, in Yolo County, California. *Agric. Water Manage.*, 117:70–82, 2013.
- Menzel, L. and Matovelle, A. Current state and future development of blue water availability and blue water demand: A view at seven case studies. *J. Hydrol.*, 384:245–263, 2010.
- Meza, F., Silva, D., and Vigil, H. Climate change impacts on irrigated maize in Mediterranean climates: evaluation of double cropping as an emerging adaptation alternative. *Agric. Syst.*, 98:21–30, 2008.
- Milano, M., Ruelland, D., Fernandez, S., Dezetter, A., Fabre, J., and Servat, E. Facing global changes in the Mediterranean basin: How could the current water stress evolve by the medium-term? *C. R. GeoSci.*, 344:432–440, 2012.
- Milano, M., Ruelland, D., Dezetter, A., Fabre, J., Ardoin-Bardin, S., and Servat, E. Modeling the current and future capacity of water resources to meet water demands in the Ebro basin. *J. Hydrol.*, 500:114–126, 2013a.
- Milano, M., Ruelland, D., Fernandez, S., Dezetter, A., Fabre, J., Servat, E., Fritsch, J.-M., Ardoin-Bardin, S., and Thivet, G. Current state of Mediterranean water resources and future trends under climatic and anthropogenic changes. *Hydrol. Sci. J.*, 58:498–518, 2013b.
- Milly, P., Betancourt, J., Falkenmark, M., Hirsch, R., Kundzewicz, Z., and Lettenmaier, D. Stationarity is dead: Whither water management? *Science*, 319:573–574, 2008.

References

- Mitchell, B. Integrated water resource management, institutional arrangements, and land-use planning. *Environment and planning A*, 37(8):1335–1352, 2005.
- MMA –Ministero de Medo Ambiente. *Libro blanco del agua en España*, 2000.
- Molle, F. Why enough is never enough: the societal determinants of river basin closure. *Water Resour. Dev.*, 24:217–226, 2008.
- Molle, F. and Mollinga, P. Water poverty indicators: conceptual problems and policy issues. *Water Policy*, 5:529–544, 2003.
- Molle, F., Venot, J., Lannerstad, M., and Hoogesteger, J. Villains or heroes? farmers' adjustments to water scarcity. *Irrig. and Drain.*, 59:419–431, 2010a.
- Molle, F., Wester, P., and Hirsch, P. River basin closure: Processes, implications and responses. *Agric. Water Manage.*, 97:569–577, 2010b.
- Monreal, T., Calvo-Rubio, F., and Lorenzo, F. *Evaluación de los recursos hídricos en el Libro Blanco del Agua en Espana. El Libro Blanco del Agua*, 6:125–138, 1999.
- Montanari, A., Young, G., Savenije, H., Hughes, D., Wagener, T., Ren, L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Blöschl, G., Sivalapan, M., Beven, K., Gupta, H., Hipsey, M., Schaeffli, B., Arheimer, B., Boegh, E., Schymanski, S., Baldassarre, G. D., Yu, B., Hubert, P., Huang, Y., Schumann, A., Post, D., Srinivasan, V., Harman, C., Thompson, S., Rogger, M., Viglione, A., McMillan, H., Characklis, G., Pang, Z., and Belyaev, V. 'Panta Rhei –Everything flows': Change in hydrology and society –the IAHS Scientific Decade 2013–2022. *Hydrol. Sci. J.*, 58:1256–1275, 2014.
- Morán-Tejeda, E., Ceballos-Barbancho, A., Llorente-Pinto, J., and López-Moreno, J. Land-cover changes and recent hydrological evolution in the Duero Basin (Spain). *Reg. Environ. Change*, 12:17–33, 2012.
- Nam, W., Choi, J., and Hong, E. Irrigation vulnerability assessment on agricultural water supply risk for adaptive management of climate change in South Korea. *Agric. Water Manage.*, 152:173–187, 2015.
- Nkomozepe, T. and Chung, S. The effects of climate change on the water resources of the Geumho River Basin, Republic of Korea. *J. Hydro-environ. Res.*, 8:358–366, 2014.
- Olesen, J., Trnka, M., Kersebaum, K., Skjelvag, A., and Seguin, B. Impacts and adaptation of European crop production systems to climate change. *European J. of Agronomy*, 34: 96–112, 2011.
- Olmstead, S. Climate change adaptation and water resources management: A review of the literature. *Energy Econ.*, 46:500–509, 2014.
- Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andréassian, V., Anctil, F., and Loumagne, C. Which potential evapotranspiration input for a lumped rainfall-runoff model?: Part 2 –towards a simple and efficient potential evapotranspiration model for rainfall-runoff modelling. *J. Hydrol.*, 303:290–306, 2005.

References

- Oxley, T., McIntosh, B., Winder, N., Mulligan, M., and Engelen, G. Integrated modelling and decision support tools: a Mediterranean example. *Environ. Model. Softw.*, 19: 999–1010, 2004.
- Palazzoli, I., Maskey, S., Uhlenbrook, S., Nana, E., and Bocchiola, D. Impact of prospective climate change on water resources and crop yields in the Indrawati basin, Nepal. *Agric. Syst.*, 133:143–157, 2015.
- Panagopoulos, G. Assessing the impacts of socio-economic and hydrological factors on urban water demand: A multivariate statistical approach. *J. Hydrol.*, 518:42–48, 2014.
- Paredes, P., Rodrigues, G., Alves, I., and Pereira, L. Partitioning evapotranspiration, yield prediction and economic returns of maize under various irrigation management strategies. *Agric. Water Manage.*, 135:27–39, 2014.
- Patt, A., Klein, R., and de la Vega-Leinert, A. Taking the uncertainty in climate change vulnerability assessments seriously. *C.R. Geosci.*, 337:411–424, 2005.
- Patwardhan, A., Downing, T., Leary, N., and Wilbanks, T. Towards an integrated agenda for adaptation research: theory, practice and policy. *Current Opinion in Environmental Sustainability*, 1:219–225, 2009.
- Perera, B., James, B., and Kularathna, M. Computer software tool REALM for sustainable water allocation and management. *J. Environ. Manage.*, 77:291–300, 2003.
- Perrin, C., Michel, C., and Andreassian, V. Improvement of a parsimonious model for streamflow simulation. *J. Hydrol.*, 10:282–290, 2003.
- Perry, C. Efficient irrigation; inefficient communication; flawed recommendations. *Irrigation and Drainage*, 56:367–378, 2007.
- Pielke, R. Collateral damage from the death of stationarity. *GEWEX Newsletter*, May 2009:5–7, 2009.
- Pielke, R. J. Room for doubt. *Nature*, 410:151–151, 2001.
- Plan Bleu. Adaptation au changement climatique dans le secteur de l'eau en Méditerranée: situation et perspectives. *Les cahiers du Plan Bleu*, 10, 2011.
- Plummer, R., de Loë, R., and Armitage, D. A systematic review of water vulnerability assessment tools. *Water Resour. Manage.*, 26:4327–4346, 2012.
- PNUE PAM. Stratégie Méditerranéenne pour le Développement Durable. Un cadre pour une durabilité environnementale et une prospérité partagée, 2005.
- Pulido-Velazquez, D., Sahuquillo, A., Andreu, J., and Pulido-Velazquez, M. An efficient conceptual model to simulate water body-aquifer interaction in conjunctive use management model. *Water Resour. Res.*, 43, 2007. doi: 0.1029/2006WR005064.
- Pulido-Velazquez, D., Garrote, L., Andreu, J., Martin-Carrasco, F.-J., and Iglesias, A. A methodology to diagnose the effect of climate change and to identify adaptive strategies to reduce its impacts in conjunctive-use systems at basin scale. *J. Hydrol.*, 405: 110–122, 2011.

References

- Pulido-Velazquez, D., Sahuquillo, D., and Andreu, J. A conceptual-numerical model to simulate hydraulic head in aquifers that are hydraulically connected to surface water bodies. *Hydrol. Process.*, 26:1435–1448, 2012.
- Purkey, D., Joyce, B., Vicuna, S., Hanemann, M., Dale, L., Yates, D., and Dracup, A. Robust analysis of future climate change impacts on water for agriculture and other sectors: a case study in the Sacramento Valley. *Climatic Change*, 87:109–122, 2008.
- Quevauviller, P. Adapting to climate change: reducing water-related risks in Europe –EU policy and research considerations. *Environ. Sci. Policy*, 14:722–729, 2011.
- Quintana-Segui, P., Moigne, P. L., Durand, Y., Martin, E., Habets, F., Baillon, M., Canellas, C., Franchisteguy, L., and Morel, S. Analysis of near-surface atmospheric variables: validation of the SAFRAN analysis over france. *J. Appl. Meteorol. Clim.*, 47:92–107, 2008.
- Quintana-Seguí, P., Míguez-Macho, G., and Llasat, M. d. C. Extending the SAFRAN meteorological analysis system to the Iberian Peninsula and the Balearic Islands. Analysis of its performance and applications. In *EGU General Assembly Conference Abstracts*, volume 17 of *EGU General Assembly Conference Abstracts*, page 3854, April 2015.
- Ragab, R. and Prudhomme, C. Climate change and water resources management. in arid and semi-arid regions: prospective and challenges for the 21st scentury. *Biosyst. Eng.*, 81:3–34, 2002.
- Raje, D. and Mujumdar, P. Reservoir performance under uncertainty in hydrologic impacts of climate change. *Advances in Water Resources*, 33:312–326, 2010.
- Rasilla, D., Garmendia, C., and García-Codron, J. Climate change projections of stream-flow in the Iberian peninsula. *Int. J. Water Resour. Dev.*, 29:184–200, 2013.
- Reynard, E., Bonriposi, M., Graefe, O., Homewood, C., Huss, M., Kauzlaric, M., Liniger, H., Rey, E., Rist, S., Schädler, B., Schneider, F., and Weingartner, R. Interdisciplinary assessment of complex regional water systems and their future evolution: how socioeconomic drivers can matter more than climate. *WIREs Water*, 1:413–426, 2014.
- Rinaudo, J. Urbanisme, habitat et demande en eau potable –Scénarios 2030 pour le Pays Coeur d'Hérault. Technical Report BRGM/RP-60368-FR, BRGM, 2011.
- Räisänen, J. How reliable are climate models? *Tellus*, 59A:2–29, 2007.
- Rogers, D. Leaking water networks: an economic and environmental disaster. *Procedia Engineering*, 70:1421–1429, 2014.
- Romero, P., Gil-Muñoz, R., del Amor, F. M., Valdés, E., Fernández, J. I., and Martínez-Cutillas, A. Regulated deficit irrigation based upon optimum water status improves phenolic composition in Monastrell grapes and wines. *Agric. Water Manage.*, 121: 85–101, 2013.
- Rotstayn, L. D., Jeffrey, S. J., Collier, M. A., Dravitzki, S. M., Hirst, A. C., Syktus, J. I., and Wong, K. K. Aerosol- and greenhouse gas-induced changes in summer rainfall and circulation in the australasian region: a study using single-forcing climate simulations. *Atmospheric Chemistry and Physics*, 12:6377–6404, 2012.

References

- Ruelland, D., Brisset, N., Jourde, H., and Oyarzun, R. Modeling the impact of climatic variability on the groundwater and surface flows from a mountainous catchment in the Chilean Andes. In *Cold regions hydrology in a changing climate (Proceedings of Symposium H02 held during IUGG 2011 in Melbourne, Australia, July 2011)*, volume 346, page 171–179. IAHS Publ., 2011.
- Ruelland, D., Ardoin-Bardin, S., Collet, L., and Roucou, P. Simulating future trends in hydrological regime of a large Sudano-Sahelian catchment under climate change. *J. Hydrol.*, 424–425:207–216, 2012.
- Ruelland, D., Dezetter, A., and Hublart, P. Sensitivity analysis of hydrological modeling to climate forcing in a semi-arid mountainous catchment. In *Hydrology in a changing world: environmental and human dimensions (Proc. 7th FRIEND Int. Conf., Montpellier, France, 7–10 Oct. 2014)*, volume 363, page 145–150. IAHS Publ., 2014.
- Ruelland, D., Hublart, P., and Tramblay, Y. Assessing uncertainties in climate change impacts on runoff in Western Mediterranean basins. *Proceedings of the International Association of Hydrological Sciences*, 371:75–81, 2015.
- Salvador, R., Martínez-Cob, A., Cavero, J., and Playán, E. Seasonal on-farm irrigation performance in the Ebro basin (Spain): Crops and irrigation systems. *Agric. Water Manage.*, 98:577–587, 2011.
- Santesteban, L., Miranda, C., and Royo, J. Regulated deficit irrigation effects on growth, yield, grape quality and individual anthocyanin composition in *Vitis vinifera* L. cv. ‘Tempranillo’. *Agric. Water Manage.*, 98:1171–1179, 2011.
- Schleich, J. and Hillenbrand, T. Determinants of residential water demand in Germany. *Ecol. Econ.*, 68:1756–1769, 2009.
- Schwank, J., Escobar, R., Girón, G., and Morán-Tejeda, E. Modeling of the Mendoza river watershed as a tool to study climate change impacts of water availability. *Environ. Sci. Policy*, 43:91–97, 2014.
- Shamir, E., Megdal, S., Carillo, C., Castro, C., Chang, H., Chief, K., Corkhill, F., Eden, S., Georgakakos, K., Nelson, K., and Prietto, J. Climate change and water resources management in the Upper Santa Cruz River, Arizona. *J. Hydrol.*, 521:18–33, 2015.
- Sieber, J. and Purkey, D. User guide for WEAP 21 (Water Evaluation and Planning System), 2007.
- Sivapalan, M., Savenije, H. H., and Blöschl, G. Socio-hydrology: A new science of people and water. *Hydrol. Process.*, 26:1270–1276, 2012.
- SMBFH—*Syndicat Mixte du Bassin du Fleuve Hérault*. Gestion quantitative de la ressource. état des lieux version 4. SAGE du bassin du fleuve Hérault, june 2005. URL www.sage.herault.fr. last access: August 2014.
- Smit, B. and Wandel, J. Adaptation, adaptive capacity and vulnerability. *Global Environ. Change*, 156:282–292, 2006.

References

- Stevens, B., Giorgetta, M., Esch, M., Mauritsen, T., Crueger, T., Rast, S., Salzmann, M., Schmidt, H., Bader, J., Block, K., Brokopf, R., Fast, I., Kinne, S., Kornblüeh, L., Lohmann, U., Pincus, R., Reichler, T., and Roeckner, E. Atmospheric component of the MPI-M Earth System Model: ECHAM6. *J. Adv. Model. Earth. Syst.*, 5:146–172, 2013.
- Sullivan, C. and Meigh, J. Targeting attention on local vulnerabilities using an integrated index approach: the example of the Climate Vulnerability Index. *Water Sci. Technol.*, 51(5):69–78, 2005.
- Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M., Ciais, P., Guimberteau, M., Traore, S., and Baron, C. Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. *Environ. Research Letters*, 8:014040, 2013.
- Swiech, T., Ertsen, M., and Pererya, C. M. Estimating the impacts of a reservoir for improved water use in irrigation in the Yarabamba region, Peru. *Physics and Chemistry of the Earth, Parts A/B/C*, 47–48:64–75, 2012.
- Taub, D. Effects of rising atmospheric concentrations of carbon dioxide on plants. *Nat. Educ. Knowl.*, 3:21, 2010.
- Timmerman, P. Vulnerability resilience and collapse of society. Technical Report 1, Institute for Environmental Studies, University of Toronto, 1981.
- Turner, B., Kasperson, R., Matson, P., MacCarthy, J., Corell, R., Christensen, L., Eckley, N., Kasperson, J., Luers, A., Martello, M., Polsky, C., Pulsipher, A., and Schiller, A. A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America*, 100:8074–8079, 2003.
- Vandecasteele, I., Bianchi, A., e Silba, F. B., Lavalle, C., and Batelaan, O. Mapping current and future European public water withdrawals and consumption. *Hydrol. Earth Syst. Sci.*, 18:407–416, 2014.
- Varela-Ortega, C., Blanco-Gutiérrez, I., Swartz, C., and Downing, T. Balancing groundwater conservation and rural livelihoods under water and climate uncertainties: An integrated hydro-economic modeling framework. *Global Environ. Change*, 21:604–619, 2011.
- Vaze, J., Post, D., Chiew, F., Perraud, J., Viney, N., and Teng, J. Climate non-stationarity – validity of calibrated rainfall-runoff models for use in climate change studies. *J. Hydrol.*, 394:447–457, 2010.
- Vicente-Serrano, S. and López-Moreno, J. Influence of atmospheric circulation at different spatial scales on winter drought variability through a semiarid climatic gradient in North-East Spain. *Int. J. Climatol.*, 26:1427–1453, 2006.
- Vidal, A., van Koppen, B., and Blake, D. The green-to-blue water continuum: An approach to improve agricultural systems' resilience to water scarcity. *On the Water Front*, page 66–72, 2009.
- Vidal, J., Martin, E., Franchisteguy, L., Baillon, M., and Soubeyroux, J. A 50-year high-resolution atmospheric reanalysis over France with the SAFRAN system. *Int. J. Climatol.*, 30:1627–1644, 2010.

References

- Vogel, C., Moser, S., Kasperson, R., and Dabelko, G. Linking vulnerability, adaptation, and resilience science to practice: Pathways, players, and partnerships. *Global Environ. Change*, 17:349–364, 2007.
- Voldoire, A., Sanchez-Gomez, E., Salas y Mélia, D., Decharme, B., Cassou, C., Sénési, S., Valcke, S., Beau, I., Alias, A., Chevallier, M., Déqué, M., Deshayes, J., Douville, H., Fernandez, E., Madec, G., Maisonnave, E., Moine, M.-P., Planton, S., Saint-Martin, D., Szopa, S., Tyteca, S., Alkama, R., Belamari, S., Braun, A., Coquart, L., and Chauvin, F. The CNRM-CM5.1 global climate model: description and basic evaluation. *Climate Dynamics*, 40:2091–2121, 2013.
- von Salzen, K., Scinocca, J. F., McFarlane, N. A., Li, J., Cole, J. N. S., Plummer, D., Versegny, D., Reader, M. C., Ma, X., Lazare, M., and Solheim, L. The canadian fourth generation atmospheric global climate model (CanAM4). part i: Representation of physical processes. *Atmosphere-Ocean*, 51:104–125, 2013.
- Vörösmarty, C., Green, P., Salisbury, J., and Lammers, R. Global water resources: vulnerability from climate change and population growth. *Science*, 289:284–288, 2000.
- Vörösmarty, C., McIntyre, P., Gessner, M., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S., Sullivan, C., Liermann, C. R., and Davies, P. Global threats to human water security and river biodiversity. *Nature*, 467:555–561, 2012.
- Walker, B., Holling, C. S., Carpenter, S. R., and Kinzig, A. Resilience, adaptability and transformability in social-ecological systems. *Ecol. Soc.*, 9(2), 2004. URL <http://www.ecologyandsociety.org/vol9/iss2/art5>.
- Walker, W., Harremoës, P., Rotmans, J., van der Sluijs, J., van Asselt, M., Janssen, P., and von Krauss, M. K. Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. *Integr. Assess.*, 4:5–17, 2003.
- Wanders, N. and Wada, Y. Human and climate impacts on the 21st century hydrological drought. *J. Hydrol.*, 526:208–220, 2015.
- Ward, F. and Pulido-Velazquez, M. Water conservation in irrigation can increase water use. *PNAS*, 105:18215–18220, 2008.
- Watanabe, M., Suzuki, T., O'ishi, R., Komuro, Y., Watanabe, S., Emori, S., Takemura, T., Chikira, M., Ogura, T., Sekiguchi, M., Takata, K., Yamazaki, D., Yokohata, T., Nozawa, T., Hasumi, H., Tatebe, H., and Kimoto, M. Improved climate simulation by MIROC5: Mean states, variability, and climate sensitivity. *J. Climate*, 23:6312–6335, 2010.
- Welsh, W., Vaze, J., Dutta, D., Rassam, D., Rahman, J., Jolly, I., Wallbrink, P., Pdger, G., Bethune, M., Hardy, M., Teng, J., and Lerat, J. An integrated modelling framework for regulated river systems. *Environ. Model. Softw.*, 39:81–102, 2012.
- Weng, P. and Dörfliger, N. Projet PACTES –module: contribution des eaux souterraines aux crues et inondations; site de l'Hérault. Technical Report BRGM/RP-51718-FR, BRGM, 2002.

References

- Wilby, R. Imagine a world without climate models, 2011. URL pielkeclimatesci.wordpress.com/2011/01/17/imagine-a-world-without-climate-models-by-rob-wilby-of-loughborough-university last access: September 2015.
- Wilby, R. Evaluating climate model outputs for hydrological applications. *Hydrol. Sci. J.*, 55:1090–1093, 2010.
- Wilby, R. and Dessai, S. Robust adaptation to climate change. *Weather*, 65:180–185, 2010.
- Wilby, R. and Harris, I. A framework for assessing uncertainties in climate change impacts: low-flow scenarios for the River Thames, U.K. *Water Resour. Res.*, 42, 2006. doi: 10.1029/2005WR004065.
- Wilby, R., Orr, H., Hedger, M., Forrow, D., and Blackmore, M. Risks posed by climate change to the delivery of Water Framework Directive objective in the UK. *Environ. Int.*, 32:1043–1055, 2006.
- Wolf, S., Hinkel, J., Hallier, M., Bisaro, A., Lincke, D., Ionescu, C., and Klein, R. J. Clarifying vulnerability definitions and assessments using formalisation. *Int. J. Clim. Change Str. Manage.*, 5:54–70, 2013.
- Woznicki, S., Nejadhashemi, A., and Parsinejad, M. Climate change and irrigation demand: Uncertainty and adaptation. *J. Hydrol. Reg. Stud.*, 3:247–264, 2015.
- Yao, H. and Georgakakos, A. Assessment of Folsom Lake response to historical and potential future climate scenarios - 2. Reservoir management. *J. Hydrol.*, 249:176–196, 2001.
- Zarrouk, O., Francisco, R., Pinto-Marijuan, M., Brossa, R., Santos, R. R., Pinheiro, C., Costa, J. M., Lopes, C., and Chaves, M. M. Impact of irrigation regime on berry development and flavonoids composition in Aragonez (Syn. Tempranillo) grapevine. *Agric. Water Manage.*, 114:18–29, 2012.

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Appendix A

Article published in the proceedings of the FRIEND-Water 2014 conference

ASSESSING THE LONG-TERM EVOLUTION OF WATER SUPPLY CAPACITY: COMPARISON OF TWO MEDITERRANEAN CATCHMENTS

Fabre, J., Collet, L., Milano, M., Ruelland, D., Dezetter, A., Ardoin-Bardin, S., Servat, E.

Abstract This study aims at defining the main stakes in the development of a generic, multidisciplinary approach to evaluate water supply capacity and its spatial and temporal variability over long time periods. A common modelling framework was applied over two Mediterranean basins with different physical and anthropogenic characteristics: the Ebro (85 000 km², Spain) and the Hérault (2 500 km², France) catchments. Runoff and river flow regulations were simulated using conceptual hydrological models and reservoir management models, respectively. Water demand was estimated from population and unit water consumption data for the domestic sector, and from irrigated area, crop, soil and climatic data for the agricultural sector. A ratio comparing water resource availability to water demand was computed on each catchment. Working on two catchments with different geographical scales and water management issues underlines the challenges in the development of a reliable and generic water allocation assessment method.

Keywords integrated modelling; River Ebro; River Hérault; water supply; water demand; water demand satisfaction

Assessing the long-term evolution of water supply capacity: comparison of two Mediterranean catchments

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Abstract This study aims at defining the main stakes in the development of a generic, multidisciplinary approach to evaluate water supply capacity and its spatial and temporal variability over long time periods. A common modelling framework was applied over two Mediterranean basins with different physical and anthropogenic characteristics: the Ebro (85 000 km², Spain) and the Hérault (2500 km², France) catchments. Runoff and river flow regulations were simulated using conceptual hydrological models and reservoir management models, respectively. Water demand was estimated from population and unit water consumption data for the domestic sector, and from irrigated area, crop, soil and climatic data for the agricultural sector. A ratio comparing water resource availability to water demand was computed on each catchment. Working on two catchments with different geographical scales and water management issues underlines the challenges in the development of a reliable and generic water allocation assessment method.

Key words integrated modelling; River Ebro; River Hérault; water supply; water demand; water demand satisfaction

INTRODUCTION

In a context of climate change and socio-economic development, water demand has increased. Water supply capacity is essential in the Mediterranean region, which has been identified as one of the most vulnerable regions to water crisis (Alcamo et al., 2007). As a result of climate change, water resources could decrease by 30 to 50% by the 2050 horizon. Combined with increasing water demand, this could lead Mediterranean catchments of Spain and of the southern and eastern rims to face severe water stress (Milano et al., 2012; 2013a). These water supply stakes call for water sharing and efficient allocation between different users, while maintaining sufficient water flows for aquatic and humid environments. Furthermore, projections of hydro-climatic changes encourage water planning with a medium-to-long-term perspective in order to anticipate possible water stress.

Multidisciplinary approaches that simulate water resource developments and demand growth under long-term socio-economic and climatic scenarios are essential to water planning and adaptation to climate change. These approaches can also support decision-making by providing indicators representing water demand satisfaction and its spatial and temporal variability. In order to build realistic scenarios and indicators in line with water policy concerns, it is necessary to link research work on these questions with local management agencies.

This paper investigates these issues by comparing two studies that attempted a representation of water demand satisfaction over long time periods on contrasting Mediterranean catchments: the Ebro (Spain) and the Hérault (France). The aim is to compare the methods and results on both catchments in order to draw prospects for the development of a generic method able to represent the spatial and temporal variability of water demand satisfaction, in areas with varied water management issues.

STUDY AREAS

The Ebro (85 000 km², Spain) and the Hérault (2500 km², France) catchments differ by their geographical and anthropogenic characteristics. Climatic conditions on the Ebro basin are complex due to the contrasting influences of the Atlantic Ocean and the Mediterranean Sea, and of the various mountain ranges, particularly the Pyrenees. Consequently, hydrological regimes vary from nival (snowmelt) to Mediterranean. The Hérault catchment is characterized by a Mediterranean climate influenced by the Cévennes Mountains.

The Ebro is a large, complex and highly regulated hydro-system with a total of 234 dams, amounting to a storage capacity of 60% of total runoff, whereas five dams with a total storage capacity of 8% of total runoff can be accounted for in the Hérault basin. While water is mostly used for irrigation on the Ebro basin, water demand on the Hérault basin has evolved from mostly agricultural in the 1960s to mostly domestic since the 1990s. Finally, a decrease in runoff has been observed at the outlet of both basins: a statistical break was detected in 1979 on the Ebro (Milano et al., 2013b) and in 1980 on the Hérault (Collet et al., in press).

METHOD

A common integrated modelling framework

Both studies relied on information provided by local water management agencies: the Confederación Hidrográfica del Ebro (CHE) and the Syndicat Mixte du Bassin du Fleuve Hérault (SMBVH). In order to correctly determine the vulnerability of each study area to water shortage, a representation of the spatial distribution of resource vs. demand was set up. Each basin was divided into portions defining water supply nodes, transporting water to one or more demand nodes. The Ebro and Hérault were divided into nine and six portions, respectively. The division took into account the main geographical and hydro-climatic heterogeneities with the constraint of data availability, while isolating the catchments which contribute most to runoff at the outlet. The main irrigated areas and water demand heterogeneities, as well as the main storage dams (three on the Ebro, one on the Hérault) were also considered (Collet et al., 2013; Milano et al., 2013b).

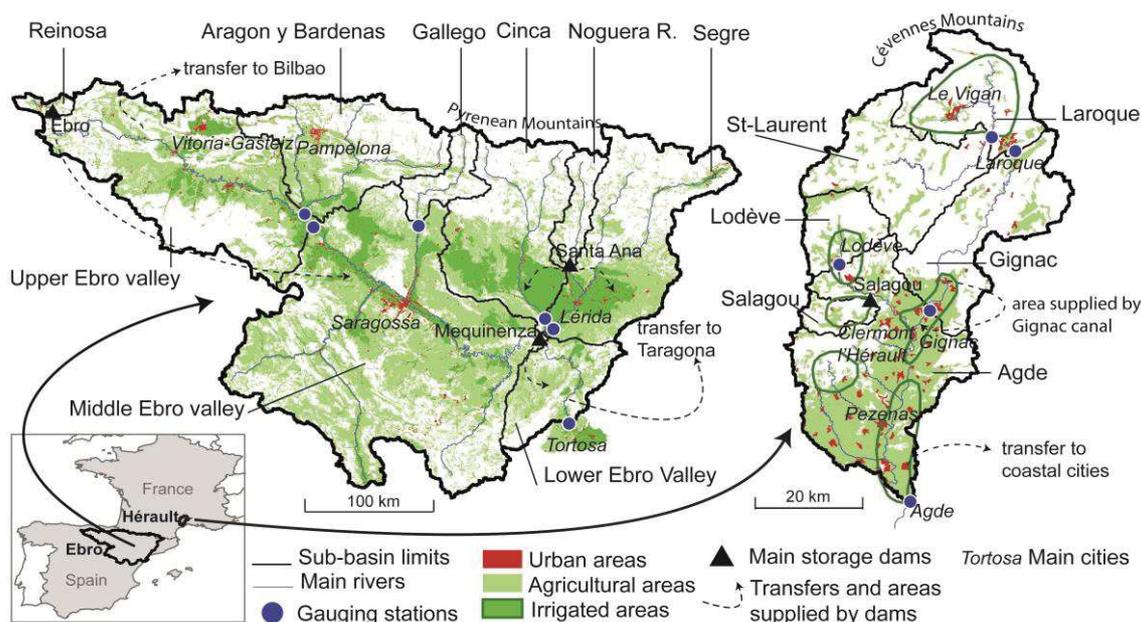


Fig. 1 The Ebro and the Hérault catchments: location of the main human pressures (urban and agricultural areas, main storage dams and water transfers) on water resources.

A common modelling framework relying on the comparison of water resource availability to water demand was applied to both areas. Water resource availability was defined by river flows at the outlet of each studied area, taking into account regulations by storage dams. Water demand was evaluated separately for the domestic and agricultural sectors. A water demand satisfaction rate (WDSR) based on a ratio of water availability to water demand was then computed as an indicator of the potential ability of each portion to satisfy the main water demands. Water supply priority was attributed to domestic demand over agricultural demand on both basins. In order to test the ability of the modelling chain to evaluate spatial and temporal variability of the basins' water supply capacity over the long term, the models were run over 20 years (1971–1990) on the

Ebro basin and 50 years (1961–2010) on the Hérault basin. On the Ebro catchment portions WDSR was calculated at a monthly time step and averaged over the 1971–1990 period. Seasonal values were then calculated and results were analysed over the summer. WDSR was calculated at a 10-day time step from 1961 to 2010 on the Hérault catchment portions and analysed as a frequency of years presenting at least one unsatisfactory 10-day period.

Runoff simulation

Two conceptual hydrological models were used to simulate runoff. The GR2M model (Makhlouf & Michel, 1994), which runs at a monthly time step, was adapted to be applied on the Ebro basin (Milano et al., 2013b). On the Hérault basin, the GR4j model (Perrin et al., 2003) was run at a daily time step and calibrated over 10-day periods. Both models were calibrated using multi-objective functions aggregating different goodness-of-fit criteria, including the Nash-Sutcliffe efficiency index (NSE) and the cumulative volume error (VE). The hydrological models rely on precipitation (P) and potential evapotranspiration (PE) inputs. On the Ebro basin, daily temperature and precipitation measurements from 61 and 208 stations, respectively, were interpolated on a 10×10 km grid using the inverse distance weighted method. PE was then calculated for each grid cell using a simple formula based on mean temperature and extra-terrestrial radiation (Oudin et al., 2005). Over the Hérault, daily climate forcings were extracted from an 8×8 km grid from the Météo France meteorological analysis system, SAFRAN (Quintana Segui et al., 2008). PE was calculated based on the FAO Penman-Monteith formula (Allen et al., 1998). Calibration over the Ebro was based on estimated natural river flows provided by the CHE, whereas observed runoff was used to calibrate the model GR4J over the Hérault catchment.

River flow regulations on the Ebro basin were accounted for through a generic storage-dam management model applied to the three main dams. The model considered reservoir management to be demand-driven. It took into account incoming flows and downstream demands and evaluated outflows depending on the reservoir level and two empirical parameters based on observed management practices over the 1971–1990 period (Milano et al., 2013b). A specific dam management model driven by the reservoir level was set up for the Salagou dam in the Hérault basin (Collet et al., 2013).

Evaluation of water demands

Domestic water demand (DWD) was considered to depend on population, unit water demand (UWD) and the efficiency of distribution networks. On the Ebro basin it was evaluated at an annual time step for 2007 and distributed at a monthly time step using coefficients provided by the CHE (2011). Monthly DWD calculated for 2007 was applied to the years 1971–1990. On the Hérault, annual variations of population and UWD from 1961 to 2010 were taken into account. As the monthly distribution of DWD was only available for 2007, the same distribution was applied to every year of the period. The monthly DWD series were disaggregated evenly to a 10-day time step.

On both basins, agricultural water demand (AWD) was estimated through water balances based on FAO recommendations (Allen et al., 1998). On the Ebro, an evaluation of crop water needs conducted by the CHE was used to determine unit water needs at each demand node and was multiplied by the irrigated area for 2007. Unit crop water needs were determined by the difference between efficient precipitation and maximum crop evapotranspiration. On the Hérault, an irrigation model based on P, PE, cropping patterns, and soil characteristics was run at a 10-day time step for each portion from 1961 to 2010 (Collet et al., 2013). On both basins the efficiency of irrigation systems was considered.

RESULTS

Freshwater availability

The performances of both hydrological models are summarized in Table 1. In the Aragón y Bardenas and Ebro valley catchments, runoff dynamics (represented by NSE) and volumes

(represented by VE) are correctly reproduced. NSE and VE show acceptable values on the Pyrenean basins of Gallego, Cinca and Segre, and less satisfactory on the two smallest portions, Reinosa and Noguera. In these areas, winter flows tend to be overestimated whereas spring flows are underestimated. On the Hérault, results are very satisfactory for calibration and validation periods, except on the Agde portion, where high flows and low flows are both underestimated.

Table 1 Hydrological model efficiency and mean annual discharge produced in each catchment portion.

| Ebro basin portions (discharge (m ³ /s), 1971–1990) | Calibration/Validation | | Hérault basin portions (discharge (m ³ /s), 1990–2010) | Calibration/Validation | |
|-------------------------------------------------------------------|------------------------|------------|----------------------------------------------------------------------|------------------------|-----------|
| | NSE | VE (%) | | NSE | VE (%) |
| Reinosa (11.6) | 0.37/0.48 | -17.2/13.1 | Saint-Laurent (9.9) | 0.89/0.78 | 0.1/14.8 |
| Upper Ebro Valley (123.3) | 0.92/0.92 | 0.85/-5.0 | Laroque (8.7) | 0.81/0.71 | 0.1/-17.2 |
| Aragón y Bardenas (134.3) | 0.78/0.80 | -7.2/2.2 | Gignac (7.6) | 0.82/- | 0.4/- |
| Gallego (33) | 0.71/0.74 | 1.4/3.3 | Lodève (4.1) | 0.84/0.89 | 0.0/3.3 |
| Middle Ebro valley (37.7) | 0.88/0.77 | 0.16/-1.8 | Salagou (1.0) | 0.94/- | 0.2/- |
| Noguera (19.2) | 0.42/0.14 | 0.3/7.5 | Agde (8.9) | 0.37/- | -11.3/- |
| Cinca (77.2) | 0.64/0.60 | 1.2/12.2 | | | |
| Segre (92.6) | 0.58/0.52 | 0.2/-1.8 | | | |
| Lower Ebro valley (7.1) | 0.90/0.73 | -1.5/-16.2 | | | |

Concerning the dam management models, dynamics and volumes of outflows from the Mequinenza dam on the Ebro and from the Salagou on the Hérault are well reproduced, with NSE and VE values of 0.89 (0.86) and 0.8% (3%) in Mequinenza (Salagou). The generic model produced less satisfactory results on the Ebro (NSE 0.49, VE 10.3%) and Santa Ana (NSE 0.35, VE 1.2) dams.

Water demand

On the Ebro catchment total water demand amounted to 8857 hm³/year. DWD is concentrated mostly in the Ebro valley (cities of Saragossa and Tortosa, Fig. 1) and represents 4% of total water demand with a low seasonal variability. AWD amounts to 96% of total water demand and is highly seasonal, reaching a maximum in July. The highest AWDs are located in the Middle and Lower Ebro valley and in the Pyrenean basins of Aragón y Bardenas, Cinca and Segre (Fig. 1).

Total water demand on the Hérault catchment varied from an average of 60 hm³/year before 1980 to 80 hm³/year after 1980. This increase is due to a high population growth coupled with a rise in unit demand from the 1990s to the mid-2000s, which led to an increase in DWD on the portions of Saint-Laurent, Lodève and Agde. DWD on the Hérault presents more seasonal variations than on the Ebro, reaching a peak in summer, when the population can triple due to tourism. As for AWD, it has not varied in the Hérault basin (42 hm³/year before 1980, 40 hm³/year after 1980). However, it has decreased in the Saint-Laurent and Laroque portions as a consequence of farmland abandonment and in the Gignac portion due to the modernization of irrigated systems, and increased in the Lodève, Salagou and Agde portions with the expansion of irrigated areas. AWD also peaks in the summer, with the highest values in July and no demand in winter.

Water supply capacity

Water demand satisfaction criteria are different in each local water agency; however, in order to compare results on both catchments, WDSR classes from the Hérault were applied on the Ebro. Results are presented in Fig. 2.

On the Ebro basin, DWD is estimated as satisfied in all catchment portions. Moderate WDSR values are found for AWD in the irrigated areas of Aragón y Bardenas, the Middle Ebro valley, the Segre and areas of the Cinca irrigated by the Santa Ana dam, while AWD satisfaction is low on the Cinca portion (Fig. 2(a)). Figure 2b shows results for the Hérault catchment portions of Laroque, Gignac and Agde only, as no unsatisfactory year appeared on the other portions. Contrasting trends can be noted within the area: satisfaction of AWD improved in Laroque and Gignac as a

result of the decrease in AWD, while it started to deteriorate in the 2000s in Agde (very low WDSR in August, as shown by Fig. 2(c)) consequently to a decrease in water availability combined with a strong increase in water demand. Agde is also the only portion showing DWD satisfaction problems, with WDSRs reaching low to very low levels in the summer (Fig. 2(c)).

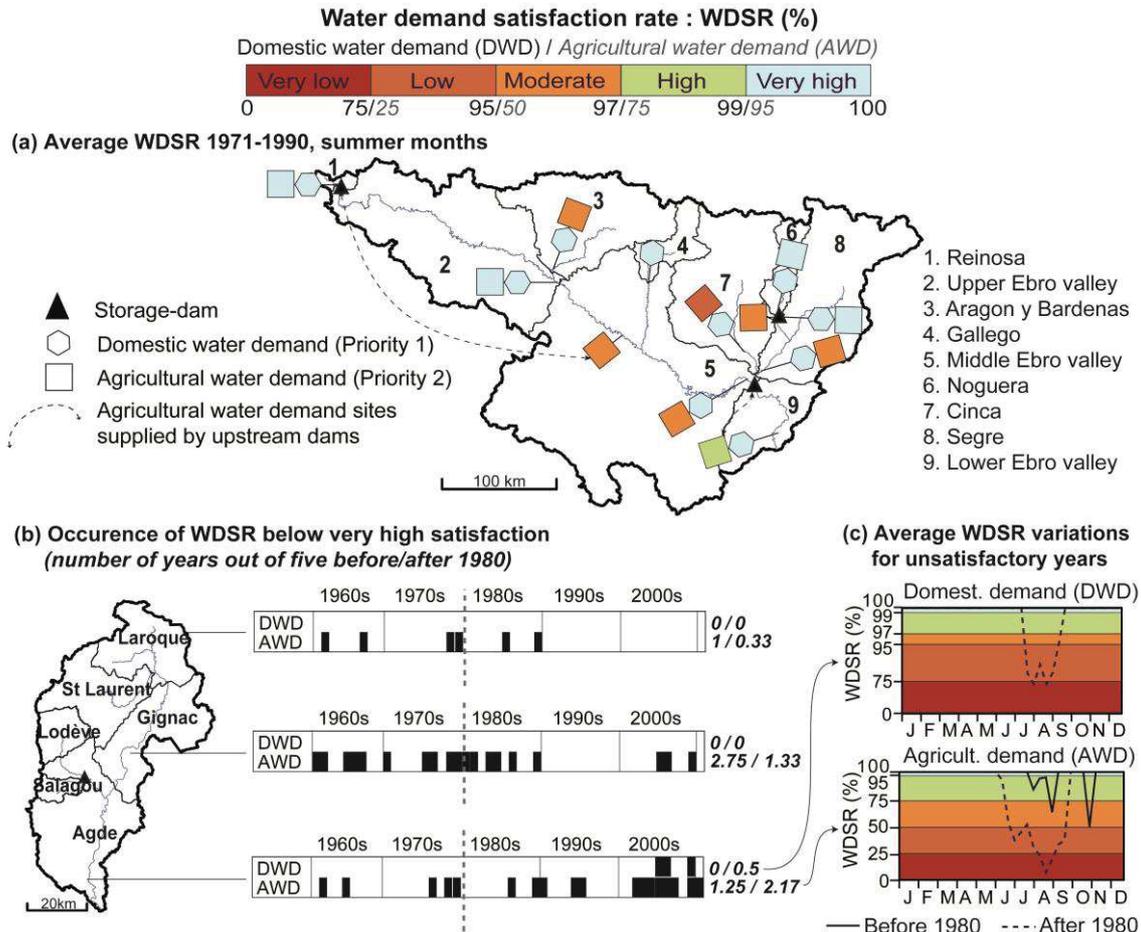


Fig. 2 Water demand satisfaction rates (WDSR) over the Ebro (a) and Hérault (b), (c) basins: (a) mean WDSR for summer months (July, August, September) for 1971–1990; (b) yearly occurrence of WDSR below “very high” for DWD and AWD and frequency of occurrence out of five years, before and after 1980; (c) 10-day WDSR variations, averaged on unsatisfactory years for 1961–1980 and 1981–2010.

CONCLUSIONS AND PROSPECTS

By applying an integrated modelling framework over two Mediterranean basins, their capacity to satisfy the main water demands was evaluated over long time periods. The areas most vulnerable to water stress were found. Schematic views of both basins were presented. Water resources were evaluated by simulating runoff and reservoir levels from climatic variability and dam management rules, and water demand was estimated based on population dynamics and unit consumption for the domestic sector, and on irrigated areas, crop types and climatic variability for agriculture.

Both approaches present limits and should be analysed in view of being sufficiently generic to be applied on various catchments. On the Ebro catchment, the hydrological model’s performance was moderately satisfactory in Pyrenean sub-catchments. This is most likely due to the influence of snowmelt on runoff, which could be taken into account by adding a snow reservoir to the hydrological model. Moreover, only the three main dams were considered, limiting the representation of river flow regulations. A division into more portions, taking into account additional dams and hydrological regimes, could come closer to representing the geography of water management on the Ebro basin. Furthermore, inter-annual water demand variations were not

evaluated on the Ebro catchment. Finally, a monthly time step does not seem sufficient to grasp resource and demand variability and their evolution under climate change scenarios. A 10-day time step, as applied on the Hérault catchment, seems to be more adapted to highly variable Mediterranean conditions. On the Hérault catchment, the hydrological model performed poorly on the downstream portion of Agde. However, total discharge was correctly simulated, as runoff from upstream portions, contributing to 78% of total discharge, was well evaluated. Another limit in this portion is the lack of evaluation of groundwater contribution to total resource, considering most of the domestic demand is supplied by groundwater.

In view of applying such integrated modelling approaches under climatic and anthropogenic change scenarios, it is essential to test their robustness in varying conditions. The comparison of studies carried out on the Ebro and the Hérault basins opens prospects on the development of a generic approach applicable to different basins. In addition to the limits underlined here above, questions on the method arise: which indicators better translate water supply capacity issues? What is their sensitivity to the different inputs? Can the same methods be applied to basins with different water management stakes and levels of complexity? These questions are the subject of on-going research.

Acknowledgements This work was carried out as part of the GICC REMedHE project funded by the French Ministry of Ecology, Sustainable Development and Energy for the period 2012–2015. The authors would like to thank the Confederación Hidrográfica del Ebro and the Syndicat Mixte du Bassin du Fleuve Hérault for providing the necessary data and documents for this study as well as for sharing their knowledge of water resources management in the studied basins.

REFERENCES

- Alcamo, J., Flörke, M. & Marker, M. (2007) Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrol. Sci. J.* 52(2), 247–275.
- Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. (1998) Crop evapotranspiration - guidelines for computing crop water requirements. *FAO Irrigation and drainage paper* 56, 300 pp.
- CHE–Confederación Hidrográfica del Ebro (2011) Propuesta de Proyecto de Plan Hidrológico de la cuenca del Ebro. Memoria versión 3.7. 281 pp. <http://oph.chebro.es/>
- Collet, L., Ruelland, D., Borrell-Estupina, V., Dezetter, A. & Servat, E. (2013) Integrated modelling to assess long-term water supply capacity of a meso-scale Mediterranean catchment. *Sci. Tot. Env.* 461–462, 528–540.
- Collet, L., Ruelland, D., Borrell-Estupina, V. & Servat, E. (2013) Assessing the long-term impact of climatic variability and human activities on the water resources of a meso-scale Mediterranean catchment. *Hydrol. Sci. J.* (in press).
- Makhlouf, Z. & Michel, C. (1994) A two-parameter monthly water balance model for French watersheds. *J. Hydrol.* 162, 299–318.
- Milano, M., Ruelland, D., Fernandez, S., Dezetter, A., Fabre, J. & Servat, E. (2012). Facing global changes in the Mediterranean basin: How could the current water stress evolve by the medium-term? *C. R. Geoscience*, 344, 432–440.
- Milano, M., Ruelland, D., Fernandez, S., Dezetter, A., Fabre, J., Servat, E., Fritsch, J.-M., Ardoïn-Bardin, S. & Thivet, G. (2013a) Current state of Mediterranean water resources and future trends under climatic and anthropogenic changes. *Hydrol. Sci. J.* 58(3), 498–518.
- Milano, M., Ruelland, D., Dezetter, A., Fabre, J., Ardoïn-Bardin, S. & Servat, E. (2013b) Modeling the current and future capacity of water resources to meet water demands in the Ebro basin. *J. Hydrol.* 500, 114–126.
- Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andréassian, V., Anctil, F. & Loumagne, C. (2005) Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 2 – towards a simple and efficient potential evapotranspiration model for rainfall-runoff modelling. *J. Hydrol.* 303, 290–306.
- Perrin, C., Michel, C. & Andréassian, V. (2003) Improvement of a parsimonious model for streamflow simulation. *J. Hydrol.* 10, 282–290.
- Quintana-Seguí, P., Le Moigne, P., Durand, Y., Martin, E., Habets, F., Baillon, M., Canellas, C., Franchisteguy, L. & Morel, S. (2008) Analysis of near-surface atmospheric variables: validation of the SAFRAN analysis over France. *J. Appl. Meteorol. Clim.* 47, 92–107.

Appendix B

Article published in the proceedings of the FRIEND-Water 2014 conference

SELECTING AN OPTIMAL CLIMATIC DATASET FOR INTEGRATED MODELLING OF THE EBRO HYDROSYSTEM

Dezetter, A., Fabre, J., Ruelland, D., Servat, E.

Abstract This study aims at defining a method for selecting an optimal interpolated climatic dataset in the context of an integrated modelling of the Ebro (85 000 km², Spain) hydro-system. Two different sets of temperature and precipitation were chosen according to data availability criteria, and each set was interpolated on an 8 × 8 km grid covering the basin, with and without a monthly or annual altitudinal gradient applied by geographical area (Pyrenees, Cantabrian and Iberian ranges) over 1000 m a.m.s.l. Seven basins (464 to 2 975 km²) representing different flow regimes of the Ebro catchment were chosen to evaluate the performance of 24 different climatic datasets for modelling water resources. We used a conceptual model (GR4j) at a daily time step to test the sensitivity of hydrological modelling to the different sets of precipitation and temperature. A global score was attributed to each dataset according to the different hydrological modelling criteria in order to discriminate the best-performing dataset.

Keywords climatic datasets; interpolation; rainfall–runoff modelling; Ebro basin; hydro-system modelling; selection method

Selecting an optimal climatic dataset for integrated modelling of the Ebro hydrosystem

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Key words climatic datasets; interpolation; rainfall–runoff modelling; Ebro basin; hydro-system modelling; selection method

INTRODUCTION

The Mediterranean basin is characterized by limited and unevenly distributed water resources. It was identified as one of the world's most vulnerable regions to climatic and anthropogenic changes (Alcamo *et al.*, 2007). According to Milano *et al.* (2012, 2013a), a 30–50% decline in freshwater resources is projected by the 2050 horizon over most of the Mediterranean basin, while anthropogenic pressures on water resources are expected to increase.

In this context the question of water resources' capacity to meet demand is essential. The GICC-REMedHE project (<http://www.remedhe.org>, *Identification et impacts du changement climatique sur la gestion intégrée des Ressources en Eau en Méditerranée : évaluation comparative Hérault-Ebre*), aims to develop a generic approach to represent and simulate Mediterranean hydro systems of different geographical scales and levels of complexity: the Hérault (2500 km², France) and the Ebro (85 000 km², Spain) catchments. In order to develop this approach's ability to simulate hydro-system evolutions under complex climatic and anthropogenic long-term scenarios, it must be tested over long past time periods (30–50 years). As a result a precise representation of water resources and their availability are essential in this integrated modelling context.

In this paper, we focus on the Ebro catchment's water resources. The Ebro is a highly regulated basin (over 200 dams) that hosts 60% of the Spain's fruit production and 25% of its hydro-electric power production. The contrasting hydro-climatic conditions within the basin call for an accurate representation of climatic inputs in view of evaluating water resources through rainfall–runoff modelling.

This study aims at proposing a method to interpolate precipitation and temperature data on an 8x8 km grid over the Ebro catchment, taking into account climatic heterogeneities through altitudinal gradients and considering the objective of water resources evaluation. This method should lead to reference data-grids for precipitation and temperature over a nearly 30-year period.

STUDY AREA

The Ebro catchment is the largest basin in Spain. It drains an area of about 85 000 km² in the northeast of the country (Fig. 1). It is characterized by a Mediterranean valley, surrounded by mountains including the Pyrenees and Cantabrian range to the north, the Iberian massif to the south and the coastal Catalan chain to the east. Altitudes range from 4 to 3383 m a.m.s.l. according to the SRTM (<http://srtm.csi.cgiar.org>) digital elevation model (DEM). The main stream Ebro is a 910 km long river flowing from the Cantabrian Mountains to the Mediterranean Sea.

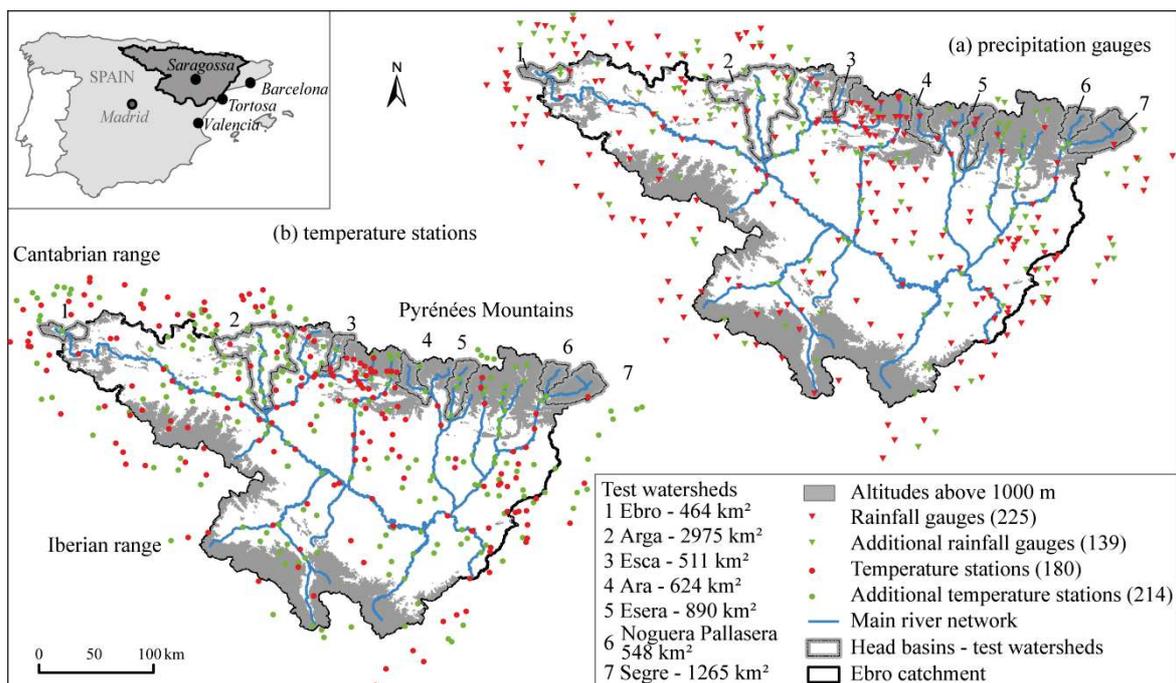


Fig. 1 Location of the Ebro basin, location of altitudes above 1000 m a.m.s.l. and test watersheds: (a) set of precipitation gauges and (b) set of temperature stations.

The heterogeneous topography of the catchment as well as the climatic influence of both the Atlantic Ocean and the Mediterranean Sea lead to a complex spatial distribution of climate variables (Vicente-Serrano & López-Moreno, 2006; Milano *et al.*, 2013b). Mean annual precipitation and temperatures vary with altitude, ranging from more than 1400 mm and 8°C in the Pyrenees to less than 400 mm and 18°C in the Ebro valley, averaged over the 1969–2002 period. These climatic differences are reflected in the hydrological regimes. According to López-Moreno *et al.* (2010), Pyrenean sub-catchments contribute most to outlet runoff. They produced, on average, 56% of the outlet's river flows over the 1950–2005 period, although only covering 11% of the total area of the Ebro basin.

DATA AND METHODS

Data

Daily precipitation (P) and temperature (T) data were provided by the Spanish meteorological agency (Agencia Estatal de Meteorología, AEMET). Data from over 1 000 measurement stations were available, however the period covered by each station and the rate of gaps in the series were very variable. Precipitation and temperature stations were selected in order to have homogeneous spatial distribution of as much data as possible for the 1969–2002 period, using data with a minimum of gaps in the daily series. Two selections were made in both precipitation and temperature stations: stations presenting fewer than 30% and 50% daily gaps per decade or on the whole period, for precipitation and temperature data respectively. These criteria enabled 225 or 364 precipitation gauges (Fig. 1(a)) and 180 or 394 temperature stations (Fig. 1(b)) to be selected.

Altitudes were extracted from the DEM SRTM (V 4.1) and daily river flows were provided by the CEDEX (Centro de Estudios y Experimentación de Obras Publicas). Seven sub-catchments (representing 37% of Ebro's mean annual discharge at the outlet) with little or no regulation by dams and good data availability were chosen (Fig. 1). These basins all include altitudes over 1000 m a.m.s.l., which allowed the influence of altitudinal gradients to be tested in data interpolation.

METHODS

The method consists of two steps: (a) determining the precipitation and temperature altitudinal gradients in order to interpolate the daily grids; and (b) testing the sensitivity of water resources modelling to climatic inputs and rating results.

(a) determining the gradients and interpolating the daily grids Observed P and T gradients were calculated by geographical area (see Fig. 1(b)) at a monthly and annual time step using stations with altitudes over 1000 m a.m.s.l. Data were interpolated on an 8×8 km grid at a daily time step, using the inverse distance squared weighted method. The gradients were applied daily based on the altitude difference between the DEM resampled at an 8 km scale and the altitude interpolated from the stations presenting data.

(b) water resource modelling and result scoring The GR4j model (Perrin *et al.*, 2003) was calibrated over the seven selected catchments, with and without the snowmelt module developed by Ruelland *et al.* (2011). This daily conceptual model uses four parameters without the snowmelt module (this module relies on three additional parameters), as well as precipitation (P), evapotranspiration (PE) and temperature (T) input data. PE was calculated using a simple formula depending on mean T and extra-terrestrial radiation (Oudin *et al.*, 2005).

An automatic calibration of the model was carried out on each basin and for each tested dataset, over the 1971–2002 period with a 2-year warm-up (1969–1970). The model was calibrated using a multi-objective function (F_{agg}) proposed by Ruelland *et al.* (2012) and aggregating a daily Nash-Sutcliffe efficiency (NSE) index, a cumulative volume error and a mean annual volume error. Automatic calibration followed three steps. (1) A random draw of 3000 parameter combinations in the model parameter space (four or seven parameters) made it possible to identify the best parameter set that was then used as the starting point of a nonlinear Rosenbrock (1960) optimization of the production function parameters, followed by a second Rosenbrock optimization of the transfer function parameters; (2) 100 repetitions of the first step allowed the best performing combination of parameters to be identified; and finally, (3) a local refining of the parameters around the optimum, using Nelder and Mead's simplex method (1965) was used to optimize all the parameters based on the combination chosen at step (2).

Results were rated using a ranking of the datasets on each basin according to the F_{agg} values, the lowest value being attributed the best score. A global score was attributed to each dataset by adding up scores from all basins.

A second score was used: where on each basin, each dataset was attributed a score calculated by averaging the difference in F_{agg} values between the given dataset and all other datasets. This mean value showed whether choosing one dataset over the others improved (negative value) or deteriorated (positive value) the water resources evaluation on each basin. Finally these values were averaged for each dataset over the seven basins.

RESULTS

Determining the gradients and interpolating the daily grids

For precipitation stations, only an annual gradient (2.14 mm/1000 m) could be determined in the Pyrenees. It was applied for grid cells with altitudes above 1000 m a.m.s.l. No gradient was found in the Cantabrian and Iberian ranges. The selection of this gradient and two sets of precipitation gauges (225 and 364) results in four precipitation grids: where the two selections of gauges were interpolated with or without the annual gradient.

For temperature stations, the Pyrenean range annual gradient is close to the average lapse rate of $6.5^{\circ}\text{C}/1000$ m, while the Cantabrian range gradient is lower (Fig. 2). The Iberian annual gradient is almost insignificant as confirmed by the monthly variations shown in Fig. 2. The mean monthly gradient of the Pyrenean range is higher in summer, unlike the Cantabrian one. As a result, six different grids of temperatures that associate the two selections of temperature stations (180 or 394, Fig. 1) and the three interpolation modes (without gradient, with annual gradient, with monthly gradient) were used.

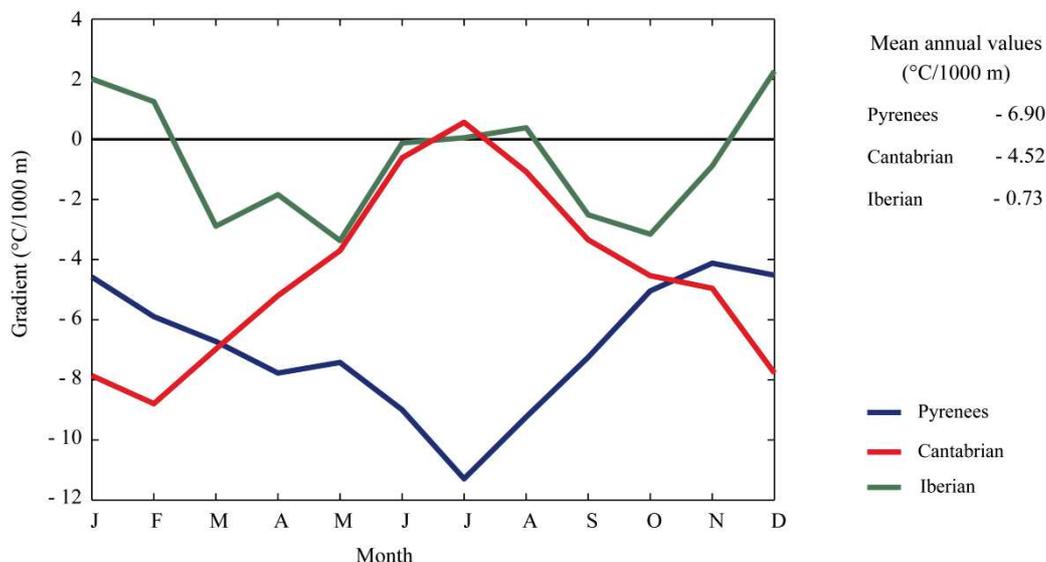


Fig. 2 Observed annual and monthly temperature gradients by geographical zone.

A total of 24 climatic datasets were then built by combining these four precipitation grids and six temperature grids.

Water resources modelling and result scoring

Calibration over the 1971–2002 period was thus carried out for the 24 datasets and for the seven selected basins with the GR4j model run with or without a snowmelt module. Results show that the snowmelt module is needed for all test basins, except for the Arga basin (Fig. 1) that has only 8.8% of area above altitudes of 1000 m a.m.s.l. Modelling reproduces water resources accurately on all basins, with volume errors always approaching zero and NSE values around 0.75 for the best dataset.

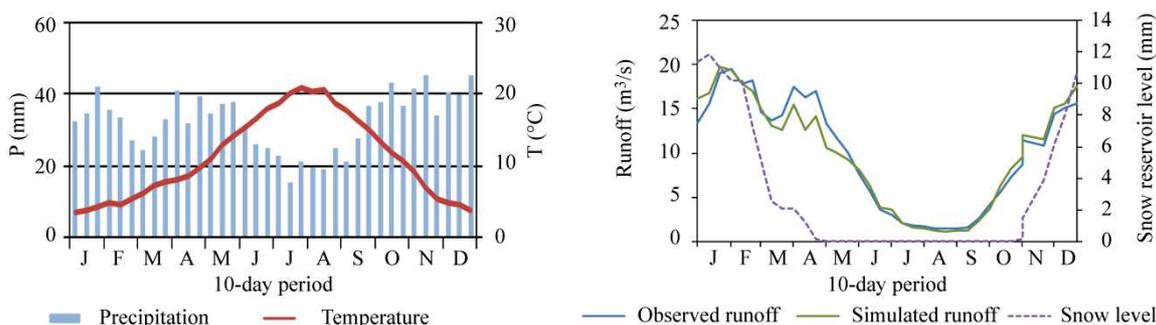


Fig. 3 Mean interannual 10-day values for the Esca basin over 1971–2002 with the best performing dataset (P364_wa_T394_wo)

Table 1 shows rankings for all basins considering the two ways of scoring. The table is sorted according to the second scoring method, the best performing dataset being in the first row (in bold). The last column indicates the dataset’s ranking with the first scoring method (FSM). The best performing dataset comes out first with both methods of scoring. Datasets using the maximum number of stations (i.e. including significant gap periods) are often top ranked in comparison with datasets with fewer stations. In the 12 first rows (datasets that do not worsen the modelling compared to all other datasets), precipitation datasets based on 364 stations occur seven times, as

well as temperature datasets based on 394 stations. Almost the same occurrence arises for datasets using altitudinal gradients (seven times over 12 with altitude for precipitation datasets and eight times over 12 for temperature datasets). The best performing dataset is the only one improving hydrological modelling for all basins. Considering all these criteria, two datasets can be considered as reference datasets for the Ebro basin: P364_wa_T394_wo and P364_wo_T394_wa_an (first and third row in Table 1).

Figure 3 gives an example of mean interannual 10-day values over the 1971–2002 period of the climate forcing and water resources modelling for the Esca basin with the best performing dataset, showing the good performance of the model.

Table 1 Ranking of all datasets over the seven test basins – datasets are named following this rule Pxxx_wy_Tzzz_wy_t where Pxxx is the number of precipitation stations used for interpolation, wy where y can be a or o respectively for with altitude and without altitude, Tzzz is the number of temperature stations used for interpolation, t can be an or mo respectively for annual gradient or monthly gradient for temperature interpolation. Dataset in bold is the best performing dataset according to this ranking. Negative values (*italic*) show improvements in modelling compared to all other datasets.

| Dataset/Basin | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Mean | FSM |
|------------------------|-------------|------------|------------|------------|------------|-------------|-------------|------------|----------|
| P364_wa_T394_wo | <i>-11%</i> | <i>-1%</i> | <i>-7%</i> | <i>-1%</i> | <i>-3%</i> | <i>-14%</i> | <i>-14%</i> | <i>-7%</i> | 1 |
| P225_wa_T394_wo | 3% | 1% | 5% | 0% | -8% | -20% | -14% | -5% | 6 |
| P364_wo_T394_wa_an | <i>-13%</i> | <i>-1%</i> | <i>-7%</i> | 0% | 2% | 6% | -20% | -5% | 2 |
| P225_wa_T394_wa_mo | 10% | 1% | 7% | 0% | -7% | -20% | -14% | -3% | 12 |
| P364_wo_T180_wa_an | -8% | 0% | -7% | -1% | 4% | 9% | -18% | -3% | 4 |
| P225_wa_T180_wo | 10% | 1% | 5% | -1% | -6% | -16% | -14% | -3% | 8 |
| P364_wa_T394_wa_mo | <i>-4%</i> | <i>-1%</i> | <i>-5%</i> | <i>-1%</i> | <i>-3%</i> | <i>-14%</i> | 10% | <i>-2%</i> | 3 |
| P364_wa_T180_wo | <i>-6%</i> | 0% | <i>-6%</i> | <i>-1%</i> | <i>-2%</i> | <i>-8%</i> | 10% | <i>-2%</i> | 7 |
| P225_wo_T394_wa_an | 2% | 1% | 6% | 1% | -1% | -1% | -18% | -2% | 14 |
| P225_wo_T180_wa_an | 6% | 1% | 6% | 0% | 2% | 1% | -16% | 0% | 16 |
| P364_wo_T394_wo | <i>-11%</i> | <i>-1%</i> | <i>-8%</i> | 1% | 8% | 16% | -5% | 0% | 10 |
| P364_wa_T180_wa_mo | 4% | 0% | -4% | -1% | -1% | -9% | 12% | 0% | 11 |
| P364_wo_T394_wa_mo | <i>-4%</i> | <i>-1%</i> | <i>-5%</i> | 1% | 8% | 15% | -5% | 1% | 15 |
| P225_wa_T180_wa_mo | 16% | 1% | 8% | -1% | -5% | -16% | 11% | 2% | 20 |
| P225_wo_T394_wo | 4% | 1% | 5% | 2% | 4% | 6% | -3% | 2% | 19 |
| P364_wo_T180_wo | <i>-6%</i> | 0% | -7% | 0% | 10% | 19% | 3% | 3% | 17 |
| P225_wo_T394_wa_mo | 10% | 1% | 7% | 2% | 5% | 6% | -4% | 4% | 22 |
| P364_wa_T394_wa_an | <i>-12%</i> | <i>-1%</i> | <i>-6%</i> | <i>-1%</i> | <i>-5%</i> | 12% | 41% | 4% | 5 |
| P364_wo_T180_wa_mo | 4% | 0% | -4% | 0% | 11% | 19% | 3% | 5% | 21 |
| P225_wo_T180_wo | 7% | 1% | 7% | 1% | 7% | 10% | 3% | 5% | 24 |
| P364_wa_T180_wa_an | -8% | 0% | -4% | -2% | -4% | 13% | 42% | 5% | 9 |
| P225_wo_T180_wa_mo | 17% | 1% | 8% | 1% | 7% | 10% | 2% | 7% | 23 |
| P225_wa_T394_wa_an | 2% | 1% | 6% | 0% | -9% | 5% | 44% | 7% | 13 |
| P225_wa_T180_wa_an | 5% | 1% | 6% | -1% | -7% | 7% | 43% | 8% | 18 |

DISCUSSION AND CONCLUSION

Considering the context of integrated modelling of the Ebro hydro-system and the need to have a long-term representative climatic dataset of this large basin, a method has been proposed to determine which climatic dataset would be selected for the ongoing project.

Some limitations can be discussed. The first one concerns equifinality in model parameters, especially with the snowmelt module adding three parameters to the four existing parameters. This issue was addressed using a robust calibration method, however compensations may persist. The fact that an altitudinal gradient is needed either for interpolating precipitation, or for interpolating temperature (rows 1 and 3 of Table 1) is a demonstration of these compensations. The snowmelt module has a threshold temperature parameter controlling snow melt. When no gradient is used, this threshold is higher than when an altitudinal gradient is used but parameters are able to compensate this interpolation shortcoming.

The second limitation concerns scoring methods that could be considered questionable or biased. In fact, considering the goal of the climatic grid obtained, this scoring method is well adapted. The interpolation method takes into account the best available information on stations and altitudes of the basin, and grids are tested on the more contributory basins. Gradients were applied on parts of the basin with altitudes over 1000 m a.m.s.l. and for other parts, no gradient was applied. Other uses of the grid in the integrated chain are not affected, especially in the central valley of Ebro where agricultural demands will be calculated with the chosen climatic dataset. In addition, the Noguera Pallasera and Segre basins (Fig. 1), where the density of precipitation and temperature stations is lower, have the highest improvement in water resources modelling when using gradients. Modelling of water resources in upper basins of the Ebro is satisfactory using the GR4j model with a snowmelt module. This snowmelt module is needed for these basins, except for the Ara basin which has only 8.8% of its area above 1000 m a.m.s.l. and does not receive much snow during winter.

Other investigations will be conducted in the project with the two datasets “P364_wa_T394_wo” and “P364_wo_T394_wa_an” to determine sensitivity of all components of the integrated modelling chain to the climatic interpolated grid. These two datasets have gradients either for precipitation or for temperature interpolations. Modelling of water resources has shown its ability to adapt its parameters to accurately simulate observed runoff. Other components, such as water demand estimation or the dam module, could be more sensitive to precipitation or temperature gradients. This would be another criterion to select the reference climatic dataset.

In conclusion, the method elaborated in this paper enabled the choice of two datasets for the 1969–2002 period over the Ebro catchment for integrated modelling of this large and complex hydro-system. Modelling of water resources in upper basins needs to take into account snowmelt. Ongoing work will allow further discrimination of the datasets.

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REFERENCES

- Alcamo, J., Florke, M. & Marker, M., (2007). Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrol. Sc. J.* 52(2), 247–275.
- López-Moreno, J. I., Vicente-Serrano, S. M., Moran-Tejada, E., Zabalza, J., Lorenzo-Lacruz, J. & García-Ruiz, J. M. (2010) Impact of climate evolution and land use changes on water yield in the Ebro basin. *Hydrol. Earth Syst. Sci. Discuss.* 7, 2651–2681.
- Milano, M., Ruelland, D., Fernandez, S., Dezetter, A., Fabre, J. & Servat, E. (2012). Facing climatic and anthropogenic changes in the Mediterranean basin: what will be the medium-term impact on water stress? *CR Geoscience* 344, 432–440.
- Milano, M., Ruelland, D., Fernandez, S., Dezetter, A., Fabre, J., Servat, E., Fritsch, J.-M., Ardoin-Bardin, S. & Thivet, G. (2013a) Current state of Mediterranean water resources and future trends under climatic and anthropogenic changes. *Hydrol. Sci. J.* 58(3), 498–518.
- Milano, M., Ruelland, D., Dezetter, A., Fabre, J., Ardoin-Bardin, S., & Servat, E. (2013b). Modeling the current and future capacity of water resources to meet water demands over the Ebro basin. *J. Hydrol.* (in press). <http://dx.doi.org/10.1016/j.jhydrol.2013.07.010>.
- Nelder, J. A. & Mead, R. (1965) A simplex method for function minimization. *Computer Journal* 7(4), 308–313.
- Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andréassian, V., Anctil, F., Loumagne, C. (2005) Which potential evapotranspiration input for a lumped rainfall–runoff model? Part 2 – towards a simple and efficient potential evapotranspiration model for rainfall–runoff modelling. *J. Hydrol.* 303, 290–306.
- Perrin, C., Michel, C. & Andréassian, V. (2003) Improvement of a parsimonious model for streamflow simulation. *J. Hydrol.* 279, 275–289.
- Rosenbrock, H. H. (1960) An automatic method for finding the greatest or least value of a function. *Computer Journal* 3(3), 175–184.
- Ruelland, D., Brisset, N., Jourde, H. & Oyarzun, R. (2011). Modelling the impact of climatic variability on the groundwater and surface flows from a mountainous catchment in the Chilean Andes. In: *Cold Regions Hydrology in a Changing Climate* (Proc. 25th IUGG General Assembly, Melbourne, Australia, 28 June–7 July 2011) (ed. by Daqing Yang et al.), 171–179. IAHS Publ. 346. IAHS Press, Wallingford, UK.
- Ruelland, D., Ardoin-Bardin, S., Collet, L. & Roucou, P. (2012) Simulating future trends in hydrological regime of a large Sudano-Sahelian catchment under climate change. *J. Hydrol.* 424–425, 207–216.
- Vicente-Serrano, S. & López-Moreno, J. I. (2006) Influence of atmospheric circulation at different spatial scales on winter drought variability through a semiarid climatic gradient in North-east Spain. *Int. J. Climatol.* 26(11), 1427–1453.

Appendix C

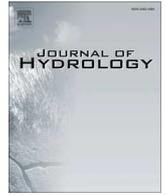
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HISTORICAL RECONSTRUCTION AND 2050 PROJECTIONS OF WATER DEMAND UNDER ANTHROPOGENIC AND CLIMATE CHANGES IN TWO CONTRASTED MEDITERRANEAN CATCHMENTS

Grouillet, B., Fabre, J., Ruelland, D., Dezetter, A.

Abstract This paper presents an integrative conceptual framework developed to simulate the spatial and temporal dynamics of water demand caused by human influences and climate change, at the river basin management scale. The past dynamics of urban, agricultural, and industrial components of water demand were simulated at a 10-day time step for the period between 1970 and 2009. The same model was used to forecast water demand at the 2050 horizon under water use scenarios based on local projections, trends observed in the past, and climate scenarios. Climate prediction uncertainties were taken into account using a wide range of climate scenarios downscaled from 9 IPCC-AR5 GCMs under RCP8.5. To test how widely and easily our approach can be applied, we tested it in two river basins facing different kinds of human pressure and different water management issues: the Herault basin (2 500 km²) in France and the Ebro basin (85 000 km²) in Spain. Results showed that water demand has increased significantly in the last 40 years in both the Herault basin (+29%) and the Ebro basin (+57%), and revealed spatially heterogeneous variations in water demand. Identifying the main drivers of water demand and their past dynamics enabled us to build water use trend scenarios at the 2050 horizon. Simulations of water demand under anthropogenic and climate trends in 2050 revealed a significant increase in total water demand in both basins (Herault +38% to +50%, Ebro +35% to +58%). These projections show that changes in the pressure of human activities will influence variations in water demand more than climate change. The broader aim of this research is to assess the balance between water demand and supply through a comprehensive modeling framework to evaluate the sustainability of water uses in a changing environment.

Keywords water demand; anthropogenic changes; climate change impacts; River Ebro; River Herault



Historical reconstruction and 2050 projections of water demand under anthropogenic and climate changes in two contrasted Mediterranean catchments



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SUMMARY

This paper presents an integrative conceptual framework developed to simulate the spatial and temporal dynamics of water demand caused by human influences and climate change, at the river basin management scale. The past dynamics of urban, agricultural, and industrial components of water demand were simulated at a 10-day time step for the period between 1970 and 2009. The same model was used to forecast water demand at the 2050 horizon under water use scenarios based on local projections, trends observed in the past, and climate scenarios. Climate prediction uncertainties were taken into account using a wide range of climate scenarios downscaled from 9 IPCC-AR5 GCMs under RCP8.5. To test how widely and easily our approach can be applied, we tested it in two river basins facing different kinds of human pressure and different water management issues: the Herault basin (2500 km²) in France and the Ebro basin (85,000 km²) in Spain. Results showed that water demand has increased significantly in the last 40 years in both the Herault basin (+29%) and the Ebro basin (+57%), and revealed spatially heterogeneous variations in water demand. Identifying the main drivers of water demand and their past dynamics enabled us to build water use trend scenarios at the 2050 horizon. Simulations of water demand under anthropogenic and climate trends in 2050 revealed a significant increase in total water demand in both basins (Herault +38% to +50%, Ebro +35% to +58%). These projections show that changes in the pressure of human activities will influence variations in water demand more than climate change. The broader aim of this research is to assess the balance between water demand and supply through a comprehensive modeling framework to evaluate the sustainability of water uses in a changing environment.

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1. Introduction

1.1. On the lack of knowledge regarding water demand in the Mediterranean region

The Mediterranean basin is characterized by limited water resources and increasing human activities, resulting from a 70% increase in population since 1970 (United Nations, 2013). Further substantial increases in both the population and seasonal tourism are forecasted in many Mediterranean countries (Burak et al., 2004; Gober, 2010), particularly in coastal regions. These changes will most likely result in an increase in agricultural production to meet the needs of the growing population, in turn leading to an

increase in water demand and to significant changes in water use patterns. In regions where water stress is already high, the combined impact of increasing needs and decreasing water availability due to climate change could lead to severe water shortages and major water use conflicts (Milano et al., 2013a). Although dedicated studies on the southern rim (e.g. Hoekstra and Chapagain, 2007) underlined the very probable intensification of the water crisis, the question still remains whether future water demand on the northern rim can be satisfied even if population growth is lower.

In recent decades, national water management strategies in the Mediterranean region that favor supply-side policies have mostly led to overexploitation of groundwater and river systems, and to environmental degradation due to the proliferation of dams and canals. Recent studies (Collet et al., 2013; Milano et al., 2013b) confirmed that some basins on the northern rim of the Mediterranean already faced water scarcity periods of varying intensity in the recent past. This has led local policymakers, through the Mediter-

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anean Strategy for Sustainable Development (Plan Bleu, 2005), to suggest to “reorient water policies to integrate water demand management in agriculture and other sectorial policies; and encourage demand-side approaches”.

At the basin scale, these new strategic guidelines have led policy-makers and local managers to consider implementing demand-side approaches throughout their territory. However, knowledge of water demand is limited, and its assessment can be complex. Although local stakeholders on the northern rim of the Mediterranean often have basic knowledge of current water withdrawals and their distribution between different uses, there is a serious lack of information on the dynamics of different water uses in space and over time. To tackle these issues, the scientific community has begun to incorporate water uses in water resources management studies (e.g. Charlton and Arnell, 2011; Collet et al., 2013; Griffin et al., 2013), combining physical and human features and causing interdisciplinary problems.

As water management increasingly turns to demand-side approaches, reliable methods of assessing water demand are indispensable. Such methods should be able to assess the dynamics and determine the main drivers of each type of water demand, and be able to project future water uses. In parallel, global scale studies have highlighted the potentially significant impact of climate change on future water demand (Alcamo et al., 2003; Vörösmarty, 2000) and raise the question of its effects at the local scale or at the management unit scale. The forecasting dimension of water demand assessments at a local scale is an integral part of water management strategies to ensure the sustainability of water supply (e.g. Reynard et al., 2014).

1.2. Scientific and technical challenges in the assessment of water demand

A review of the literature revealed that water demand is most often tackled in studies that compare water supply and demand in terms of water stress and/or the vulnerability of territories to climate change (e.g. de Graaf et al., 2004; Beck and Bernauer, 2011; Collet et al., 2014; Dawadi and Ahmad, 2013; Milano et al., 2013b; Hejazi et al., 2014). Three main issues were identified in these studies: (i) water demand is not always considered as a whole i.e., not all its components (agricultural, urban, industrial, energy) are accounted for; (ii) spatialization of data is not always consistent with the goals of connection with water supply assessment; and (iii) the reduced time depths and large time steps usually used, do not accurately account for the temporal variability of the drivers of water demand.

Although the assessment of water demand requires interdisciplinary approaches, often only one of its components is analyzed. For example, in Breyer et al. (2012), water use patterns only focused on residential water requirements. In the same way, Ruijs et al. (2008) only considered the effect of water pricing policies on urban water demand. Numerous studies focused on agricultural water needs based on irrigation water (e.g. Rosenzweig et al., 2004; Thomas, 2008; Schaldach et al., 2012; Mullen et al., 2009; Minacapilli et al., 2008; Wu and Chen, 2013). This is probably because in many regions irrigation is the main water use and the development of irrigated areas is often considered as a strategic way to maintain agricultural activity. However, prioritizing water uses requires taking all water demands, even those that consume the least water (including water for the habitats for fauna or immaterial uses such as the landscape use of waters), into account.

As underlined by Boithias et al. (2014), the assessment of water demand needs to be spatially distributed, as the results can differ depending on the spatial scale considered (Syrbe and Walz, 2012). Hejazi et al. (2014) also point to the need to spatially downscale water demand to be consistent with representations of water avail-

ability. To be compared with available water resources, water demand needs to be represented on a relevant scale that is compatible with the main hydrological features (storage dams, river catchments). The spatial aggregation of water demand into demand nodes also needs to account for heterogeneities in water uses throughout the territory (water withdrawals and transfers, main irrigation systems). In addition, the availability and the quality of data strongly influence the definition of water demand nodes. Consequently, defining demand nodes consistent with hydrological constraints is becoming a key issue for water demand studies.

The choice of the time depth and time step influences the results of water demand assessments. Multi-decadal time periods should be used to characterize historical variations in water uses, trends, and discontinuities in human activities. Highlighting and understanding these dynamics along with breaks that occurred in the past makes it possible to identify the main drivers of changes in water demand and, consequently, enables the design of more realistic future water use scenarios. Previous studies (Collet et al., 2013; Milano et al., 2013b) identified trends and breaks in water demand in recent decades in northern Mediterranean regions. They showed that human-induced changes such as population growth, expansion of irrigated areas or improvement of network efficiency can have a significant impact on water demand, which cannot be identified if the focus is limited to current water uses. Time depth also makes it possible to capture the influence of climatic variability on irrigation needs, for example. In addition, water demand assessments can be strongly influenced by the time step chosen for the analysis. The choice of a time step is generally closely linked to the spatial scale and to the time depth of the study: the larger the spatial scale and/or time depth, the larger the time step. While global scale studies rely on yearly analysis (e.g. Alcamo et al., 2003; Döll, 2002; Vörösmarty, 2000), a monthly time step is generally used at the basin scale (e.g. Koch and Vögele, 2009; López-Moreno et al., 2011; Salvador et al., 2011). This finer time step is appropriate when studying urban and agricultural demands, which are seasonally driven by tourism and crop phenology, respectively. Notably, irrigation water requirements generally decrease with an increase in the time interval, as pointed out by Green (2008). In addition, a narrow time step makes it possible to take the water recharge of the soil buffer reservoir into account more accurately in an irrigation water model. However, a monthly time step does not account for infra-monthly rainfall variability that can be very high in the Mediterranean region. In a theoretical assessment model of irrigation water requirements, considering the soil and its buffering effect, the infra-monthly distribution of rainfall and, to a lesser extent, the temperature, can have a significant impact on water requirements.

1.3. An integrative approach to reach these goals

Water management stakes on the northern rim of the Mediterranean and the shortcomings identified in the scientific literature underline the need to quantify water demand by accounting for human and climatic drivers at appropriate spatial and temporal scales. The purpose of this paper is thus to present an integrative conceptual framework to accurately simulate water demand under anthropogenic and climate changes. First, we assess each component of water demand and its spatial and temporal dynamics over a long past time period. Second, we use the same framework to forecast water demand at the 2050 horizon under water use scenarios based on local projections and following trends observed in the past, and climate scenarios built according to recent runs of IPCC climate models. To test how widely and easily our approach is applicable, we decided to tackle these issues by analyzing two different territories facing strong but diverse anthropogenic pressures and different water management issues.

2. Study areas

Two contrasted catchments on the Northern Mediterranean rim were chosen for the study: the Hérault basin and the Ebro basin.

The Hérault catchment (2500 km²) is located in the South of France (Fig. 1a). The Hérault River flows 150 km from the Cévennes Mountains in the north to the Mediterranean Sea in the south. The population of approximately 150,000 permanent residents can double in the summer as a result of tourism. The population density is heterogeneous, reaching 200 inhab./km² in the downstream areas but only 25 inhab./km² in the upstream ones. Currently, urban water demand represents about half of the total water demand including transfers outside the basin. The Florensac transfer (Fig. 1a) supplies water to towns located outside the Hérault catchment, and accounts for 27% (22 hm³ in 2009) of water withdrawals. Most irrigated areas are located downstream and have been steadily growing in the south in contrast to the agricultural decline underway since the 1970s in the north. Vineyards currently account for 54% of the agricultural land, with a continually increasing irrigation rate. To understand the spatial distribution of water demand in the basin and to identify the spatial heterogeneity of variations in water demand, the Hérault basin was divided into six sections corresponding to six demand nodes, as described by Grouillet et al. (2014).

The Ebro catchment (85,000 km²) is boarded in the north by the Pyrenean and Cantabrian mountain ranges, which contribute to 56% of basin runoff (López-Moreno et al., 2011; Milano et al., 2013b) and the Iberian system in the south. This basin includes a semi-arid plain where irrigated areas (Fig. 1b), covering 700,000 ha in 2009, are supplied by large networks of canals and storage dams that provide water which mainly originates in the Pyrenean range. The population of the basin is 3,100,000 inhabitants, and, except in a few highly urbanized areas (e.g. Zaragoza, Lleida, Vitoria-Gasteiz), the population density is usually <50 inhab./km². In 2009, agricultural water needs accounted for 87% of total water needs at 6700 hm³. We divided the Ebro basin into 17 sections according to its hydrologic conditions, the main irrigation systems, and associated storage dams. Each section was attributed to a demand node.

3. Method

3.1. An integrative modeling framework to assess water demand

An integrative conceptual framework based on physical and socio-economic drivers (Fig. 2) was created to simulate the combined effect of population growth, urban unit water consumption,

agricultural developments, industrial processes, and climate variability on water demand. Urban water demand (UWD) includes water demand for domestic and commercial use and for the maintenance of parks and gardens. Agricultural water demand (AWD) represents water required for irrigation. We assumed that water withdrawals for livestock were negligible in comparison with withdrawals for irrigation. A third type of water demand “other water demands” (OWD) was used to account for the demand for water for industrial processes and cooling systems of nuclear power plants in the Ebro catchment. Water demand for hydropower was not included mainly because neither hydropower production models (generally provided by hydropower operators) nor data of the minimum flow needed to operate the turbines of the hydroelectric plants were available for the study areas. Environmental demand, generally defined as the minimum water flow needed to ensure ecological sustainability, will be considered in the next step of this study, which will assess the water allocation capacity of each hydro-system.

Urban water demand was assessed by multiplying population by unit water allocation. Population included water users supplied by water withdrawn in the basin, i.e. the residential population and the seasonal population, the latter being deduced from touristic activity (see Section 3.2). Unit water allocation is the volume of water allocated per capita for all urban needs. Allocations were calculated by dividing withdrawals by population in municipalities and years where these data were reliable and available. Allocations were then averaged per basin. In this work, unit water allocations thus included (i) mainly domestic water demand, which corresponds to water used per capita; (ii) water demand for parks and gardens; and (iii) commercial water demand converted per capita. Unit water allocations also included the efficiency of water supply networks.

Simulated agricultural water demand was based on total irrigation requirements, as recommended by the FAO (Allen et al., 1998) and presented in Fig. 2. Evapotranspiration under standard conditions (ET_C) refers to the amount of water consumed by evapotranspiration in optimal growth conditions, and was assessed for each irrigated crop using the crop coefficient approach (Fig. 2). The crop coefficient (K_C) combines the characteristics that distinguish a specific crop from the reference crop and hence ET_C from the reference evapotranspiration ET₀. The soil reservoir is primarily filled by effective precipitation, and emptied by crops. Crop irrigation requirements (CIR) are primarily satisfied by the soil water content and, when the soil reservoir is depleted, by the supply of irrigation water. Rice water needs were assessed according to a specific model inspired by the FAO methodology (Allen et al., 1998) taking into account RAW, a global value for soil saturation and an average

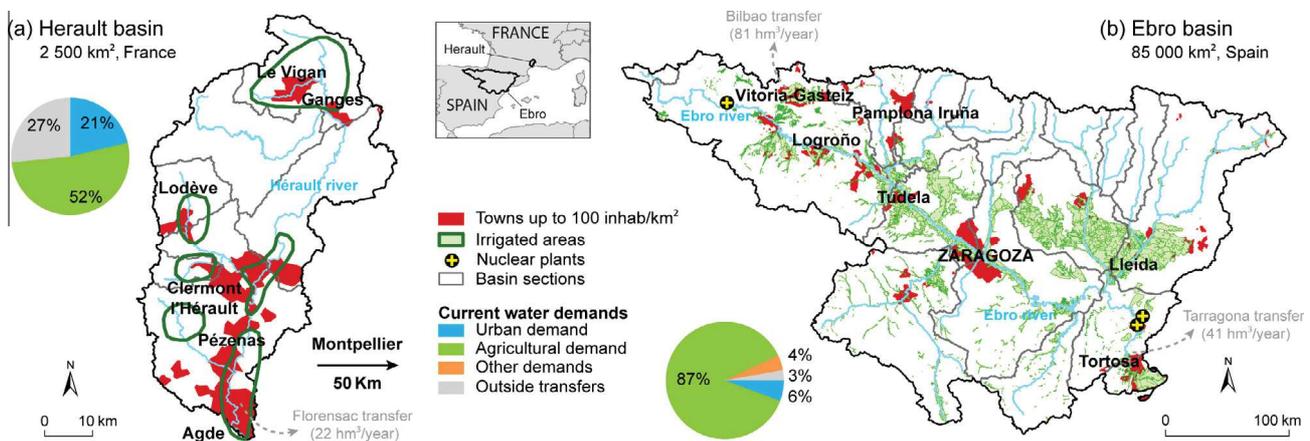


Fig. 1. Main anthropogenic pressures and water demands in the Hérault and Ebro basins.

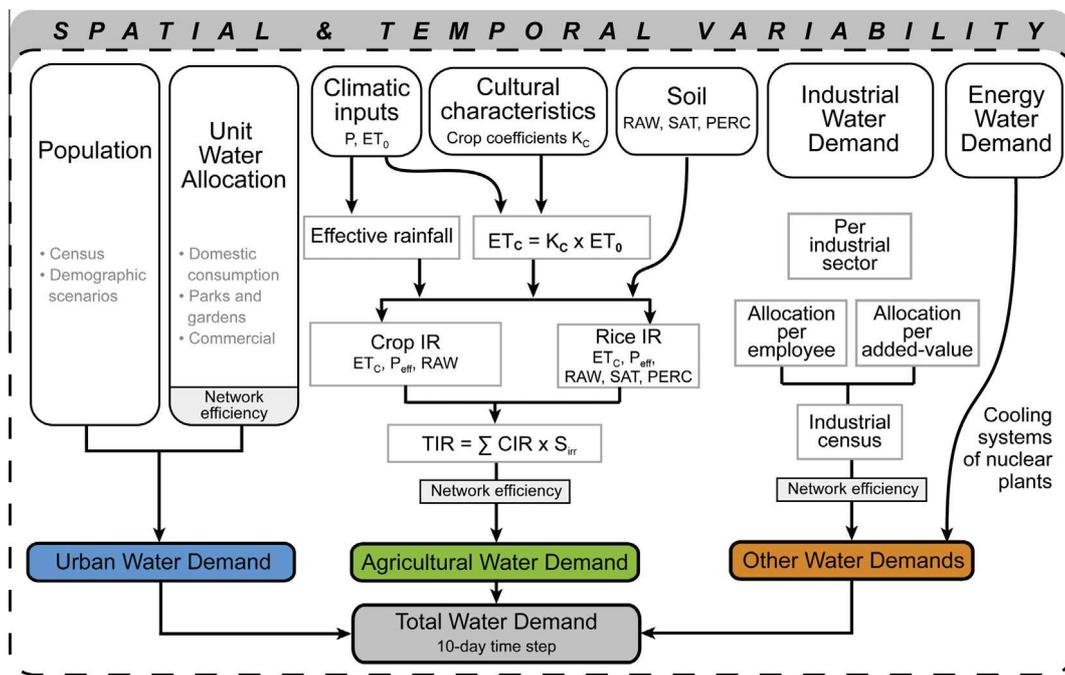


Fig. 2. Integrative conceptual framework to assess urban, agricultural, and other water demands. *P*: precipitation, *ET*₀: potential evapotranspiration, *K*_c: crop coefficient, RAW: readily available water, SAT: soil saturation, PERC: soil percolation rate, *ET*_c: Crop evapotranspiration under standard conditions, *P*_{eff}: effective rainfall, Crop IR: crop irrigation requirements, Rice IR: rice irrigation requirements, TIR: total irrigation requirements, *S*_{irr}: irrigated areas.

value of percolation according to the main soil type in the rice crop area.

Effective rainfall was computed at a 10-day time step according to the USDA Natural Resources Conservation Service formula (Eq. (1)) recommended by the FAO.

$$P_{\text{eff}} = \frac{P \times (125 - 0.6 \times P)}{125} \quad \text{if } P \leq \frac{250}{3} \text{ mm} \quad (1)$$

$$P_{\text{eff}} = \frac{125}{3} + 0.1 \times P \quad \text{if } P > \frac{250}{3} \text{ mm}$$

where *P*_{eff} is the 10-day effective precipitation and *P* is the 10-day precipitation.

The soil reservoir was considered as an average per basin section according to the readily available water (RAW) data from GIS maps of the European Soil Database (EC, 2004). Irrigation water needs were calculated for each crop at the municipality scale. Considering irrigated areas, the theoretical need for irrigation (TIR – Fig. 2) was also obtained at the municipality scale. Total irrigation requirements (TIR) were then divided by the efficiency of irrigation indicated by local managers (SMBFH, 2005; CHE, 2011), which included the efficiency of the water supply networks (canals, drains) and the efficiency of the irrigation system.

Industrial demand was not taken into consideration in the Hérault basin because there is little industrial activity and because the majority of factories are connected to the urban water supply network. In the Ebro basin, industrial demand was estimated at the municipality scale (CHE, 2011) based on the sector of the industrial activity concerned, and a water allocation was assigned per employee and per added-value. This allocation was defined according to the number of employees and the product added value at constant production prices (Fig. 2). Energy demand was taken into consideration only in the Ebro basin due to the presence of nuclear power plants in the area (Fig. 1). We assumed that the energy demand corresponds to the volume of water evaporated by the open-air cooling system of the nuclear reactor.

3.2. Processing techniques applied on the raw socio-economic and environmental data

A key step in simulating water demand based on the proposed conceptual framework consisted in normalizing raw data to provide the water demand models with usable inputs distributed in space and over time. This was done by computing climatic and socio-economic inputs at a 10-day time step for the period 1971–2009 at the scale of water management units defined with the local stakeholders according to the hydrologic context (water system, gauges and storage dams) and data availability. The choice of a 10-day time step was a compromise between the need to accurately represent the seasonal dynamics of water demand (especially agricultural demand) and the inevitable limitations in providing information at a finer time scale through the temporal disaggregation of available data. Table 1 presents the key variables and associated processing techniques used to compute the data used as model inputs.

Urban water demand (UWD) was calculated based on population and unit water allocations. Population data, available from national census of the French (INSEE) and the Spanish (INE) Statistics Institutes, provided residential population per municipality (Table 1). In the Hérault basin, a monthly ratio of additional tourists was produced based on the monthly distribution of overnight stays available for 2009. The residential and seasonal populations, which were available for roughly one year per decade in the period 1970–2009, were then interpolated to reconstitute inter-annual dynamics over 40 years at a 10-day time step. These data were then aggregated spatially per management unit by attributing each municipality to a demand node. After selecting usable withdrawal data and defining the areas supplied by these withdrawals, unit water allocations were calculated by dividing withdrawal volumes by the population of the area being supplied. As a result, time series were built to reproduce variations in unit water allocations over the past 40 years.

Table 1
Key variables and associated processing techniques used to compute data. (*): R: Raw data, S: Spatial operations to compute data, T: Temporal operations to compute data.

| Key variables | (*) | Raw data and processing techniques | |
|---------------------------------------|-----|---------------------------------------------------------------|---------------------------------------------|
| | | Herault | Ebro |
| <i>Urban water demand</i> | | | |
| Population | R | Annual census data (municipality) | Annual census data (municipality) |
| | S | Assigning municipality to demand nodes | Assigning municipality to demand nodes |
| | T | Non-linear interpolation | Non-linear interpolation |
| Unit water allocation | R | Annual withdrawals and population data | Annual withdrawal and population data |
| | S | Assigning municipality to demand nodes | Assigning municipality to demand nodes |
| | T | Extrapolation & non-linear interpolation | Extrapolation & non-linear interpolation |
| Urban network efficiency | R | Annual withdrawal/consumption data | Basin manager valuation: 80% |
| | S | Aggregated per section | At the basin scale |
| | T | Extrapolation and non-linear interpolation | Constant |
| Seasonal population | R | Local tourism data (overnight stays) | Non applicable |
| | S | Based on hydrogeological context where the water is withdrawn | |
| | T | Based on annual rate of holiday homes | |
| <i>Agricultural water demand</i> | | | |
| Climatic inputs (P , T°) | R | SAFRAN daily data | AEMET daily data |
| | S | Interpolated on an 8×8 km grid | Interpolated on an 8×8 km grid |
| | T | Daily data averaged at a 10-day time step | Daily data averaged at a 10-day time step |
| PET | R | Penman–Monteith formula + T° | Hargreaves formula + T° |
| | S | Interpolated on an 8×8 km grid | Interpolated on an 8×8 km grid |
| | T | Daily data averaged (10-day time step) | Daily data averaged (10-day time step) |
| Crop coefficients and calendars | R | FAO, Mediterranean climate | FAO, recalculated locally by the CHE |
| | S | Allocated to the corresponding crop | Allocated to the corresponding crop |
| | T | Constant | Constant |
| Irrigated areas | R | Agricultural census data (municipality) | Agricultural census data (municipality) |
| | S | GIS maps + allocation to node | GIS maps + allocation to node |
| | T | Annual data computed (10-day time step) | Annual data computed (10-day time step) |
| Agricultural network efficiency | R | Basin manager valuation | Basin manager valuation: 60% |
| | S | At the section scale | At the basin scale |
| | T | Extrapolation and non-linear interpolation | Constant |
| <i>Other demands</i> | | | |
| Industrial demand | R | Non applicable | CHE industrial census (municipality) |
| | S | | Assignment of municipality to node |
| | T | | Based on evolution of industrial activities |
| Energy demand | R | Non applicable | Evaporation data of 2 nuclear plants |
| | S | | Assignment to a demand node |
| | T | | Constant during operation period |

Agricultural water demand (AWD) was calculated based on irrigated areas, crop types, and soil types as well as evapotranspiration and precipitation data. Irrigated crops and their corresponding areas were available at the municipal scale from agricultural censuses in 4 and 20 distinct years between 1970 and 2009 in the Herault and the Ebro respectively (Table 1). Each municipality was assigned to a demand node according to its links with the main irrigation systems or spatially if not.

In the Herault basin, daily climatic data (precipitation, temperature, wind, humidity, radiation) for the 1970–2009 period were extracted from the 8×8 km meteorological analysis system SAFRAN, provided by Meteo France and validated over France by Quintana-Segui et al. (2008). Evapotranspiration ET_0 was calculated using the FAO Penman–Monteith method (Allen et al., 1998). In the Ebro basin, daily precipitation and temperature data from AEMET weather stations were spatially interpolated on an 8×8 km grid using the inverse distance weighted method for the period 1970–2009 and lapse rates computed from observations (Dezetter et al., 2014). The lack of sufficient wind, humidity, and solar radiation data on the Ebro basin prevented us from using the FAO Penman–Monteith method for ET_0 calculation, instead we used the Hargreaves equation (Hargreaves and Samani, 1985), using maximum and minimum temperature, extraterrestrial radi-

ation, and an empirical factor locally adjusted by Martínez-Cob and Tejero-Juste (2004) for the effect of the wind in the Ebro basin. In both areas, P and ET_0 daily data were computed at a 10-day time step cumulating daily values.

Climatic data were averaged for each demand node. GIS maps of irrigated areas were used to locate irrigated areas and hence to average climatic data only over the irrigated areas of each management unit. Assessing the spatial dynamics of irrigated areas is a challenge because GIS maps of irrigated areas are rarely available at an annual scale. For the Herault basin, large sectors of irrigated areas in 2005 were available (Fig. 1). For the Ebro basin, a GIS map of irrigated areas in 2004 was used. For both basins, the spatial distribution of irrigated areas was kept equal over time for the purpose of averaging climatic data. The size of the irrigated areas varied for the calculation of total irrigation requirements, according to annual irrigated data per municipality provided by the annual agricultural census linearly aggregated over the period 1970–2009. For the Herault basin, irrigation network efficiency included the efficiency of the water supply network (canals, drains) and the efficiency of the irrigation system was provided by local managers (SMBFH, 2005). Values between 60% and 80% depend on the rate of pressurized irrigation system in the basin section, except in the Gignac section where network efficiency was provided by the canal

stakeholder. For all the sections of the Ebro basin, irrigation network efficiency was provided to 60% by local managers (CHE, 2011).

Except climatic inputs, the monthly distribution of the population of tourists and the crop calendars, all the data used in this study are at a time step of more than a year. Since this work aimed to assess water demands at a 10-day time step, each variable had to be downscaled from annual to 10-day data. The downscaling method depended on the type of variable. For example, residential population or irrigated areas keep the same value all year round. In contrast, withdrawal volumes or water allocations have to be distributed at each time step.

3.3. Water use and climate scenarios at the 2050 horizon

To be able to project water demand in the two basins at the 2050 horizon, trend scenarios were built for each study area using water use projections. The water use scenarios were coupled with nine climate scenarios to account for the potential impact of climate on future agricultural water demand. The 2050 horizon (2036–2065) was chosen based on the necessary compromise between ability of local managers to project water uses (forecasts generally do not exceed the 2030 horizon) and the availability of reliable climate projections (a climate change signal is easier to distinguish from climatic variability in the medium term than in the short term). Water use scenarios at the 2050 horizon are based on basin managers' 2030 projections for the Herault basin (adapted from SMBFH, 2005) and on 2027 projections for the Ebro basin (CHE, 2011). Except for population, the data (irrigated areas, crop types, network efficiency, unit water demand and tourism) that came from these projections were spatially distributed and down-scaled at the 10-day time step to fit with model requirements. In addition, to build urban water uses scenarios, unit water allocation was split according to the average distribution of the main components of the urban demand (domestic, gardens and parks, commercial and network efficiency) in the 2000s. Thus changes in these components could be considered separately in future projections.

In the Herault basin, the water use scenario was based on the trend scenario of INSEE (called "Scenario central") for population growth. A 39% increase in the residential population is expected between the 2000s and 2050. Water users supplied by the Florensac transfer are expected to increase by 38% and the seasonal population by 74%. As suggested by Rinaudo (2011), a 12% decrease in domestic unit consumption between the 2000s and 2050 was applied linked with forecasted behavioral changes and improved control of water consumption by household appliances. Based on basin manager's projections (SMBFH, 2005; CHE, 2011), urban network efficiency should increase by 5% at the basin scale with heterogeneities within the basin. Irrigated areas should increase by 80%. According to the projections of irrigation system optimization and network improvements, cumulated efficiency should reach 80% in 2050 vs. 57% in the 2000s.

In the Ebro basin, based on INE national population projections, the residential population should increase by 26% between the 2000s and 2050 within the basin and in the areas supplied by transfers from the basin. Unit water allocation should increase by 14% mainly due to a higher connection rate of green spaces and stores to urban water networks. Based on CHE projections (CHE, 2011) for 2027, areas with irrigation rights should increase by 57% whereas effectively irrigated areas should increase by 46%. Industrial water allocations should increase significantly (+95%).

Regarding climate scenarios, outputs from nine Global Climate Models (CanESM2, CNRM, CSIRO, GFDL_ESM2G, HADGEM2_CC, HADGEM2_ES, IPSL-MR, MIROC5, MPIM) were downloaded from the IPCC's Data Distribution Centre, which provided simulations from its last report (IPCC, 2013). Using a set of GCMs is recommended to cover a wide range of potential climatic projections

because the dispersion mainly originates in the climate models (Arnell et al., 2004). All simulations of climate change were based on the historical Representative Concentration Pathway (RCP) over the reference period (1976–2005) and the RCP 8.5 at the 2050 horizon (2036–2065). The RCP 8.5 was selected because it is characterized by increasing greenhouse gas emissions over time (Riahi et al., 2007). High-resolution climate change data were obtained by a basic downscaling technique known as the perturbation method, which assumes that climate models reproduce the relative change in climatic variables better than their absolute values. This method consists in producing future climate scenarios by simply modifying the observed climatic series so as to reproduce the mean monthly variations obtained between the reference and future climatic simulations from GCMs. For more details on this method, see Ruelland et al. (2012).

To distinguish the relative weight of anthropogenic and climate changes, we simulated water demand projections through three analyses: (i) projections of water demand under anthropogenic change only, (ii) projections of water demand under climate change only and (iii) projections of water demand under combined anthropogenic and climate changes.

4. Results

4.1. Reconstruction of past water demand dynamics

To reflect the distribution of water demand in space and over time, we present the spatial distribution of water demand in the 2000s (2000–2009) and past variations over a 40-year period (1970–2009) in the Herault basin (Fig. 3) and the Ebro basin (Fig. 4). Mean demand in the 2000s was used as a reference for the recent period in order to represent the meaningful variability of the impact of the climate on agricultural water demand.

4.1.1. Past variations in the Herault catchment

Fig. 3 shows variations in water demand over the last 40 years in the Herault basin. Water demand is concentrated in the downstream sections of the basin (Fig. 3a). While demand reached 35.5 hm³/y on average in the 2000s in the Agde section, it did not exceed 0.5 hm³/y in the St Laurent section. The Agde and Gignac sections account for 87% of the water demand of the entire basin (75.5 hm³/y). The Gignac canal (the main irrigation canal in the basin) and the Florensac withdrawals represented respectively 40% and 26% of total water demand in the basin in the 2000s. The ratio of water demands was nevertheless balanced with 47% for agriculture, 22% for urban needs and 31% for outside transfers in the late 2000s. At the basin scale, water demand increased significantly from 59 hm³/y in the 1970s to 76 hm³/y in the 2000s. Peak demand (9.5 hm³ per 10-day period) was in July but extended from June to September (Fig. 3c), in accordance with vineyard water needs, dry climate conditions, and the influx of tourists.

Three sections, Agde, Gignac and Laroque, are representative in terms of their contribution to total water demand in the basin and in the past dynamics of anthropogenic changes. In these representative sections, the 2000s were characterized by an increase in urban and agricultural demand linked with recent population growth. In the rural upstream area of Laroque, agricultural water demand decreased in the 1980s and the 1990s (Fig. 3b), which is consistent with the decline in agriculture observed during this period. The Gignac section is mainly influenced by a large-scale irrigation system supplied by the Gignac Canal. Agricultural water demand reached 93% of the total water demand in this section in the 2000s. Thanks to a combination of restoring the main canal and converting secondary networks to pressurized systems, a new policy to improve the efficiency of the out-of-date canal sig-

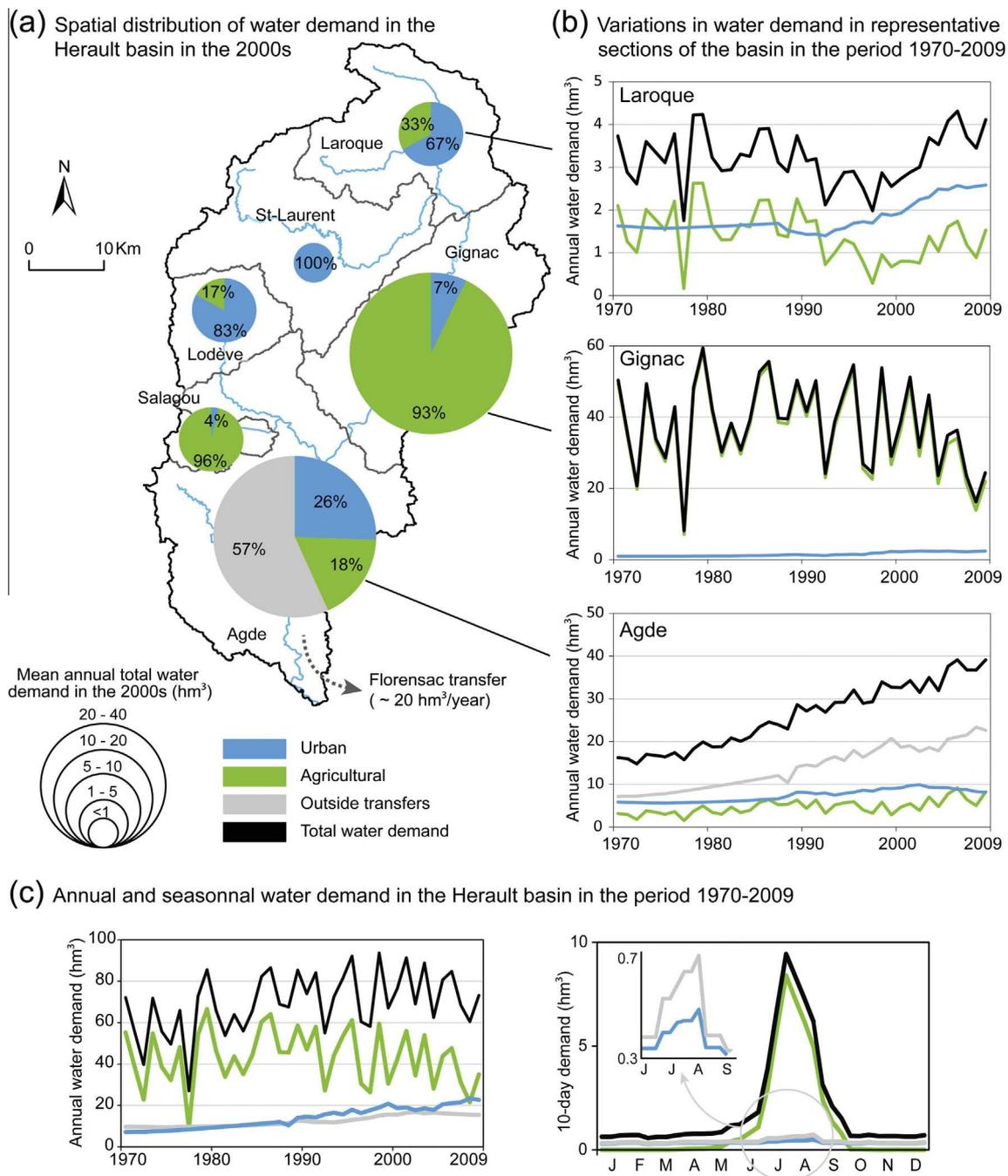


Fig. 3. (a) Spatial distribution of water demand in the 2000s and past reconstruction of 10-day water demand in the period 1970–2009 in (b) three areas representative of the heterogeneities in the Herault basin and (c) in the Herault basin as a whole.

nificantly reduced water demand in this section: –40% between 2000 and 2009. The past variations in agricultural demand reveal its sensitivity to climate conditions, as underlined by a relative 40% standard deviation of the annual agricultural water demand in the Gignac section, for example. In the Agde section, water demand grew steadily, mainly driven by outside water transfers, which reached 57% of the total demand in the 2000s. A shift in the increase in urban demand occurred in the 2000s, corresponding to a decrease in household consumption during this period.

4.1.2. Past variations in the Ebro catchment

Agricultural water demand is predominant and heterogeneously distributed over the basin. Five sections of the central

plain, mainly distinguished by the presence of large-scale irrigation systems, accounted for 86% of the water demand in the basin in the 2000s but only 51% of total surface area (Fig. 4a). Past variations in water demand in the Ebro basin are presented for a selection of sections that are representative of the basin's main characteristics and heterogeneities. Like in most other sections of the basin, the main demand in the Bajo Cinca section is for irrigation, which has been increasing steadily since the 1970s. The slight stabilization of irrigated land in the 2000s led to a drop in agricultural water demand (see Bajo Ebro, Bajo Cinca, Alto Ebro sections in Fig. 4b). In Alto and Bajo Ebro, urban and other water demands, through inside or outside needs, reached respectively 36% and 26% of the water demand in this section in the 2000s. The example

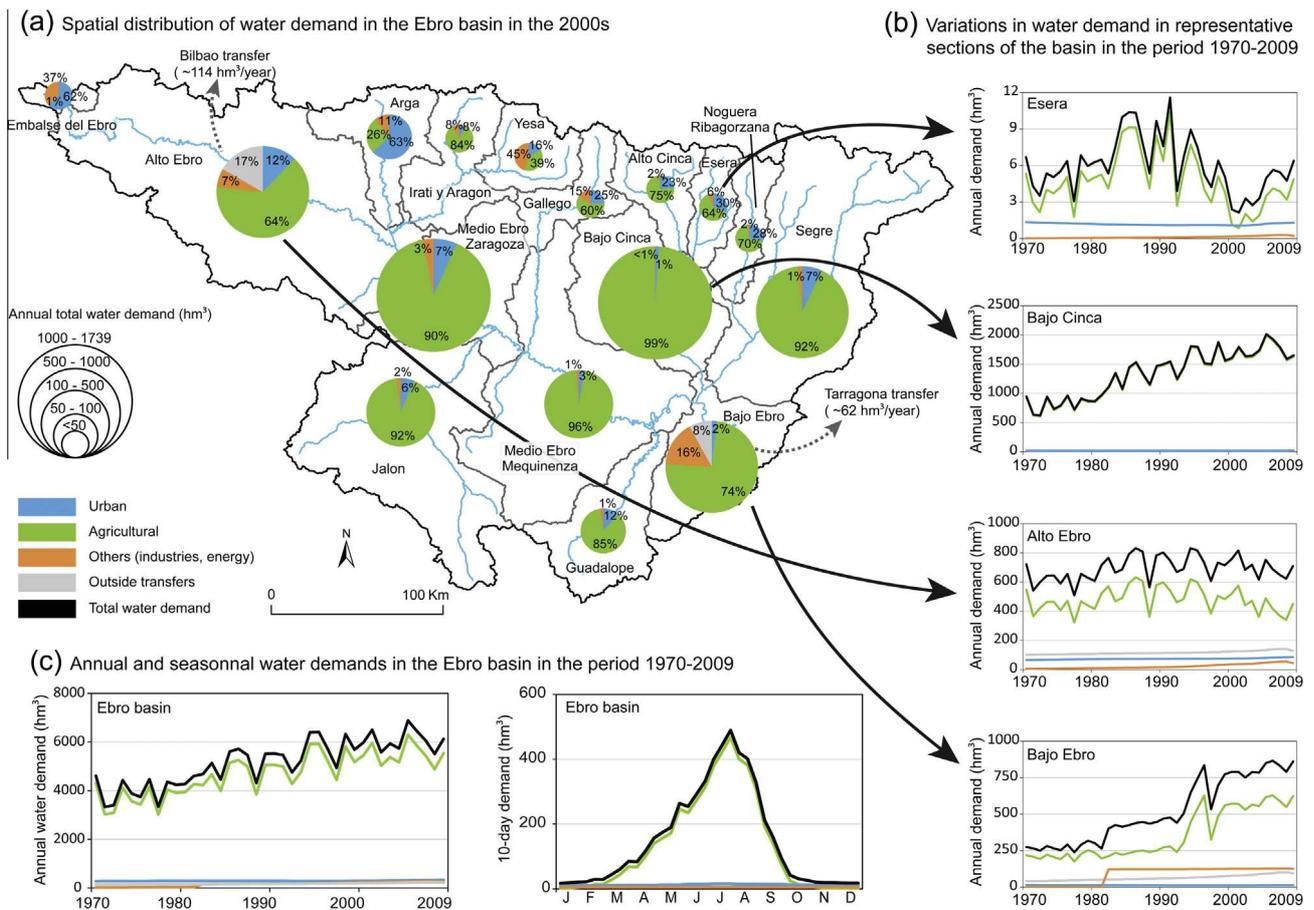


Fig. 4. (a) Spatial distribution of water demands in the 2000s and past reconstruction of 10-day water demands for the period 1970–2009 in (b) three areas representative of the heterogeneities in the Ebro basin and (c) in the Ebro basin as a whole.

of industrial demand in Bajo Ebro reveals the impact of a new nuclear power plant on the total demand in the 1980s. The decrease in the population in the mountainous upstream sections, such as Esera, led to a decrease in water demand during the 1980s and 1990s. The impact of the economic crisis in Spain at the end of the 2000s is recognizable in the graphs reconstructing past water demand in the Esera and Alto Ebro sections by the significant decrease in other water demands (see Fig. 4b). At the basin scale, water demand increased significantly from 4150 hm³/y in the 1970s to 6340 hm³/y in the 2000s. With a maximum of 500 hm³ per 10-day period in July, the seasonality of the water demand (Fig. 4c) is quite extensive to meet water needs of a diversified agricultural production.

4.2. Variations in water demand forecasted for 2050

4.2.1. Under anthropogenic changes only

At the scale of the Herault basin under socio-economic projections only, water demand could increase by 54% to reach 88 hm³/y. The spatial distribution of variations in water demand from the 2000s to the 2050 horizon is also very heterogeneous (Fig. 5a). Water demand is projected to decrease by 28% in the Gignac section whereas it could increase by 96% in the Agde section. The forecasted decrease in the Gignac and Salagou sections are mainly due to improvement in network efficiency and to the priority given to more efficient irrigation systems. The significant increase projected in the Agde section can be explained by a 91% increase in irrigated areas, a 26% increase in population, and a 20% increase in tourism, hence a 6% improvement in the efficiency of the distribution network will not compensate for the three drivers.

At the scale of the Ebro basin, water demand could increase by 37% to reach 7805 hm³/y. The different sections considered are also characterized by marked differences in the variations in water demand (from +16% to +206%) according to the projected population in 2050 (Fig. 6a). Despite significant increases in the upstream sub-basins (up to +100%), the volumes withdrawn remain low (under 70 hm³/y). In the sections with the highest water demand, the increase could reach +16% to +63%, slightly higher in summer (+32% to +63%) as the main irrigation needs are in summer. These increases are mainly due to the policy of continuing expansion of irrigated land forecasted for the 2050 horizon. In several sections, including Alto Ebro, water demand could also increase significantly (54%) in winter due to high urban and industrial water demand. The monthly distribution of water demand shows that demand is expected to increase throughout the year (+36% in summer).

4.2.2. Under climate changes only

The impact of future climate change on water demand was estimated assuming the current anthropic context (2000s) under a range of future climatic conditions (2050). The reference period for climate (1976–2005) and the future period (2036–2065) were chosen to compare mean climatic inputs over a long time period (30 years). Climatic uncertainties were accounted for by the range of the projections in nine climate scenarios. The boundaries of this range (see Figs. 5 and 6) were represented by the minimum and the maximum of the nine climate scenarios for each time step. The 2050 temperature projections reveal a clear increasing trend in the temperature signal in both basins (Table 2) all year round, but particularly marked in summer (+1.4 °C to +4.2 °C in the Herault basin, +1.9 °C to +4.4 °C in the Ebro basin). As a result, evapo-

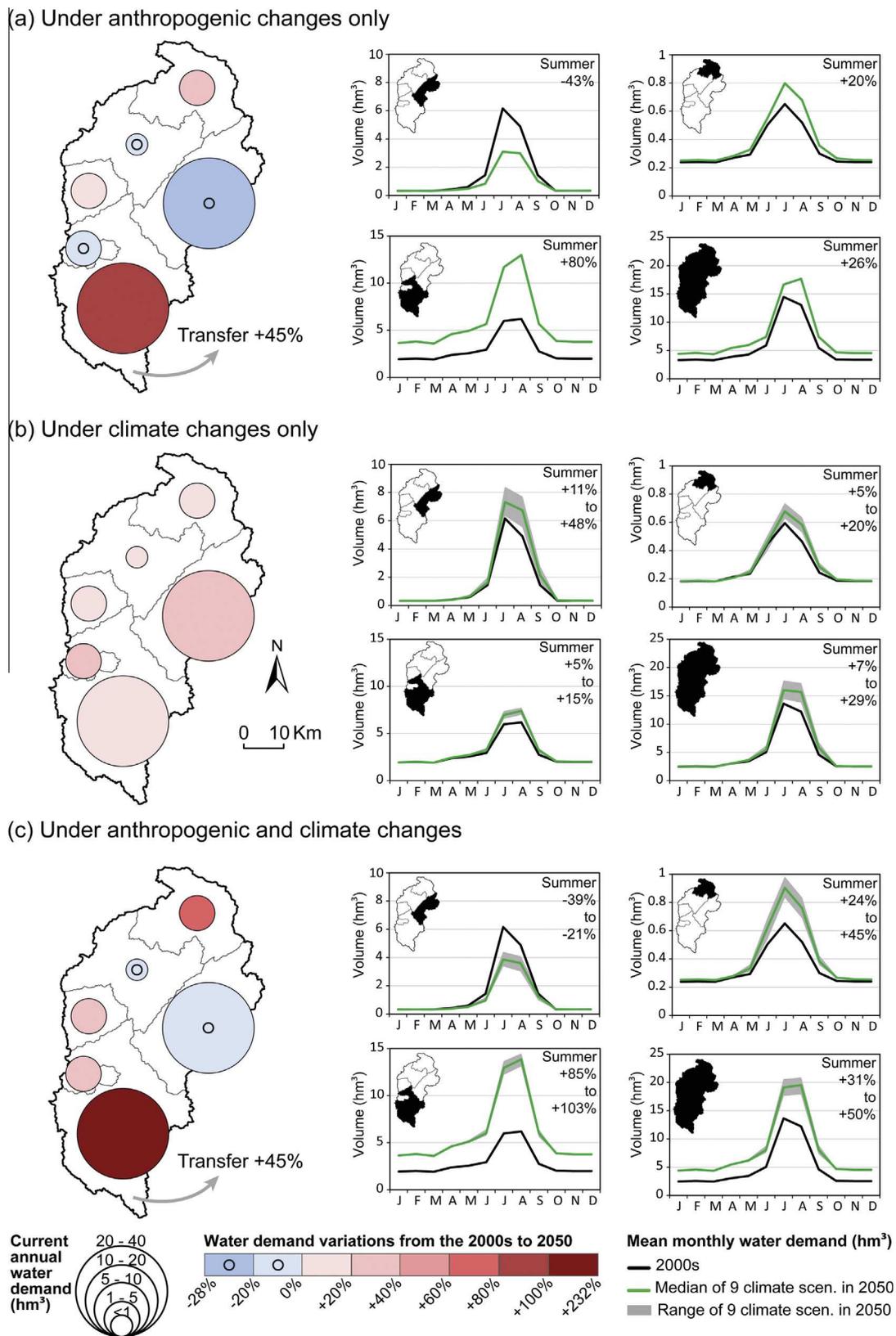


Fig. 5. Variations in water demand from the 2000s to the 2050 horizon under anthropogenic and climatic changes in the Herault basin.

transpiration could increase significantly, leading to a significant increase in crop water needs. The precipitation trends are less clear than the temperature trends. However, a decrease in spring and

summer precipitation could occur in the Herault basin (respectively -25% to +2% and -47% to +7%) and in the Ebro basin (respectively -31% to +4% and -35% to +4%).

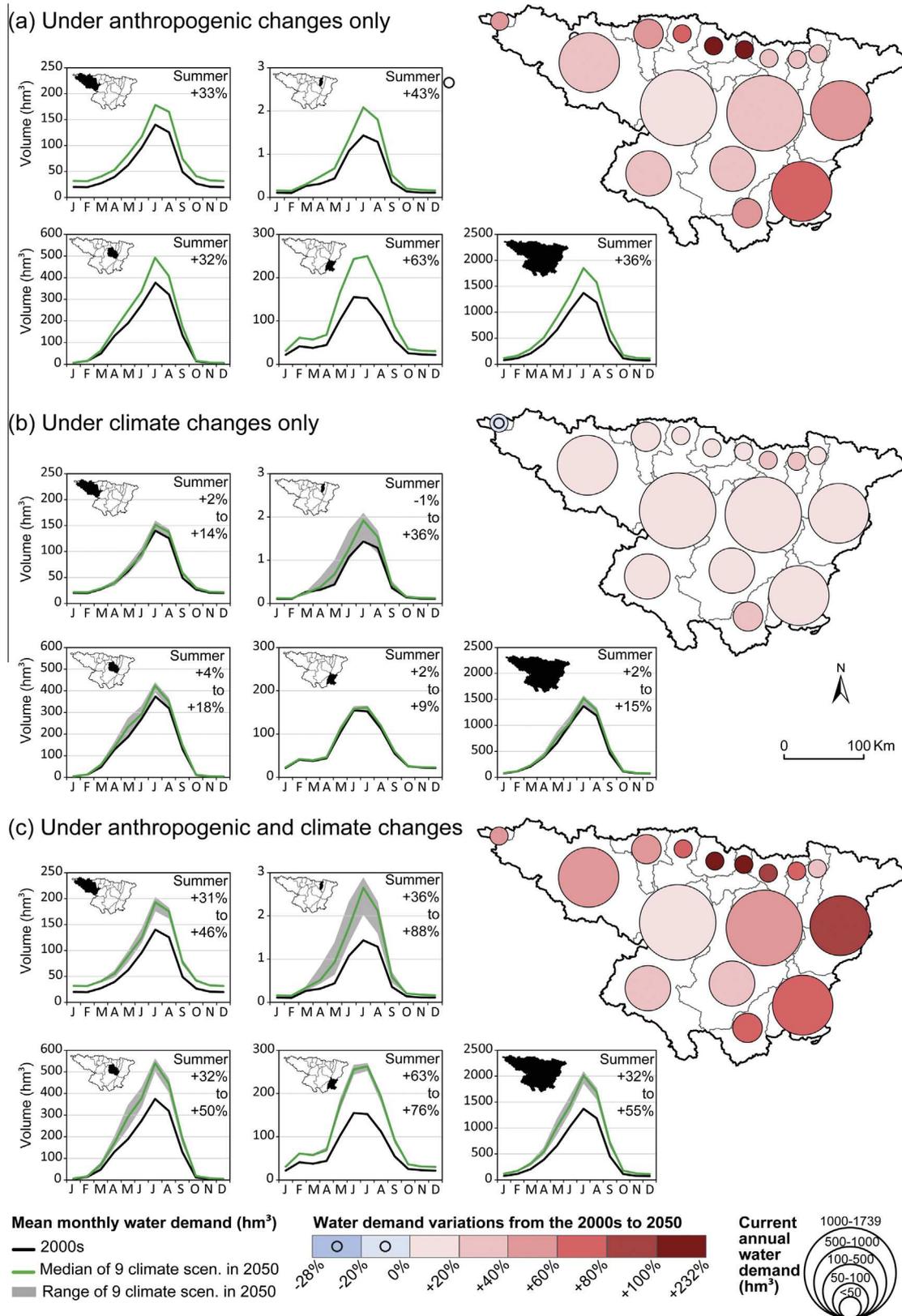


Fig. 6. Variations in water demand from the 2000s to the 2050 horizon under anthropogenic and climatic changes in the Ebro basin.

In the Herault, basin under climate changes only, water demand could increase by 11% to reach 64 hm³/y. These climate projections based on anthropic conditions in the 2000s (Fig. 6a), could lead to a spatially contrasted increase in water demand (from +5% to +26%).

The contrast results from the impact of climate projections on agricultural demand and on the characteristics of the section (proportion of agricultural demand, the geographic location of the section and main crop types). In the Agde section, total water demand could

Table 2
Forecasted variations in temperature and precipitation between 1976–2005 and 2036–2065 under nine climate scenarios in the Hérault basin and the Ebro basin: minimum, median and maximum variations in temperature and precipitation from the nine climate scenarios are shown for each season in both basins.

| | | Temperature | | | | Precipitations | | | |
|---------|--------|--------------------|--------------------|--------------------|--------------------|-------------------|-------------------|-------------------|-------------------|
| | | Winter JFM (°C) | Spring AMJ (°C) | Summer JAS (°C) | Autumn OND (°C) | Winter JFM (%) | Spring AMJ (%) | Summer JAS (%) | Autumn OND (%) |
| Hérault | Min | +0.7 | +0.8 | +1.4 | +0.6 | –11 | –25 | –47 | –13 |
| | Median | +1.5 | +1.9 | +3.1 | +1.9 | +5 | –12 | –20 | +5 |
| | Max | +2.3 | +2.5 | +4.2 | +2.8 | +26 | +2 | +7 | +25 |
| Ebro | Min | +0.9 | +1.4 | +1.9 | +1.0 | –11 | –31 | –35 | –17 |
| | Median | +1.7 | +2.3 | +3.5 | +2.1 | 0 | –11 | –18 | 0 |
| | Max | +2.3 | +2.8 | +4.4 | +3.1 | +23 | +4 | +4 | +21 |

increase from +11% to 48% in summer as a result of variations in agricultural demand. In the Ebro basin, water demand could increase by 10%. Depending on the section concerned, the increase could range from 0% to +32%. The spatial heterogeneity of variations in water demand under each climate scenario depends on the spatial distribution of the impacts of climate change and on the predominance of agricultural water needs in the area.

4.2.3. Under anthropogenic and climate changes

For a global overview, we then considered the combined impact of anthropogenic and climate changes on variations in water demand at the 2050 horizon. These variations could vary from –16% to +105% over the Hérault basin (Fig. 5c). In the Gignac section for example, while the projections forecast a 25% increase in water demand under climate changes only, combining anthropogenic and climate changes leads to a projected decrease of 16%. In this case, the impact of improvements in efficiency could be offset by the impact of climate change. However, at the basin scale, an increase in water demand between +31% and +50% is expected in the Hérault basin in 2050. Water demand is expected to increase from +17% to +232% in all sections of the Ebro basin (Fig. 6c). Both agricultural and non-agricultural areas could be impacted by a significant increase in water demand. In the Bajo Ebro section, for example, while projections forecast a 4% increase in water demand under climate changes only, combining both changes involves a projected 70% increase. These examples show that the effect of climate change is generally added to the impact of anthropogenic changes on water demand.

In the whole Hérault basin or in the Bajo Ebro section, a slight shift in the peak of water demand in summer from July in the 2000s to August in 2050 is simulated (see Figs. 5 and 6). This shift can be explained by a higher impact of tourism in August than in July and by changes in climate conditions during the summer months (Figs. 5b and 6b).

5. Discussion and conclusion

5.1. Outcome

This paper demonstrates the ability of an integrative approach to provide an overview of the distribution of past and current water demand in two Mediterranean catchments in space and over time. Using approaches that tackle anthropic and climatic variability separately, we were able to accurately evaluate the impact of these changes on water demand over a multi-decadal past period. On the whole, water demand has increased significantly in the last 40 years throughout the Hérault and the Ebro basins, except where evidence of adaptive behavior is already apparent or in areas where human activities have significantly declined. The heterogeneity of changes in water demand in space was reproduced for recent decades. Simulations of water demand under anthropogenic and climatic trends at the 2050 horizon, point to a significant

increase in total water demand in both basins, while simultaneously revealing heterogeneous spatial distribution in the two basins. In addition, this work points to the predominance of the impact of anthropogenic changes over climate changes on water demand at the 2050 horizon.

In contrast to studies focused on a single component of water demand (e.g. Fischer et al., 2007; Mullen et al., 2009; Breyer et al., 2012), a key contribution of the present study was separating the assessment of the components of water demand and their main drivers, and computing them in normalized time series (time step, time depth). This study shows that distinguishing between the components of water demand is absolutely necessary to understand the drivers of changes in water demand and to identify separate trends. The dynamics of each water demand component and their proportion can differ considerably depending on the section concerned and also within one section depending on the period considered, highlighting the main advantage of using integrative approaches that consider each component of water demand separately through a common pattern.

One of the major outcomes of this study is to have provided series of water demand data at a spatial scale compatible with water resources planning. In most studies that quantify water demand, the choice of spatial sub-divisions is mainly determined by the constraints of the hydrological model (e.g. Léville et al., 2003; Poussin et al., 2010), or by administrative limits (SMBFH, 2005; CHE, 2011). In the present study, the water demand nodes were defined in connection with hydrological sub-basins so as to fit water resources assessment and anthropic features (storage dams, canals, large irrigation systems). A preliminary geographical analysis is needed to grasp complex supply systems that include canals, dams and large irrigation systems. Areas affected by human activities like the Mediterranean region, often show variability of water uses and volumes withdrawn. This study shows that past trends of water demand differ significantly depending on the section considered. Although basin managers usually have a good overview of current water needs across their territory, they also hugely require better knowledge of the spatial and temporal dynamics of water demand from the scientific community. Using knowledge of these dynamics, basin managers will be able to design concrete measures appropriate for the implementation of local water plans.

Another main contribution of this study was the reconstruction of water demand over a 40-year period. This unconventional time depth enabled us to reveal clear trends and discontinuities in the spatial and temporal dynamics of water demand that is subject to anthropogenic and climate variability. A multi-decadal analysis is a key asset when considering the impact of climate variability on agricultural water demand, and when aiming to capture the impact of anthropogenic changes including changes in population, in agricultural practices, the extent of irrigated land, and the development of industrial and energy sectors. The study also accounts for the dynamics resulting from adaptation measures (improved efficiency, changes in irrigation systems, reduced domestic con-

sumption, etc.). An accurate past reconstruction was shown to be an essential first step in identifying the temporal dynamics and spatial disparities before assessing possible future changes in water demand under trend scenarios. This reconstruction made it possible to identify the main drivers of local water demand and their inter-annual variability. The spatially distributed knowledge of dynamics of the main drivers (population, tourism, the extent of irrigated land, and the impact of water management plans) makes it possible to objectivize our projections. For example, the identification of a reduction in water demand in the 2000s due to an increase in the efficiency of the water supply in some areas of the Hérault basin enabled us to estimate the influence of the efficiency driver on the assessment of water demand.

The study also made it possible to distinguish the impact of future anthropogenic and climate changes by means of water use and climate scenarios, whose impacts on water demand were assessed separately. As a result, we were able to show that the impact of anthropogenic changes is stronger than that of climate changes on water demand projections at the 2050 horizon under the conditions we tested. For instance, despite a substantial impact of climate change on water demand and a significant increase in irrigated area forecast in the Gignac section at the 2050 horizon, total water demand could decrease significantly due to a planned increase in efficiency. In the main irrigation systems in the Ebro basin, the forecasted increase in irrigated areas could have two to 12 times more impact on water demand than the forecast climate change. This highlights the advantage of integrating anthropic and climatic drivers in simulations of water demand, to be able to apply adaptation strategies that will be efficient in limiting water demand in target areas, as a function of water availability.

5.2. Uncertainties and limitations

The evaluation of future water demand is limited by many uncertainties in future projections, as underlined by Arnell (1999). It is important to note that the assessment of current and past water demand involves uncertainty at every step. For example, the processing techniques (upscaling, downscaling, spatial interpolation, and extrapolation) used to compute raw data, are inherently uncertain. Moreover, despite the relative reliability of population censuses, the uncertainty of withdrawal data used in water allocation assessments introduces further uncertainty in urban water demand. Likewise, Döll (2002) states that theoretical irrigation requirement models tend to somewhat overestimate actual water use. Such overestimations are accentuated in the case of adaptive behavior by irrigators involving less consumption of water. For example, a misestimating of the historical practice of deficit irrigation in the Hérault vineyards tends to overestimate our simulations, and this was confirmed by basin managers. In another connection, additional work would make it possible to include the effects of variations in atmospheric concentrations of carbon dioxide ($[\text{CO}_2]$) on crop behavior (Taub, 2010). Reductions in leaf stomatal conductance with increasing concentrations of atmospheric carbon dioxide could reduce evapotranspiration by the vegetation (<10%) and hence reduce crop water use (Bunce, 2004). This could moderate the impacts of climate on agricultural demand.

Forecasts of climate change are obviously also very uncertain. Uncertainty concerning future climate change derives from different sources (forcing, model response, and internal variability) as noted by Deser et al. (2012). In this study, the uncertainties connected with projections were taken into consideration by using a wide range of potential climatic projections. Considering that the dispersion in the climate projections provided by the IPCC came primarily from climate models based on greenhouse gas emission scenarios (see e.g. Arnell, 2004), we preferred to use many recent GCM simulations under one pessimistic representative concentra-

tion pathway to test the impacts of climate scenarios on water demand. If we consider that climate projections at the 2050 horizon are more uncertain on precipitation and more reliable on temperature, in the end, uncertainties related to the impact of climate projections on water demand are only moderate. This can be explained by the importance of evapotranspiration (related to temperature) in agricultural demand assessment and by the buffer role of the soil water reservoir and of the calculation of effective precipitation in the impact of rainfall variability on agricultural water demand at a 10-day time step.

Finally, accurate validation of the modeling approach was not possible due to incomplete and/or unreliable withdrawal data for the two basins. On the other hand, this lack of data is also precisely what leads to the need to estimate long-term water demand. However, analysis of the results suggests that our simulations of water demand are realistic. Indeed the orders of magnitude, seasonal distributions, and past variations are in agreement with the few withdrawal data available and with local managers' knowledge. Mean annual water demand simulated in the 2000s in the Hérault basin ($55 \text{ hm}^3/\text{y}$) was close to local withdrawal data without transfers ($56 \text{ hm}^3/\text{y}$ in SMBFH, 2005). In the Ebro basin, simulations of total water demand in the 2000s were $6340 \text{ hm}^3/\text{y}$ while CHE's withdrawal assessment was $7914 \text{ hm}^3/\text{y}$ in 2005 (CHE, 2011). This difference is mainly due to the fact that the CHE assessment method was based on water rights for agricultural water demand, which are not directly related to the theoretical needs of plants.

5.3. Prospects

Although anthropogenic changes should have a greater impact on water demand than climatic changes, one must assume that satisfying water demand will depend largely on the supply of water, which, in turn, will be affected by climate change (Arnell, 2004; Collet et al., 2013; Milano et al., 2013b). Hence, the broader aim of this research (currently conducted in the framework of the GICC-REMedHE project) is assessing the balance between water demand and supply through a more comprehensive modeling framework, with the aim of evaluating the sustainability of current water use (Fabre et al., 2014).

To prevent water shortages, adaptation strategies will be needed to either increase the water supply capacity (new transfers, storage dams, etc.) or to reduce water demand. This work improves our understanding of the key drivers of water demand, as well as of the complex interactions between each of them and their sensitivity to climate change. This knowledge will help the design of alternative water demand scenarios that aim to maintain the balance between water demand and availability in the study areas presented here. In the future studies, measures such as restricting the expansion of irrigated areas or implementing incentive-based policies to reduce domestic consumption will be tested to explore their effectiveness in achieving sustainable water management under climate change.

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References

- Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rosch, T., Siebert, S., 2003. Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions. *Hydrol. Sci. J.* 48, 339–348.
- Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. *Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements*. Irrigation and Drain, Paper No. 56 FAO, Rome, Italy, 300p.
- Arnell, N.W., 1999. Climate change and global water resources. *Global Environ. Change* 9, 831–849.
- Arnell, N.W., 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environ. Change* 14, 31–52.
- Arnell, N.W., Livermore, M.J.L., Kovats, S., Levy, P.E., Nicholls, R., Parry, M.L., Gaffin, S.R., 2004. Climate and socio-economic scenarios for global-scale climate change impacts assessments: characterising the SRES storylines. *Global Environ. Change* 14, 3–20.
- Beck, L., Bernauer, T., 2011. How will combined changes in water demand and climate affect water availability in the Zambezi river basin? *Global Environ. Change* 21, 1061–1072.
- Boithias, L., Acuña, V., Vergoñós, L., Ziv, G., Marcé, R., Sabater, S., 2014. Assessment of the water supply:demand ratios in a Mediterranean basin under different global change scenarios and mitigation alternatives. *Sci. Total Environ.* 470–471, 567–577.
- Breyer, B., Chang, H., Parandvash, G.H., 2012. Land-use, temperature, and single-family residential water use patterns in Portland, Oregon and Phoenix, Arizona. *Appl. Geography* 35, 142–151.
- Bunce, J.A., 2004. Carbon dioxide effects on stomatal responses to the environment and water use by crops under field conditions. *Oecologia* 140, 1–10.
- Burak, S., Dogan, E., Gazioglu, C., 2004. Impact of urbanization and tourism on coastal environment. *Ocean Coast. Manage.* 47, 515–527.
- Charlton, M.B., Arnell, N.W., 2011. Adapting to climate change impacts on water resources in England – an assessment of draft water resources management plans. *Global Environ. Change* 21, 238–248.
- Confederación Hidrográfica del Ebro, CHE, 2011. *Propuesta de Proyecto de Plan Hidrológico de la cuenca del Ebro*. Memoria versión 3.7. 281p.
- Collet, L., Ruelland, D., Borrell-Estupina, V., Dezetter, A., Servat, E., 2013. Integrated modelling to assess long-term water supply capacity on a meso-scale Mediterranean catchment. *Sci. Total Environ.* 461–462, 528–540.
- Collet, L., Ruelland, D., Borrell-Estupina, V., Servat, E., 2014. Assessing the long-term impact of climatic variability and human activities on the water resources of a meso-scale Mediterranean catchment. *Hydrol. Sci. J.* 59, 1457–1469.
- Dawadi, S., Ahmad, S., 2013. Evaluating the impact of demand-side management on water resources under changing climatic conditions and increasing population. *J. Environ. Manage.* 114, 261–275.
- De Graaf, I.E.M., van Beek, L.P.H., Wada, Y., Bierkens, M.F.P., 2004. Dynamic attribution of global water demand to surface water and groundwater resources: effects of abstractions and return flows on river discharges. *Adv. Water Resour.* 64, 21–33.
- Deser, C., Phillips, A., Bourdette, A., Tend, H., 2012. Uncertainty in climate change projections: the role of internal variability. *Clim. Dyn.* 38, 527–546.
- Dezetter, A., Fabre, J., Ruelland, D., Servat, E., 2014. Selecting an optimal climatic dataset for integrated modelling of the Ebro hydrosystem. In: *Hydrology in a changing world: environmental and human dimensions*. Proc. 7th FRIEND-Water Int. Conf., Montpellier, France, 7–10 Oct. 2014. IAHS Publ., 363, 355–360.
- Döll, P., 2002. Impact of climate change and variability on irrigation requirements: a global perspective. *Climatic Change* 54, 269–293.
- EC, 2004. EC (European Commission) European Soil Database (distribution version V2.0). Joint Research Centre, European Commission Office of Official Publications, Luxembourg.
- Fabre, J., Ruelland, R., Dezetter, A., Grouillet, B., 2014. Simulating changes in the balance between water demand and availability and assessing their main drivers over the past 40 years in two contrasted Mediterranean catchments. *Hydrol. Earth Syst. Sci. Discuss.* 11, 12315–12364.
- Fischer, G., Tubiello, F.N., van Velthuisen, H., Wiberg, D.A., 2007. Climate change impacts on irrigation water requirements: effects of mitigation, 1990–2080. *Technol. Forecast. Soc. Chang.* 74, 1083–1107.
- Gober, P., 2010. Desert urbanization and the challenges of water sustainability. *Curr. Opin. Environ. Sustainability* 2, 144–150.
- Green, S., 2008. Implication of time step on crop irrigation requirements. Hawke's Bay Regional Council, Envirolink Project No. HBRC46. <<http://envirolink.govt.nz/PageFiles/383/430-HBRC46.pdf>>.
- Griffin, M.T., Montz, B.E., Arrigo, J.S., 2013. Evaluating climate change induced water stress: a case study of the lower cape fear basin. *Appl. Geography* 40, 115–128.
- Grouillet, B., Fabre, J., Ruelland, D., Collet, L., Boyer, J.-F., 2004. Assessing past and future water demands under climate change and anthropogenic pressures on two Mediterranean basins. In: *Hydrology in a changing world: environmental and human dimensions* (Proc. 7th FRIEND-Water Int. Conf., Montpellier, France, 7–10 Oct. 2014). IAHS Publ., 363, 185–190.
- Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. *Appl. Eng. Agric.* 1, 96–99.
- Hejazi, M., Edmonds, J., Clarke, L., Kyle, P., Davies, E., Chaturvedi, V., Wise, M., Patel, P., Eom, J., Calvin, K., Moss, R., Kim, S., 2014. Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technol. Forecast. Soc. Chang.* 81, 205–226.
- Hoekstra, A.Y., Chapagain, A.K., 2007. The water footprints of Morocco and the Netherlands: global water use as a result of domestic consumption of agricultural commodities. *Ecol. Econ.* 64, 143–151.
- IPCC, 2013. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1535.
- Koch, H., Vögele, S., 2009. Dynamic modelling of water demand, water availability and adaptation strategies for power plants to global change. *Ecol. Econ.* 68, 2031–2039.
- Lévite, H., Sally, H., Cour, J., 2003. Testing water demand management scenarios in a water-stressed basin in South Africa: application of the WEAP model. *Phys. Chem. Earth* 28, 779–786.
- López-Moreno, J.I., Vicente-Serrano, S.M., Moran-Tejeda, E., Zabalza, J., Lorenzo-Lacruz, J., García-Ruiz, J.M., 2011. Impact of climate evolution and land use changes on water yield in the Ebro basin. *Hydrol. Earth Syst. Sci.* 15, 311–322.
- Martínez-Cob, A., Tejero-Juste, M., 2004. A wind-based qualitative calibration of the Hargreaves ETo estimation equation in semiarid regions. *Agric. Water Manage.* 64, 251–264.
- Milano, M., Ruelland, D., Fernandez, S., Dezetter, A., Fabre, J., Servat, E., Fritsch, J.M., Ardoin-Bardin, S., Thivet, G., 2013a. Current state of Mediterranean water resources and future trends under climatic and anthropogenic changes. *Hydrol. Sci. J.* 58, 498–518.
- Milano, M., Ruelland, D., Dezetter, A., Fabre, J., Ardoin-Bardin, S., Servat, E., 2013b. Modeling the current and future capacity of water resources to meet water demands in the Ebro basin. *J. Hydrol.* 500, 114–126.
- Minacapilli, M., Iovino, M., D'Urso, G., 2008. A distributed agro-hydrological model for irrigation water demand assessment. *Agric. Water Manage.* 95, 123–132.
- Mullen, J.D., Yu, Y., Hoogenboom, G., 2009. Estimating the demand for irrigation water in a humid climate: a case study from the southeastern United States. *Agric. Water Manage.* 96, 1421–1428.
- Plan Bleu, 2005. *L'Eau*. In: *Méditerranée, les perspectives du Plan Bleu sur l'Environnement et le Développement*, Ed. de l'Aube, 71–107.
- Poussin, J.C., Pouget, J.C., D'Hont, R.L., 2010. ZonAgri: a modeling environment to explore agricultural activities and water demands on a regional scale. *Land Use Policy* 27, 600–611.
- Quintana-Seguí, P., Le Moigne, P., Durand, Y., Martin, E., Habets, F., Baillon, M., 2008. Analysis of near-surface atmospheric variables: validation of the SAFRAN analysis over France. *J. Appl. Meteorol. Climatol.* 47, 92–107.
- Reynard, E., Bonriposi, M., Graefe, O., Homewood, C., Huss, M., Kauzlaric, M., Liniger, H., Rey, E., Rist, S., Schädler, B., Schneider, F., Weingartner, R., 2014. Interdisciplinary assessment of complex regional water systems and their future evolution: how socioeconomic drivers can matter more than climate: interdisciplinary assessment of complex regional water systems and their future evolution. *WIREs Water*, 413–426.
- Riahi, K., Gruebler, A., Nakicenovic, N., 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol. Forecast. Soc. Chang.* 74, 887–935.
- Rinaudo, J.-D., 2011. *Urbanisme, habitat et demande en eau potable – Scénarios 2030 pour le Pays Cœur d'Hérault*. BRGM/RP-60358-FR.
- Rosenzweig, C., Strzepek, K.M., Major, D.C., Iglesias, A., Yates, D., Mccluskey, A., Hillel, D., 2004. Water resources for agriculture in a changing climate: international case studies. *Global Environ. Change* 14, 345–360.
- Ruelland, D., Ardoin-Bardin, S., Collet, L., Roucou, P., 2012. Simulating future trends in hydrological regime of a large Sudano-Sahelian catchment under climate change. *J. Hydrol.* 424–425, 207–216.
- Ruijs, A., Zimmermann, A., Van den Berg, M., 2008. Demand and distributional effects of water pricing policies. *Ecol. Econ.* 66, 506–516.
- Salvador, R., Martínez-Cob, A., Cervero, J., Playán, E., 2011. Seasonal on-farm irrigation performance in the Ebro basin (Spain): Crops and irrigation systems. *Agric. Water Manage.* 98, 577–587.
- Schalldach, R., Koch, J., Aus der Beek, T., Kynast, E., Flörke, M., 2012. Current and future irrigation water requirements in pan-Europe: an integrated analysis of socio-economic and climate scenarios. *Global Planet. Change* 94–95, 33–45.
- SMBFFH, 2005. *Gestion quantitative de la ressource. Etat des lieux version 4*. SAGE du bassin du fleuve Hérault.
- Syrbe, R.U., Walz, U., 2012. Spatial indicators for the assessment of ecosystem services: providing, benefiting and connecting areas and landscape metrics. *Ecol. Ind.* 21, 80–88.
- Taub, D., 2010. Effects of rising atmospheric concentrations of carbon dioxide on plants. *Nat. Educ. Knowl.* 3, 21.
- Thomas, A., 2008. Agricultural irrigation demand under present and future climate scenarios in China. *Global Planet. Change* 60, 306–326.
- United Nations, Department of Economic and Social Affairs, Population Division, 2013. *World Population Prospects: The 2012 Revision, Highlights and Advance Tables*. Working Paper No. ESA/P/WP. 228.
- Vörösmarty, C.J., 2000. Global water resources: vulnerability from climate change and population growth. *Science* 289, 284–288.
- Wu, Y., Chen, J., 2013. Estimating irrigation water demand using an improved method and optimizing reservoir operation for water supply and hydropower generation: a case study of the Xinfengjiang reservoir in southern China. *Agric. Water Manage.* 116, 110–121.

Appendix D

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ACCOUNTING FOR HYDRO-CLIMATIC AND WATER USE VARIABILITY IN THE ASSESSMENT OF PAST AND FUTURE WATER BALANCE AT THE BASIN SCALE

Fabre, J., Ruelland, D., Dezetter, A., Grouillet, B.

Abstract This study assesses water stress by 2050 in river basins facing increasing human and climatic pressures, by comparing the impacts of various combinations of possible future socio-economic and climate trends. A modelling framework integrating human and hydro-climatic dynamics and accounting for interactions between resource and demand at a 10-day time step was developed and applied in two basins of different sizes and with contrasted water uses: the Hérault (2 500 km², France) and the Ebro (85 000 km², Spain) basins. Natural streamflow was evaluated using a conceptual hydrological model (GR4j). A demand-driven reservoir management model was designed to account for streamflow regulations from the main dams. Urban water demand was estimated from time series of population and monthly unit water consumption data. Agricultural water demand was computed from time series of irrigated area, crop and soil data, and climate forcing. Indicators comparing water supply to demand at strategic resource and demand nodes were computed. This framework was successfully calibrated and validated under non-stationary human and hydro-climatic conditions over the last 40 years before being applied under four combinations of climatic and water use scenarios to differentiate the impacts of climate- and human-induced changes on streamflow and water balance. Climate simulations from the CMIP5 exercise were used to generate 18 climate scenarios at the 2050 horizon. A baseline water use scenario for 2050 was designed based on demographic and local socio-economic trends. Results showed that projected water uses are not sustainable under climate change scenarios.

Keywords water use dynamics; climate variability; influenced streamflow; integrative modeling; water balance; river basin



Accounting for hydro-climatic and water use variability in the assessment of past and future water balance at the basin scale

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Abstract. This study assesses water stress by 2050 in river basins facing increasing human and climatic pressures, by comparing the impacts of various combinations of possible future socio-economic and climate trends. A modelling framework integrating human and hydro-climatic dynamics and accounting for interactions between resource and demand at a 10-day time step was developed and applied in two basins of different sizes and with contrasted water uses: the Herault (2500 km², France) and the Ebro (85 000 km², Spain) basins. Natural streamflow was evaluated using a conceptual hydrological model (GR4j). A demand-driven reservoir management model was designed to account for streamflow regulations from the main dams. Urban water demand was estimated from time series of population and monthly unit water consumption data. Agricultural water demand was computed from time series of irrigated area, crop and soil data, and climate forcing. Indicators comparing water supply to demand at strategic resource and demand nodes were computed. This framework was successfully calibrated and validated under non-stationary human and hydro-climatic conditions over the last 40 years before being applied under four combinations of climatic and water use scenarios to differentiate the impacts of climate- and human-induced changes on streamflow and water balance. Climate simulations from the CMIP5 exercise were used to generate 18 climate scenarios at the 2050 horizon. A baseline water use scenario for 2050 was designed based on demographic and local socio-economic trends. Results showed that projected water uses are not sustainable under climate change scenarios.

1 Introduction

Streamflow variability in recent decades is a consequence of both climatic and anthropogenic forcings (Fabre et al., 2015). Moreover, due to climate and socio-economic changes, mid-latitude areas could experience increased water stress along the 21st century (Heinrichs et al., 2012). The question of the balance between water demand and availability can be addressed by using models to help assess the sustainability of different water use scenarios in a changing climate. These models need to be able to simulate water resources and its availability for human water uses, but also water demand and its hydrological influence in river basins: streamflow regulations, withdrawals, return flows, etc. Thus integrative approaches accounting for hydro-climatic and water use vari-

ability in space and in time are needed to assess water supply capacity at the basin scale (Montanari et al., 2014). Before they are used in prospective studies, these approaches need to prove their ability to represent past variations in natural and influenced streamflow.

This study assesses water balance at the 2050 horizon in river basins facing increasing human and climatic pressures, by comparing the impacts of various combinations of possible future socio-economic and climate trends. The modelling framework was developed and applied in two basins with contrasting hydro-climatic and water use characteristics: the Herault (France, 2500 km²), and the Ebro (Spain, 85 000 km²) basins. The Herault is characterized by competing urban and agricultural water demands, both highly seasonal with a summer peak in tourism and irrigation demands,

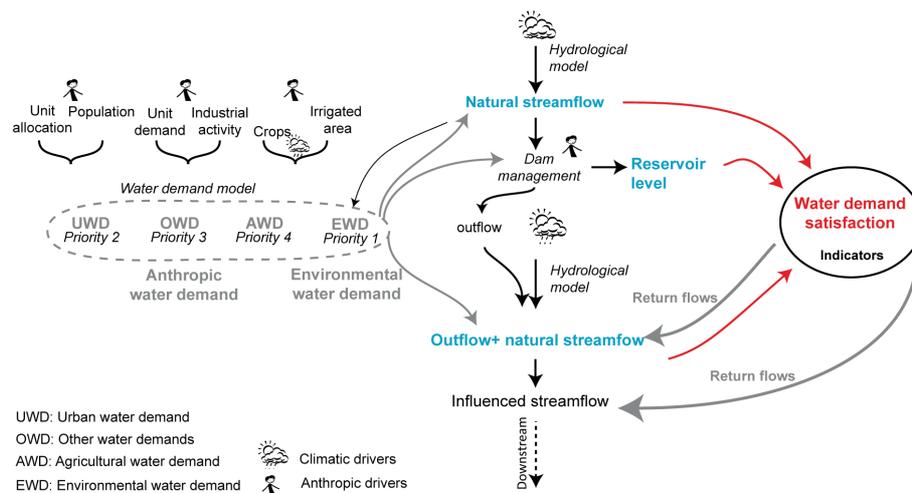


Figure 1. Integrative modelling framework applied on the Hérault and Ebro hydrosystems.

associated with a low storage capacity. In the Ebro basin water demand is mostly agricultural, with extensive irrigation systems supplied by a large network of storage dams and canals.

2 Material and methods

2.1 Modelling the balance between water demand and availability in managed hydrosystems

2.1.1 Comparing water demand and availability in an integrative modelling framework

Each basin was divided into sub-basins accounting for the water supply to one or more demand nodes. The Hérault and the Ebro basins were divided respectively into six and 20 sub-basins (see maps in Fig. 3a). The conceptualization of both hydrosystems accounted for climatic gradients and water use contrasts (Collet et al., 2013; Fabre et al., 2015).

An integrative modelling framework (Fig. 1) was then applied in both basins. Anthropogenic water demands were simulated and aggregated at each demand node (see Fabre et al. (2015) for more details). Three types of demand were simulated: urban water demand (UWD), agricultural water demand (AWD) and other water demands (OWD). Other water demands, comprising water demands for industries and energy production, were considered negligible in the Hérault basin. Natural streamflow was simulated in each sub-basin, and a minimum environmental flow was computed at each water resource node. Streamflow regulations and storage were accounted for with a reservoir management model.

Water demand and availability were compared at the main water demand nodes. An order of priority was considered for water uses (Fig. 1). In case of insufficient water availability, a deficit was computed, defined as the percentage of water demand that could not be satisfied by available wa-

ter resources. The modelling chain enabled us to simulate: (i) natural water resources and their availability considering water management rules and infrastructures; (ii) the ability to satisfy water demands throughout the basin; and (iii) the influenced streamflow resulting from hydro-climatic conditions and human influence (water withdrawals, return flows and dam management).

2.1.2 Using indicators to characterize water demand satisfaction

Three indicators were used to characterize the water supply capacity for the main water demands, i.e. urban and agricultural: (i) F : frequency of years with at least one significant deficit (greater than 50 % for AWD, greater than 5 % for UWD), (ii) Def_{10} : average deficit at a 10-day time step and (iii) Def_{AN} : average annual deficit. For all three indicators values ranged from 0 (no deficit) to 1 (maximum frequency or intensity of deficit).

2.2 Calibrating and validating the modelling chain over a multi-decadal past period

2.2.1 Reconstructing past changes in water demand from 1971 to 2009

Details regarding the reconstruction of past water demand between 1971 and 2009 at the sub-basin scale in the Hérault and the Ebro basins can be found in Grouillet et al. (2015). UWD was estimated from time series of population and monthly unit water consumption data. AWD was computed from time series of irrigated area, irrigation efficiency, crop and soil data, and climate forcings. OWD in the Ebro basin was computed from industrial activity and allocations per employee and per added-value, and from water consumed by the open-air cooling systems of nuclear plants.

Table 1. Trend water use scenarios at the 2050 horizon in the Herault and the Ebro basins: variation of the main variables between the 2000s and the 2050s. UWD: urban water demand, AWD: agricultural water demand, OWD: other water demand.

| | | Herault | Ebro |
|-----|-----------------------------------|---------|-------|
| UWD | Permanent population | +39 % | +18 % |
| | Touristic population | +74 % | NA |
| | Transfers | +38 % | +27 % |
| | Unit allocation | +21 % | +4 % |
| | Network efficiency | +5 % | +0 % |
| OWD | Industrial activity | NA | +95 % |
| AWD | Irrigated areas | +80 % | +46 % |
| | Network and irrigation efficiency | +22 % | +9 % |

2.2.2 Simulating the variability of water availability in highly influenced hydrosystems

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. To assess natural runoff in each sub-basin, the model was calibrated only against runoff data that were considered natural, i.e. not influenced by withdrawals or dam management. Due to the lack of data, the influence of withdrawals on streamflow was considered to be negligible when simulated AWD was negligible (Fabre et al., 2015).

River flow regulations were accounted for by developing a demand-driven reservoir management model, which was applied to the largest dam in the Herault basin and to 11 major dams in the Ebro basin. Inputs of the model are incoming streamflow, evaporation, the initial reservoir level and water demand at a 10-day time step. The model then calculates the volume of water released into associated canals and the river downstream from the dam during each time step, and the reservoir level at the end of each time step (see Fabre et al. (2015) for more details).

2.2.3 Calibrating and validating past simulations

The modelling chain was calibrated and validated over 1971–2009. This nearly 40-year period includes a warmer and drier period (1981–2009), used for calibration, and a colder and wetter decade (1971–1980), used for validation. Automatic calibration and validation of the hydrological model were performed against natural streamflow data using a three-step algorithm (Dezetter et al., 2014) that minimized a multi-objective function aggregating three goodness-of-fit criteria: the Nash-Sutcliffe efficiency index (NSE), the cumulative volume error (VE) and the mean annual volume error (VEM). The simulation of water demand could not be thoroughly validated for lack of data. The simulation of influenced streamflow was validated against observed streamflow data at each resource node (see Sect. 3.1) by calculating the

values of the NSE, VE and NSE_{LF} (NSE on low flows, i.e. from June to August) criteria per decade over 1971–2009.

2.3 Projecting climate and water use impacts on water demand satisfaction at the 2050 horizon

2.3.1 Combining water use and climate scenarios

The modelling chain was then applied under four combinations of climate and water use scenarios to distinguish the impacts of human- and climate-induced changes on water supply capacity at the 2050 horizon. Two water use scenarios were considered: water uses of the 2000s and a trend water use scenario at the 2050 horizon. Regarding climate scenarios, we considered a reference climate over 1976–2005 and 18 climate change scenarios at the 2050 horizon. Climate forcings over 1976–2005 were extracted from the 8×8 km grids presented in Fabre et al. (2015). Climate scenarios at the 2050 horizon (2036–2065) were then built based on climate change simulated by nine Global Climate Models (GCMs) from the last IPCC report, with the Representative Concentration Pathways (RCPs) 8.5 and 4.5. Using a change factor method (Ruelland et al., 2012), the reference climatic series were modified so as to reproduce the mean monthly variations obtained between the reference and future climatic simulations from GCMs.

2.3.2 Building water use scenarios

The water use scenarios at the 2050 horizon were built based on projections from the local water management agencies and continuation of recent trends (Grouillet et al., 2015). The variations of the main variables between the 2000s and the 2050s are shown in Table 1.

Environmental water demand was also accounted for in the prospective part of the study. Since minimum flows have not yet been defined by local water agencies, they were considered as the value of natural streamflow exceeded 95 % of the time over the study period at the Herault sub-basin outlets, and as 10 % of the mean annual flow at the Ebro sub-basin ones (or 5 % of mean annual flow if it exceeded $80 \text{ m}^3 \text{ s}^{-1}$).

2.3.3 Accounting for variations in water availability

Natural streamflow at the 2050 horizon was assessed by using the climate variables from the 18 scenarios described in Sect. 2.3.1 as inputs to the GR4j model while keeping the parameters calibrated over the reference period. Inputs to the dam management model varied depending on the climate and water use scenarios. Entering streamflow and evaporation were computed based on each climate scenario, while the water demand associated to each dam was dependent on the water use scenario. Future water use scenarios also included infrastructure and management projects under way in the Ebro, such as the doubling of the Yesa dam's capacity.

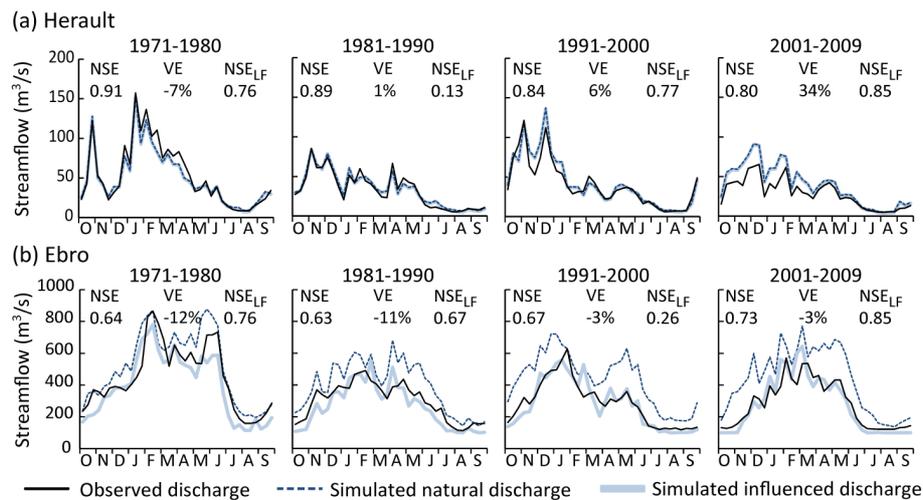


Figure 2. Average observed and simulated discharge per decade and values of Nash (NSE), Volume error (VE) and low flow Nash (NSE_{LF}) criteria at the outlet of (a) the Hérault and (b) the Ebro basins between 1971 and 2009.

In this case, the target reservoir levels were changed accordingly in the future water use scenario.

3 Results

3.1 Validation of the modelling chain over 1971–2009

Simulated influenced streamflow were in good agreement with observed discharge at the outlet of each studied basin (cf. NSE and VE values shown in Fig. 2 for each decade). Comparison of the influenced vs. natural streamflow (Fig. 2) as simulated by the model allowed the level of anthropogenic pressure on the water resources to be estimated in the Hérault and Ebro basins: anthropogenic consumptive use amounted to 2% of the natural discharge on average over the period 2001–2009 in the Hérault basin, while it amounted to 38% over the same period in the Ebro basin.

3.2 Hydro-climatic and water demand changes at the 2050 horizon

Temperature projections showed a clear increasing trend, particularly marked in the summer (Fig. 3a). Projections for precipitation were more uncertain and differed among the 18 scenarios considered. However, a decrease in spring and summer precipitation could occur in both basins. These climatic trends could result in changes in natural streamflow: while scenarios diverged in fall, winter and spring, all 18 scenarios resulted in a decrease in summer low flows.

Water demand variations are presented in Fig. 3b for two illustrative demand nodes in each basin. Results showed that climate change could have a clear impact on AWD in the Gignac and Agde areas in the Hérault basin. However in the Gignac area a significant increase in efficiency in the trend water use scenario (from 22% in the 2000s to 70% in the

2050s) could compensate the increase in demand caused by warmer and drier conditions and a 65% increase in irrigated areas. This differed from the Agde area where a 90% increase in irrigated areas could lead to a high increase in AWD. The water use trend scenario in the Ebro basin projected an irrigated area increase in all areas, particularly in the Segre irrigation system. In this area the impact of the increase in irrigated areas could be stronger than the impact of climate change. On the contrary in the Bardenas area the impact of climate change could be higher than the impact of the water use scenario.

3.3 Water demand satisfaction under water use and climate scenarios

3.3.1 Reference scenario: current water uses in a reference climate

In the reference scenario, results showed that of the four areas presented here, only the Segre area in the Ebro basin had balanced water demand and availability (Fig. 4). In the Gignac and Agde areas in the Hérault basin, restrictions on urban and agricultural water withdrawals were simulated to occur every two years, with an annual deficit of approximately 30% on AWD in both areas. In the Ebro basin, of the large left bank systems only the Bardenas system had imbalanced demand and availability. Note that although restrictions on withdrawals were more frequent in Bardenas than in the Hérault basin, average deficits at 10-day and annual time steps were lower.

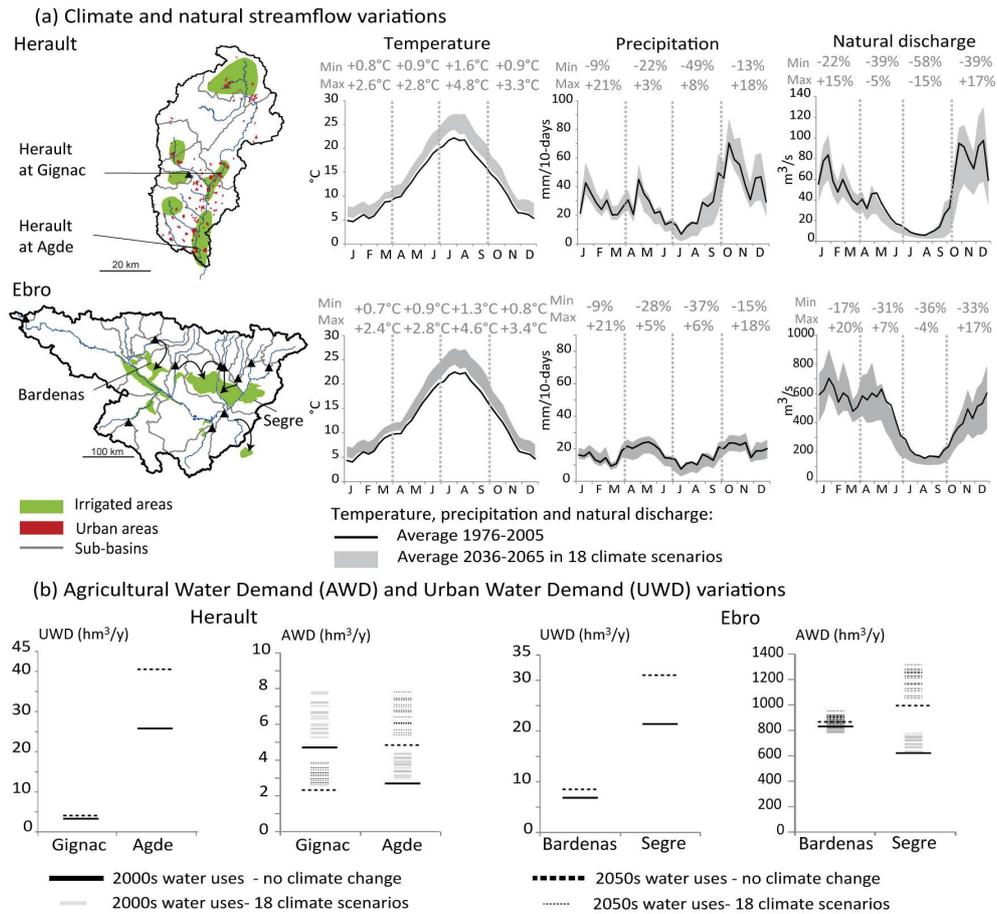


Figure 3. Projected hydro-climatic and water demand changes at the 2050 horizon at the scale of the Herault and the Ebro catchments: (a) range of 18 climatic scenarios and their potential impact on natural streamflow at the outlet and (b) variations in urban and agricultural water demand in illustrative sub-basins under combined water use and climate scenarios.

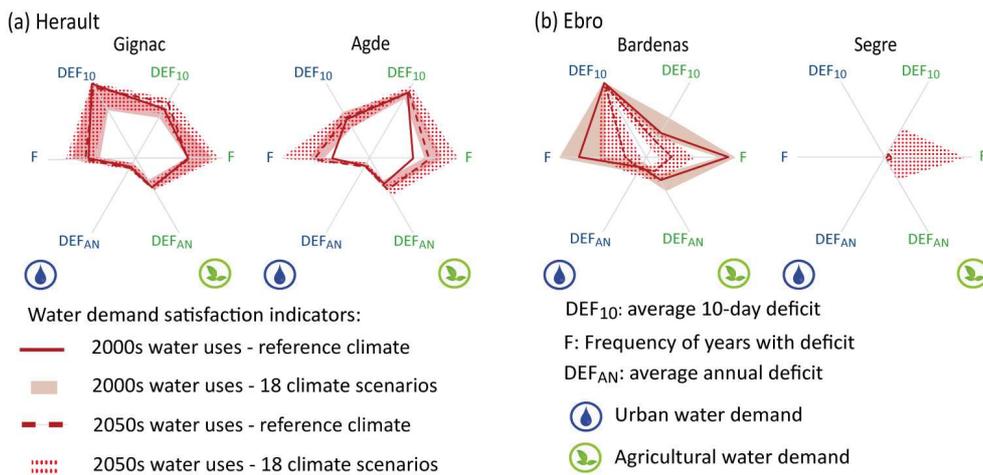


Figure 4. Water demand satisfaction indicators for urban and agricultural water demands under four combinations of water use and climate scenarios in two areas of (a) the Herault and (b) the Ebro basin. For all three indicators values range from 0 (no deficit) to 1 (maximum frequency or intensity of deficit).

3.3.2 Projections at the 2050 horizon: relative impacts of climate and water use changes

Results showed that the relative impacts of climate and water use changes on water demand satisfaction could vary depending on the area (Fig. 4). For example in the Hérault basin, the water use scenario impacted water demand satisfaction only in the Agde area. In the other areas, the climate change scenarios had a dominant impact on water demand satisfaction at the 2050 horizon. The results presented for the Ebro basin showed that sensitivity to climate change could vary according to the water use scenario taken into account: in the Segre area, climate change impacts could be acceptable without changes in water use, whereas with the trend water use scenario climate change could lead to frequent restrictions on agricultural water withdrawals. In the Bardenas area, the dam enlargement in the trend scenario could lead to an improvement in water supply, but this adaptation strategy may not be sufficient in scenarios of climate change.

4 Discussion and conclusion

This study explored the impacts of possible future socio-economic and climate trends on water stress by 2050 in river basins facing increasing human and climatic pressures. This was achieved by developing a modelling chain integrating human and hydro-climatic inputs and interactions between water use and availability. This chain was calibrated and validated over a past period including significant water use and climate variability, and results showed its ability to represent the dynamics of influenced streamflow. Scenarios of water use and climate change at the 2050 horizon were then designed and used as inputs to the integrative model. By using four combinations of water use and climate change scenarios, we were able to project water demand satisfaction and to separate the potential impacts of anthropogenic and climatic changes in both basins.

The variability of water demand simulated over the past 40 years and the high level of water use influence on streamflow showed that non-stationarity in anthropogenic forcings is a key element to be considered in hydrological modelling. Simulations were obviously not perfect due notably to the non-exhaustive consideration of all storage-dams and to our limited knowledge on water withdrawals, which led to an impossible validation of water demand simulations and to a debatable hypothesis concerning the modelling of natural streamflow. Moreover while variability in anthropogenic and climate forcings were accounted for over the 1971–2009 period, climate projections at the 2050 horizon only accounted for mean monthly changes, due to the downscaling method used. Also, note that the water use scenarios were built with constant anthropogenic drivers over 30 years. Consequently, the prospective study was based on strong assumptions regarding the stationarity of hydrological processes and of water management, which may be seen as unrealistic.

Despite these limitations applying this model in different combinations of scenarios helped to answer the question of the risk of water shortage, and to determine the causes of this risk. Future research includes studying the sensitivity of future changes in water demand satisfaction to variations in the water use scenarios.

Acknowledgements. This work was carried out as part of the GICC REMedHE project funded by the French Ministry of Ecology, Sustainable Development and Energy for the period 2012–2015. The authors thank the *Syndicat Mixte du Bassin du Fleuve Hérault* and the *Confederación Hidrográfica del Ebro* for providing the necessary data and for sharing information on water management in the studied basins. Climatic data for the Ebro basin was provided by the *Agencia Estatal de Meteorología* (AEMET).

References

- Collet, L., Ruelland, D., Borrell-Estupina, V., Dezetter, A., and Servat, E.: Integrated modeling to assess long-term water supply capacity of a meso-scale Mediterranean catchment, *Sci. Total Environ.*, 461–462, 528–540, 2013.
- Dezetter, A., Fabre, J., Ruelland, D., and Servat, E.: Selecting an optimal climatic dataset for integrated modeling of the Ebro hydrosystem, in: *Hydrology in a changing world: environmental and human dimensions* (Proc. 7th FRIEND Int. Conf., Montpellier, France, 7–10 October 2014), 363, 355–360, IAHS Publ., 2014.
- Fabre, J., Ruelland, D., Dezetter, A., and Grouillet, B.: Simulating past changes in the balance between water demand and availability and assessing their main drivers at the river basin scale, *Hydrol. Earth Syst. Sci.*, 19, 1236–1285, doi:10.5194/hess-19-1263-2015, 2015.
- Grouillet, B., Fabre, J., Ruelland, D., and Dezetter, A.: Historical reconstruction and 2050 projections of water demand under anthropogenic and climate changes in two contrasted Mediterranean catchments, *J. Hydrol.*, 522, 684–696, 2015.
- Heinrichs, T., Lehner, B., and Alcamo, J.: An Integrated Analysis of Change in Water Stress in Europe, *Int. Assess.*, 3, 15–29, 2012.
- Montanari, A., Young, G., Savenije, H., Hughes, D., Wagener, T., Ren, L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Blöschl, G., Sivalapan, M., Beven, K., Gupta, H., Hipsey, M., Schaefli, B., Arheimer, B., Boegh, E., Schymanski, S., Baldassarre, G. D., Yu, B., Hubert, P., Huang, Y., Schumann, A., Post, D., Srinivasan, V., Harman, C., Thompson, S., Rogger, M., Viglione, A., McMillan, H., Characklis, G., Pang, Z., and Belyaev, V.: *Panta Rhei – Everything Flows? Change in hydrology and society – The IAHS Scientific Decade 2013–2022*, *Hydrol. Sci. J.*, 58, 1256–1275, 2014.
- Perrin, C., Michel, C., and Andreassian, V.: Improvement of a parsimonious model for streamflow simulation, *J. Hydrol.*, 10, 282–290, 2003.
- Ruelland, D., Ardoin-Bardin, S., Collet, L., and Roucou, P.: Simulating future trends in hydrological regime of a large Sudano-Sahelian catchment under climate change, *J. Hydrol.*, 424–425, 207–216, 2012.

Appendix E

Poster presented at the 6th IAHS-EGU International Symposium on Integrated Water Resources Management, 2014

ASSESSING CHANGES IN THE BALANCE BETWEEN WATER DEMAND AND
AVAILABILITY AND THEIR MAIN DRIVERS OVER THE PAST 40 YEARS IN
TWO CONTRASTED MEDITERRANEAN CATCHMENTS

Fabre, J., Ruelland, D., Dezetter, A., Grouillet, B.

Abstract Over the past 40 years, climatic and anthropogenic pressures have been increasing in the Mediterranean region. According to projections of climatic and socio-economic changes, this area could experience higher water stress by 2050. In this context, integrated modeling approaches are needed to assess water allocation scenarios and assist decision-making for water resources planning. This study aims at developing a generic, multidisciplinary approach to model water supply capacity and its spatial and temporal variability over long time-periods. A common integrated modeling framework was applied over two Mediterranean basins with different physical and anthropogenic characteristics: the Hérault (France, 2 500 km²) and the Ebro (Spain, 85 000 km²) catchments. Water resources were evaluated using a conceptual hydrological model at a daily time step over a nearly 40-year period. River flow regulations were accounted for through a generic demand-driven reservoir management model applied to the largest dam in the Hérault basin and to the 11 major dams on the Ebro basin. Over both catchments, water demands were estimated from population and monthly unit water consumption data for the domestic sector and from irrigated area, crop and soil data and climatic forcing for irrigation. Spatial and temporal water demand variability were thus reconstituted over 1971--2009 on both catchments. Finally, a ratio comparing water supply to water demands at strategic resource and demand nodes was computed at a 10-day time-step. Analysis of the variability of this ratio over space and time shows the evolution of the vulnerability of each catchment in terms of water supply capacity, taking into account climatic and anthropogenic pressures and the evolution of water management strategies over time. This study is a first step in exploring the sustainability of water management on two Mediterranean catchments by the medium term, under uncertain and non-stationary climatic and socio-economic scenarios.

Assessing changes in the balance between water demand and availability and their main drivers over the past 40 years in two contrasted Mediterranean catchments

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Bologna IAHS 2014
 8th IAHS-EGU International Symposium on Integrated Water Resources Management, Bologna 4-6 June 2014

Context

Over the past 50 years, climatic and anthropogenic pressures have been increasing in the Mediterranean region. According to projections of climatic and socio-economic changes, this area could experience higher water stress along the 21st century. In this context, integrated modelling approaches are needed to build water allocation scenarios and assist decision-making and water resources planning.

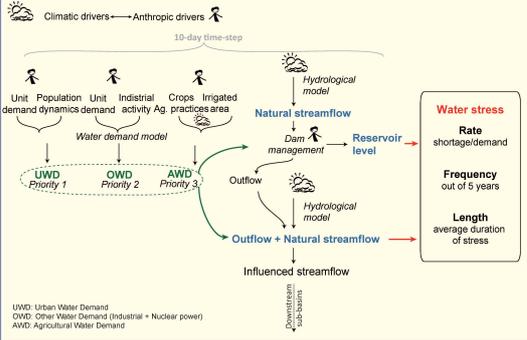
At the management scale (basins from 1 000 to 100 000 km²), there is a critical lack of knowledge on the past change in the balance between water demand and availability, on the past vulnerability of hydrosystems to anthropogenic and climatic pressures, and on the existing strategies to adapt to water stress.

Purpose

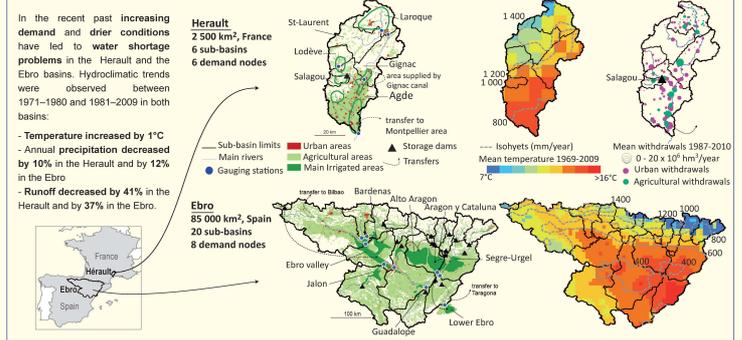
- To combine human and hydroclimatic data in an integrative modelling framework to represent water stress and its spatial and temporal dynamics over a period of 40 years.
- To develop this framework on two contrasted Mediterranean catchment in order to constrain its conception to various scales and stakes.
- To use the model to assess vulnerability to water stress in two contrasted catchments under anthropogenic and climatic pressure.

Method and study areas

Applying an integrative modelling chain...

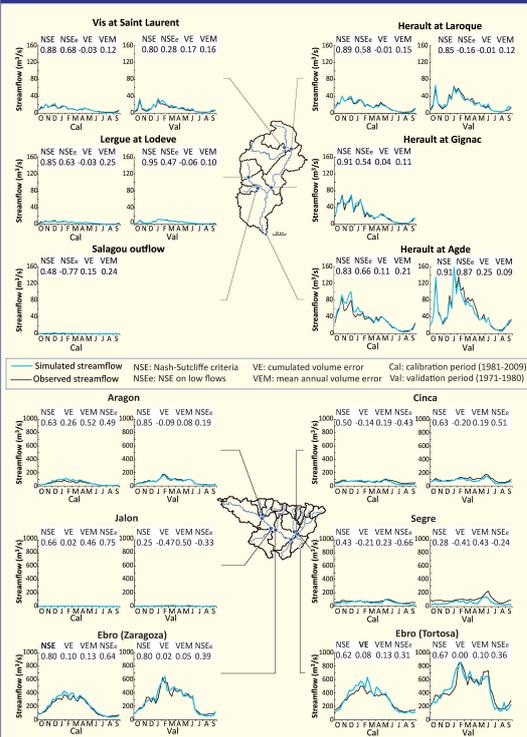


... in two contrasted Mediterranean catchments

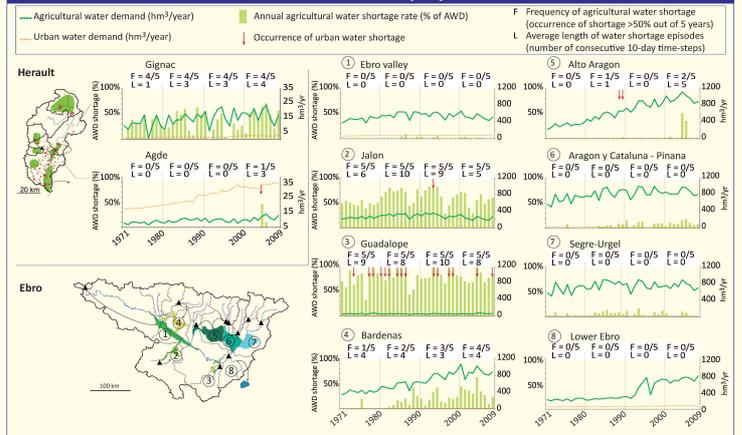


Results

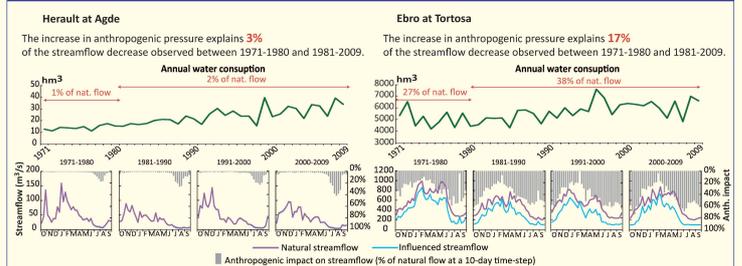
Simulation of influenced streamflow



Balance between water demand and availability: dynamics between 1971 and 2009



Relative impact of climatic and anthropogenic conditions on streamflow



Conclusion

- ### Summary
- Socio-economic and hydroclimatic data were used to model water resources and demand over a 40-year period.
 - Interactions between resource and demand were modeled using an integrative framework.
 - We successfully represented water stress changes in space and time in two contrasted basins.
 - Variations in anthropogenic human pressure had more effect on streamflow in the Ebro basin than in the Herault basin.
 - Water shortage increased in the Herault basin and in some key irrigated areas in the Ebro basin.

- ### Prospects
- Understanding local vulnerability to water shortage in the past is a necessary first step in the planning of adaptation to the impacts of climate change.
 - This integrative framework will enable the modeling and comparison of the effects of a wide range of possible future climates and human adaptation measures on water stress.
 - Changes in water stress under different scenarios of climatic and anthropogenic pressures will be assessed, leading to a better understanding of vulnerability to water shortage in an uncertain future.

References
 Fabre, J., Collet, L., Milano, M., Ruelland, D., Dezetter, A., Ardoin-Bardin, S., & Servat, E. (2014). Assessing the long-term evolution of water supply capacity: comparison of two Mediterranean catchments. In: Hydrology in a changing world: environmental and human dimensions (Proc. 7th FRIEND Int. Conf., Montpellier, France, 7-10 Oct. 2014). IAHS Publ. 363, in press.

This work was funded as part of the project "Gestion et Impacts du Changement Climatique - Identification et Impacts du changement climatique sur la gestion intégrée des ressources en eau en Méditerranée: évaluation comparative Herault-Ebro" (GICC-REMEDI) funded by the French Ministry of Ecology, Sustainable Development and Energy for the period 2012-2015.



Appendix F

Poster presented at the conference *Our Common Future under Climate Change, 2015*

BALANCING WATER USES AND AVAILABILITY UNDER HUMAN- AND CLIMATE-INDUCED CHANGES AT THE 2050 HORIZON

Fabre, J., Ruelland, D., Dezetter, A., Grouillet, B.

Abstract Over the past decades, human and climatic pressures on water resources have been increasing in the Mediterranean region, and the area could experience higher water stress over the 21st century. This study aims to assess water stress by 2050 in Mediterranean river basins facing increasing human and climatic pressures, and to compare the impacts of a wide range of possible future socio-economic and climate trends. A modeling framework integrating human and hydro-climatic dynamics and accounting for interactions between resource and demand at a 10-day time step was developed and applied in two basins of different scales and with contrasted 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. Urban water demand was estimated from time series of population and monthly unit water consumption data. Agricultural water demand was computed from time series of irrigated area, crop and soil data, and climate forcing. Environmental flows were accounted for by defining streamflow thresholds under which withdrawals were strictly limited. Indicators comparing water supply to demand at strategic resource and demand nodes were computed. This framework was calibrated and validated under non-stationary human and hydro-climatic conditions over the last 40 years before being applied under four combinations of water use and climatic scenarios to differentiate the impacts of human- and climate-induced changes on streamflow and water balance. Climate simulations from the CMIP5 exercise were used to generate 18 climate scenarios at the 2050 horizon (from nine climate models and two Representative Concentration Pathways). Two water use scenarios were considered: water uses of the 2000s and a trend water use scenario at the 2050 horizon, based on demographic and local socio-economic trends. The sensitivity of water stress to variations in the main drivers of water demand and availability under

the trend water use and climate change scenarios was tested to assess the efficiency of potential adaptation measures. Temperature projections show a clear increasing trend, particularly marked in the summer. Projections for precipitation are more uncertain and differ among the 18 scenarios considered. However, a decrease in spring and summer precipitation is expected in both basins. These climatic trends should result in changes in natural discharge: while scenarios diverge in fall, winter and spring, all 18 scenarios result in a decrease in summer low flows. Simulations revealed a significant increase in total water demand under anthropogenic and climate trends in 2050 in both basins. Results also show that projected water uses are not sustainable under climate change scenarios. While anthropogenic drivers could influence variations in water demand more than climate change, in the Hérault basin the impact of climate change could be more determining than water use changes for the balance between water uses and availability. In some areas of the Ebro basin water use changes could have a larger impact than climate change on water stress. The combination of the trend water use scenario and climate change scenarios could also have a high impact on the respect of minimum environmental flows in both basins. Finally, water stress showed little sensitivity to individual variations in the drivers of water demand. This study points out the areas most vulnerable to human- and/or climate-induced changes by 2050 in two basins. In both basins a combination of adaptation measures leading to a large decrease in water demand and an optimized management of water availability will be necessary in order to supply enough water to satisfy demand while limiting anthropogenic pressure on water resources to sustainable levels.

Keywords water balance, water use dynamics; climate change; environmental flows.

Balancing water uses and availability under human- and climate-induced changes at the 2050 horizon

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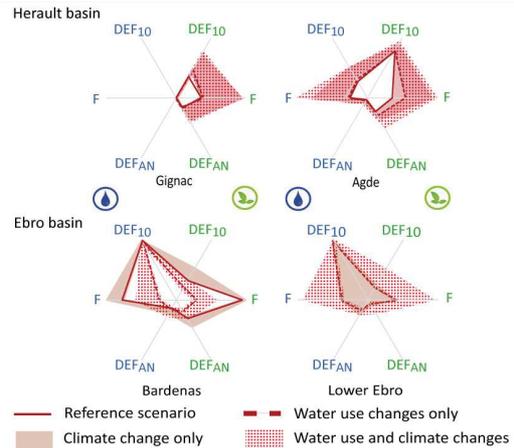
This study shows that the impact of climate change on both water availability and demand could question the water allocations and environmental constraints currently planned for the coming decades in the Hérault (France) and the Ebro (Spain) basins. A combination of adaptation measures leading to a large decrease in water demand and an optimized management of water availability will be necessary in order to supply enough water to satisfy demand while limiting anthropogenic pressure on water resources to sustainable levels.

Planned water uses are not sustainable under climate change scenarios at the 2050 horizon

A modeling framework integrating human and hydro-climatic dynamics enabled us to simulate natural water resources and their availability considering water management rules and infrastructures, and the ability to satisfy water demands throughout two river basins in different water use and climate scenarios.

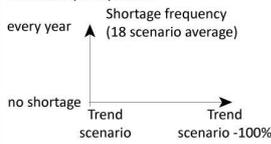
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- Climate change only:** 2000s water uses - 18 climate scenarios (2036-2065)
- Water use changes only:** 2050s water uses - Reference climate (1976-2005)
- Water use and climate changes:** 2050s water uses - 18 climate scenarios (2036-2065)

Water demand satisfaction indicators were calculated in each combination:

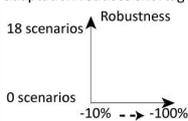


Water shortage shows little sensitivity to individual variations in the drivers of water demand

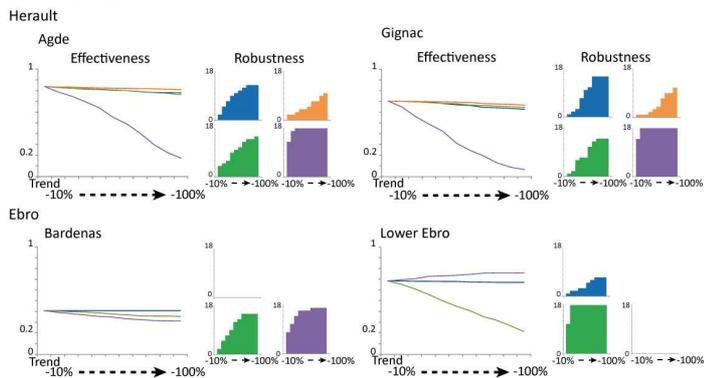
Adaptation effectiveness:
 decrease in shortage frequency induced by adaptation



Adaptation robustness:
 number of climate scenarios in which adaptation reduces shortage frequency

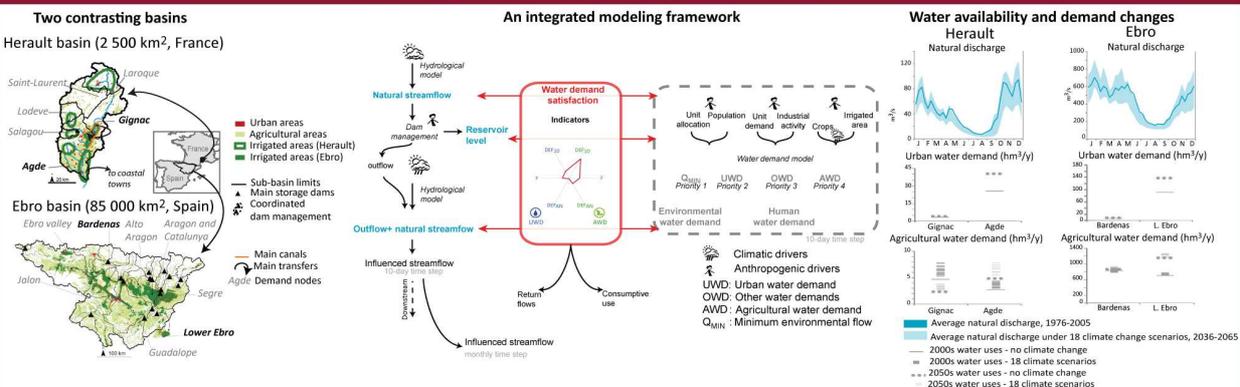


Sensitivity of agricultural water demand satisfaction to variations in individual drivers of water demand



Effectiveness and robustness of adaptation are highly dependent on the basin's characteristics. Results call for a combination of adaptation measures leading to a large decrease in water demand and an optimized management of water availability.

Methodological framework and intermediate results



For more details:

Fabre, J., Ruelland, D., Dezetter, A., Grouillet, B. (2015). Simulating past changes in the balance between water demand and availability and assessing their main drivers at the river basin scale. *Hydrological Earth Syst Sci* 19, 1263–1285.
 Fabre, J., Ruelland, D., Dezetter, A., Grouillet, B. (2015). Accounting for hydro-climatic and water use variability in the assessment of past and future water balance at the basin scale. *Proc. IAHS* 371, 43–48.
 Fabre, J., Ruelland, D., Dezetter, A., Grouillet, B. (2015). Reducing the gap between water demand and availability under climate and water use changes: assessing the effectiveness and robustness of adaptation. *Proc. SHF Congress*, October 2015, subm.
 Grouillet, B., Fabre, J., Ruelland, D., Dezetter, A. (2015). Historical reconstruction and 2050 projections of water demand under anthropogenic and climate changes in two contrasted Mediterranean catchments. *J. Hydrol.* 522, 684–696.

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Appendix G

Ma thèse en 180 secondes –Languedoc-Roussillon regional finals

Aura-t-on assez d'eau en 2050?

20 mai 2050 : AVIS DE SECHERESSE. La ville de Montpellier fait de nouveau appel à la solidarité régionale. Cette fois, ce sont les Toulousains qui vont vendre de l'eau aux Montpellierains, pour que ceux-ci puissent de nouveau tirer leur chasse d'eau. COLERE DES AGRICULTEURS : la vigne a soif ! Si les propriétaires du barrage refusent de nouveau de lâcher de l'eau, 2050 pourrait s'avérer la pire année pour le vin depuis la canicule de 2042. Mais les touristes affluent en masse sur le lac du barrage : laisser baisser son niveau et faire face à une nouvelle grève des loueurs de planche à voile, ce serait simplement signer l'arrêt de mort de la base nautique.

Mais revenons en 2015... Dans ma thèse, je cherche à savoir si l'on risque de manquer à l'avenir, et à trouver des solutions pour éviter ce genre de scénario catastrophe pour 2050. Dans nos régions méditerranéennes, bon nombre d'activités économiques sont en effet largement dépendantes de la ressource en eau. Or, face à un climat de plus en plus chaud et sec tel qu'on pourrait le connaître au cours de ce siècle, des questions cruciales se posent : Aura-t-on moins d'eau dans les rivières ? Comment pourra-t-on répartir moins d'eau entre plus d'habitants ? De plus, qui dit plus chaud, dit... plus soif. Alors comment concilier les besoins des plantes cultivées, qui augmenteront, avec ceux des habitants, qui voudront se rafraîchir dans leurs piscines, tout en laissant assez d'eau dans la rivière pour les touristes, qui préféreront la rivière quand la mer aura englouti le camping de la plage ? Sans oublier l'eau pour les poissons...

Ainsi, s'adapter au changement climatique, c'est s'efforcer d'anticiper toutes ses questions, et, pourquoi pas, d'y répondre. Pour cela, nous utilisons des modèles, c'est-à-dire des calculs (dans nos ordinateurs) qui permettent de simuler de manière simplifiée des processus de la vie réelle. Dans mon cas, mes modèles simulent l'évolution des demandes et des ressources en eau, en fonction des activités humaines et du climat. J'ai d'abord vérifié que mes modèles fonctionnaient bien, en reconstituant les demandes et les ressources en eau autour d'un fleuve en France et un fleuve en Espagne durant les 40 dernières années. Ensuite, j'ai construit des récits de futurs possibles. Par exemple : en 2050, la population a doublé, le tourisme stagne, et on arrose 2 fois plus de vignes qu'en 2015. Il fait 2 degrés de plus, et il pleut moins en été mais beaucoup plus en automne. Mes modèles m'ont ensuite permis de traduire ces récits : dans ces conditions, y-aura-t-il assez d'eau pour tout le monde ? Ou faudra-t-il choisir entre boire du vin et remplir sa piscine ?

Appendix H

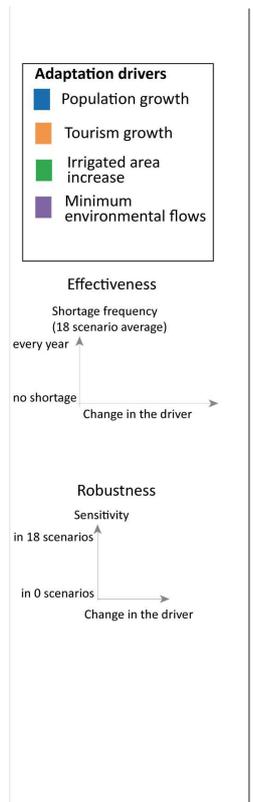
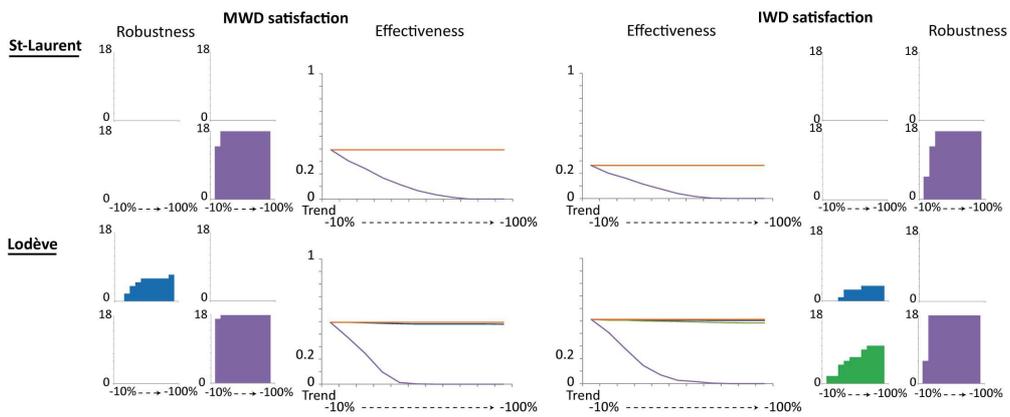
Technical appendices

1. Calibrated parameter values for GR4j

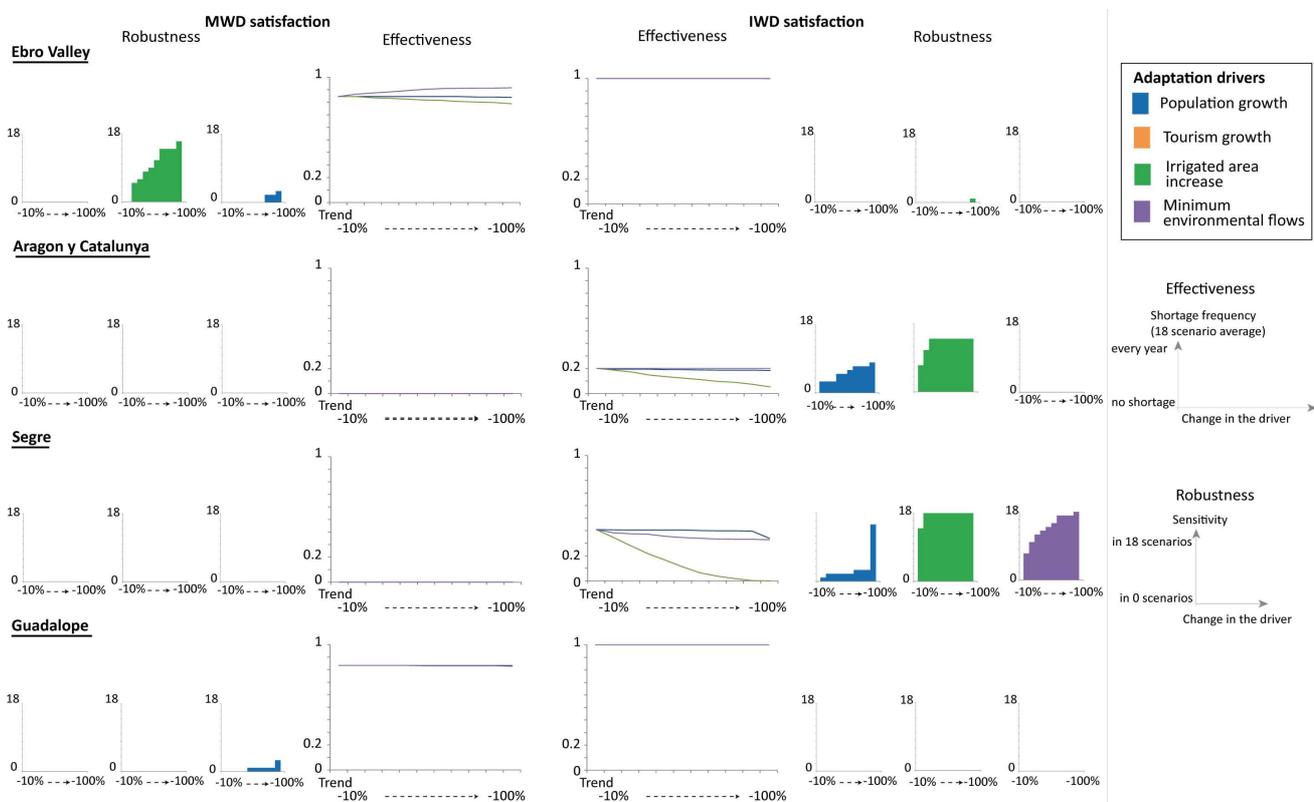
Parameter values obtained by calibration of the hydrological model GR4j for the simulation of natural streamflow in the Hérault and the Ebro basins. NB: Because of the poor calibration results and of their minor contribution to total discharge, the contribution of basins 13, 14 and 20 of the Ebro basin were set to zero for all simulations. Hence the parameters shown in this table were not used.

| | | GR4j parameters | | | | Snow module parameters | | |
|-------------------------------------------------------------------------------------|-------------------------|-----------------|-----------|-----------|-------------|------------------------|----------|----------|
| | | X1 | X2 | X3 | X4 | X5 | X6 | X7 |
| | | <i>mm</i> | <i>mm</i> | <i>mm</i> | <i>days</i> | <i>°C</i> | <i>%</i> | <i>%</i> |
| Hérault | | | | | | | | |
|  | 1. Vis at St-Laurent | 1385 | -0.7 | 32 | 1.1 | | | |
| | 2. Hérault at Laroque | 661 | -1.4 | 93 | 1.6 | | | |
| | 3. Hérault at Gignac | 176 | -0.1 | 2 | 3.2 | | | |
| | 4. Lergue at Lodeve | 511 | 0.1 | 110 | 1.2 | | | |
| | 5. Salagou | 151 | -0.4 | 7 | 2.1 | | | |
| | 6. Hérault at Agde | 38 | -5.3 | 530 | 0.9 | | | |
| Ebro | | | | | | | | |
|  | 1. Ebro at Arroyo | 315 | 1.9 | 18 | 1.1 | 2.8 | 83 | 9.9 |
| | 2. Ebro at Castejon | 523 | 1.1 | 16 | 0.4 | | | |
| | 3. Arga | 280 | 0.1 | 0 | 3.5 | | | |
| | 4. Irati at Liedena | 336 | 0.7 | 26 | 2.0 | 3.1 | 70 | 7.7 |
| | 5. Aragon at Yesa | 296 | 0.5 | 4 | 3.0 | 7.8 | 26 | 1.7 |
| | 6. Gallego at Ardisa | 625 | 2.0 | 41 | 2.2 | 8.6 | 24 | 0.7 |
| | 7. Cinca at Grado | 272 | 0.9 | 5 | 2 | 7.6 | 57 | 0.5 |
| | 8. Esera | 345 | 0.6 | 3 | 2.4 | 10.1 | 40 | 1.1 |
| | 9. Noguera Ribagorzana | 427 | 0.8 | 4 | 2.1 | 9.1 | 50 | 1.1 |
| | 10. Noguera Pallaresa | 317 | 0.9 | 5 | 3.2 | 7.0 | 60 | 1.6 |
| | 11. Segre at Oliana | 284 | 0.5 | 2 | 3.3 | 8.2 | 41 | 2.3 |
| | 12. Aragon at Caparroso | 332 | 0.2 | 8 | 4.8 | | | |
| | 13. Ebro at Zaragoza | 570 | 0.8 | 6 | 6.1 | | | |
| | 14. Ebro at Mequinenza | 2616 | 12.3 | 808 | 1.7 | | | |
| | 15. Cinca at Fraga | 1 | -34.5 | 240 | 1.2 | | | |
| | 16. Segre at Seros | 254 | 0.3 | 29 | 6.0 | | | |
| | 17. Piedra | 1088 | 2.8 | 78 | 1.0 | | | |
| | 18. Jalon en Grisen | 800 | 0.1 | 3 | 5.4 | | | |
| | 19. Guadalope | 346 | -1.9 | 40 | 3.6 | | | |
| | 20. Ebro at Tortosa | 234 | 12.0 | 383 | 0.5 | | | |

2. Effectiveness and robustness of adaptation measures

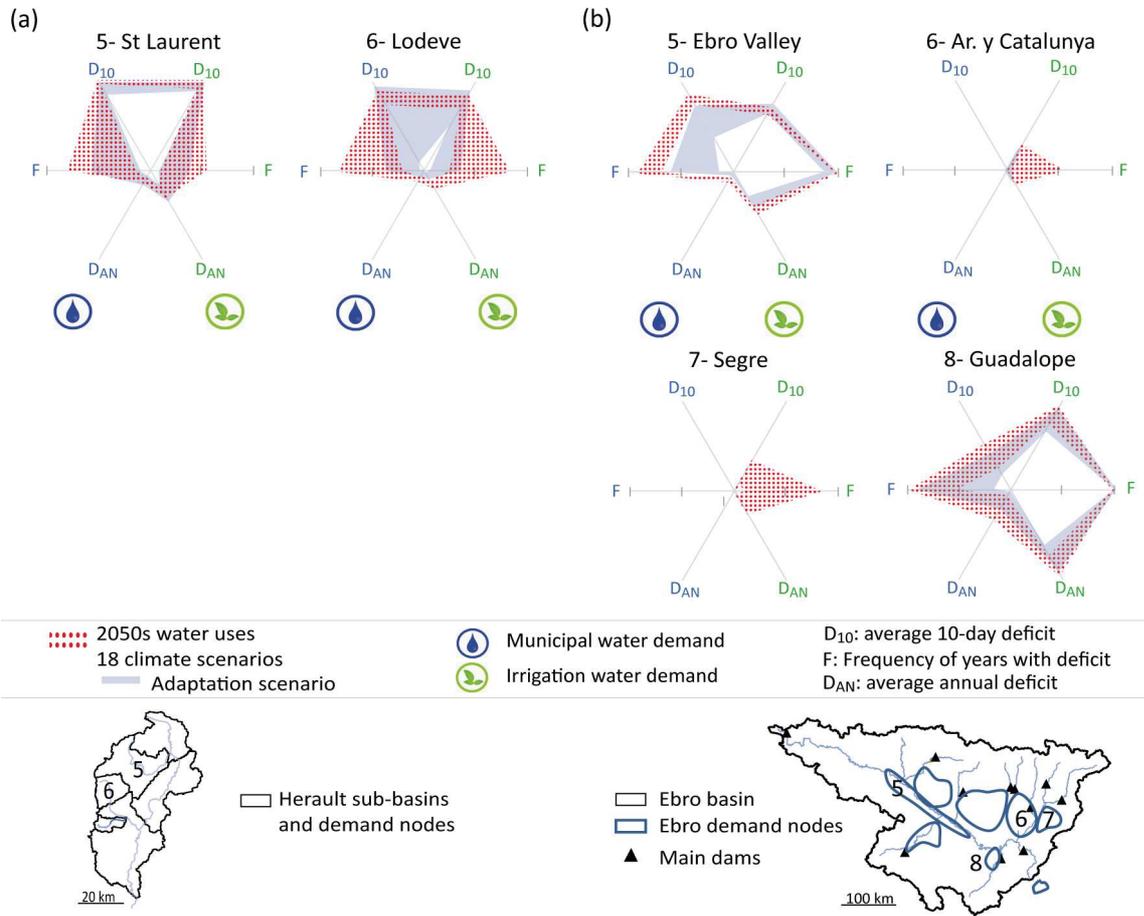


Effectiveness and robustness of variations in drivers of water demand in reducing the gap between water demand and availability in four areas of the Saint-Laurent and Lodeve areas of the Herault basin. Effectiveness is measured by the changes in the water shortage frequency (averaged over the 18 climate scenarios). Robustness is measured by the number of climate scenarios in which the shortage frequency is reduced.



Effectiveness and robustness of variations in drivers of water demand in reducing the gap between water demand and availability in the Ebro Valley, Aragon y Catalunya, Segre and Guadalupe areas of the Ebro basin. Effectiveness is measured by the changes in the water shortage frequency (averaged over the 18 climate scenarios). Robustness is measured by the number of climate scenarios in which the shortage frequency is reduced.

3. Effectiveness and robustness of two adaptation scenarios



Water demand satisfaction indicators for urban and agricultural water demands under climate change scenarios combined with the trend water use scenario and adaptation scenarios in (a) two areas of the Herauld basin and (b) four areas of the Ebro basin. Indicators values range from 0 (no deficit) to 1 (maximum frequency or intensity of deficit).