Assessment of Groundwater Resources based on IT Platform of GIS-Mathematical Model to Account for Climate Change in the Sahel Aquifer (Morocco)

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Keywords: Sahel, climate change, intensive pumping, GIS, thematic maps, groundwater models, IT techniques.

Abstract: The Sahel is part of the coastal Sahel basin of Doukkala that borders the Atlantic Ocean on the northwest and covers an area of approximately 4146 km^2. It includes several urban centres and a large industrial complex. In this area, the Sahel aquifer is vulnerable to Climate Change (CC) and intensive pumping mainly in the coastal fringe, where the agricultural activities are significant. The main objectives of this study are to develop IT (Information Technology) platform based on a Geographic Information System (GIS) and mathematical modelling environment to produce thematic maps for analysing and treatment of spatial and temporal characteristics with respect to groundwater flow and water resources management and CC of the Sahel aquifer. Based on this GIS database, a conceptual model followed by groundwater models were designed and simulated piezometric levels, drawdowns and water balance under steady state conditions. The obtained results show the pertinence of different IT techniques used and evaluate their contribution and also their possible constraints in a coastal environment, including the improvement of the Sahel aquifer knowledge on water resources that assist managers in monitoring, planning and operating measures to satisfy water supply and irrigation demand under CC constraints in the Sahel area.

1 INTRODUCTION

Climate change (CC) refers to significant changes and measures of climate like temperature and precipitation over long time periods and large geographic area. It's human activities from pollution to overpopulation are driving up the temperature and fundamentally changing the world around us. CC has consequences for our oceans, our weather, our food sources and our health, others forecast rising sea levels which could flood coastal areas around the world. Weather patterns could change making weather more extreme (Stott et al., 2016). This means not only more intense major storms floods and heavy snowfall, but also longer and more frequent droughts, less stream flow and less groundwater recharge and indirectly through changes in groundwater abstraction and use patterns.

Morocco currently faces major water challenges related to the sustainable management of water resources and the delivery of water services for domestic, agricultural and industrial use. CC and climate variability can increase the risks and the costs of water resources management, impact the quantity and quality of water resources, and generate secondary effects that influence socio-economic vulnerability and environmental sustainability (El-Fadel and Bou-Zeid, 2005). This is the case of the coastal zones which are heavily urbanized, a fact that makes the need for freshwater even more acute. Inappropriate management of coastal aquifers may lead to the intrusion of saltwater into freshwater wells, destroying them as sources of freshwater supply. The degradation or the unavailability of groundwater present a great risk for the future of Drinking Water Supply/Industry (DWSI) and irrigation agriculture, since some farms and pumping wells for DWSI in the coast would be abandoned. So, they would result in serious socio-economic consequence to people living there. Hence, a clear understanding of these risks and impacts is necessary to inform policy formulation and decision-making in

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support of efforts to achieve sustainable development in Morocco.

The Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR) (ACSAD and ESCWA, 2017) has shown that the Arab region will experience an increase of temperature and a decrease of precipitation. More specifically, the temperature increases one to two degrees on average by mid-century and by end we will get two to three degrees increasing in temperature under Representative Concentration Pathway (RCP) 4.5. At the higher emission scenario, the RCP 8.5, by mid-century we will reach temperatures of two to three degrees increase and by the end we could even reach four to five degrees Celsius increase temperatures on average (Graham and Sjökvist, 2017 ; ACSAD and ESCWA, 2017). Hence, it is projected that these groundwater resources will be affected by CC due to a reduction in natural recharge from reduced precipitation, the rise in temperature and the decrease in evapotranspiration caused in part by lower precipitations.

2 BACKGROUND

The Sahel aquifer is located in the Oum Er Ribia basin and belongs to the Western Moroccan Meseta, between latitudes, 32°15'and 33°15' and between longitudes, West 7°55'and 9°15'. It covers the coastal front of the hydrogeological basin between Safi and El Jadida (Fig. 1). This region borders the: (1) Atlantic Ocean on the northwest; (2) Sahel of Safi on the south; (3) Oum-Er-Rbia and the El Jadida plateau on the north; (4) Doukkala plain on the east.

In general, the Sahel is located between the Doukkala region and the coast with an area of approximately 4146 km^2, it appears as a band 25 to 44 km wide and 140 km long covering the coastal front of the hydrogeological basin between Safi and El Jadida.

The Sahel is defined by the tabular regime of the secondary and tertiary deposits on primary grounds strongly pleated by the hercynian mountain chain and described four main hydrogeological units closely dependent, with age ranging from cretaceous to Plio-Quaternary (Ferré and Ruhard, 1975). It is the main supplier of water resources for drinking water of several urban centers of the area (the cities of El Jadida and Safi) and the industrial water supply of the OCP installations and the processes of phosphate washing (Jorf Lasfar). Furthermore, the Sahel aquifer is suffering from intensive pumping mainly in the coastal fringe, where the agricultural activities are carried out significantly to produce vegetable crops by irrigation from several pumping wells (ABHOER, 2012).

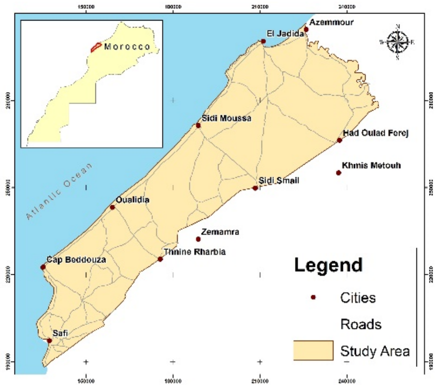

Figure 1: Location map of the study area.

For this purpose, all collected information (relevant technical reports and RICCAR data relevant to datasets and outputs of the study area) were processed and led to: (i) Study the hydrogeology characteristics and hydrodynamic functioning of the SCA ; (ii) Analyse the CC impact on groundwater resources in the SCA based on emission scenarios (RCP 4.5 and 8.5) ; (iii) Elaborate a GIS database to produce decisional thematic maps for the area ; (iv) Design a conceptual three-dimensional groundwater model of the Sahel Aquifer; and (v) Develop a Three-dimensional model in steady state to assess the water balance.

2.1 Hydrogeological Setting

The hydrogeologic formations are dominated by limestone and formed mainly by four hydrogeological units (Ferré and Ruhard, 1975):

- Sandstone and limestone of the Plio-quaternary;
- Limestones of the Middle Cenomanian;
- Dridrate limestones of the upper Hauterivian;
- Marl-limestones of the Lower Cretaceous.

These aquifer units constitute water resources of variable importance according to sectors.

In the Sahel, the piezometric evolution depends on the natural conditions of aquifer system recharge/discharge which were modified by the projects of hydro-agricultural development, the Under-Service irrigated perimeter in Doukkala and pumping for irrigation purposes in coastal Sahel. The extensive extraction of groundwater for the irrigation caused in many places deteriorated water quality linked to the salinity increase of groundwater due to the saltwater intrusion (ABHOER, 2012).

2.2 Impacts of Climate Change

Datasets used in this assessment comprises a combination of regional climate modelling projections data generated from RICCAR, and a set of local observation datasets for precipitation, temperature for our study area. This section is based on extracting time series of Pr (Precipitation) and Ta (Temperature) variables for the entire time period from 1951 to 2100. We read NetCDF files (.nc) using MATLAB to extract time series of Pr (Precipitation) and Ta (Temperature) variables for the entire time period from 1951 to 2100. We extract data for a specific latitude and longitude coordinates. The location of our study area is at latitude = 33° North and longitude = 8.36° West.

Based on the RICCAR data, we could present some plots of time series that summarize and show the updated knowledge on the climatology of our study area. We have displayed and edited some in Fig. 2 and 3, which show the evolution of projected P, T for various climate models and scenarios. The main trends of the parameter variation are also provided to analyse and measure the CC trends. The procedure to extract Pr data is provided in Fig. 5.

These figures show clearly that temperatures are mainly increasing, while precipitations are mainly decreasing for both scenarios. Hence, the CC impacts in the area cause recurrent droughts and decrease in aquifer recharge (Fig. 4) that directly affects the groundwater level (e.g. increase of water depth as demonstrated in the well no. 26/122).

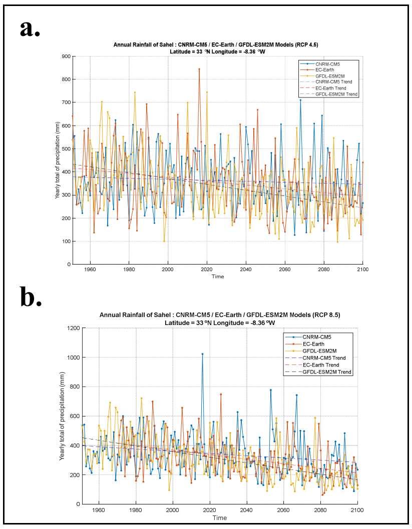

Figure 2: Precipitations over time (1951-2100) in the study area for: a. RCP 4.5 and b. RCP 8.5.

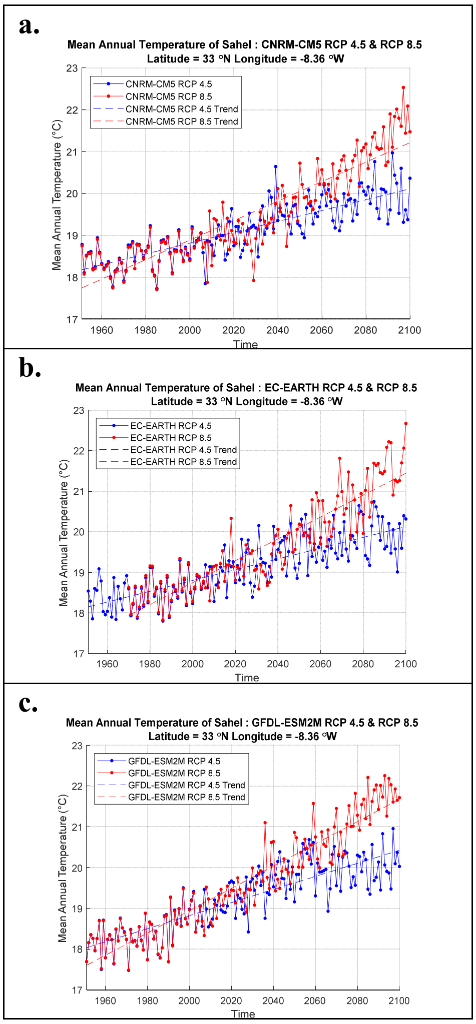

Figure 3: Mean temperature (°C) over time (1951-2100) in the study area for climate models : a. CNRM- CM5, b. EC-EARTH and c. GFDL- ESM2M (RCP 4.5 and RCP 8.5).

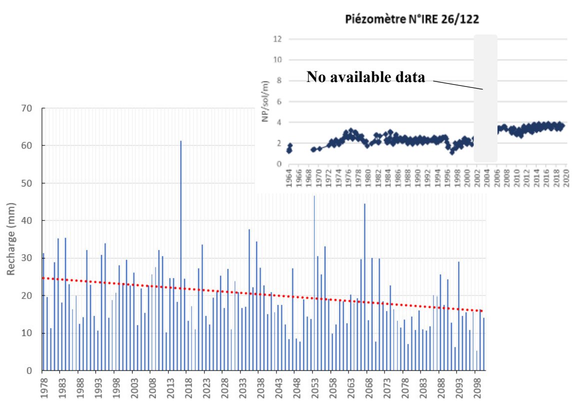

Figure 4: Annual variation of natural recharge from 1978 to 2100 (e.g. CNRM-CM5, RCP 8.5) and observed piezometric records for observation well 26/122 from 1964 to 2020 located in the coast near sidi moussa city.

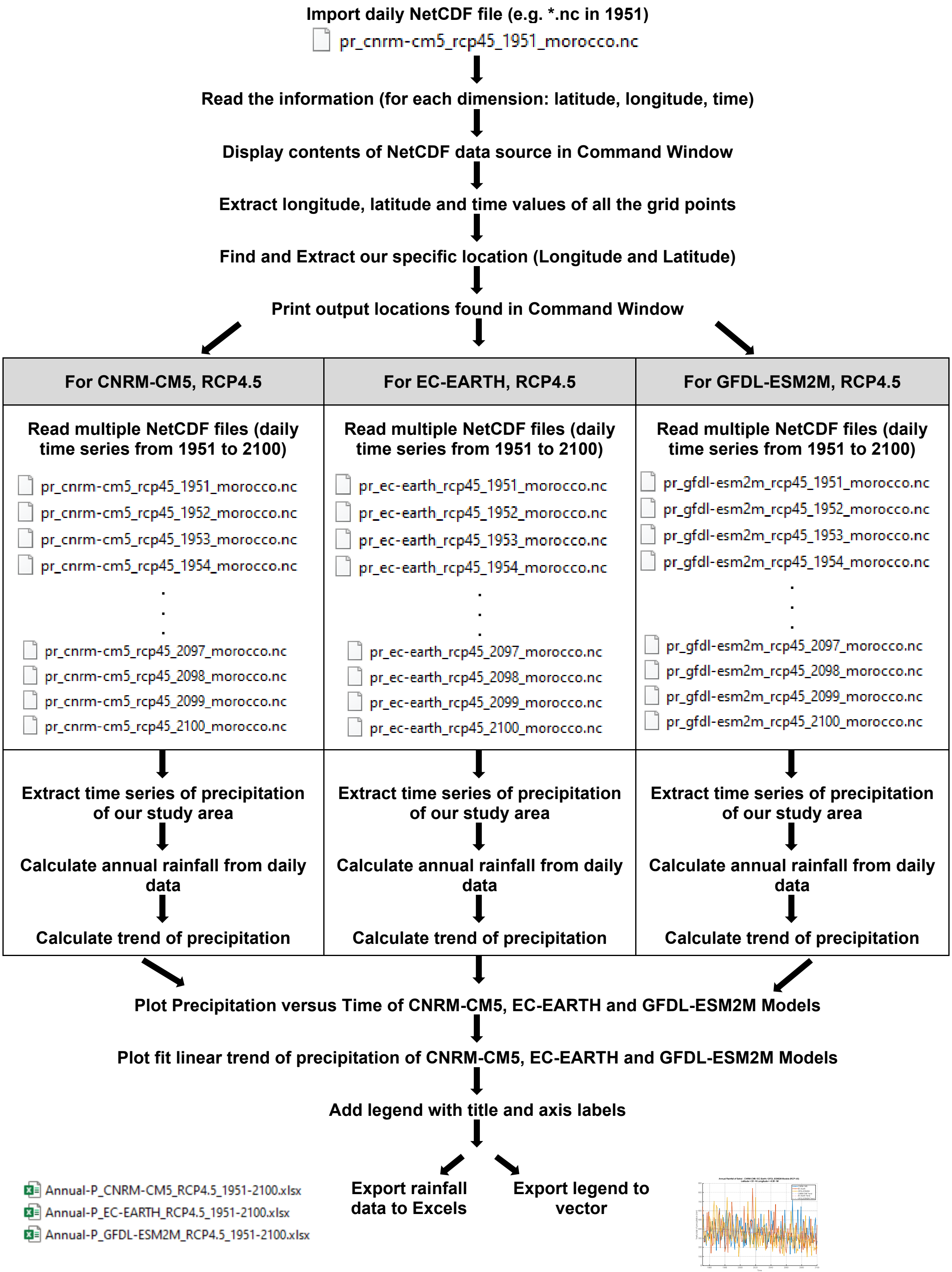

Figure 5: Flow chart of the steps followed for extraction of precipitations versus time (1950-2100) for CNRM-CM5, EC-EARTH and GFDL-ESM2M climate Models, RCP4.5 scenarios.

2.3 Hydrogeological Database

This section is the results from the development of the hydrogeological geodatabase (Fig. 6) to produce decisional thematic maps and diagrams, providing more information layers to managers in water resources. The obtained thematic layers were organized according to the needs of managers and decision makers. This action facilitates consultation, customization and duplication of information in relation to the various aspects of water resources.

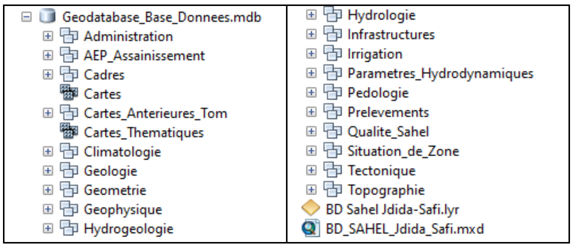

Figure 6: Geodatabase structure of the SCA with layers.

The lateral and vertical measurements carried out in well O45 are integrated in our GIS. The results show an increase of water Electrical Conductivity (EC) horizontally and within the depth, due to seawater intrusion as illustrated by figure 7 (Fadili et al., 2018). This led to groundwater quality degradation (by salinisation), especially in the Oualidia sector.

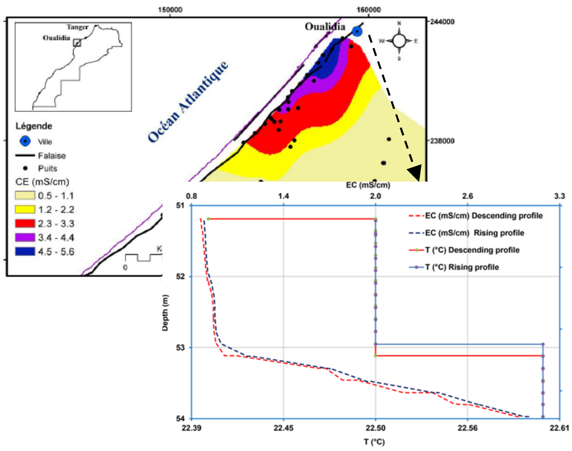

Figure 7: Map and vertical profile of water EC in well O45 and Oualidia sector (in 2011), (Fadili et al., 2018).

2.4 Groundwater Management Model

Based on the GIS database, the conceptual model of the SCA was established on the basis of the hydrogeological characteristics, the hydrodynamic parameters and the spatial variations of the aquifer piezometry in 1976, which allowed understanding the hydrogeological functioning of the SCA, its structure and its geometrical extension based on the hydrogeological database developed in this work.

Then, the formulation of this conceptual model led to develop a three-dimensional numerical groundwater flow model. It simulates this flow, under steady state conditions, by solving Equation (1) (McDonald and Harbaugh, 1988) by means of the Visual Modflow (USGS, 2005).

Equation (1):

$$\frac{\partial}{\partial x}\left(K_{xx} * \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy} * \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz} * \frac{\partial h}{\partial z}\right) \pm W = 0$$

Where Kxx, Kyy, and Kzz are the hydraulic conductivities along the x, y, and z coordinate axes (L/T), h is hydraulic head (L), W is the volumetric flux per unit volume and represents sources and (or) sinks of water (T^{-1}).

2.4.1 Discretization and Calibration

The 3D discretization method used is the finite difference. The domain was cut into grid square cells of 1000 m side oriented along the main Cartesian axes. Thus, the idealized domain has 125 columns along the X axis and 136 rows along the Y axis. The number of active cells is 4114 (Fig. 8). Vertically, we have considered one layer only. The blue cells represent the inactive cells.

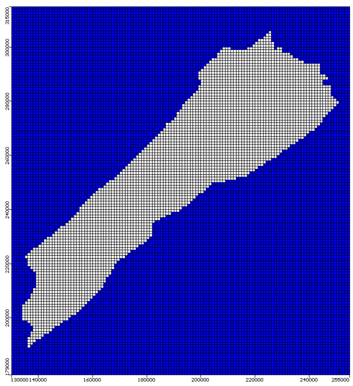

Figure 8: Discretization of the simulated domain by the finite difference technique.

The calibration of the model is performed by comparing the simulated piezometric heads obtained by the model to the measured piezometric heads, and the water balance dealt in the hydrogeological characterization section. As for the measurement network, 12 observation wells are available from 1976 and cover the whole area of SCA to carry out the periodic piezometric measurements. The Kriging method has been used to interpolate a data set to the model grid.

2.4.2 Simulation and Results

The initial distribution of hydraulic conductivity obtained mainly by the distribution of four hydrogeological units allowed to shorten the calibration. However, the initial calibration was undertaken in ways, that not only minimizing the difference between the measured and simulated piezometric heads at 12 observation wells, but also, to restore at best the general structure of the reference piezometric head map of 1976 (Fig. 9).

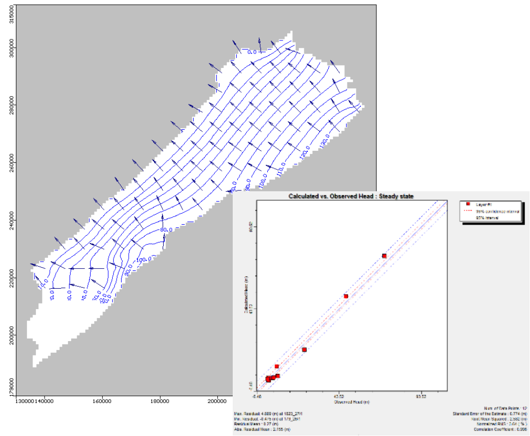

Figure 9: Simulated piezometry (m) and correlation between measured and simulated heads for 1976.

At the end of this initial calibration, the model provides the simulated water balance of the aquifer system, where different terms of the water balance are assessed. Calculated fluxes in each cell of the model can locate the hydraulic exchange zones, especially at the boundaries. The results in Table 1 shows that the main inflow consists of the boundary inputs from Doukkala aquifer and the main outflow is composed of the natural drainage to the sea.

Table 1: Water balance of the aquifer system calculated after calibration in steady state.

Inputs (in Mm^3/year)		Outputs (in Mm^3/year)	
Rain-infiltration	101.6	Agricultural pumping	36
Irrigation	4	DWSI pumping	10
Boundary inputs	574	Boundary outputs/sea	633.6
Total	679.6	Total	679.6

3 CONCLUSION

The IT platform composed of the established hydrogeological database and the groundwater model for the SCA has contributed to better understand the hydrogeological characteristics and hydrodynamic functioning of the aquifer, especially under CC. Indeed, these results (1st step) are of great importance to identify the impacts of CC (Pr and Ta for various climate models extracted from 1951 to 2100) on groundwater resources by coupling them to a transient groundwater flow model (1976-2100, last step going on). The final results will analyse the implication these pose for socio-economic vulnerability and sustainable development and identify vulnerability hotspots that the managers have to take into account for water resources management.

ACKNOWLEDGEMENTS

Data were collected from RICCAR, ABHOER, ORMVA, and ONEE institutions. This research work is also funded by the OCP Foundation (FOCP).

REFERENCES

ABHOER, 2012. *Etude de la recharge de la nappe du Sahel-Doukkala*, MARCHE N°18/2012/ABHOER. https://doi.org/10.4000/books.pub.896

ACSAD and ESCWA, 2017. *Impact of Climate Change on Extreme Events in Selected Basins in the Arab Region*, RICCAR Report, https://arabsdgs.unescwa.org/en/read-digital-library.

El-Fadel, M., Bou-Zeid, E.R., 2005. Climate Change and Water Resources in the Middle East: Vulnerability, Socio-Economic Impacts, and Adaptation. *SSRN Electron. J.* https://doi.org/10.2139/ssrn.278514

Fadili, A., Malaurent, P., Najib, S., Mehdi, K., Riss, J., Makan, A., 2018. Groundwater hydrodynamics and salinity response to oceanic tide in coastal aquifers: case study of Sahel Doukkala, Morocco. *Hydrogeol. J.* 26, 2459–2473. https://doi.org/10.1007/s10040-018-1812-4

Ferré, M., Ruhard, J.-P., 1975. *Les Bassins des Abda-Doukkala et du Sahel de Azemmour à Safi.* Ressources en Eau du Maroc, Tome 2, Editions du Service Géologique du Maroc.

Graham, P., Sjökvist, E., 2017. *Regional Climate Modelling and Regional Hydrological Modelling Applications in the Arab Region*, RICCAR, https://arabsdgs.unescwa.org/en/read-digital-library.

McDonald, M.G., Harbaugh, A.W., 1988. *A modular three-dimensional finite-difference groundwater flow model*, Techniques of Water-Resources Investigations Report,

06-A1. Tech. Water-Resources Investig. United States Geol. Surv. 588.
Stott, P.A., Christidis, N., Otto, F.E.L., Sun, Y., Vanderlinden, J.P., van Oldenborgh, G.J., Vautard, R., von Storch, H., Walton, P., Yiou, P., Zwiers, F.W., 2016. Attribution of extreme weather and climate-related events. *Wiley Interdiscip. Rev. Clim. Chang.* 7, 23–41. https://doi.org/10.1002/wcc.380
USGS, 2005. *MODFLOW-2005 , The U . S . Geological Survey Modular Ground-Water Model — the Ground-Water Flow Process MODFLOW-2005* , The U . S . Geological Survey Modular Ground-Water Model — the Ground-Water Flow Process.