Climate Change impacts on the *Water Highway* project in Morocco

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Abstract. The hydrology of Morocco is characterized by a significant spatial variability. Precipitation follows a sharp gradient decreasing from the north to the south. In order to redistribute available water, a project is proposed to transfer 860 million m^3 per year from the wet north to the arid southern regions, *{Water Highway}*. The present study aims to address the viability of the project after accounting for the impacts of climate change in the watersheds located in the north. We perform Regional
5 Climate Model (RCMs) simulations over the study region using boundary conditions from five different global circulation models (GCMs) and assuming two emissions scenarios RCP4.5 (with mitigation) and RCP8.5 (business as usual). The impact on precipitation and temperature are assessed and the decrease of available water quantity is estimated. Under RCP 8.5 the project is likely not feasible. However under the RCP 4.5 a rescaled version of this project may be feasible depending on how much water is allocated to satisfy the local water demand in the north.

10 *Copyright statement.* TEXT

1 Introduction

In many regions in the world, water scarcity is a critical issue that should be seriously addressed by stakeholders. Greve et al. (2018) define water scarcity as the ratio between the natural supply and the local demand in water. As a result, water scarcity depends mainly on two factors: hydro-climatology and socio-economics (Wada et al. (2014)). While a study shows that Mo-
15 rocco is not much threatened by the increase of population (Boke-Olén et al. (2017)), several studies suggest that arid and semi arid regions like Morocco should develop new policy in order to adapt to climate change (Kahil et al. (2015); Batisani and Yarnal (2010); Lioubimtseva and Henebry (2009)). As reported by Greve et al. (2018), different policies could be adopted, including investments in structures for transferring water from a basin to another.

Hydrology in Morocco is characterized by strong spatial and temporal variability (Driouech et al. (2010); Tramblay et al.
20 (2013)). This uneven distribution of water has led the Moroccan government to develop hydraulic infrastructure to improve the local management of water resources in the Kingdom. In 1967, King Hassan II launched a project to irrigate 1 million hectares by the year 2000. More precisely, the plan was to build a dam every year. The outcomes of this strategy helped to achieve food

security, increase cash crops production for export and improve the social and economic level of local farmers. More implicitly the construction of these infrastructures has helped communities to adapt to climate variability. Previous studies (Doukkali (2005)) showed that although these efforts resulted in a significant optimization of water resources management in Morocco, they remain insufficient to insure water and food security. A new policy is needed to complement all these efforts. By 2020 only the watersheds in the north of Morocco will have excess of water compared to the demand (Minoia and Brusarosco (2006)). The proposed North-South Water Transfer project (*Water Highway*) aims to supply water in the arid southern regions from the watersheds in the north (see Figure 2). The projected quantity of water to be transfered by this project is 860 million m^3 per year (Water-Office (2017)).

Other countries adopted similar policy in order to alleviate water scarcity problems. In China (Gu et al. (2012)), water is transferred from the tropical southern region to the very dense, industrialized and arid north, and the project is named South-North Water Transfer Project (SNWTP). The goal of this project is to transfer 44.5 km^3 each year from the Yangtze River basin. Although the economic benefit of the project is appreciated in the region (Feng et al. (2007)), yet it has raised some controversies (Berkoff (2003)). First transferring water in open channels increases risk of pollution (Tang et al. (2014)). Traffic accidents specially involving trucks represent a threat to water quality. Moreover, the risk of salinization of both basins (due to the transfer for the receiving one and due to the sea water intrusion in the other basin) is highlighted by Zhang (2009). Therefore, significant efforts are to be carried in order to improve watersheds management (Zhang et al. (2009)). *Water Highway* could also lead to a dramatic increase of water cost. These concerns have been raised in the case of SNWTP by two studies (Wei et al. (2010); Yang and Zehnder (2005)). In fact, the project relies significantly on water availability in the south of China. And as it has been suggested by Liu and Zheng (2002) and Li et al. (2015), water quantity will decrease in the donor watersheds due to global climate change. This decrease will not affect the viability of the project in the Chinese case nonetheless. In contrast it is not clear for the Moroccan case, if the change in precipitation would not change the viability of the project. Therefore the goal of the present study is to assess the viability of the *Water Highway* including the climate change impact.

Global change is impacting the African climate. Indeed, many studies showed that regional climate of Africa is likely to change during the upcoming decades (Sowers et al. (2011)). This change is likely to have considerable socio-economical and environmental impacts. A recent study that used the IPCC AR4 (4th Assessment Report of the Intergovernmental Panel on Climate Change) emissions scenarios to predict climate change in Africa, reported that the northern part is more likely to suffer from an increase in temperature and a decrease of precipitation in amount and frequency (Vizy and Cook (2012)). As a result, North Africa will be vulnerable to climate change (Döll (2009)).

In last decades, Morocco has built one of the strongest economies in Africa (101 billion US Dollar in GDP as reported by the World Bank "https://data.worldbank.org/country/morocco"). This economy, however efficient compared to other developing countries, depends significantly on water availability (Agriculture represents 15% of the GDP). Water imbalance between demand and supply is growing (Hellegers et al. (2013)). In Morocco, water demand is affecting water scarcity more intensely than climate change (Vörösmarty et al. (2000)). On one hand, the urban population is expected to be increasing by about 270 thousand inhabitant per year due to urbanization, as reported by the Moroccan High Commission for Planning Website (http://www.hcp.ma/). On the other hand, the improved irrigation schemes has certainly intensified cash crops production in

Morocco, but has also increased water demand. Indeed, Ward and Pulido-Velazquez (2008) show that the increase of efficiency increases water use. Furthermore, climate change projections predict that Morocco will experience a dry future (Giorgi and Lionello (2008); Kang et al. (2019)) and a decrease in precipitation (Patricola and Cook (2010)). For all these reasons among others, the country is increasingly vulnerable to global change and adaptation policies are therefore a must for the development
5   of the country under such conditions (Schilling et al. (2012)).

The purpose of the present work is to study the viability of the North-South Water Transfer project, considering the impact of climate change. More precisely, the study aims to assess the effect of climate change on water availability in the northern basins. In order to evaluate climate change impact on this project, multi-model climate simulations were performed. Forcing boundary conditions from five GCMs (MPI, GFDL, IPSL, CSM, ACCESS) were considered in order to quantify the uncertainty
10 in future climate projections (Tebaldi and Knutti (2007)). The simulations performed using MRCM (MIT Regional Climate Model) simulates plausibly the global change impact on precipitation and temperature (Eltahir et al. (2013)). We choose to assess the impact of climate change for a 30 years duration mainly for two reasons. The first one is linked to climate change. In fact, this project has been designed in order to face future climate change impacts on the southern Moroccan areas. If the project may jeopardize the water security of the northern region how can it face the southern region water demand as well? The
15 second reason is purely from a feasibility perspective. The project will need more than 10 years to be fully built, not to mention that the project has not started yet (constructions were planned to start in 2018). In addition, the Moroccan government has only made available the budget for the first phase. The second and the third phase are still waiting for the necessary funds, which will certainly delay the project for another 10 years.The impact on runoff and therefore on water availability is assessed using the runoff elasticity (Sankarasubramanian and Vogel (2003); Tang and Lettenmaier (2012)) based on available data and
20 RCM simulations. Such methodology can be used to evaluate the impact of climate change on water availability in regions where hydrological modelling may not be feasible. We confronted the results of our work with other published works on the assessment of climate change impact on water availability in the region.

The article is presented as follows: The second section describes the North-South Water transfer project in Morocco, the
25 northern region that ought to supply water to the arid regions in the South, and the available datasets needed to perform the analysis. The third section is dedicated to present methodologies used in order to assess the expected loss of water in the northern watersheds. Finally the fourth section presents the results. Conclusion and perspectives are described in section 5

2   North-South Water transfer project

2.1   Water distribution in Morocco

30 Morocco is located in the North-West of Africa. Given this geographical position, the climate is characterized by a strong spatial variability. Indeed the southern part of the country is affected by the extreme dry climate of the Sahara desert, and the north-western part benefits from the moderate climate of Mediterranean sea and Atlantic ocean. In addition, the topography of Morocco varies also in space. The coastal region is flat while, in the north and the east, the country's topography is shaped
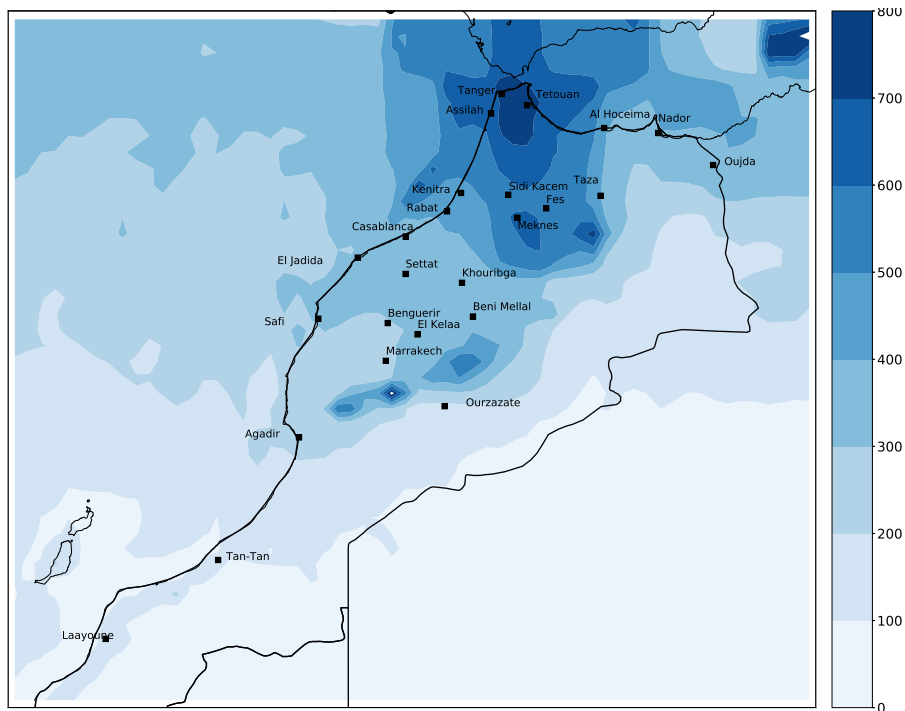
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Figure 1. Annual precipitation (mm) in Morocco using TRMM data

by the Rif mountains and Atlas mountains respectively. Climate therefore can vary from sub-humid to arid over the country (Born et al. (2008)). As a result, the precipitation over Morocco varies strongly in space. Figure 1 displays the annual mean precipitation over Morocco using TRMM (Tropical Rainfall Measuring Mission) data (Huffman and Bolvin (2013)). The annual precipitation reaches up to $800\ mm/yr$ in the north, while the south barely receives $100\ mm/yr$. As a result, only the extreme north-west part of the country enjoys excess in water supply.

2.2 The general features of the project

As reported by the Moroccan department in charge of water, plans are ready to launch the project of water transfer from north to south Water-Office (2017). The water balance analysis prepared in the studies carried out by the Moroccan Department of Water shows that southern basins notably Tensift and Oum Er Rbia are in deficit. On the other hand the northern basins discharge excess water to the sea. A transfer from the northern basins, which are much better equipped with hydraulic structures, would relieve these deficits thus consolidating national integration in water management. The preliminary pre-feasibility studies conducted by the Department of Water has shown that roughly 860 million m^3 could be transferred on average from basins of Oued Laou, Loukkos and Mjara (See Figure 3) to the basins of Bouregreg, Oum Er Rbia and Tensift (See Figure 2). The project implementation schedule as well as the institutional and financial setup will be defined by the studies in progress by both concerned ministerial departments namely water and agriculture.
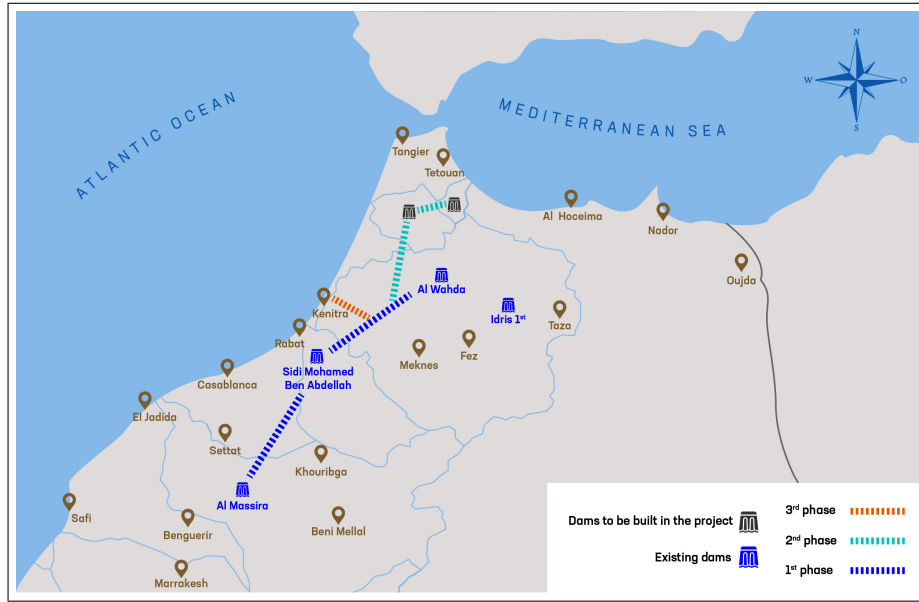
Figure 2. The planned Water Transfer Project

Phase	Start Point	End point	Water Amount (million m^3/yr)	Cost (billion MAD)	Cost (billion US $)
Phase 1	Kodiat al Borna (near Al Wahda Dam)	Al Massira Dam	392	16.3	1.63
Phase 2	Beni Mansour (Oued Laou)	Al Makhazine Dam	726=334 + 392	13	1.3
Phase 3	Oued Sebou	Phase 1 pipeline route	860= 726 + 134	1.7	0.17
Project	Oued Sebou, Loukkos, Oued Laou	Al Massira Dam	860	40	4

Table 1. The three phases of the project. These numbers are given as an indication, the remaining amount of the budget will be dedicated for the rehabilitation of existing hydraulic infrastructures

The project, following three phases as described in Table 1, will involve the construction of 9 pumping stations, 2 new dams and $500 \ km$ of channels and pipes to transfer water from Oued Laou, Loukkos and Sebou to Al Massira Dam.

2.3 Description of watersheds of interest

The purpose of this study is to analyse the effect of climate change on the project. In order to address the viability of the project, global climate change impact on the hydrology of the donor watersheds should be assessed. Figure 3 presents the

three watersheds that will supply the project, namely Loukkos, Oued Laou and Mjara (presented in a red contour). The latter is a sub-watershed of Sebou watershed, supplying most of the Sebou water. The three water basins are located in the northern region of Morocco, where the precipitation levels are relatively high. There is a spatial gradient of elevation from the north-east to the south-west due to the presence of Rif Mountains (see Figure 4).
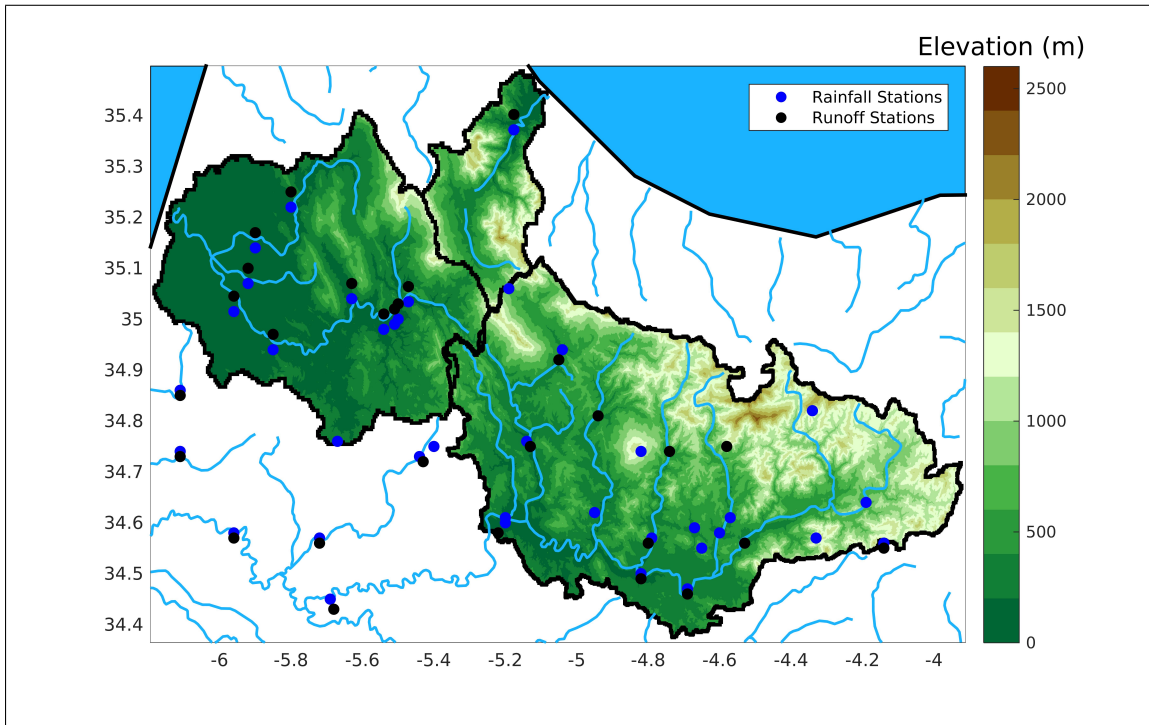

Figure 3. Watersheds of interest

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Figure 4. Mapping of the elevation and the position of gauge stations in Oued Laou, Loukkos and Mjara watersheds.

3 Datasets and methodologies

3.1 Datasets

In order to perform this study, we accessed several datasets. Table 2 summarizes the available data. Each data is available at a monthly time step.

3.1.1 Spatial Data

Spatial data helps to understand the temporal as well as the spatial variability of precipitation. For the present case we use the data from the space mission TRMM (Tropical rainfall measurement mission) (Huffman and Bolvin (2013)). We downloaded remote sensing data only for the region of Morocco and extracted it for the three watersheds considered in this analysis.

3.1.2 Gauge station data

Gauge station data was also used. The sources of data that have been used here are: river basin agency of Sebou and river basin agency of Loukkos. In Morocco, river basin agencies (ABH *"Agence du bassin hydraulique"*) are in charge of the evaluation, the planning and the general management of water resource within a watershed. In our case, Mjara watershed is managed by

Data Source	Nature	Period (Precipitation)	Period (Runoff)
TRMM 3B43	Remote Sensing Observation	1998-2016	-
ABH Loukkos (Loukkos)	River gauge stations	1961-2017	1971-2017
ABH Loukkos (Oued Laou)	River gauge stations	1964-2017	1971-2012
ABH Sebou (Mjara)	River gauge stations	1978-2017	1959-1996

Table 2. Datasets used for the study.

ABH Sebou (contoured with black in Figure 3). For this watershed, 17 rainfall stations and 24 runoff stations are available. Loukkos and Oued Laou on the other hand, are managed by ABH Loukkos. This agency made 11 rainfall and runoff stations available for the purpose of this study. All the gauge stations used in this study are displayed in Figure 4.

These data has the advantage of being more accurate than the spatial data, but are more likely to include missing values. In order to use them, one method of filling the missing values ($\sim 5\% - 10\%$) is to replace them by their longterm mean. There are other methods that can be used to fill the missing value, but only this method will be used in this study, since it seemed accurate enough for our purposes.

3.2 Regional Climate modeling

The present study used the MIT-Regional Climate Model (MRCM) based on ICTP-Regional Climate Model Version 3 (RegCM3, Pal et al. (2007)) but with several improvement. A detailed description of the MRCM is given by Im et al. (2014a). There are substantial differences between MRCM and RegCM3. In particular, based on the simulations using MRCM-IBIS over the West Africa, the use of IBIS as the land surface scheme results in better representation of surface energy and water budgets in comparison to RegCM3-BATS. Furthermore, the addition of a new irrigation scheme to IBIS makes it possible to investigate the effects of irrigation over West Africa (Im et al. (2014b); Alter et al. (2015)).

Building on the good performances of MRCM in previous studies, we project multi-model ensemble regional climate change using this model to advance our understanding of the future conditions in response to anthropogenic GHGs (greenhouse gases) over Morocco. To achieve this, a total of fifteen 31-year projections under multi-GCMs (Global Climate Model: IPSL-CM5A-LR, GFDL-ESM2M, CCSM4, MPI-ESM-MR, ACCESS1.0, Table 3) and multi-scenarios of emissions (Historical, RCP4.5, RCP8.5) are dynamically downscaled using MRCM with $12\ km$ horizontal resolution over Morocco (Figure 5). The first year of MRCM simulations in both the baseline and future periods is used for model spin up and has been discarded in the analysis. Five GCMs are selected based on a rigorous evaluation (NRMSE "*Normalized Root Mean Square Error*", PCC "*Pattern Correlation Coefficient*" and annual cycle) of their performances in simulating regional climate over Morocco while RCP4.5 and RCP8.5 represent mitigation and business-as-usual scenarios, respectively. We refer the reader to the companion paper (Kang et al. (2019)) for a detailed discussion about the RCM simulations and model performance.
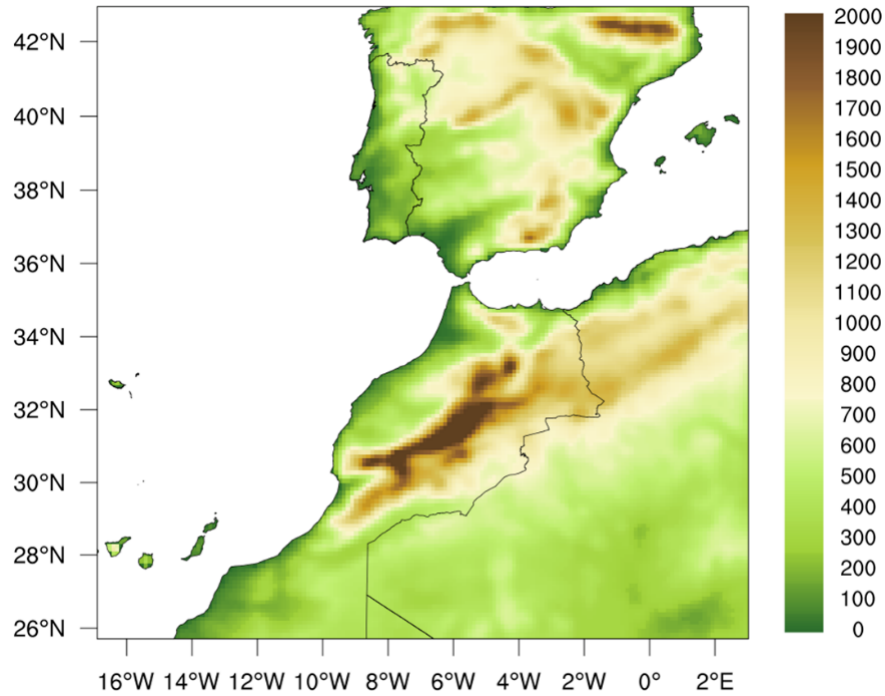
Figure 5. MRCM simulation domain and topography (unit: meter above mean sea level).

Model name	ATM resolution (lat x lon)	OCN resolution (lat x lon)	Main reference
ACCESS 1.0	1.25° x 1.875°	$1/3^\circ \sim 1^\circ$	[Bi et al. (2013)]
CCSM4	0.9° x 1.25°	1.11° x $0.27^\circ \sim 0.54^\circ$	[Gent et al. (2011)]
GFDL-ESM2M	2° x 2.5°	1° x $1/3^\circ \sim 1^\circ$	[Dunne et al. (2012)]
IPSL-CM5A-LR	1.875° x 3.75°	2° x $0.5^\circ \sim 2^\circ$	[Dufresne et al. (2013)]
MPI-ESM-MR	T63 ($\sim 1.875^\circ$)	0.4° x 0.4°	[Giorgetta et al. (2013)]

Table 3. Description of global climate models selected as lateral boundary forcings for MRCM simulation in the study.

3.3 Runoff Elasticity

The issue of sensitivity of runoff to climate change has been investigated in different studies. There are several methodologies to address this issue as reported by Sankarasubramanian et al. (2001). One of the most common approaches is to use a calibrated hydrological model. Then, with the help of RCM's simulations of future climate, one is able to study the sensitivity of runoff. The major difficulty of this method lies in the calibration of model parameters from a finite set of observations. One assumes that the parameters values do not change through time. This assumption has been extensively discussed in the community, and several studies demonstrated the importance of a dynamical correction of model parameters (Reichle et al. (2002); Moradkhani et al. (2005)) .

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Another approach is the application of simple water balance models, and to analytically derive elasticity coefficient. One could explain the sensitivity of runoff to all climatic variables as in (Yang and Yang (2011)). Indeed, this study concludes that the hydrological cycle is influenced by other climatic variables than precipitation and temperature, and compute runoff sensitivity to net rediation and wind speed at a height of 2m above the ground. On the other hand, following *Budyko* hypothesis, the long term mean runoff is mainly driven by the long term mean of precipitation and potential evapotranspiration rate. Therefore, runoff elasticity coefficient should be an explicit function of precipitation and potential evapotranspiration rate. Following this idea, different studies have developed empirical relationships (Schreiber (1904); Ol'Dekop (1911); Turc (1953); Pike (1964); Zhang et al. (2001)). Niemann and Eltahir (2005) demonstrated that the estimation of runoff elasticity coefficient with these analytical formulas is consistent with the one calculated from a physically based hydrological model (Niemann and Eltahir (2004)).

Another method to derive runoff sensitivity to climate change is the use of observations datasets. One is able to examine how runoff changes as climatic variables change. This assumes that the response of annual runoff to the variability of annual climatic forcing is the same as the response of the long term mean runoff to the changes of the long term mean climatic variables. This approach has been tested in Risbey and Entekhabi (1996) and Sankarasubramanian et al. (2001). The first study showed that Sacremento river runoff is insensitive to changes in temperature while it is more sensitive to precipitation. In the second study, the authors performed a similar methodology in the major rivers of the United States. They showed that when the rivers are located in dry areas, the sensitivity of runoff is mostly explained by precipitation. However when the rivers are located in areas with an important contribution of snow-packs to water balance, the runoff is less sensitive to precipitation.

In the present study, as we lack sufficient data to develop a well calibrated hydrological model, we choose to evaluate the potential change in runoff with the last two approaches described above. First, we evaluate the potentiel change in runoff through empirical equations first defined by (Dooge et al. (1999); Arora (2002)). Following these studies, long term change in runoff is mainly driven by the long term change in precipitation and the long term change in potential evapo-transpiration (PET). Therefore, one can write:

$$\frac{\Delta Q}{Q} = \epsilon \frac{\Delta P}{P} - \epsilon_{PET} \frac{\Delta E_0}{E_0}. \tag{1}$$

Where $\frac{\Delta Q}{Q}$, $\frac{\Delta P}{P}$ and $\frac{\Delta E_0}{E_0}$ are long term normalized changes in runoff, precipitation and potentiel evapotranspiration respectively. Consequently, the evaluation of runoff sensitivity to climate change requires the estimation of ϵ (runoff sensitivity to precipitation)and ϵ_{PET} (runoff sensitivity to PET). In Arora (2002); Yang and Yang (2011) these coefficients are computed using empirical equations:

$$\epsilon = 1 + \beta. \quad \epsilon_{PET} = \beta \tag{2}$$

where $\beta = \frac{\phi F'(\phi)}{1 - F(\phi)}$. The estimation of the runoff sensitivity coefficients are therefore a function of the aridity index ϕ and the mathematical function $F(\phi)$ relating the runoff ratio to precipitation (or PET) to the aridity index. These fonctions have been defined as empirical relations in different studies. Although those formulas have been developed to find the ratio of evapo-transpiration rate over the potential evapotranspiration rate, they could be rearranged to runoff sensitivity to climate change

Functional form	Name	Source
$F'(\phi) = e^{-\phi}$	Schreiber	Schreiber (1904)
$F'(\phi) = tanh(\frac{1}{\phi}) - \frac{4}{\phi(e^{-\frac{1}{\phi}}+e^{\frac{1}{\phi}})^2}$	Ol'dekoop	Ol'Dekop (1911)
$F'(\phi) = -\frac{1}{\phi^3\left[1+(\frac{1}{\phi})^2\right]^{3/2}}$	Turc-Pike	Turc (1953)-Pike (1964)
$F'(\phi) = \frac{\frac{2}{\phi}+\frac{1}{\phi^2}}{(1+\phi+\frac{1}{\phi})^2}$	Zhang	Zhang (2009)

Table 4. Mathematical form of $F'(\phi)$. Where ϕ refers to the aridity index and $F(\phi)$ is a mathematical function relating the runoff ratio to precipitation (or PET) to the aridity index

as in Niemann and Eltahir (2005); Yang and Yang (2011)(See Table 4). In the present work, we compare the results from different empirical relationships. The long term change in precipitation is estimated through RCMs (Regional climate model simulations), and the long term change of potential evapotranspiration is derived from Penmann-Monteith equation (Monteith et al. (1965)) and using RCMs simulations results. This method is preferred rather than Thornthwaite equation (Thornthwaite and Mather (1957)) equation for the reasons described in Yang et al. (2017).

The second approach used here is to evaluate the changes of runoff as a result to climate change through data analysis. The sensitivity of runoff to climate change is computed through the runoff elasticity coefficient. First we use the definition given by Yang and Yang (2011) and references therein. The Runoff Elasticity ($\epsilon(Q)$) is defined as the fractional change in runoff (Q) due to a fractional change in precipitation (P) as shown in the following equation:

$$\epsilon(Q) = \frac{\partial Q}{\partial P} \cdot \frac{\overline{P}}{\overline{Q}} \tag{3}$$

In the present case the estimation is done with the following parameters: $\overline{P}$ is the annual mean precipitation, $\overline{Q}$ is the annual mean runoff and $\frac{\partial Q}{\partial P}$ is estimated using linear regression.

3.4 Presentation of study areas

3.4.1 Loukkos

Loukkos watershed is one of the wettest regions in Morocco. The annual precipitation there is around $790\ mm$ and the hydrological regime is characterized by a wet winter and a dry summer with a maximum of precipitation during November and/or December (see Figure 6(a)). However, precipitation there varies significantly from year to year. The annual precipitation could reach $1400\ mm$ in some years (See Figure 6(b)). Indeed, the coefficient of variation of annual precipitation computed using the ABH Loukkos data is 28%. Given this variability, water resources management is a challenging task.
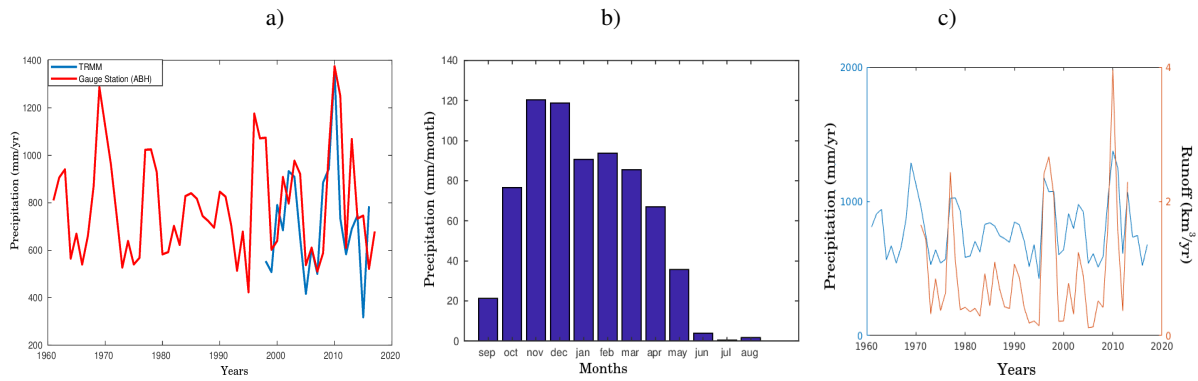
a)   b)   c)

Figure 6. The Hydrology of Loukkos watershed. a) Inter-annual variability of precipitation and comparison with TRMM. b) Monthly variability of precipitation. c) Annual precipitation vs annual runoff.

The strong inter-annual variability of precipitation leads to a strong inter-annual variability in runoff (see Figure 6 c)). The pattern of runoff is similar to those of precipitation. The annual mean runoff is $1\ km^3/yr$. Given its topography, this watershed represents a good site for Morocco to store water. However, this region lacks the infrastructure needed to store water and to optimize water resources management.

3.4.2   Oued Laou

The watershed of Oued Laou is the smallest one considered in this analysis. However due to its geographical position, the region receives a large amount of precipitation compared to the other areas in the country. The annual mean precipitation is about $740\ mm$ which represents a large quantity of water falling on the relatively small area of the watershed ($919\ km^2$). However, the variability of precipitation is tremendous as the coefficient of variation is 43% (see Figure 7), which makes the forecasting of water availability very difficult. The plot in Figure 7 c) presents the variability of the runoff and precipitation over Oued Laou. The variability of runoff seems to follow that of precipitation. The annual mean runoff in Oued Laou is $0.4\ km^3$.

3.4.3   Mjara

The hydrology in Mjara is also characterized by a significant monthly variability. The annual mean precipitation is $655\ mm$, and the coefficient of variation is about 43%. Thanks to gauge station at Mjara, we were able to estimate runoff. As seen in Figure 8 c), the variability of water availability at Mjara follows the variability of precipitation. This statement is especially remarkable during the drought years, that Morocco has experienced during the 1990s, when the variability of runoff has followed very tightly that of precipitation. All in all, the annual average of runoff from Mjara, considered as the wettest region in Morocco and where the largest (namely *AlWahda*) dam of the country is located, is $3\ km^3/yr$.
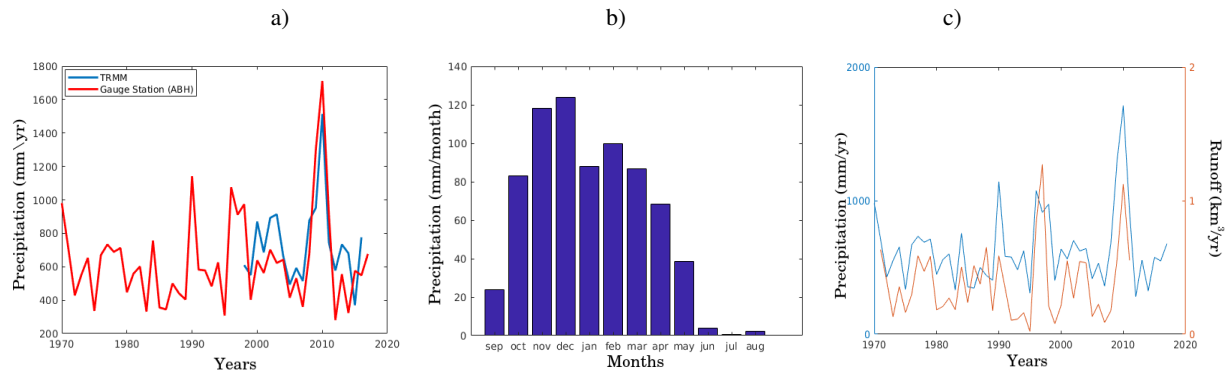
Figure 7. The Hydrology of Oued Laou watershed. a) Inter-annual variability of precipitation and comparison with TRMM. b) Monthly variability of precipitation. c) Annual precipitation vs annual runoff.

Figure 8. The Hydrology of Mjara watershed. a) Inter-annual variability of precipitation and comparison with TRMM. b) Monthly variability of precipitation. c) Annual precipitation vs annual runoff.
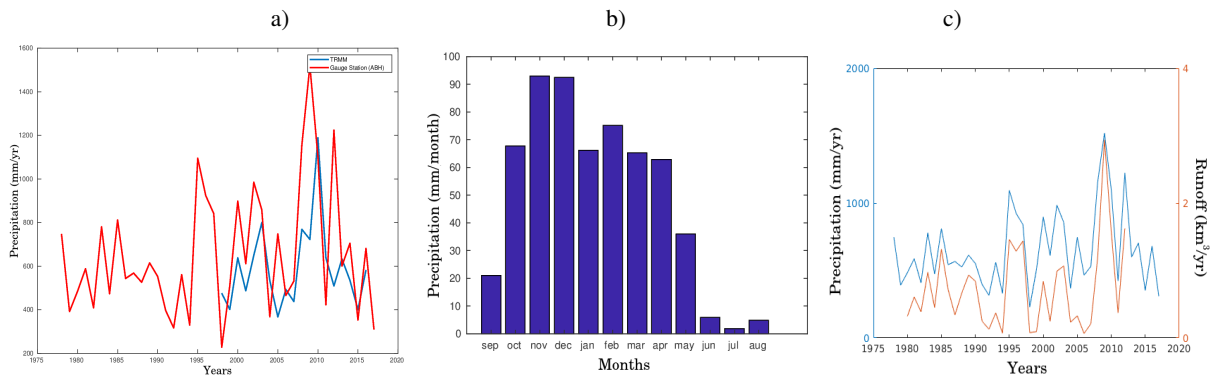
4   Results

4.1   Future changes in precipitation

In order to assess climate change impact on water availability, we have performed numerical simulations (Kang et al. (2019)) as described in section 3.2. Overall, the resulting simulations forced by the 5 GCMs agree that precipitation will decrease in the future for the region of interest. However depending on the boundary condition and on the scenario considered, the magnitude of the decrease is different. All of these results are summarized in Table 5. There is a large uncertainty about the amount of precipitation in the future for the study region. As it was shown in earlier studies (Déqué et al. (2007)) the greater source of uncertainties in RCMs simulation remains to be boundary condition forcing. This would explain the difference in results in our case when we change the forcing GCMs, even for the same scenario. However, for one fixed boundary conditions and for the

		Oued Laou	Mjara	Loukkos
MPI	RCP4.5	-16%	-17 %	-19%
	RCP 8.5	-32 %	-34%	-33%
GFDL	RCP4.5	-27%	-28 %	-27%
	RCP 8.5	-40 %	-44%	-43%
IPSL	RCP4.5	-36%	-31 %	-36%
	RCP 8.5	-69 %	-71%	-69%
CSM	RCP4.5	-16%	-0.5 %	-11%
	RCP 8.5	-36 %	-37%	-36%
ACCESS	RCP 4.5	-34%	-36 %	-36%
	RCP 8.5	-50 %	-54%	-52%

Table 5. A summary of the potential changes in precipitation following the $RCP4.5$ and $RCP8.5$ simulations with MRCM for the 5 different GCMs forcing.

same scenario, the amount of precipitation decrease is similar over the three watersheds. Following RCP 4.5, the minimum of the decrease is simulated when the forcing GCMs is CCSM, the estimated amount of change is roughly around -10%. The maximum of the decrease is simulated when the model is forced with ACCESS, and the amount is roughly equal to -35%. As a result, following RCP 4.5, the projected quantity of precipitation change is between -35% and -10% for this region. On the other hand following RCP 8.5, the minimum of the decrease is achieved when the boundary conditions are described by MPI and is roughly equal to -33%, however the maximum of the decrease is simulated when the RCM is forced by IPSL, and is estimated to be around -70%. As a result, if the future is driven by the scenario RCP 8.5, the precipitation are expected to decrease by 33% in the best case and by 70% in the worst case. On average, following RCP 4.5 precipitation is going to decrease by 24%, while under the scenario RCP 8.5 the decrease would achieve 47%. To sum up, precipitation is likely going to decrease in the future for this region, however the magnitude of the decrease is uncertain. The range of uncertainty has been quantified.

These simulations results concur reasonably well with different others studies (Patricola and Cook (2010); Droogers et al. (2012); Marchane et al. (2017)). For example, Tramblay et al. (2018) adopted a multi-model simulations strategy using different RCMs with high resolution (12km) to assess climate change impact on water resources in the Maghreb region. Simulations converge towards a decrease in precipitation over Morocco, however the amount of the decrease is subject to similar uncertainty demonstrated in our simulations. The decrease of precipitation is generally manifested by a decrease of rainy days and the intensity of precipitation (Tramblay et al. (2013)). Nonetheless the occurrence of heavy rains events is identified as the main uncertain object (Filahi et al. (2017)).

	Oued Laou	Mjara	Loukkos
Elasticity	1.65	1.6	1.7
Range of Uncertainty in Elasticity	[1.12 2]	[1.4 1.8]	[1.3 1.8]
Turc Pike	1.8	1.6	1.6
Ol'Dekoop	1.6	1.4	1.4
Zhang	1.9	1.7	1.7
Schreiber	1.8	1.6	1.6

Table 6. Elasticity of runoff to precipitation estimation with uncertainty quantification compared with analytical formulas given in Table 4.

4.2 Future changes in Runoff

4.2.1 Using data analysis

The first approach used here to assess climate change impact on water availability is the estimation of runoff elasticity coef-
25 ficient through analysis of available data. We follow the definition described in section 3.3. The objective is to estimate the potential loss of water that would result from the decrease of precipitation using available precipitation and runoff data over each watershed. We assume that the relationship between precipitation and runoff is well represented by past data. This relationship is first described by the slope of the runoff-precipitation relationship as documented in observations (see Figure 9). Then we normalize this relationship by dividing with the ratio of long-term runoff to long-term precipitation.

30 For the specific case of Oued Laou, only one precipitation gauge station is present. In order to alleviate bias creation in the calculation of the elasticity coefficient, we use TRMM observations. Figure 9 shows the estimation of runoff elasticity coefficient for the study region. The three watersheds seem to behave in the same manner when forced by precipitation variability. In general, the elasticity coefficient is around 1.6 which means that a change of 10% in precipitation would lead to 16% change in runoff. When using linear regression, the uncertainty range could be quantified. In the present case, a confidence range was added to the elasticity value as presented in Table 6. The uncertainty range is large for the case of Oued Laou. This is due to the complex topography of this very small watershed. Mjara and Loukkos have the same range of uncertainty.
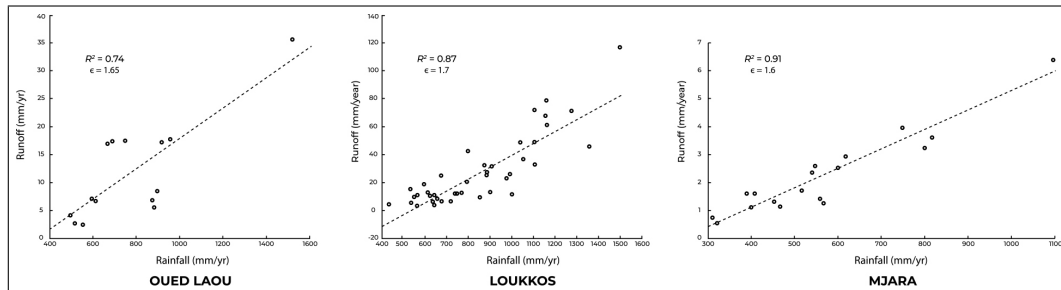

Figure 9. Elasticity coefficient estimation for the three watersheds with regression method

		Oued Laou (km^3/yr)	Mjara (km^3/yr)	Loukkos (km^3/yr)	Available water (km^3/yr)	$\frac{\text{Project}}{\text{Total}}$ (%)	Range of Uncertainty
	Present	0.4	3	1	4.4	20 %	
MPI	RCP45	0.3	2.2	0.68	3.18	27%	[25% 28%]
MPI	RCP85	0.19	1.4	0.44	2.33	42%	[35% 50%]
GFDL	RCP45	0.22	1.4	0.5	2.12	40%	[31% 40%]
GFDL	RCP85	0.14	0.81	0.27	1.22	70%	[47% 92%]
IPSL	RCP45	0.16	1.47	0.39	2.02	43%	[34% 48%]
IPSL	RCP85	0	0	0	0	-	-
CSM	RCP45	0.3	2.76	0.82	3.88	22%	[20% 22%]
CSM	RCP85	0.16	1.23	0.39	1.78	48%	[38% 59%]
ACCESS	RCP45	0.17	1.26	0.39	1.82	47%	[38% 56%]
ACCESS	RCP85	0.07	0.42	0.12	0.62	139%	[70% 140%]

Table 7. A summary of the expected loss of water in the three watersheds, and how the project will affect water availability. We are assuming the project design of transferring $0.86 km^3/yr$. The available water is referring to how much water is available in the whole study region. $\left(\frac{\text{Project}}{\text{Total}}\right)$ is the ratio of the amount of water to be allocated for the project, if kept as in the original design, over the potential total available water in the study region following each simulation. Based on the uncertainty range given by the regression in the estimation we could quantify the uncertainty in our results as presented in the last column

Based on the calculation of runoff elasticity coefficients and given the projected decrease of precipitation described in the previous section, we are able to estimate the potential total available water in the three watersheds in the future. Table 7 summarizes the results. As a metric of the vulnerability of water availability in the region to the project, we show the ratio of the total amount of water to be transferred ($0.86\ km^3/yr$) to the total available water. In the current climate, about 20% of the total available water is allocated for the the *Water Highway* in the initial design. On average, following the projection RCP 4.5 it is expected that only 40% of the actual available water would be lost in the future compared to the current climate. As a result 33% of the available water will be allocated for the project if the design is kept the same as in the current climate.

Based on the latest reports of the Moroccan High Commission for Planning (http://www.hcp.ma/), a 27% increase of demography along with an agricultural intensification, which has already lead to seriously increase water consumption (Molle and Tanouti (2017)), is expected. As a result and following the actual policies water demand will increase by 25%.

Consequently, the project will probably turn the region into a water-scarcity one. Given this analysis and to ensure that the project does not impact the region negatively, the amount of the transfer should be rescaled down. On the other hand, following RCP 8.5 only 27% of actual quantity of water is expected to be left in the region, meaning that the total available water in the region would be $1.19 km^3/yr$. If the project is kept as in the initial design, $72\%(=\frac{0.86}{1.19})$ of the total available water in the region will be transferred. Given this result, the project becomes infeasible, as the local precipitation would probably be short

	Oued Laou		Mjara		Loukkos	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
β	0.8		0.6		0.6	
$\frac{\Delta P}{P}$	-25%	-45%	-22%	-48%	-26%	-47%
$\frac{\Delta E_0}{E_0}$	11%	22%	11%	25%	10%	21%
$\epsilon\frac{\Delta P}{P}$	-45%	-81%	-35%	-77%	-42%	-75%
$\epsilon_{PET}\frac{\Delta E_0}{E_0}$	9%	18%	7%	11%	6%	13%
$\frac{\Delta Q}{Q}$	-54%	-99%	-42%	-92%	-48%	-88%
Future available water (km^3/yr)	0.18	0.04	1.74	0.24	0.52	0.12

Table 8. Summary of runoff sensitivity to precipitation and PET under climate change using the mean of the multimodel simulations and the estimation of future total available water in the region

of satisfying the local water demand.
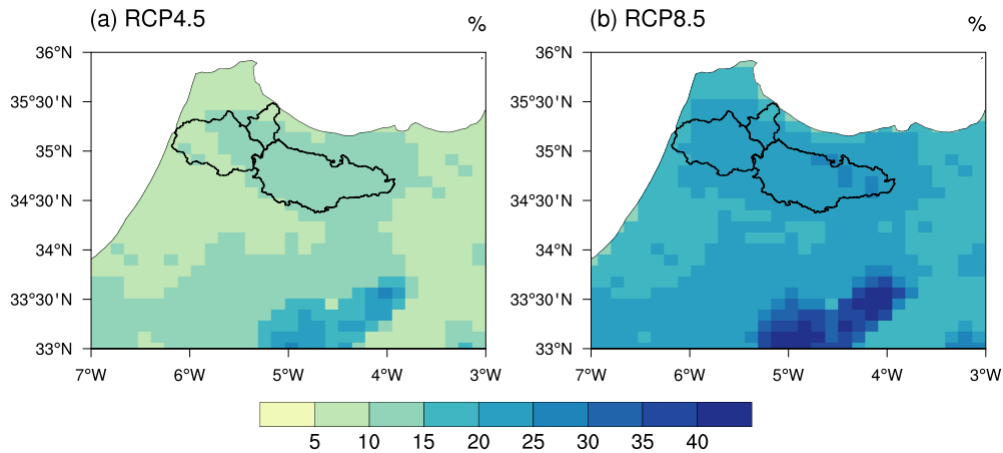
4.2.2 Using empirical formulas and RCMs

Figure 10. Future changes in PET computed using Penmann-Monteith equation and RCMs following RCP 4.5 (a) and RCP 8.5 (b) respectively. The three watersheds of interest are contoured

As described in section 3.3, we consider here the effect of climate change on runoff. First ϵ and ϵ_{PET} are estimated using empirical formulas according to Table 4. Table 8 reports the values of ϵ and the comparison with the corresponding ones from regression analysis, we remind that $\epsilon_{PET} = 1 - \epsilon$. These results are similar to previous conclusions on sensitivity changes in runoff in arid and semi-arid areas (Sankarasubramanian and Vogel (2003)). Moreover as we compare the results of data analysis with the empirical equations (see Table 6), the results are similar. The sensitivity of runoff to precipitation is around 1.6. In

the work of Tang and Lettenmaier (2012), the authors estimate runoff sensitivity to changes in precipitation for the major global rivers in the world. We found a good agreement between their results for this particular region and ours. According to the results reported in Table 8, change in runoff is largely sensitive to precipitation. If we compute the sensitivity index of precipitation changes S_P according to the index defined by Saltelli (2002), we find $S_P = \frac{\epsilon^2}{\epsilon^2 + \epsilon_{PET}^2} = 0.88$. Meaning that 88%

15 of the changes in runoff due to climate change are attributed to changes in precipitation. Ultimately changes in PET contribute only to 12% changes of runoff.

Following Eq.(1) and in order to fully evaluate changes of runoff due to climate change, an assessment of changes of PET is needed, as the changes of precipitation has already been discussed in previous section. Using Penmann-Monteith equation and RCMs results, we plot figure 10, where we show changes in PET according to RCP 4.5 and RCP 8.5 respectively. The

5 watersheds of interest are contoured in black in the map. Following RCP 4.5, PET is going to increase by 11% on average, whereas the increase will achieve 22% following RCP 8.5. All those results are summarized in Table 8.

Based on this analysis, we are able to say that future water availability is very likely to decrease in the region. This decrease is mainly explained by the two factors that are described in Eq.(2):

1. Precipitation which is the main water supplier in the region will likely decrease significantly.

2. The increase of PET will lead to increase in the loss of available water by evapotranspiration due to the presence of significant energy at the surface, described by the increase of temperature in the simulations.

As a result we are able to quantify the future potential changes of available water in the region as reported in Table 8. Following RCP 4.5, the study area will likely lose 44% of its actual available water, meaning that the region will have only 2.44 km^3/yr

5 for supply. Therefore and given the actual scale of the project 35% of the total available water will be transferred. Following RCP 8.5, the region is very likely to suffer water scarcity, as the supply reduces dramatically.

In this study, due to lack of data we were not able to perform hydrological modeling. In their report, RICCAR [RICCAR (2017)] were able to assess the vulnerability of water resources in the whole arab region to climate change. As a matter of fact, they used RCMs results to force two hydrological models (VIC and HYPE) to assess changes in runoff over all the Arab

10 region. Their conclusion for Moroccan highlands, where the sensitivity of runoff to other parameters like vegetation have been taken into account, are similar with the findings of our research: All the coupled climate-hydrological models simulations agree that the region is subject to a decrease in runoff due to a decrease in precipitation and an increase in temperature. Moreover, under RCP 4.5, the decrease of runoff in the region ranges in $[-40\%, -20\%]$, and in $[-60\%, -50\%]$ under RCP 8.5. The main differences with our study come from the fact that the hydrological modelling was performed over a global scale.

15 ### 4.2.3 Feasability of the *Water Highway* project

Based on the previous analysis, we are able to address the problem of viability of the *Water Highway* project. The project aims to transfer 0.86 km^3/yr from the northern watersheds considered in this analysis (Oued Laou, Loukkos and Mjara) to the southern regions. The numerical simulations have proven that the donor watersheds are going to lose significant amount of precipitation due to global warming, therefore water availability would also decrease. Following RCP 4.5, the results based
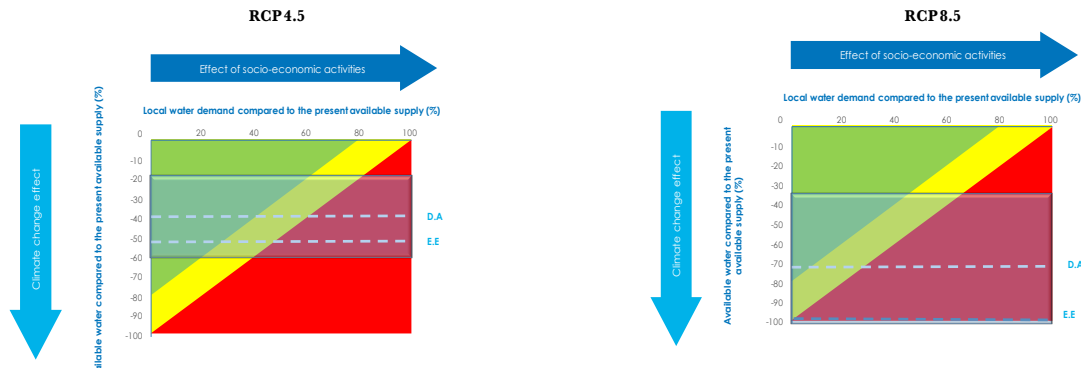
Figure 11. Mapping of vulnerability function of local water demand and supply following RCP4.5 scenario(left) and RCP8.5 scenario (right). The green region is where the project is feasible, the yellow where it should be rescaled and the red where it cannot be feasible.The shadowed regions represent the uncertainty levels. D.A: Data analysis, E.E: Empirical equations.

20   on estimation of runoff elasticity from data analysis shows that the expected (average from the different simulations) amount of loss is 40%, while the second study based on the empirical equations shows that the decrease could reach 44%. As the uncertainty has also been quantified, the best case scenario given by Table 8 is achieved when the project takes only 20% of the total available water. In that case the only limiting factor will be the local water demand. This is mainly why the feasibility of such project should be done in a phased manner. Alternatively the worst case scenario show that the project is willing to

5   take 56%. In that case, there is a clear necessity to scale the project. On the other hand and following RCP 8.5 the first analysis forecasts 73% of loss while the second shows that the region would suffer from severe water scarcity with little water available in rivers. Furthermore, in this case the uncertainty related to analysis is considerably large. Indeed, the confidence level of the ratio of the expected water allocation for this project to the total available water in the region ranges from 35% to 100%. This is more reason to advocatea phased implementation.

10   To make things worse, climate change is not the only limiting factor in the region. The northern part of Morocco has known lately an intensification of water demanding activities, like agriculture. Therefore, the feasibility of the project depends also on the amount of water allocated to satisfy the local demand. Figure 11 maps the regions where the project could be feasible (green), need to be rescaled (yellow) or not feasible at all (red), according to an assumed level of water demand (computed on the basis of the present available water) and the supply given by each scenario and each method used to estimate water

15   availability. While the vertical axis corresponds to the stress caused by climate change, the horizontal axis shows how the socio-economic activities will affect the feasibility of the project. The horizontal line of the figure, corresponding to zero in the vertical axis, represents the present state. Under current climate the design of *Water Highway* requires allocation of 20% of the total available water ($\frac{0.86}{4.4}$). That leaves 80% of the available water to satisfy local water demand. We plot also lines corresponding to the projected water quantities that are going to be lost following RCP 4.5 and RCP 8.5 respectively.

20   Following the mitigation projection, the northern regions are going to lose 40% (based on data analysis study) and 44% (based

on the second analysis) of the actual water quantities. This means that if the project is kept as in the initial design of the current available water of $4.4\ km^3/yr$, the water demand in the region should not exceed 45% ($20\% + 45\% + 35\% = 100\%$) of the present available water. On the other hand, if the future is driven by business-as-usual projection, the project is unlikely to be feasible as the supply would definitely not be sufficient to satisfy local demand. Little water is likely to flow in streams (more than 90% of the total actual available water will likely be lost).

5   Conclusions

The North-South Water Transfer project (*Water Highway*) in Morocco aims to supply the vulnerable regions in the south with water. The project will benefit from the excess water in the northern regions to transfer $0.86\ km^3$ each year. This water transfer will follow three phases, and it will include the building of two dams, several pumping stations and $500\ km$ of pipes from the northern region southward until Al Massira dam. The project will contribute to alleviate water stress in the south, especially supporting the sustainability of agriculture. However despite of its great potential positive impacts, the project is largely sensitive to the amount of water that will be available in the future. Therefore, its feasibility remains unclear given climate change, which is going to affect precipitation over Morocco in general. Regional climate models (RCMs) agree in predicting that the future will bring less water. However, there is a significant uncertainty about the quantity of water that will be lost. There are several reasons behind this uncertainty in the simulations results. Boundary conditions given by GCMs (Global circulation models) are the main contributors to this uncertainty. Furthermore, the future simulations are also driven by different scenarios of greenhouse gas emissions, which lead to different climate projections. In the present study, we have used two projections: RCP 4.5 (with mitigation) and RCP 8.5 (business as usual). Following each of the aforementioned scenarios, the precipitation will decrease in the northern water basins. Following RCP 4.5 the amount of the decrease is expected to be in the range $[-33\%, -10\%]$. In comparison, following RCP 8.5 the amount of the decrease is expected to be in the range $[-70\%, -34\%]$.

In order to assess the water quantities that will be lost, we used two different approaches: data analysis and sensitivity analysis using empirical equations. In the first approach, we have computed the runoff elasticity coefficients based on field observations. Overall this analysis shows that a 10% change in precipitation will lead to 16% change in runoff. Compared to the results of the expected decrease in precipitation, the elasticity analysis indicates that runoff is going to be even more sensitive to climate change. In the second approach, we assessed the sensitivity of runoff to climate change through different empirical relationships. The conclusions are similar to previous results. We found that changes in runoff are mainly driven by the decrease of precipitation. Furthermore, we estimated the potential amount of loss: following RCP 4.5 runoff is going to decrease by 44%, however under RCP 8.5 a very little amount of water is likely to flow in rivers as more than 90% of the total available water is likely to be lost.

Finally, we have developed a map of vulnerability given each climate simulation and the future local water demand. This analysis have helped to assess the viability of the project based on assumed water demand in the donor watersheds. Under RCP 8.5 the project is likely unfeasible. However under RCP 4.5 a rescaled version of this project may be feasible depending on

how much is assumed for the local water demand. Our results agree in general with the conclusions of Greve et al. (2018) who discussed the issue with the global scale. Given all the uncertainties introduced by climate change and reported in this study, water transfer project as an example of water resources planning needs to be carried out carefully and implemented in a phased manner.

25 Based on this work, there are several questions that still need to be addressed. First, given the large uncertainties in the climate model simulation results and the climate scenarios, further research is needed to assess this uncertainty. Second, given the complex hydrological behaviour of the watersheds, there is a need to perform hydrological modelling in order to assess more accurately how climate change will affect the runoff. Finally, in order to address a global critical analysis of the feasibility of the project, the future local water demand driven by the expected population growth and the future water demanding activities

30 should be quantified.

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