Proc. IAHS, 371, 43–48, 2015
proc-iahs.net/371/43/2015/
doi:10.5194/piahs-371-43-2015

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

J. Fabre[1], **D. Ruelland**[1], **A. Dezetter**[2], **and B. Grouillet**[1]

[1]CNRS, HydroSciences Laboratory, Place Eugene Bataillon, 34095 Montpellier, France
[2]IRD, HydroSciences Laboratory, Place Eugene Bataillon, 34095 Montpellier, France

Correspondence to: J. Fabre (jfabre@um2.fr)

Received: 11 March 2015 – Accepted: 11 March 2015 – Published: 12 June 2015

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 km^2, France) and the Ebro (85 000 km^2, 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 variability 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 km^2), and the Ebro (Spain, 85 000 km^2) basins. The Herault is characterized by competing urban and agricultural water demands, both highly seasonal with a summer peak in tourism and irrigation demands,

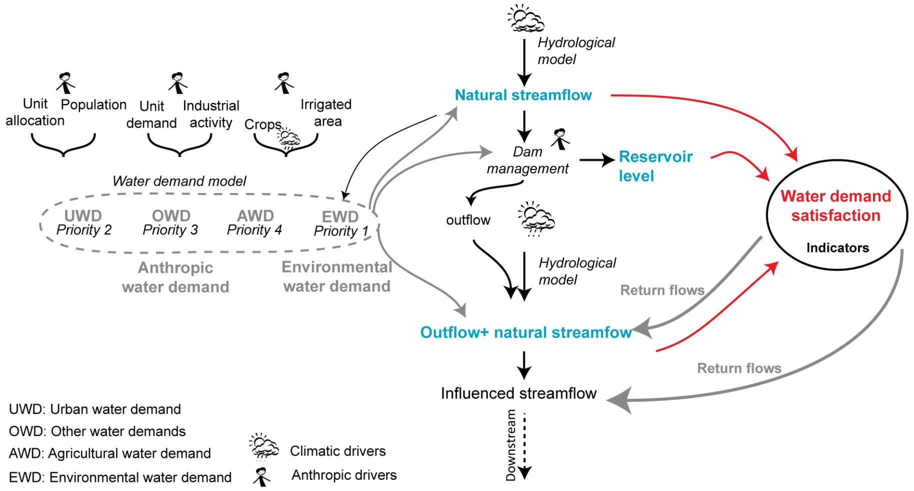

Figure 1. Integrative modelling framework applied on the Herault and Ebro hydrosystems.

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 Herault 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 Herault 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 water 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) $\mathrm{Def}_{\mathrm{AN}}$: 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 Herault 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.

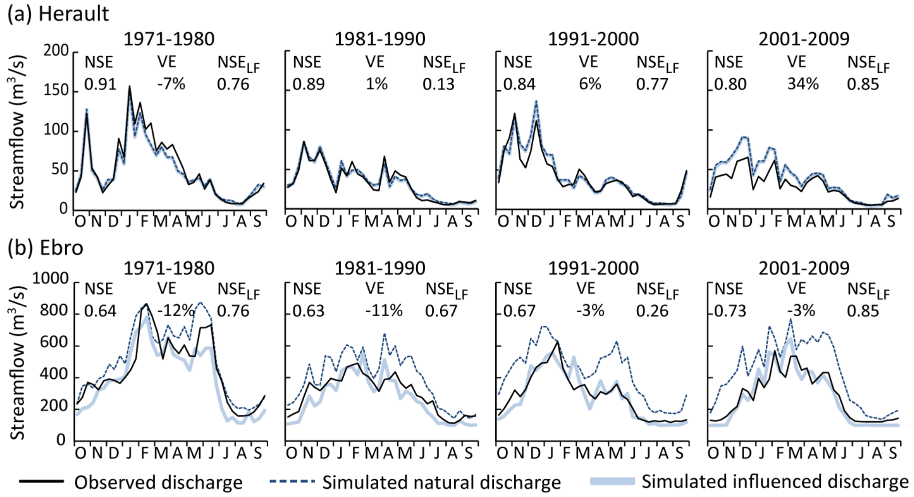

Figure 2. Average observed and simulated discharge per decade and values of Nash (NSE), Volume error (VE) and low flow Nash (NSE_{LF}) criteria at the outlet of **(a)** the Herault and **(b)** the Ebro basins between 1971 and 2009.

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 Herault and Ebro basins: anthropogenic 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.

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 Herault 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 Herault 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 Herault basin, average deficits at 10-day and annual time steps were lower.

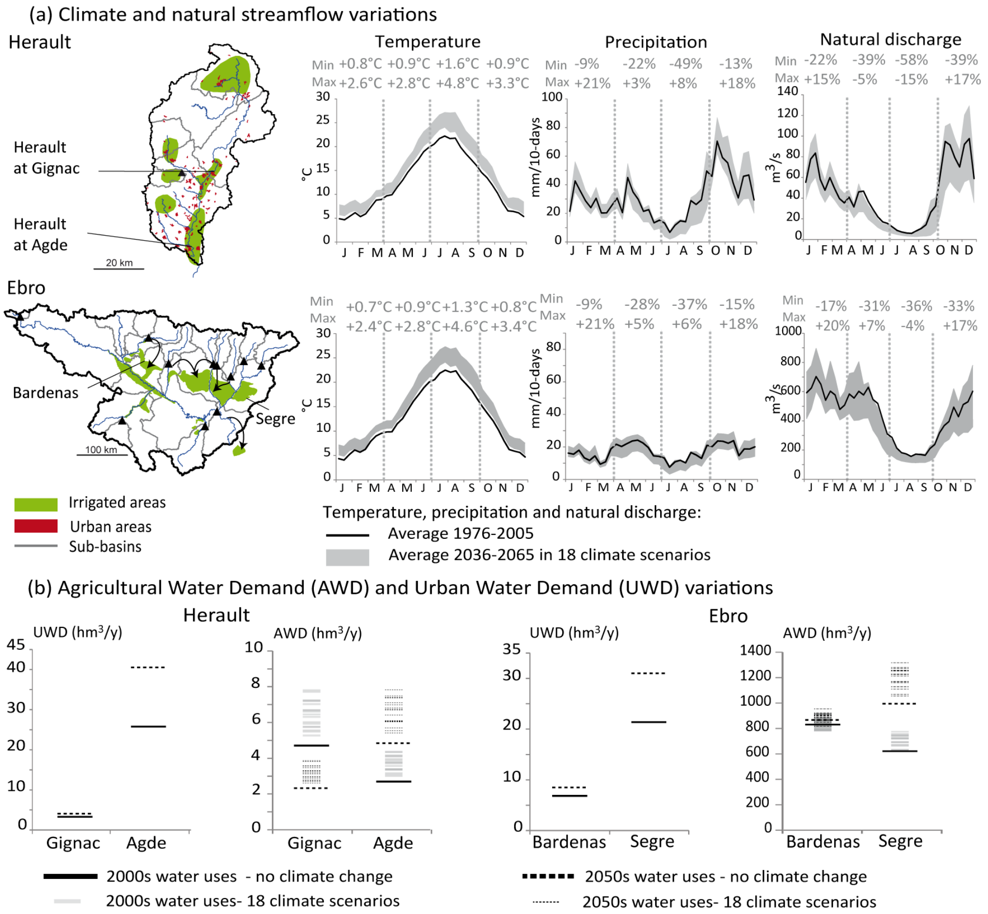

Figure 3. Projected hydro-climatic and water demand changes at the 2050 horizon at the scale of the Herault and the Ebro catchments: **(a)** range of 18 climatic scenarios and their potential impact on natural streamflow at the outlet and **(b)** variations in urban and agricultural water demand in illustrative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

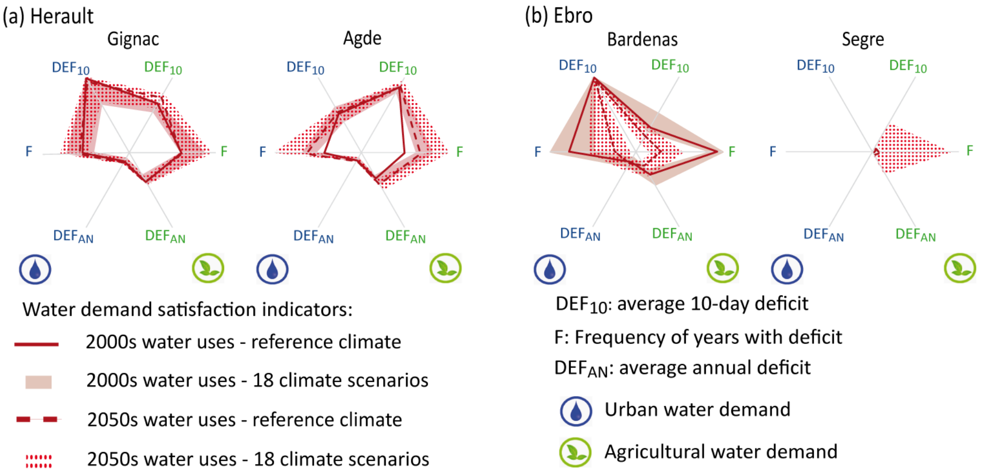

Figure 4. Water demand satisfaction indicators for urban and agricultural water demands under four combinations of water use and climate scenarios in two areas of **(a)** the Herault and **(b)** the Ebro basin. For all three indicators values range from 0 (no deficit) to 1 (maximum frequency or intensity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