



Effects of Climate Change at the 2040's Horizon on the Hydrology of the Pluvio-Nival Rheraya Watershed Near Marrakesh, Morocco

Youssef Hajhouji¹(✉), Younes Fakir^{1,2}, Vincent Simonneaux³,
Simon Gascoin³, El Houssaine Bouras¹,
and Abdelghani Chehbouni^{2,3}

¹ Faculty of Sciences Semlalia, Department of Geology, Cadi Ayyad University, Av. Prince My Abdellah, P.O. Box 2390, Marrakech, Morocco

hajhoujiyoussef@gmail.com

² CRSA (Center for Remote Sensing Application), UM6P, Benguerir, Morocco

³ CESBIO, Université de Toulouse, IRD/UPS/CNRS/CNES, Toulouse, France

Abstract. The present study aims at modeling and analyzing the climate change effects on the runoff of the Rheraya stream (Morocco), taking into account the snow component. For this purpose, we combined the GR4J conceptual rainfall-runoff model with the CemaNeige snow module calibrated over 1989–2009, for daily time step simulations. Med-Cordex climate projections for the period 2020–2040 were used to simulate the future evolution of precipitations, snow cover area and runoff according to the Representative Concentration Pathway scenarios (RCP); RCP 4.5 (stabilization of emissions) and RCP 8.5 (trend scenario).

The results showed a decrease in rainfall, snow cover area and runoff for both RCP 4.5 and RCP 8.5 scenarios at the 2040's horizon when compared to the 1989–2009 baseline. The annual rainfall decreases by –18.4% for the RCP 4.5 scenario and –19.6% for the RCP 8.5 scenario. The snow cover area decreases by –38% and –48% for RCP 4.5 and RCP 8.5, respectively. Finally, the average annual runoff decreases by –9% for RCP 4.5 and –28% for RCP 8.5 scenarios. The forthcoming consequences would seriously affect irrigation and ground-water availability in the area.

Keywords: CemaNeige · GR4J · Hydrologic modeling · Snow · RCP scenarios · Tensift-El Haouz watershed

1 Introduction

The Climate Change (CC) modifies regional hydrological cycles and affect the quantity and quality of regional water resources (e.g. Gleick 1989; Versini et al. 2016). As a consequence, CC could impact hydrologic regimes and water resources management throughout the world (e.g. Brekke et al. 2009; Schnorbus et al. 2014). The CC also affects agriculture and food production in complex ways (Schmidhuber and Tubiello

2007) as the agriculture is very sensitive to climate conditions (e.g. Parry and Carter 1989; Reilly 1995). Mediterranean areas are subject to significant changes in the sustainability, quantity, quality of water resources. Around the Mediterranean basin and at the 2050's horizon, temperature increases from 2 to 3 °C were mentioned in the report of Intergovernmental Panel on Climate Change (IPCC). This augmentation might be associated with a decrease in precipitation of about -20 to -30% (Giorgi and Lionello 2008).

Recently several studies have examined the effects of CC on the hydrology and water resources (García-Ruiz et al. 2011; Milano et al. 2013; Tramblay et al. 2013). To this end many studies combines hydrological models with climate scenarios (Chiew et al. 2009; Senatore et al. 2011; Marchane et al. 2017). Climate scenarios provide climate variables (precipitation and temperature) and the hydrological models simulate the streamflow. For this purpose, two types of approaches have been used: the "mechanistic or physical" (e.g. Fatichi et al. 2014) and the "conceptual" (Tramblay et al. 2013, Lespinas et al. 2014). In the Rheraya watershed, object of the present study, Marchane et al. (2017) used a combination of two conceptual models at a monthly time step: the GR2M proposed by Mouelhi et al. (2006) and the water balance model (MWBM) of McCabe and Markstrom (2007). The results of this study at the 2065's showed a decrease in streamflow up to 30%. The impacts of CC on groundwater were not addressed in the area due to lack of hydrogeological monitoring. Another difficulty in evapotranspiration estimation is the requirement for large data sets that are not easily available (Fowler et al. 2007), this can attribute to the inaccuracy of the evapotranspiration estimate. In addition, the difficulty of determining the underground flows which largely beyond the scope of this work.

In this paper we aim to evaluate the effects of CC on the precipitation, temperature, snow cover area and runoff at the 2040's horizon in the Rheraya watershed at a daily time step. To this end, the MEDCORDEX simulations for the period 1990–2005 and the hydrological conceptual models (CemaNeige-GR4J) has been used. MEDCORDEX simulations are used to calculate anomalies to correct rainfall and temperature series for the objective to produce future climate scenarios (2020–2040). The precipitation and temperature scenarios are then integrated in daily hydrological simulations (CemaNeige-GR4J) to generate the streamflow at the Rheraya watershed gauging station. GR4J is a daily rainfall runoff model (Perrin et al. 2003), while CemaNeige allows the differentiation of liquid and solid precipitation, to calculate the SCA, Snow Water Equivalent (SWE) and the quantity of water transmitted to the GR4J hydrological model. The daily time step was chosen to characterize the specific Rheraya hydrological regime which is strongly influenced by the rapid responses of runoff to the precipitations events (Hajhouji et al. 2018). In addition, the daily time step allows a better representation of the snow processes such as the separation of the precipitation into rainfall or snowfall, which is hardly captured with monthly averages in Mediterranean and semi-arid regions (Fayad et al. 2017).

2 Study Area (Rheraya Watershed)

The Rheraya basin located in Tensift-El Haouz watershed, covers a surface of 225 km² (see Fig. 1). It is characterized by a highly variable topography (altitude between 1084–4167 m). Rheraya is characterized by spatio-temporal variability of precipitations (Chaponniere et al. 2008) which vary from 600 mm.year⁻¹ in the in high mountain to 356 mm.year⁻¹ in low mountain. About 30% to 50% of the precipitations fall as snow (Boudhar et al. 2009). The average runoff recorded at the Tahanaout gauge station is 1.15 m³s⁻¹. The hydrological regime of the Rheraya River is pluvio-nival with a unimodal distribution whose maximum in April is linked with snowmelt. It is at this time of the year that downstream populations are most vulnerable to the flow deficit because irrigated crops come into their growth period (Hajhouji et al. 2018).

The Rheraya watershed is part of the western High-Atlas mountains, where 60% of the area is occupied by metamorphic and eruptive rock (andesite, granite, low permeability). At the limit with the plain, the geology is dominated by limestone, marl, sandstone and red clay (40% of the area).

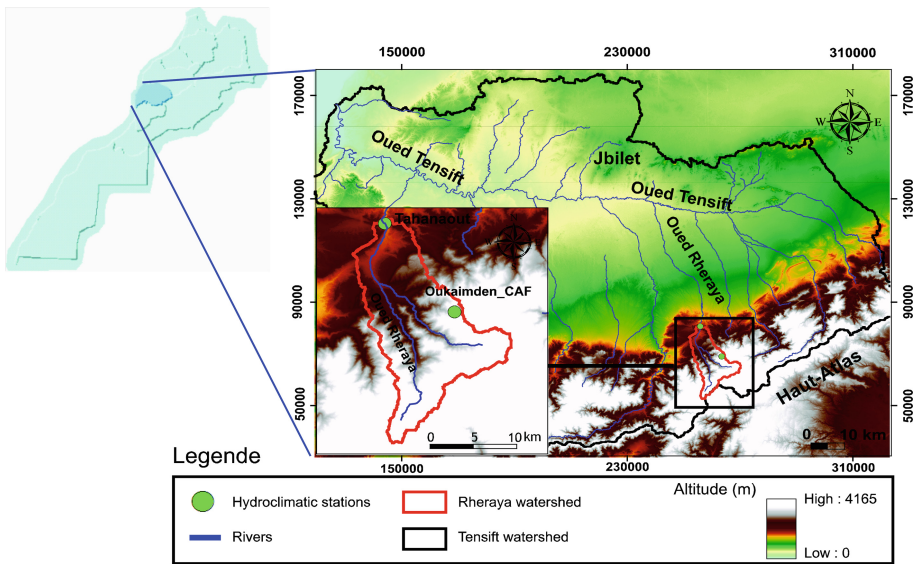


Fig. 1. The Rheraya watershed and location of rain gauge stations.

3 Materials and Methods

Rainfall, Snow and Temperature. Daily rainfall, snow and temperature data are collected at the Oukaimden CAF station provided by the joint international laboratory TREMA (Remote Sensing of Water Resources in Semi-Arid Mediterranean Areas) for the period 1989–2008. Rainfall is also measured at Tahanaout station (see Fig. 1).

Runoff. The daily runoff of the Rheraya river is measured at the Tahanaout station by the Tensift Basin Agency (ABHT) for the period 1962–2017. In this study, we used the daily runoff for the period 1990–2008.

In order to study the runoff evolution of the Rheraya river at the 2040's horizon, we used the Regional Climate Model (RCM) simulations database at a spatial resolution of 50 km from the Med-CORDEX project (<http://www.medcordex.eu/>). The following climate simulations were used (see Fig. 2): (i) Historical runs (HIST) are simulations for the control period (1990–2005) with RCM forced by the different Global Climate Models (GCM). (ii) Scenario runs (RCP4.5/RCP8.5) are simulations for future projections (2020–2040) with RCMs forced by different GCMs according to the emissions scenarios RCP4.5 and RCP8.5.

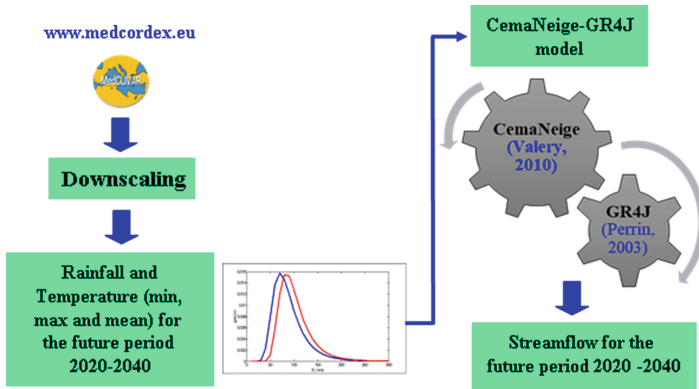


Fig. 2. Methodology applied for analyzing the climate change effects on the streamflow in the Rheraya river for both RCP 4.5 and RCP 8.5 scenarios at the 2040's horizon.

Given the small size of the Rheraya watershed (225 km²) compared to the Med-CORDEX outputs (50 km), these datasets must be downscaled based on observed data. Several strategies exist to realize this operation. We can either calculate a change between the outputs of the historical and future models and then apply this change factor to the observed data, or calculate a transformation into historical simulations and observations and apply it to future simulations. The calculation of the changes can be summarized to a simple factor of change (“anomaly”) on monthly values, or to calculate, always for each month, a distribution transformation between the histograms of the different data (CDF method, “cumulative distribution functions”). For this study, we chose the anomaly method applied between the historical period 1990–2005 and the RCP 4.5 and 8.5 simulations for the future period 2020–2040, and we chose to correct the observed data from the calculated change between the different Med-CORDEX simulations. To modify the rainfall, we calculated a ratio between the cumulative rainfall of all the months of the historical (P_{hist}) and future period (P_{rcp}), then we adjusted the daily observed rainfall (P_{obs}) by multiplying them by this ratio to obtain $P_{\text{obs_rcp}}$. The calculated monthly correction factors were applied on the observed dataset at the Tahanaout and Oukaimden stations for the future period (2020–2040).

$$P_{obs_rcp} = \left(\frac{P_{rcp}}{P_{Hist}} \right) * P_{obs} \tag{1}$$

To modify the temperatures (minimum, maximum and mean), we calculated the difference between the historical (T_{hist}) and the future (T_{rcp}) monthly temperatures simulated by the two scenarios (RCP 4.5 and 8.5) for the 1990–2005 and 2020–2040 periods. These differences were added to daily observed temperatures (T_{obs}) to obtain T_{obs_rcp} series.

$$T_{obs_rcp} = (T_{rcp} - T_{hist}) + T_{obs} \tag{2}$$

The obtained climatic data were input to the GR4J-CemaNeige model to simulate the runoff of the Rheraya stream. GR4J is a model with 4 parameters (Perrin et al. 2003) and CemaNeige (Valéry 2010) is a module for semi-distributed snow dynamics, whose inputs are daily temperature (min, max and mean) and rainfall, altitudinal gradients of rainfall and temperature, and five elevation zones with equal areas. They were calibrated using daily historical data of runoff and snow coverage extracted from the MODIS snow product (Hajhouji et al. 2018).

4 Results

4.1 Climatic Changes (Med-CORDEX Disaggregation)

The results show a decrease in rainfall for both RCP 4.5 and RCP 8.5 scenarios at the 2040’s horizon when compared to the 1989–2009 baseline (see Fig. 3). The annual rainfall decreases by -18.4% for the RCP 4.5 scenario and -19.6% for the RCP 8.5 scenario (Table 1). The results of the two RCPs are relatively close because we chose a near horizon (2040).

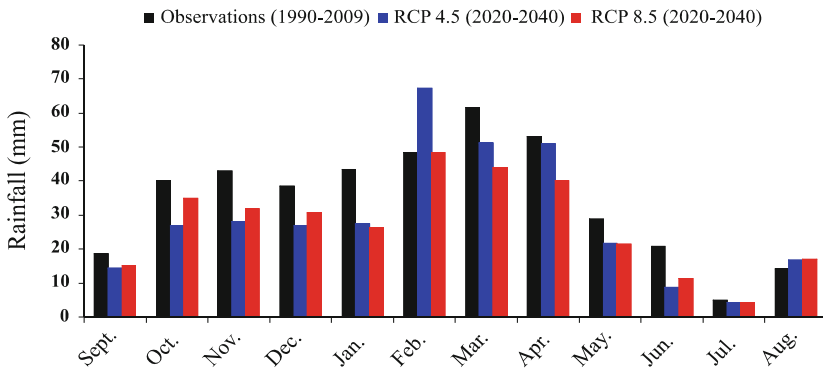


Fig. 3. Projected rainfall for the future period 2020–2040 according to the RCP 4.5 and RCP 8.5.

Table 1. Rainfall change between the historical period (1990–2009) and future period (2020–2040) for RCP 4.5 and RCP 8.5.

Month	P (RCP 8.5-Hist)	P (RCP 4.5-Hist)
	(%)	(%)
September	-19.9	-23.1
October	-12.6	-32.9
November	-25.9	-34.3
December	-20.4	-30.0
January	-39.8	-36.8
February	0.0	38.7
March	-28.7	-16.8
April	-24.4	-4.0
May	-25.1	-24.5
June	-45.4	-58.4
July	-13.3	-17.6
August	20.0	18.0
Mean (%)	-19.6	-18.5

The projected temperature for the future period (2020–2040) (see Fig. 4, Table 2) show that the average temperature increases with +0,87 °C for the RCP 4.5 scenario and +1,36 °C for the scenario RCP 8.5. The most important changes are from April to July for which the scenarios predict an increase above 2 °C. In summary, the projections indicate that the climate of the Rheraya watershed should evolve towards a drier and warmer climate.

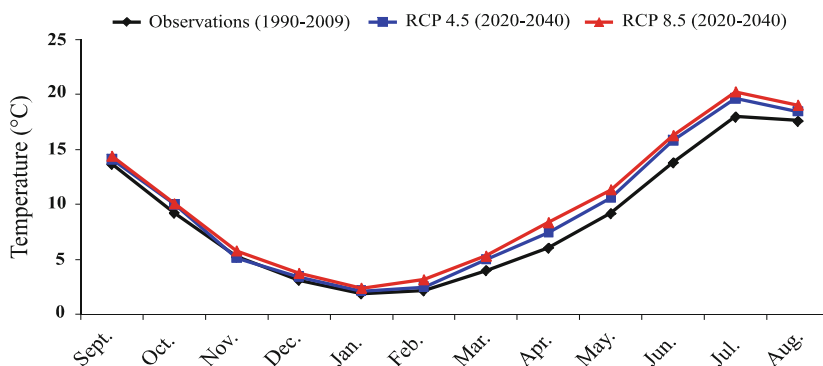


Fig. 4. Projected temperature for the future period 2020–2040 according to the RCP 4.5 and RCP 8.5.

Table 2. Temperature change between the historical period (1990–2009) and the future period (2020–2040) for RCP 4.5 and RCP 8.5.

Month	T (RCP8.5 - Hist)	T (RCP4.5 - Hist)
	(°C)	(°C)
September	0.73	0.42
October	0.84	0.79
November	0.55	-0.08
December	0.62	0.29
January	0.50	0.24
February	1.01	0.35
March	1.31	0.98
April	2.31	1.42
May	2.17	1.42
June	2.48	2.05
July	2.30	1.70
August	1.45	0.89
Mean (°C)	+1.36	+0.87

5 Hydrological Simulations (2020–2040)

Projected Snow Cover Area (2020–2040). The results of hydrological simulations of SCA show a decrease by -38% and -43% for RCP 4.5 and RCP 8.5, respectively. The decrease in SCA is recorded during all months except for February for the RCP 4.5 scenario (see Fig. 5).

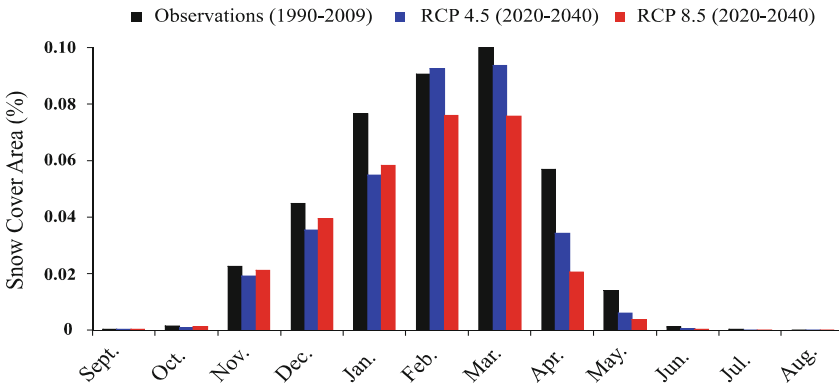


Fig. 5. Snow Cover Area (SCA) for 1990-2009 and 2020–2040.

Projected Runoff in the Rheraya River (2020–2040). The results of hydrological simulations of runoff show a decrease (see Fig. 6). The average annual runoff decreases by -9% for RCP 4.5 and -28% for RCP 8.5 scenarios. In addition, a marked change in the hydrological regime (runoff timing) is simulated with less water in spring and early summer (from March to June) due to less snow cover.

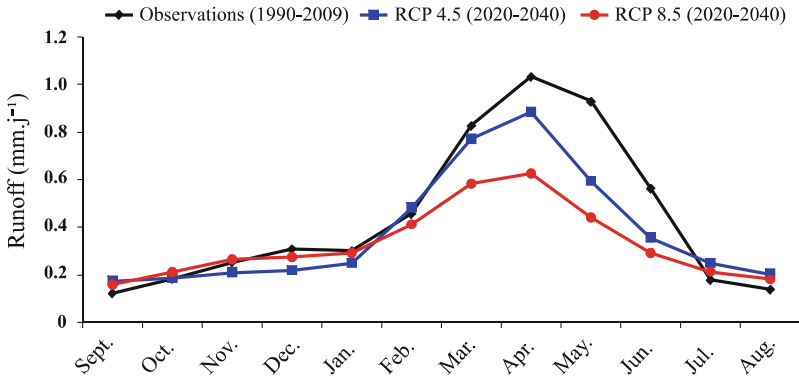


Fig. 6. Observed streamflow cycles for the reference period 1989–2009, and simulated changes in streamflow for the future period 2020–2040 according to different sets of calibrated parameters for the CemaNeige-GR4J model.

5.1 Climate Change Trends

The purpose of this paper is to evaluate trends rather than compare our results with others. The CC results show the same trends of previous studies (Table 3): increase in temperature and decrease in precipitation and runoff. As the horizon of our study is 2040, the foreseen variations are lower than those relative to studies performed for 2060's (Marchane et al. 2017; Tramblay et al. 2013) or 2100's horizon (Vicuña et al. 2011).

The results show also a higher decrease in runoff compared to precipitations; this can be explained by increase in evapotranspiration losses. Indeed, recently studies expect increase in projected evapotranspiration over Morocco, reaching about 8.9% in 2050 (Saadi et al. 2015) and 7.5% in 2056 (Tramblay et al. 2018). Generally, the predicted decrease in precipitation and an increase in evapotranspiration may have a significant impact on surface water resources (runoff) and groundwater resources (recharge).

Table 3. Comparison between different climate change studies.

Authors	Study area	Study horizon	Climatic variables		
			Temperature (°C)	Precipitations (%)	Runoff (%)
Present study	Rheraya, Morocco	2020–2040	+0.8 to +1.3	–18 to –19	–9 to –28
Marchane et al. 2017	Rheraya, Morocco	2049–2065	+1.4 to +2.6	–22 to –31	–19 to –63
Tramblay et al. 2013	Makhazine, Morocco	2041–2062	+1.3 to +1.9	–15 to –19	–30 to –57
Vicuña et al. 2011	Limarí, Chili	2070–2099	+3 to +4	–10 to –30	–19 to –21

6 Conclusions

Simulations of the different hydroclimatic variables showed an increase in temperature and decrease in precipitation, snow cover area and runoff in the Rheraya stream at the 2040's horizon. The average temperature increases were +0,87 °C for the RCP 4.5 scenario and +1,36 °C for the scenario RCP 8.5. The rainfall decreases were -18.4% for the RCP 4.5 scenario and -19.6% for the RCP 8.5 scenario. The SCA decreased by -38% and -48% for RCP 4.5 and RCP 8.5, respectively. Finally, the average annual runoff decreased by -9% for RCP 4.5 and -28% for RCP 8.5 scenarios. This forthcoming decrease is a problem in this area already experiencing water shortage.

These results highlight the important impact that climate change may cause on the snow dominated watersheds in Morocco. The RCP 4.5 scenario, even though predicting a 2% increase in the SCA during February, showed a decrease up to 28% for the month of January. These changes in SCA have a direct influence on the runoff of the Rheraya river. A sensitive change of runoff was indeed observed with less water from March to June. The simulated runoff changes could seriously affect water availability for irrigation in the area: (i) In the valleys, irrigation of olive crops, the main culture, is particularly required from March to September, and during spring to early summer is mainly based on streamflow from the high-elevation areas. (ii) The deficit of streamflow may also affect the recharge and further worsen the groundwater availability in the lowlands where agriculture is highly dependent on irrigation. Further work should focus on the characterization of the groundwater recharge processes to better evaluate the impact of the projected runoff changes on the Haouz aquifer water balance.

References

- Boudhar, A., Hanich, L., Boulet, G., Duchemin, B., Berjamy, B., Chehbouni, A.: Evaluation of the snowmelt runoff model in the moroccan high atlas mountains using two snow-cover estimates. *Hydrol. Sci. J.* **54**(6), 1094–1113 (2009)
- Brekke, L.D., Kiang, J.E., Olsen, J.R., Pulwarty, R.S., Raff, D.A., Turnipseed, D.P., Webb, R.S., White, K.D.: Climate change and water resources management—A federal perspective. U.S. Geological Survey Circular, vol. 1331, 65 p. (2009)
- Chaponniere, A., Boulet, G., Chehbouni, A., Aresmouk, M.: Understanding hydrological processes with scarce data in a mountain environment. *Hydrol. Processes* **22**(12), 1908–1921 (2008)
- Chiew, F.H.S., Teng, J., Vaze, J., Post, D.A., Perraud, J.M., Kirono, D.G.C., Viney, N.R.: Estimating climate change impact on runoff across southeast Australia: method, results, and implications of the modeling method. *Water Resour. Res.* **45**(10) (2009)
- Fatichi, S., Rimkus, S., Burlando, P., Bordoy, R.: Does internal climate variability overwhelm climate change signals in streamflow? The upper Po and Rhone basin case studies. *Sci. Total Environ.* **493**, 1171–1182 (2014)
- Fayad, A., Gascoin, S., Faour, G., López-Moreno, J.I., Drapeau, L., Le Page, M., Escadafal, Escadafal, et al.: Snow hydrology in Mediterranean mountain regions: a review. *J. Hydrol.* **551**, 374–396 (2017)

- Fowler, H.J., Blenkinsop, S., Tebaldi, C.: Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. *Int. J. Climatol.* **27**, 1547–1578 (2007)
- García-Ruiz, J.M., López-Moreno, J.I., Vicente-Serrano, S.M., Lasanta-Martínez, T., Beguería, S.: Mediterranean water resources in a global change scenario. *Earth-Sci. Rev.* **105**(3–4), 121–139 (2011)
- Gleick, P.H.: Climate change, hydrology, and water resources. *Rev. Geophys.* **27**(3), 329–344 (1989)
- Giorgi, F., Lionello, P.: Climate change projections for the Mediterranean region. *Global Planet. Change* **63**, 90–104 (2008)
- Hajhouji, Y., Simonneaux, V., Gascoïn, S., Fakir, Y., Richard, B., Chehbouni, A., Boudhar, A.: Modélisation pluie-débit et analyse du régime d'un bassin versant semi-aride sous influence nivale. Cas du bassin versant du Rheraya (Haut Atlas, Maroc). *La Houille Blanche* (3), 49–62 (2018)
- Lespinas, F., Ludwig, W., 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)
- Marchane, A., Trambly, Y., Hanich, L., Ruelland, D., Jarlan, L.: Climate change impacts on surface water resources in the Rheraya catchment (High Atlas, Morocco). *Hydrol. Sci. J.* **62** (6), 979–995 (2017)
- McCabe, G.J., Markstrom, S.L.: A monthly water-balance model driven by a graphical user interface: U.S. Geological Survey Open-File report 2007, vol. 1088, 6 p. (2007)
- Milano, M., Ruelland, D., Fernandez, S., Dezetter, A., Fabre, J., Servat, E., Fritsch, J.M., Ardoin-Bardin, S., Thivet, G.: Current state of Mediterranean water resources and future trends under global changes. *Hydrol. Sci. J.* **58**, 498–518 (2013)
- Mouelhi, S., Michel, C., Perrin, C., Andréassian, V.: Stepwise development of a two parameter monthly water balance model. *J. Hydrol.* **318**, 200–214 (2006)
- Parry, M.L., Carter, T.R.: An assessment of the effects of climatic change on agriculture. *Clim. Change* **15**, 95–116 (1989)
- Perrin, C., Michel, C., Andréassian, V.: Improvement of a parsimonious model for streamflow simulation. *J. Hydrol.* **279**(1–4), 275–289 (2003)
- Reilly, J.: Climate change and global agriculture: recent findings and issues. *Am. J. Agric. Econ.* **77**, 727–733 (1995)
- Saadi, S., Todorovic, M., Tanasijevic, L., Pereira, L.S., Pizzigalli, C., Lionello, P.: Climate change and Mediterranean agriculture: impacts on winter wheat and tomato crop evapotranspiration, irrigation requirements and yield. *Agric. Water Manage.* **147**, 103–115 (2015)
- Schmidhuber, J., Tubiello, F.N.: Global food security under climate change. *Proc. Nat. Acad. Sci.* **104**(50), 19703–19708 (2007)
- Schnorbus, M., Werner, A., Bennett, K.: Impacts of climate change in three hydrologic regimes in British Columbia. Canada. *Hydrol. Processes* **28**(3), 1170–1189 (2014)
- Senatore, A., Mendicino, G., Smiatek, G., Kunstmann, H.: Regional climate change projections and hydrological impact analysis for a Mediterranean basin in Southern Italy. *J. Hydrol.* **399**, 70–92 (2011)
- Trambly, Y., Jarlan, L., Hanich, L., Somot, S.: Future scenarios of surface water resources availability in North African dams. *Water Resour. Manage* **32**(4), 1291–1306 (2018)
- Trambly, Y., Ruelland, D., Somot, S., Bouaicha, R., Servat, E.: High-resolution Med-CORDEX regional climate model simulations for hydrological impact studies: a first evaluation of the ALADIN-Climate model in Morocco. *Hydrol. Earth Syst. Sci.* **17**, 3721–3739 (2013)

- Valéry, A.: Modélisation précipitations - débit sous influence nivale, Elaboration d'un module neige et évaluation sur 380 bassins versants. Thèse de doctorat, AgroParisTech – ENGREF (2010)
- Vicuña, S., Garreaud, R.D., McPhee, J.: Climate change impacts on the hydrology of a snowmelt driven basin in semiarid Chile. *Clim. Change* **105**(3–4), 469–488 (2011)
- Versini, P.A., Pouget, L., McEnnis, S., Custodio, E., Escaler, I.: Climate change impact on water resources availability: case study of the Llobregat river basin (Spain). *Hydrol. Sci. J.* **61**(14), 2496–2508 (2016)