Climate change and water resources management of Oran region
Rachid Bouklia-Hassane, Djilali Yebdri and Abdellatif El-Bari Tidjani

ABSTRACT

Our work aims to contribute to the literature on the prospective study of the water balance in the Oran region, a major southern Mediterranean metropolis, by considering the socioeconomic dimension of this region and the dynamic of its climate change through 2011–2030. These two dimensions are important for the analysis of future changes in water stress in the region because they affect both the demand and the supply of the water resources. Unlike other studies, our methodological approach is based on an explicit modeling of the socioeconomic evolution in the region as well as of the dynamic of climate change. For this, we used a time-series modeling framework to predict the effects of change in climate. In addition to the assessment of the effects of the socioeconomic and climate changes on the water balance of the region. Our results, based on simulations using the Water Evaluation and Planning (WEAP) software, show that the current decoupling between the drinking sector from that of irrigation in the Oran region is not sustainable. Climate change will exacerbate this vulnerability. Only by integrating these two sectors, through a reuse of wastewater, can we consider the irrigation issue from a perspective of long-term sustainability in the region.

Key words | climate change simulations, hydrological modeling, integrated water resources management, Oran province, time-series processes, WEAP model

INTRODUCTION

Water is viewed as an increasingly scarce resource. One of the principles of the so-called ‘Dublin Statement’, adopted for several years already, stipulates that water is a finite and vulnerable resource that is essential to life, development, and the environment. More recently, climate models showed that global warming has the potential to put more pressure on the availability of water by affecting the amount and pattern of precipitation and the frequency of extreme hydrological events, such as floods and droughts (Parry et al. 2007).

The water scarcity induced by climate change is not distributed evenly throughout the world. More adverse effects are experienced in arid regions or in developing countries that lack the technologies and infrastructure needed for the mobilization of water resources. By 2020, between 75 and 250 million people are projected to be exposed to increased water stress due to climate change in Africa (Pachauri & Reisinger 2007). Following Arnell (2004), under the climate scenario B1, the population at risk of increased water stress in North Africa is projected to be nearly 48 million people by 2025. In the same vein, Tubiello & Fischer (2007) stated that: ‘A consensus has emerged that developing countries are more vulnerable to climate change than developed countries, because of the predominance of agriculture in their economies, the scarcity of capital for adaptation measures, their warmer baseline climates, and their heightened exposure to extreme events.’

As a framework for planning, organizing, and operating water systems, integrated management of a hydrosystem is a response to these challenges that can contribute to the
reduction of the gap between the limited availability of water and the growing demand from the various economic and public sectors (Yebdri 2007; Yebdri et al. 2007; Grigg 2008).

The region of Oran, the second province in Algeria, is affected greatly by this issue for several reasons. First, the expansion of its population, its developmental challenges, and the low density of its hydrographic network lead to an increasing gap between the rapid evolution of water demand and the low potential of this region for the mobilization of conventional water resources. Second, the current water system in the region is characterized by a suboptimal mobilization of water resources due to the decoupling of irrigation from the rest of the hydraulics sector. Finally, climate change will put additional pressure on the water demand and the water availability in this region and will probably exacerbate the stress on the water system.

Despite this vulnerability, few studies have been devoted to the capacity of this region to continue satisfying the water needs of the various users. Notable exceptions are Abed et al. (2011) and Hamlat et al. (2013). The first authors simulated four global circulation models (GCM) developed by the CIRCE group (Climate Change and Impact Research: the Mediterranean Environment) under the A1B scenario of the Intergovernmental Panel on Climate Change to study the impact of climate change on various indicators, such as annual runoff, level of human thermal comfort, or wheat yield in the Gulf of Oran. However, the low spatial resolution of the models used, which range between 2° and 3°, makes their outputs unrepresentative of the local dynamics of climate change in the study area. The second authors analyzed the gap between the water demand and the limited availability of this resource in western Algerian watersheds under different water management options and climate change scenarios. Nonetheless, these scenarios do not rely on an explicit modeling of climate change forecast, so they appear, to some extent, as an ad hoc construction.

Our work aims to contribute to the literature on the prospective study of the water balance in the Oran region by taking into account, in a unified framework, the socioeconomic dimension of this region (population growth, rapid urbanization, standard of living, etc.) as well as the dynamic of its climate change using a large set of consistent scenarios. These two dimensions are important for the analysis of the future changes in water stress in the region because they affect both the demand and the supply of water resources.

Unlike other studies on hydrological perspectives in the region of Oran, our methodological approach is based on an explicit modeling of local climate change in order to predict its impact on the demand and the supply of water resources in the region. For this propose, we used an autoregressive integrated moving average (ARIMA) modeling framework whose forecast is based on the temporal correlation of the hydrologic time-series. In addition, unlike some other methods such as the statistical downscaling, this framework has the advantage of directly accounting for the local climatic characteristics of the region.

In addition to the assessment of the effects of climate change and socioeconomic conditions on the water balance of the region, which may support local planning, our results show that the current decoupling between the drinking sector and that of irrigation in the Oran region is not sustainable. Only by integrating these two sectors, through a reuse of wastewater, can we consider the irrigation issue from a long-term perspective in the Oran region.

We begin this work by briefly presenting the study area in the first section. Relying on the study of Boukila-Hassane et al. (2014), the second section analyzes the effect of demographic growth and other socioeconomic variables on future water resources stress under the assumption of a stationary climate (SC) environment. We first analyze the prospects of water needs of the whole sector, outside of agriculture, and the capacity of the hydrological system to satisfy those needs. Second, we introduce the agriculture sector with a simple modeling of the hydrological processes in the Water Evaluation and Planning (WEAP) environment (Yates et al. 2005) and examine the expected long-run evolution of irrigation demand and the sustainability of groundwater withdrawals in the region, under different scenarios.

In the third section, we relax the assumption of SC variables. We track the impacts of climate change on water availability through two channels: on the demand side, temperature changes affect the potential evapotranspiration (PET), and on the supply side, precipitation changes affect soil moisture supply and runoff. We show that the temperature and precipitation changes have cumulative adverse effects and exacerbate pressure on the availability of water resources in the region.
The fourth section provides, in the context of climate change, a scenario of integration of the agricultural sector to the rest of the – currently decoupled – water system through a reuse of wastewater. We show that this perspective is a response to the growing water scarcity in the region. We re-examine the results of Bouklia-Hassane et al. (2014) in the context of climate change and evaluate the potential gain in terms of extension of irrigated areas allowed by this scenario.

STUDY AREA

The province (wilaya) of Oran covers an area of more than 2,100 km² and is located in northwest Algeria. It is one of the largest metropolises in the Maghreb.

According to SOFRECO (2010), Oran region covers three sub-watersheds belonging to the Coastal Oranais basin (Côtier Oranais): the Coastal Ain Turk located to the west and on the north side of the Murdjadjo mountain; the Sebkha of Oran; and the Saline of Arzew in the northeast portion of the region.

The Oran region includes four large hydrogeological units:

- the groundwater of the Coastal plain of Ain-Turk (Ain Turck groundwater code: 31_4_1);
- the groundwater of Bredeah plain (Bredeah groundwater code: 31_4_2), bordering Sebkha of Oran, which extends to the eastern part of M’Leta plain (Tafraoui, Oued Tlelat);
- the groundwater of Murdjadjo (Murdjadjo groundwater code 31_3_1), which includes Murdjadjo Mountain and its geological extension to the east;
- the groundwater of Arbal (Tafraoui groundwater code 31_2_2) located in the Sebkha sub-watershed in the south of Bredeah groundwater (Figure 1).

Oran is characterized by a weakly developed hydrographic network which does not favor the development of large hydraulic installations. Coupled with an adverse impact of climate change in the region, this marginal mobilization of the surface runoff resources makes the hydrological system of this region particularly vulnerable, and forces, to a large extent, the recourse to resources from outside the region to supply water to the various sites of demand.

THE PROSPECTS OF ORAN WATER SYSTEM IN A STATIONARY CLIMATE ENVIRONMENT

The freshwater sector

The model

We use the modeling framework of Bouklia-Hassane et al. (2014) to highlight the future constraints on satisfying
water needs other than irrigation in the region. This model, which formalizes the regional water policy, aims to describe the repartition of domestic water between the three types of users: households, public sector providing utilities, and industry. We calibrate the model in order to reproduce the data of 2011 which we consider as the base year.

The total household water needs $B_{hh}$ depend in this model on the size of population $N$ and the per capita water needs $Bunit_{hh}$. We assume that the household water needs unit relates to the ratio of house occupation (RHO) and the standard of living (SL) (Equation (1)). In view of the lack of accurate information, it is assumed that the public sector water demand $B_{ps}$ is proportional to that of household (Equation (2)), whereas the total water needs of the industrial sector $Bunit_{ind}$ depend on the size of industrial activities $Ind$ and the unit water demand of this sector $Bunit_{ind}$ (Equation (3)). The sum of production and external transfers of water is $X_{tot}$, so that the covered demand is the minimum of the notional demand and the production of water adjusted for water losses by a rate of efficiency $tx_{eff}$ (Equation (5)):

$$B_{hh} = N \cdot Bunit_{hh}(RHO, SL)$$  \hspace{1cm} (1)  

$$B_{ps} = \alpha \cdot B_{hh}$$  \hspace{1cm} (2)  

$$B_{ind} = Ind \cdot Bunit_{ind}$$  \hspace{1cm} (3)  

$$D_{tot} = B_{hh} + B_{ps} + B_{ind}$$  \hspace{1cm} (4)  

$$\text{Covered demand} = \min(X_{tot} \cdot tx_{eff}, D_{tot})$$  \hspace{1cm} (5)  

$$X_{tot} = \text{exogenous}$$

The proportion of public sector demand $\alpha$ is set at 20% and the efficiency rate of the distribution network $tx_{eff}$ at 70% according to interviews with officials of the region’s Hydraulic Department. Model calibration – to replicate the data of the base year (2011) – was achieved with $Bunit_{hh} = 143.4$ liters per person and per day and $Bunit_{ind} = 12.3$ m$^3$ per hectare and per day for the industrial sector.

**Model simulations**

Beside the baseline scenario which is a continuation of the trend of population and industrial activity observed during the previous period, simulation of an alternative integrated scenario was realized, involving three key developments (Boukilia-Hassane et al. 2014).

**Water demand:** Per capita demand for water $Bunit_{hh}(LS, RHO)$ may be related to the standard of living $LS$ – proxied by income per capita – and, due to the economy of scale in water use, to the housing occupancy rate $RHO$ (Arbués et al. 2005). Differentiation leads to:

$$\frac{dBunit_{hh}}{Bunit_{hh}} = e_{LS}\left(\frac{dLS}{LS}\right) + e_{RHO}\left(\frac{dRHO}{RHO}\right)$$

where $e_{LS}$ and $e_{RHO}$ are, respectively, the standard of living and house occupation elasticities of water demand unit. These parameters have been fixed to 0.3 (Dalhuisen et al. 2001) and –0.6. The progress of standard living $dLS/LS$ may be estimated at 2.1% over the forecast period which is the rate of the per capita income observed at the national level between 2000 and 2009, and that of the size of household $dRHO/RHO$ at –2% (Ministry of Housing 2009). These two factors lead to an increase of unit water demand at an average rate of 1.8% annually throughout the forecast horizon. This growth rate can be broken down into a contribution of 0.3%2.1% = 0.6% per year related to the improvement of standard living and (–0.6)% (–2%) = 1.2% per year related to the reduction in the size of households.

For the industrial sector, the water consumption per hectare of the industrial estate is supposed to shift progressively – due to technological changes – from 4,495 m$^3$/hectare in 2011 to 4,000 m$^3$/hectare in 2030.

**Water policy:** In this component of the scenario, we simulate a reduction in the loss of water in transmission links which decreases gradually from 20% in 2011 to 10% in 2030. Furthermore, the rate of recycling wastewater used by the industrial firms increases from 0% of the industrial consumption in 2011 to 20% in 2030.

**Water resources:** The third component for this scenario is the installation of a desalination seawater plant with a capacity to treat 250,000 m$^3$ per day to full throttle and a
wastewater treatment plant (WWTP) with a capacity of treatment by 2030 of 250,000 m³ per day. The progress of the production of these installations follows a logistic curve and the WWTP supplies exclusively to the industrial sector.

Results and discussion

The simulation of the baseline scenario indicates that, in the absence of intervention, the water deficit in 2030 will amount to 54 million m³ per year, from which, 15 million is for households and communities and 39 million m³ is for industry.

The alternative scenario described above incorporates the expected growth of unit water demand and plans a more active management of the water resources as well as a development of new infrastructures. Such a change will allow the region water resources to face, with a coverage of 100%, the increase of water demand of the consumer sectors outside agriculture which will rise to more than 180 million m³ in 2050. Moreover, 65 million m³ of residual water will be treated by the WWTP in 2030.

Nonetheless, as is shown in Figure 2, if the water needs of the various sectors will be met without resorting to the inter-regional transfers between 2014 and 2022, the necessity of the external transfers resumes as from 2023. Thus, and despite the increase of resources of non-conventional water, the Oran region will remain unable to achieve water self-sufficiency.

The agricultural sector

The model

The agricultural sector is currently decoupled from the rest of the water system. As in Bouklia-Hassane et al. (2014), we model the agricultural sector by means of a simple rainfall–runoff model incorporated in the WEAP:

\[ P_{eff} = P_{r} + R_{p} \]  
\[ V_{p} = P_{eff} * S_{r} \]  
\[ ETC_{r} = ETO_{r} * K_{e} * S_{r} \]  
\[ D_{r} = ETC_{r} - V_{p} \]  
\[ Pr_{r} = \frac{D_{r}}{R_{eff,r}} \]  
\[ RunOff = P_{r} * (1 - R_{p}) + (1 - R_{eff,r}) * Pr_{r} \]  
\[ SRunOff = RunOff * S_{run} \]  
\[ Inf = RunOff * (1 - S_{run}) \]

The first bloc of the model describes the water demand side. Equations (6)–(8) determine the demand for water.
evapotranspiration $ET_C$ by means of cultural coefficients $K_C$ (Allen et al. 2003) and the reference evapotranspiration $ET_0$ (Equation (8)). Considering the effective rainfalls $P_{\text{eff}}$, as a proportion $R_{\text{Peff}}$ of the total precipitations $P_t$ (Equation (6)), the model determines the required irrigation $D_t$, i.e., the demand of irrigation that cannot be guaranteed by the effective rainfalls (Equation (9)).

The withdrawals $P_{\text{irr}}$ take into account the irrigation ratio of efficiency $R_{\text{irr}, \text{tr}}$ (Equation (10)).

In these equations, $S_P$ represents the surface of irrigated areas of the catchment and $V_{\text{Peff}}$ the volume of effective rainfall on the irrigated area (Equation (7)).

The second block of the model describes the water production side, i.e., the process of surface runoff and infiltration governing groundwater recharge.

Several simplifications are made. First, soil moisture content affects – in addition to the evapotranspiration process – the partition of the water runoff between surface runoff and infiltration. However, due to lack of data on the characterization of land use and soil type in Oran region, we assume that surface runoff is a given and constant fraction of the total runoff (Equation (12)). Second, we do not distinguish between sub-surface runoff and deep percolation, so that we assume that infiltration goes directly to groundwater storage (Equation (13)).

The effective rainfall rate $R_{\text{Peff}}$ was estimated at 80% according to the SOFRECO (2010), whereas the fraction of surface runoff $R_{\text{SRun}}$ was fixed at 25% based on SOGREAH (2009).

**Model simulations**

Solving the first part of the model for the current account allows estimating the region’s overall need for water irrigation at 33.1 million m$^3$ in 2011. Taking into account effective rainfall and irrigation efficiency, the water demand required for irrigation is then estimated at 23.72 million m$^3$ and is partitioned between 23.35 million m$^3$ of withdrawals from groundwater and 0.38 million m$^3$ from surface resources.

In the baseline scenario, we suppose that the irrigated areas grow steadily at a rate of 3% per annum. Beside this reference scenario, we consider an alternative scenario that is mixed and integrates:

- on the demand side, an improvement of efficiency of the irrigation system which raises the rate of efficiency from 70% in 2011 to 85% in 2030;
- on the production side, the construction of many hillside dams in the region to increase the use of surface runoff for irrigation purposes so that the share of surface resources in Coastal Ain-Turk will increase from the present level of 24% to 50% in 2030, and in the Murdjadjo complex, from 0% to 10%.

**Results and discussion**

In the baseline scenario, the pressure on resources will naturally be higher than in the current period due to the increase of the irrigated areas: the water supply requirement in the agriculture sector will reach 42.85 million m$^3$ in 2030 leading to a rise in the average rate of groundwater exploitation in the region with an overexploitation of Bredeah aquifer.

The introduction of more efficient irrigation methods in the alternative scenario induces a reduction in water withdrawals because of the economy of previous losses. As compared with the baseline scenario, the simulated reduction of water withdrawals will be 7.8 million m$^3$ in 2030. On the other hand, the infrastructural achievement will allow the mobilization of a volume of 1.7 million m$^3$ per annum of water surface runoff, which will reduce pressure on groundwater in the hydrologic units. Thus, the overall exploitation rate of groundwater will decrease but with no significative effect on the overexploitation of Bredeah groundwater.

Whatever their importance, we observe that these volumes are by far inadequate to solve the agricultural irrigation issue in the Oran region despite the supposition of a moderate growth of the agricultural sector. The mobilization of water from surface runoff alone cannot be a long-term solution to reduce the overexploitation of certain aquifers.

**CLIMATE CHANGE IMPACTS**

The results above are established in the absence of climate change. However, Oran is part of the Mediterranean region that is among regions most sensitive to climate change (Karsili 2013). In this context, we ask whether the
potential climate change will reduce or, conversely, exacerbate water deficits predicted by the scenarios examined above. Our approach in this context is to provide in a first step a projection model through a historical time-series analysis of the climate variable in the Oran region. Then, this model will be used in a second step to generate climate change scenarios for a hydrological impact assessment over the study area.

Modeling climate change in an ARIMA framework

Methods of projections of climate variables have taken various orientations. The statistical downscaling methods (SDM) are a declination at the local scale of the GCM to resolve important local features, such as topography, land-use distribution, and land use for local impact studies (Wilby et al. 2007). Other models are those belonging to the ARIMA class models whose forecasts are based on autocorrelation of past values of climatic time-series and of errors terms of the model (Hipel et al. 1977; McLeod et al. 1977).

Each of these modeling frameworks has its own advantages and limits. The SDM has a richer physical basis. However, the adjustment of the model resolution to a spatial scale much finer than that provided by the GCM is naturally the source of errors. Alternatively, modeling based on the autocorrelation of the temporal processes has the disadvantage of explaining the climatic variables’ evolution only by their past values. Nonetheless, unlike downscaling methods, it has the merit of involving variables directly observable at the local level. We have adopted this last projection approach in this work.

Autoregressive integrated moving average models (Box & Jenkins 1976) combine three types of temporal processes: the autoregressive component (AR), the integrated (I), and the moving average component (MA) (Hipel et al. 1977; Desbois 2005).

The ARMA \((p, q)\) representation of a stationary process \(Y_t\) is written in its extensive form as:

\[
Y_t - \theta_1 Y_{t-1} - \cdots - \theta_p Y_{t-p} = \varepsilon_t + \phi_1 \varepsilon_{t-1} + \cdots + \phi_q \varepsilon_{t-q}
\]

Compact writing of these models involves the lag operator \((L, Y_t = Y_{t-1})\) and its power \(L^p\) of order \(p\) \((L^p Y_t = Y_{t-p})\). With these notations, the model above may be rewritten as:

\[
\Theta(L) Y_t = \Phi(L) \varepsilon_t
\]

where \(\Theta(L)\) and \(\Phi(L)\) are two polynomials lag of order \(p\) and \(q\): \(\Theta(L) = 1 - \theta_1 L - \cdots - \theta_p L^p\) and \(\Phi(L) = 1 + \phi_1 L + \cdots + \phi_q L^q\). In the case of non-stationary but integrated process \(Y_t\) of order \(d\) and using the difference operator \(D^d\) of order \(d\) \((D^d Y_t = (1 - L)^d Y_t)\), the ARIMA representation of \(Y_t\) is \(\Theta(D^d Y_t) = \Phi(L) \varepsilon_t\). Thus, ARIMA processes are fully characterized by the three parameters \((p, d, q)\).

These models have been used notably by Momani (2009) in the case of Jordan, by Thabet & Thabet (1995) in reference to Tunisia, and by McLeod et al. (1977) for average annual Saint Lawrence river flows.

The use of non-seasonal ARIMA models is based on a methodology divided into three steps (Box & Jenkins 1976): (i) the specification of the model whose purpose is to identify the parameters \(p, d\) and \(q\) of the ARIMA; (ii) the estimation of the parameters \((\theta_1)\) and \((\phi_j)\) of the model; and (iii) the validation of the model that ensures that residuals of estimation \(\varepsilon_t\) which represent the part of the process not explained by the model actually follows white noise.

This approach is applied to the temperature and precipitation data observed at Es-Senia (Oran) station. The frequency of observations is monthly for temperature – in order to use empirical PET models, which are generally set at a monthly temporal resolution – and annual for precipitation. The observations cover the period from January 1949 to December 2008 for temperatures and 1949–2011 for precipitation.

In a first step, we begin by identifying the order of differencing needed to stationarize the climatic variables (temperature and precipitation).

The regression of temperature data on time reveals the presence of an increasing and significant trend even at the 1% level. On the other hand, precipitation shows a negative trend over the whole period although in the recent period, the trend in precipitation tends to change its sign but without a statistically significant slope.

These results suggest that the two time-series need to be stationarized. Consequently, we differentiate successively:
(a) the yearly precipitation variable to order 1 in order to mitigate the trend effects and (b) the monthly temperature to order 1 then to order 12 to control, respectively, for trend and for seasonality. The observation of the simple autocorrelation correlogram confirms that the two differentiated climatic variables are stationary. We conclude that the yearly precipitation follows an ARIMA process \((p, 1, q)\) and the monthly temperature a seasonal process SARIMA \((p', 1, q') \times (P, 1, Q)_{12}\).

Concerning the model identification, results of several iterations of the sequence identification–estimation–validation support the hypothesis of a mixed adjustment model, specifically an ARIMA \((1, 1, 1)\) for precipitation and a SARIMA \((1, 1, 1) \times (1, 1, 1)_{12}\) for temperature of the Oran region.

Concerning the estimation of the precipitation and temperature models, regression results are presented in Table 1. These results appear to be generally acceptable. The coefficients of the moving average representation (LMA and L.SMA) are significant in both estimations. However, those of the autoregressive component (L.AR and L.SAR) have a weaker degree of significance, in particular the seasonal autoregressive term of temperature (L.SAR).

Finally, as a diagnostic check, we have applied the Bartlett’s periodogram-based test to ensure that the residuals of estimation follow a white noise, i.e., a process from which we cannot extract information useful for the forecast. The evolution of the test statistic inside its upper and lower limits for the two models allows us to accept the white noise hypothesis for the residuals and thus to validate our model specification for both temperature and precipitation.

### Model simulations

#### Climate scenario generation

The results of the model predict an increase in annual temperatures of the order of 0.8°C between the average of 2000–2010 and that of 2020–2030 and a decrease in precipitation of 5.9% for the same periods. However, the evolution of the climatic variables remains uncertain and cannot reasonably be apprehended by point estimates only without taking into account the risk of errors affecting these estimates. The need to incorporate the highly uncertain information about potential climate change leads us to address the issue of the sensitivity of water resource management to climate change through three climate sequences, discussed below.

The first sequence is neutral; it reproduces the point forecasts of climatic variables and, therefore, the average trend of these variables over the forecast horizon.

Two other alternative sequences are considered with the aim to take into account climate uncertainties. They correspond to the upper and lower 80% forecast confidence interval limits and, therefore, reproduce extreme weather events (Figure 3).

The generation of these sequences allows for a multiple-scenario analysis. Seven alternative scenarios of local weather conditions are considered: the neutral one (neutral sequences of temperatures and precipitations); the two extreme scenarios that represent extreme events (warmest and driest corresponding to the hottest temperature and the driest precipitation sequences and coldest and wettest, including the coldest and the wettest hydrological years); and four ‘mid-sequences’ that combine neutral and extreme sequences of the two climate variables (neutral and driest and neutral and wettest and, symmetrically, coldest and neutral and warmest and neutral (WN)). We do not consider the

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**Table 1 | Parameter estimation of the precipitation and temperature models**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Precipitation ARIMA ((1,1,1))</th>
<th>Temperature SARIMA ((1,1,1) \times (1,1,1)_{12})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non seasonal component</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L.AR</td>
<td>(-0.259^*)</td>
<td>(0.246^{***})</td>
</tr>
<tr>
<td></td>
<td>((-1.672))</td>
<td>((6.347))</td>
</tr>
<tr>
<td>L.MA</td>
<td>(-0.816^{***})</td>
<td>(-0.967^{***})</td>
</tr>
<tr>
<td></td>
<td>((-7.108))</td>
<td>((-76.30))</td>
</tr>
<tr>
<td>Seasonal component</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L.SAR</td>
<td>(-0.0386)</td>
<td>(-0.946^{**})</td>
</tr>
<tr>
<td></td>
<td>((-1.003))</td>
<td>((-43.85))</td>
</tr>
<tr>
<td>L.SMA</td>
<td>(-0.946^{**})</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>(-0.0985)</td>
<td>(6.63 \times 10^{-5})</td>
</tr>
<tr>
<td></td>
<td>((-0.540))</td>
<td>((0.455))</td>
</tr>
<tr>
<td>Observations</td>
<td>61</td>
<td>707</td>
</tr>
</tbody>
</table>

z-statistics in parentheses.

***Significant at 1% level; * at 10% level.
wettest and warmest and driest and coldest scenarios for their lack of realism.

**Sensitivity analysis**

We use these generated climate scenarios as input to the hydrological model of the previous section and track the effects of climate change on water availability through two channels:

1. On the demand side, temperature change affects the PET and leads to variations in the water needs. To assess the impact of climate change through this channel, we use the empirical temperature-based model of Thornthwaite (1948). This author relates the monthly $PET_{NA}$ (without adjustment) to temperatures: $PET_{NA} = ct^a$ where $t$ is the monthly mean air temperature. However, the coefficients $c$ and $a$ are climate varying. An annual heat index $I = \sum_{Jan}^{Dec} (t/5)^{1.514}$ was then introduced so that the (unadjusted) $PET_{NA}$ is $16(10t/J)^a$ with $a = 675 \times 10^{-9}t^3 - 771 \times 10^{-7}t^2 + 1792 \times 10^{-5}t + 0.49239$. Finally, the equation was adjusted to account for the specific number of days per month $N$ and average daily sunshine duration $S$, depending on the season and latitude: $PET_{Thorn} (mm/d) = (S/12) + (N/30) \times PET_{NA}$. Annual $PET$ is then expressed as the sum of the 12 monthly $PET$.

This simple method, unlike the Penman PET, requires a number of meteorological parameters that are easily available at climate stations. However, the Thornthwaite approach underestimates PET in dry regions and dry seasons and overestimates it in a wet climatic environment (Mather & Ambroziak 1999; Kafle & Bruins 2003). In the particular case of the semi-arid region of Djelfa in Algeria, after comparing the performance of five methods of calculation of the PET, Bouteldjaoui et al. (2012) confirmed that Thornthwaite’s approach significantly underestimates the PET in this region.

To address this systematic bias in the Thornthwaite estimates, we use the empirical correction factor, depending on precipitations $P$, proposed by Hulme et al. (1992) and adopted by the United Nations Environment Program (UNEP 1997) to adjust the Thornthwaite estimates $PET_{Thorn}$ to agree more closely with standard Penman estimates $PET_{Adj}$:

$$PET_{Adj} = 1.3PET_{Thorn} - 0.428P + 246 \quad (14)$$
Log-differentiation of $PET_{Thorn}$ and simple derivations using notations defined above allow us to express analytically, from Equation (14), the sensitivity $\Phi_t$ and $\Phi_P$ of potential evapotranspiration $PET_{Adj}$ to change in temperatures and precipitation:

$$dPET_{Adj} = \Phi_t dt + \Phi_P dP$$

where:

$$\Phi_t = PET_{Thorn} \left[ \frac{df}{dT} \left( \frac{da}{T} \log \frac{10T}{T} - \frac{a}{T} \right) + \frac{a}{T} \right]$$

(15)

$$\Phi_P = -0.428$$

(16)

(2) On the supply side, precipitation changes affect effective precipitation as well as catchment runoff and, as a result, the natural recharge of the groundwater basins. Differentiating Equations (6), (7), and (11) gives the sensitivity of actual evapotranspiration $\Psi_P$ and runoff $\Theta_P$ to a change $dP$ in precipitations:

$$\Psi_P = \frac{dV_{peff,lr}}{dP} = R_{peff} + S_{lr}$$

$$\Theta_P = \frac{drunoff}{dP} = 1 - R_{peff}$$

Results and discussion

The combination of increased temperature and reduced rainfall would have a significant effect on water resources’ balance of the catchments in the region. As discussed below, by changing the volume of evapotranspiration and, thus, the volume of the irrigation needs, the aridity level of the climate in the region can be altered with an impact on the magnitude of groundwater withdrawals.

Future irrigation water needs

The assessment of the future needs of the agricultural sector is based on Equations (14) and (15) that relate the change in PET to the variations in temperature and precipitation. Figure 4 shows the specific contribution of climate change to the evolution of the water needs in the agricultural sector by comparing PET in the neutral climate change (NCC) scenario relative to the SC.

More generally, climate regimes where temperatures are high are naturally characterized by important water needs. For example, under the warmest and driest scenario, which describes situations of drought, the needs of the agricultural sector (PET) reach 78.3 million m$^3$ by 2030, representing an increase of 13.5 million m$^3$ over the neutral scenario and 18.5 m$^3$ compared to a SC.

This increase in water requirements, coupled with the decline in precipitation, induces a widening demand gap (demand not met by available evapotranspiration) that reaches 40.85 m$^3$ in 2030 in the climatic conditions of the neutral scenario.

The evolution of the specific contribution of climate change to the demand – as the difference between the demand in the considered scenario and in the SC scenario – is shown in Figure 5 for all the climate scenarios. All

Figure 4 | Evolution of PET, neutral change and SC scenarios (baseline).
things being equal, in the neutral regime, climate change contributes to an increase in the demand not satisfied by evapotranspiration of 5.6 million m$^3$ by 2030 relative to the stationary climatic conditions. In the extreme case of the warmest and driest scenario, this contribution reaches a volume of 37.3 million m$^3$.

**Aridity index alteration under climate change**

The volume of annual precipitations $P$ and the magnitude of the water needs (PET) can also be confronted using the aridity (humidity) index $P/PET$ (Thornthwaite 1948). This index is a synthetic indicator that captures the severity of the deficit in the soil moisture supply, when its value is below 1 (Hulme et al. 1992; UNEP 1997; Kafle & Bruins 2009).

Figure 6 presents the historical and projected values of the aridity index in the Oran region; it shows that this index decreases continuously in the neutral scenario. Due to global warming, this ratio approaches the boundary of the arid zone (0.20) in the classification of UNEP. As pointed out by Tsakiris et al. (2007), this more arid climate may lead to an increase in the frequency of droughts and, therefore, notably affect the crop yield in the region.

**Future trends of withdrawal**

In addition to increasing agricultural demand unmet by evapotranspiration, the downward trend in annual rainfall decreases the natural recharge of groundwater basins by affecting the volume of precipitation that percolates from the root-zone into the underlying aquifers. Due to the water resources imbalance, groundwater resources become more constrained.

Table 2 shows the groundwater withdrawal rates needed to achieve the growth rate of 3% of the irrigated agriculture areas with (NCC and WN scenarios) and without (SC scenario) climate change in 2030.

Similar to the SC scenario, the NCC scenario shows a reasonable intensity of exploitation of Ain-Turck Coastal, Murdjadjo Complex, and the Tafraoui groundwater. In contrast, it aggravates the situation of groundwater scarcity in Bredeah, which supplies the two largest municipalities, Misserghine and Boutlelis, by increasing the extraction rate by 20%. The climatic environment simulated by the WN scenario accentuates this imbalance between available groundwater resources and required withdrawals: extraction rates exceed 100% on average in the region as a whole, with a peak of more than 200% for Bredeah groundwater.
Figure 7 shows the extraction rate for all groundwater and all considered scenarios. Except under the wettest climate projections, all the scenarios lead to an estimated extraction rate above 100% in Bredeah. Moreover, under the driest weather environment (Scenarios 2 and 5 in Figure 7), water resources in all groundwater, except Tafraoui, would be overexploited, leading to decreasing groundwater storage in the region as a whole with severe constraints on the extension of the irrigated areas.

Table 2 | Comparison between withdrawals and mobilizable resources in SC, NCC, and WN scenarios (106 m$^3$), 2030

<table>
<thead>
<tr>
<th>Hydrogeologic units</th>
<th>Withdrawals</th>
<th>Mobilizable groundwater resources</th>
<th>Groundwater exploitation rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SC</td>
<td>NCC</td>
<td>WN</td>
</tr>
<tr>
<td>Ain-Turck Coastal</td>
<td>3.971</td>
<td>4.598</td>
<td>5.975</td>
</tr>
<tr>
<td>Bredeah</td>
<td>17.435</td>
<td>20.122</td>
<td>26.013</td>
</tr>
<tr>
<td>Murdjadjo</td>
<td>13.779</td>
<td>16.003</td>
<td>20.897</td>
</tr>
<tr>
<td>Tafraoui</td>
<td>0.108</td>
<td>0.126</td>
<td>0.164</td>
</tr>
<tr>
<td>Total region</td>
<td>35.293</td>
<td>40.849</td>
<td>53.049</td>
</tr>
</tbody>
</table>

SCENARIO OF WATER SYSTEM INTEGRATION

The discussion above highlights that – due to both climate change and the imperative of a growing agriculture sector to meet the population nutritional needs – a reduction of water resources and increased demand for irrigation systems are expected in the Oran region. The strong solicitation of the groundwater resources that may follow as a corollary indicates the necessity for a forward-looking management.
of these resources in order to face these developments and reduce the vulnerability of the region.

We argue in this context that a relevant water management plan is inseparable from the issue of the current decoupling of the drinking water and agriculture sectors. We recall, that in 2030, 66.6 million m$^3$ of water – treated by the WWTPs – will be, in the NCC scenario, rejected in natural recipients (Sebkha basin and sea). Only by integrating the drinking water and agriculture sectors, through a reuse of wastewater, can we consider the irrigation issue in the region from a perspective of long-term sustainability.

To investigate this issue, we develop a final scenario of integration of the hydrological system of the region with the following three characteristics:

- As in Bouklia-Hassane et al. (2014), we introduce, first, a project of establishment of a large irrigated perimeter (‘Grand Périmètre Irrigué’) supplied by the WWTP and located in the Tafraoui region on an area of 7,000 hectares with an extension of 1,000 hectares toward Bredeah.
- Second, in an optimal situation, the entire production of the WWTP in this scenario must be used and the water rejected by the WWTP must be nearly nil by 2030.
- Third, the withdrawals from the groundwater must not exceed their natural recharge.

By increasing, step-by-step, the rate of growth of irrigated agricultural areas, simulations of five climate scenarios show that the sizing of the WWTP is consistent with rates of growth of the irrigated areas varying from 2.7% to 11.8% depending on the climate evolution in the region (Table 3). In the particular case of a NCC and due to the reuse of wastewater, the agricultural sector will grow (6.7%) at more than twice the rate prevailing in the baseline scenario.

With these growth rates, the water rejected by the WWTPs to the sea will decrease until approximately vanishing by 2030 with a rate of groundwater exploitation equal nearly to 100% in 2030 and an optimum recovery of all demand sites.

**CONCLUSION**

This study proposed a modeling framework for the development of the hydrological system in the Oran region over the long-term period. In addition to socioeconomic variables (population growth and water need per capita as a function of the household size and standard of living), the model incorporates climate variables because of their potential impact on the agricultural sector development via changes in the irrigation requirements and the groundwater natural recharge.

Our results highlight the vulnerability of the region particularly in view of its limited surface runoff resources. Moreover, the predicted rise in temperatures and decline in precipitation aggravate this vulnerability by inducing a general reduction of water resources and increased demand for irrigation systems.

Using various simulations, we have identified management options that can help water managers face the major challenges of the predicted climate change and fast changing socioeconomic boundary conditions in the Oran region. However, a water policy in Oran region can be sustainable only if it remedies the main hindrance of the region, which is the disconnection of the agricultural sector from the water system leading to overexploitation of certain aquifers. Based on estimations of the growth rate of the irrigated areas induced by the treatment of wastewater for irrigation needs, our results show under different climate scenarios that the reuse of the wastewater through the implementation of a WWTP is a valid option for Oran region. It not only helps to preserve the groundwater resources and thus the sustainability of the regional water policy but also contributes significantly to the development of the agricultural sector and thus to the mitigation of the adverse effects of climate change in the region.

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