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Climate Change Trends in Morocco's Mediterranean & Atlantic Hydraulic Basins: Impacts on Water Resources

A. Larabi, H. El Asri, M.J. El Hamidi, S. Zhim and M. Faouzi

Regional Water Center of Maghreb, LAMERN-EMI, Mohammed V University, Rabat, Morocco

Abstract: This study investigates the climate change variability and its impact on water resources in hydraulic basins located in both Mediterranean and Atlantic fronts of Morocco, using climate and hydrological modeling. Several climate parameters and their projections in the future have been analyzed to assess climate changes, including wet and dry periods with focus on intensity and frequency. Furthermore, Modeling of the impact of this climate change on water resources based on climate scenarios is also studied to evaluate water balance components in the basin/aquifer, in addition to drawdown lowering, water table depletion and seawater intrusion extents into the coastal aquifer. The Ghis-Nekkor plain, located in the north of Morocco is a vulnerable area for climate changes, due to its influence by the Mediterranean front to the north and its strong urbanization. In this study, the influence of the decrease of precipitation (about 18%) and increase in average temperature (0.5 °C) on future drought conditions is assessed by the SPI index. The projected change in precipitation for the period (2020 - 2070) was simulated by the Regional Climate Model (RCM) Hirham5 from the Cordex Project. The results indicate that the Ghis-Nekkor plain experienced a dry period from 1980 to 1987. For the period 2040-2070, the drought severity and duration will increase under the RCP 4.5 scenario with 19% of severe drought. The OumEr-Rbia hydraulic basin, located in the mid-west part of Morocco (Atlas and Atlantic front), is one of the largest watersheds in the country (4800km²). Estimation of the regional characteristics of drought, frequency and duration using the SPI index was conducted in the basin. The results show that during these last forty years, the OumEr-Rbia basin experienced dry periods from 1980 to 1987, from 1991 to 1995, from 1997 to 2002 and from 2006 to 2008 and their intensity varies from moderate to severe. The results show also a relatively high frequency and large spatial extent of drought in the basin. During these periods, surface water and groundwater resources suffered from significant deficits, such as reduced water storage in dam reservoirs and groundwater table depletion in several aquifers. The Rmel-O. Ogbane is unconfined coastal aquifer situated near Larache city in the north of Morocco and is a part of the main sub-Atlantic coastal aquifers. An integrated approach is developed for linking climate models and GW models to investigate future impacts of CC on GW resources. Climate projections show an increase in temperature of about 0.45 °C and a reduction in precipitation of 16.7% for the period 2016-2050. The sea level will rise up from ~6.45 cm by 2017 to ~21.3 cm by 2040. Simulations of seawater intrusion corresponding to various combinations of GW extraction, predicted climate change and SLR show that the area will be contaminated on the NW sector of the coastal part, in which the interface toe would reach about 5.2 km inland and will be intruded with high salinity (15–25 g/l). Beyond these zones, the contamination of the aquifer will be limited. Face to to this situation, better strategies for GW development and management will be necessary to protect the freshwater aquifers to the marine intrusion.

Key words: Climate Change · RCP scenarios · Saltwater intrusion · Climate models · Groundwater models · Solute-transport model · Sea level Rise · Groundwater management scenarios

INTRODUCTION

Drought is an extreme event that can produce significant deleterious effects under both present and future climatic conditions according to the recent Special Report by The Intergovernmental Panel on Climate Change [1]. In fact, climate projections suggest that drought is likely to increase and may become more intense

Corresponding Author: A. Larabi, Regional Water Center of Maghreb, LAMERN-EMI, Mohammed V University, Rabat, Morocco.

in some region including the Mediterranean region which is one of the primary climate change hotspots [2]. The climate specialists anticipate during the 21th century an increase in temperature in the Mediterranean region of 3°C with a significant deficit in rainfall about 35% [1]. like the Mediterranean countries, Morocco is exposed to the risk of renewed drought, this is clearly proved by historical documents relevant to the last centuries [3] show that most of Morocco has been suffering from precipitation deficit and extended dry periods leading to several economic and environmental impacts as was the case during the 1944-1945 years, 1982-1983, 1994-1995, 1998-2000 and 2006-2007 [4]. Due to its influence by the Mediterranean front on the north, it is expected that the frequency of drought will change in several areas in Morocco such as the OumEr-Rbia, Ghis-Nekkor and Loukkos basins, because of the increase in temperature and significant deficit in rainfall. Water resources management policy is crucial especially in areas where socio-economic activity need more water resources, such as the case of the hydraulic basins subject to the current study. In fact, the large spatial-temporal rainfall variability that characterizes the climate of the studied areas is the origin of the droughts that occur there, the basin of OumErRbia (OER) is characterized by a low and erratic annual rainfall. In recent decades these basins have grown diminution rainfall which fell for the OER basin from 400 mm / year over the period 1935-1980 to 340 mm / year over the 1980- 2007 [5] causing the sharp decline in water supplies since 1980-2007 (by 40% compared with 1940-1980). Therefore, the characterization of drought then remains an essential step in the diagnostic process to facilitate the identification of the intensity, duration and spatial extension. Thus, trend identification in observed historical data and their occurrence in space and time are important in these areas where socio-economic activity need more water resources. There is also a need to assess the potential impact of climate change on future drought trend. In the few of drought trend studies that have been carried out all over the world, the Standardized Precipitation Index (SPI) has found widespread application for describing and comparing droughts. In addition, the World Meteorological Organization (WMO) [6] has recommended the use of the SPI for widespread use to determine meteorological drought. McKee *et al.* 1993 [7] developed SPI to understand the effect of precipitation deficits in both the short-term (primarily impacting agriculture) and long-term (impacting water resources). It has also advantages in terms of statistical consistency and the ability to describe both short term and long-term impacts of drought across different time scales. Thus, the aim of this study is to analysis the drought trend for historical and projected precipitation data to assess the potential impact of climate change on drought conditions in the Ghis-Nekkor plain and the OER hydraulic basin.

For coastal areas, sseawater intrusion (SWI) is a universal subject deepened by Sea Level Rise (SLR), Climate change (CC) and Excessive Over-Pumping (EOP) on coastal fresh Ground-Water (GW) resources. Many coastal areas of the world are characterized by numerous populations with about 50% of the world's population living within 60 km of the coastline [8]. In Morocco, more than 17 million people are living in the coastal cities of Morocco and this number is steadily growing. Indeed, in 2015 more than 50% of total population is living in the coastal zone, with an increasing proportion of rural population due to poverty and rural exodus. Hence, overexploitation of the GW quickly became a common issue with many coastal regions in the world such as the study area of Rmel-O. Ogbane. An integrated approach is developed for linking climate models to GW models to investigate future impacts of CC on GW resources and socio-economic vulnerability.

MEDITERRANEAN BASIN

Case of the Ghis-Nekkor plain: The study area covers the Ghis-Nekkor plain which is located in the north of Morocco on on the Mediterranean coast, at 12km South-East of Al Hoceima city (Figure 1). It is influenced by the Mediterranean front in the north which is considered as a climate change "hot spot". In the Ghis-Nekkor region, the average annual rainfall is rather low and oscillates around 300 mm. It is marked by a spatial-temporal disparity. The three rainfall stations selected for this study (Figure 1) and the description of the rainfall stations are shown in Table 1. In addition, the average monthly temperature is quite stable during the year as the annual average equals 18 ° C. In contrast, the climate of the Ghis-Nekkor plain is generally characterized by the succession of two periods: a dry one from April to October and a wet from November to March. Indeed, the use of the Emberger diagram indicates that the study case is located in a semi-arid climatic stage that characterizes its climate.

Analysis of drought trend for past and future periods: The analysis of drought trend is performed by using the drought index (SPI). This latter is calculated for two-time scale step (6 and 12 months) for past and future projected precipitations at the Ghis-Nekkor plain. The SPI is the

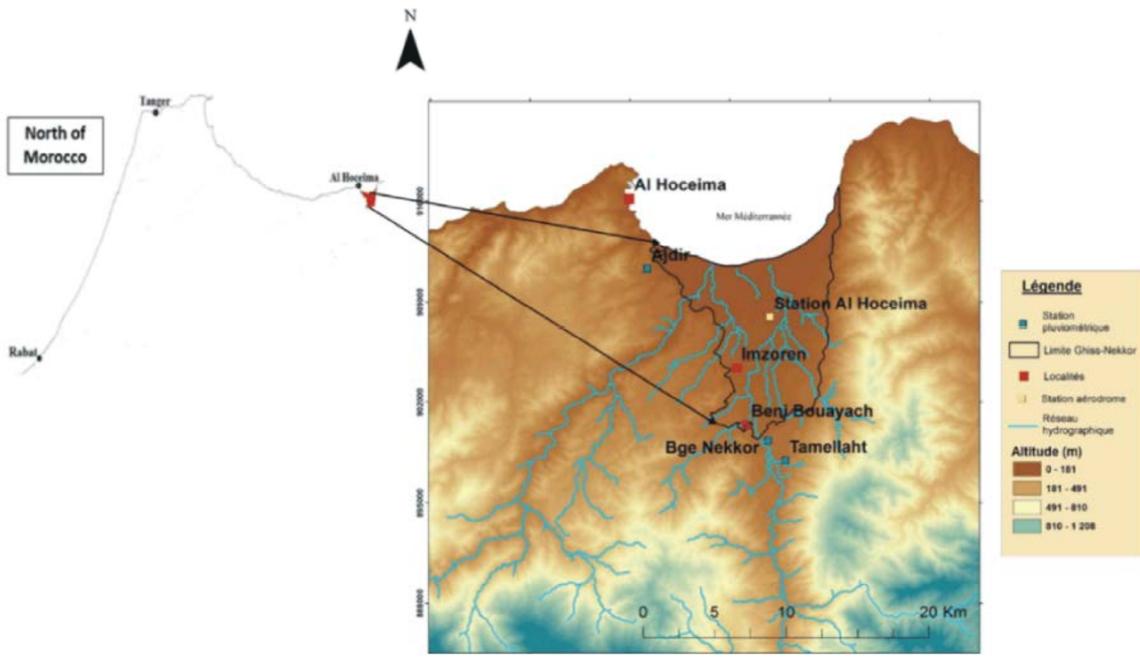


Fig. 1: Location of the study area relevant to the Ghis-Nekkor plain

Table 1: Description of rainfall stations

Station name	Location (X, Y)		Mean annual rainfall (mm)
Al Hoceima	633675	519950	374
Nekkor	644000	499400	300
Tamellaht	645300	488200	276
Ajdir	630550	488200	503

Table 2: SPI drought severity classes for wet and dry periods [7]

SPI Index	Class
2.0 or more	Extremely wet
1.5–1.99	Very wet
1.0–1.49	Moderately wet
0.99 to -0.99	Near normal
-1.0 to -1.49	Moderate drought
-1.5 to -1.99	Severe drought
-2.0 or less	Extreme drought

transformation of a given rainfall amount aggregated over a selected period (1–24 months). The longer time scales relate to hydrological drought and the shorter time scales may represent agricultural drought. The main advantage of the SPI is that it can be calculated for multiple time scales. This index can be calculated by fitting a Gamma probability function to a given frequency of total precipitation. The SPI is calculated using monthly precipitation. The mean SPI for any location is zero, positive values indicate precipitation above the mean and negative values indicate precipitation below the mean.

The SPI Is Calculated by the Following Formula:

$$SPI = \frac{(P_i - P_m)}{\sigma}$$

P_i: Total precipitation for a period i (mm), P_m: mean of recorded precipitation for the specific period (mm), σ: Standard deviation of recorded precipitation for the specific period (mm).

McKee *et al.*1 [7] defined the criteria for a drought event for any of the time scales. A drought event occurs any time that the SPI is continuously negative and reaches an intensity of 1 or less. The event ends when the SPI becomes positive. The positive sum of the SPI for all the months within a drought event can be termed the drought's 'magnitude'. Table 2 shows the SPI thresholds that are defined by McKee *et al.* [7].

To assess the impact of climate change on drought conditions in the Ghis-Nekkor plain, outputs from the RCM *Hirham5* model from the Cordex Project were used. The Cordex downscaling activities are based on the predictions generated in the 5th Coupled Model Intercomparing Project (CMIP5) required in AR5 and follow the Representative Concentrations Pathways (RCPs). The climate data used for this study include precipitation, minimum and maximum temperature. Current and predicted temperature and precipitation for the RCP 4.5 emission scenario are shown in Table 3.

Table 3: Current and projected precipitation, maximum and minimum temperature (monthly) using RCMs RACMO22T and HIRHAM5 under the RCP 4.5 scenario

	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly precipitation (mm)													
Observation	1964-1989	38	40.6	35.6	41.4	19.8	8.4	1.4	2.8	8.1	26.26	29	34.8
	1990-2014	47.3	38.6	41.3	32.1	20.5	10	1.8	3.7	15.6	47.3	53.5	40.1
Scenario RCP 4.5	2020-2045	34.4	43.7	42.7	34.6	26.8	5.08	2.1	2.4	28.9	36.7	27.3	29.95
	2045-2070	34.8	35.7	32.1	30.8	17.4	1.8	1.3	0.7	27.3	26.6	35.8	25.05
Monthly minimum temperature (°C)													
Observation	1964-1989	9.6	11.1	12.3	14.9	18.1	20.6	21.2	19.3	16.1	12.5	9.8	8.6
Scenario RCP 4.5	2020-2050	7.81	9.2	9.85	12.42	13.9	17.85	18.9	21.4	19.9	15.7	12.5	9.9
Monthly maximum temperature (°C)													
Observation	1982- 2012	16.5	17.1	18.3	19.8	21.8	24.8	27.6	27.9	25.9	22.9	19.8	17.7
Scenario RCP 4.5	2020-2050	17.3	16.9	19.9	19.1	22.4	26.3	30	29.6	25.7	23.8	21.5	17.6

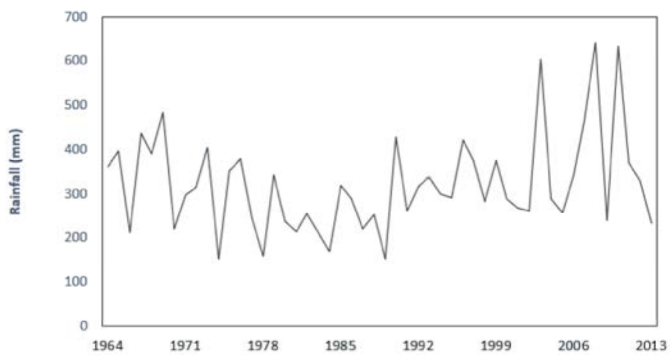


Fig. 2: Time series of the annual mean precipitation in the Ghis-Nekkor plain (1964-2013)

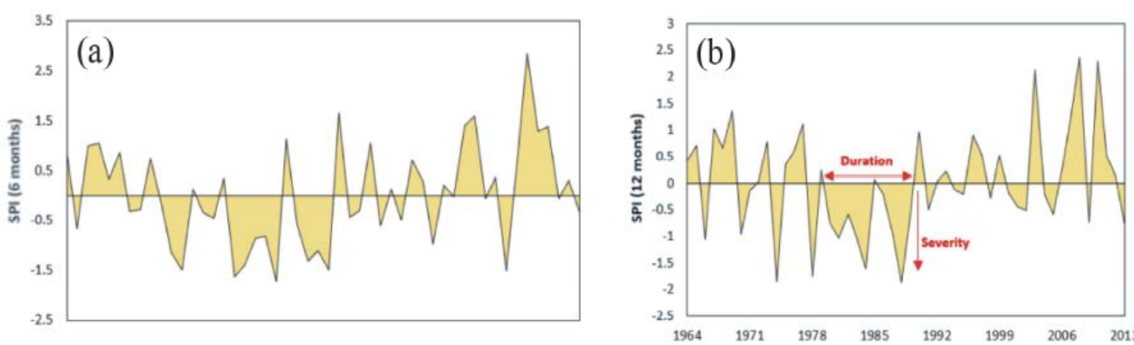


Fig. 3: SPI time series at (a) 6 months and (b) 12 months

Past Drought Trend: The long-term (1964-2014) trend of monthly rainfall in the Ghis-Nekkor plain is shown in Figure 2. Annual precipitation of the1980's period was the smallest for the observed period with only 232mm/an.

The SPI index is calculated for two-time scales of 6 and 12 months for all stations so that the severity of the drought can be estimated for both short and long-term effects. As stated before, a drought event is defined when the SPI value reaches a value of -1 or less and the drought ends with the SPI reaching a positive value. The SPI time series at 6 and 12-month time steps are given in Figure 3.

Analysis of 6 and 12-month SPI time series shows that droughts were quite frequent during the (1980-1984), (1986-1989), (1994-1995). However, several severe dry periods were identified, when only the annual minimum spatially averaged SPI value during 1974–1975 (SPI= -1.86), 1978-1979 (SPI= -1.75) and198-1984 (SPI= -1.87) was considered. In fact, with only a rate of 10% for moderate wet, the 1980s are the exception, as it is shown in Figure 3, where severe droughts occurred in this period with 55% of moderate drought and 20% of severe drought. The spatial distribution of the SPI index for the 1980s, which represents the driest period, is shown in Figure 4.

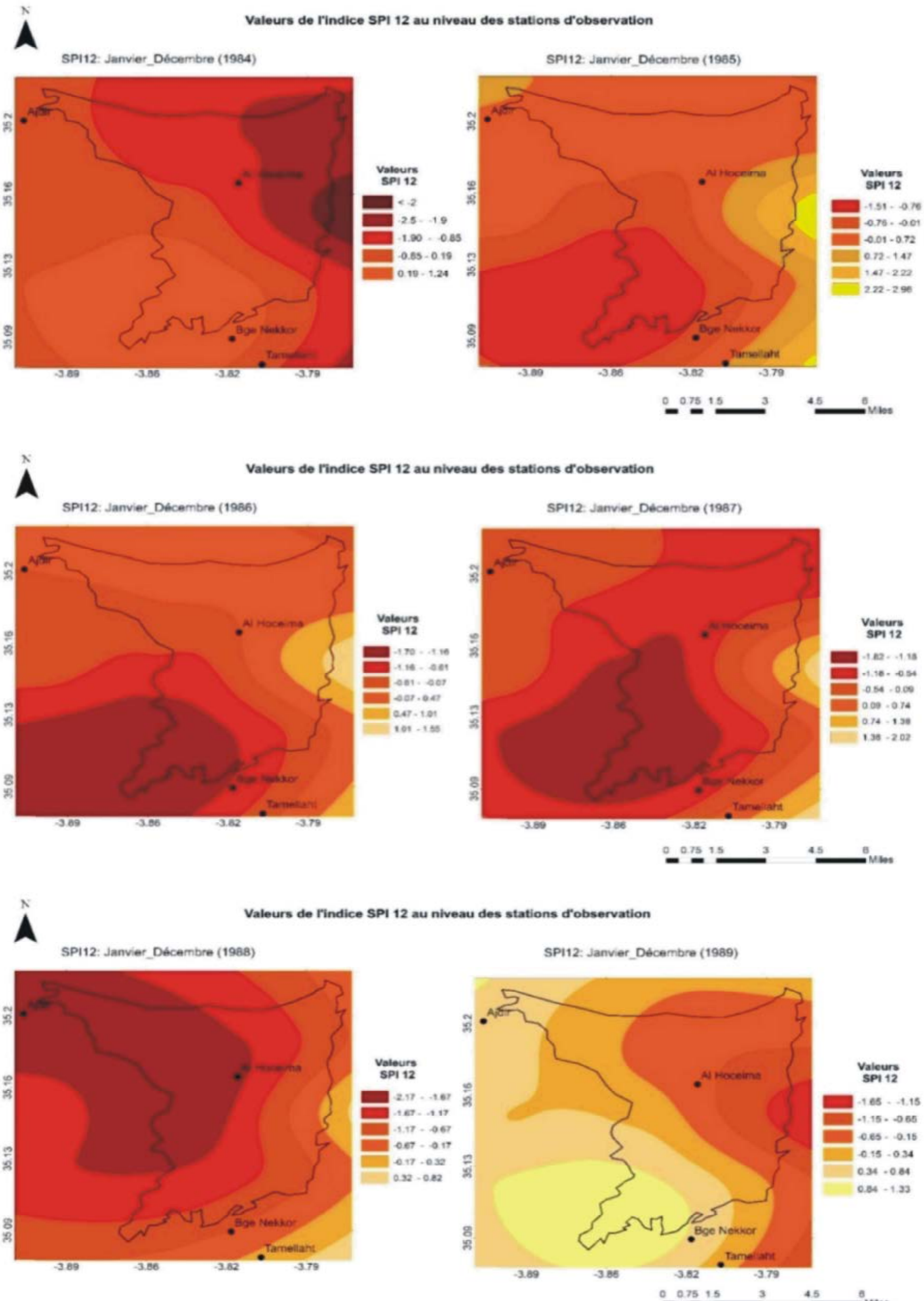


Fig. 4: Spatial distribution of drought with the SPI 12-month time step for the period between (1984 and 1989)

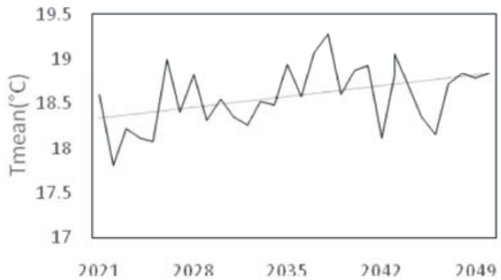


Fig. 5: Annual mean temperature variation by RACMO22T under the scenario (RCP4.5) by 2050

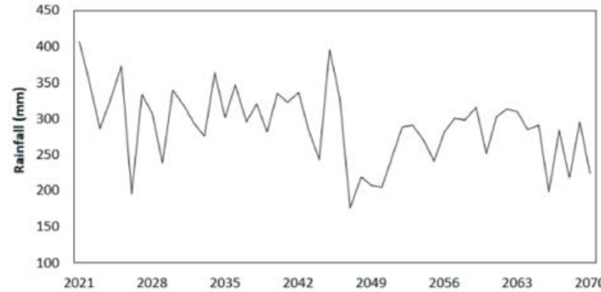


Fig. 6: Future evolution of cumulative annual rainfall in the Ghis-Nekkor plain by Hirham5 following RCP4.5 scenario by 2050

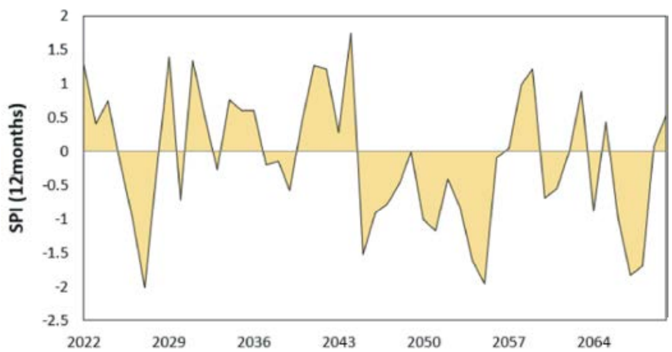


Fig. 7: SPI time series at 12 month

Table 4: Expected percentage of SPI intensity for the future period (2021-2070)

	Period				
Classification	2022-2033	2034-2044	2045-2056	2057-2070	2022-2070
Low wet	0.25%	0.45%	0.08%	0.42%	0.3%
Moderate wet	0.25%	0.27%	-	0.07%	0.14%
Low dry	0.33%	0.27%	0.5%	0.28%	0.33%
Moderate dry	0.08%	-	0.16%	0.07%	0.08%
Severe drought	0.08%	-	0.25%	0.14%	0.12%

Future Drought Trend: A reduction in precipitation accompanied by an increase in temperature, due to climate change, will affect the severity of drought. In fact, projected changes in precipitation and temperature simulated by Hirham5 and Racmo22T RCMs outputs show a downward trend for precipitation compared to the past period. The results show that the average annual rainfall in the plain might reduce up to 17% with an increase in the mean annual temperature of 0.5°C by 2050, as illustrated by Figures 5 and 6. It follows that climate change would affect, inevitably, the temperature and precipitation in the Ghis-Nekkor plain and consequently will result into future drought trend. In fact, the results obtained indicate that the drought severity and duration (SPI <0) will increase under the RCP 4.5 scenario for the period (2040-2070) as it is shown in Figure 6.

For the SPI 12 time series, the results show that the Ghis-Nekkor plain will experience dry periods from 2044 to 2049, from 2049 to 2056 and from 2066 to 2070 and their intensity varies from moderate to severe.

Despite the high frequency of the dry period expected in 2070, their intensity remains moderate to severe without reaching the extreme degree. The SPI time series 12 months step under the RCP 4.5 scenario provided by the Hirham5 model projection are shown in Figure 7. The period (2040-2070) shows a high frequency of drought compared to (2021-2040), with respectively 23% of moderate dry and 19% of severe dry. The RCP 4.5 climate change scenario indicates that the drought conditions of the period (2021-2070) will be more severe with a higher frequency. The rate predicted is about 12%, which represents the double compared to the reference

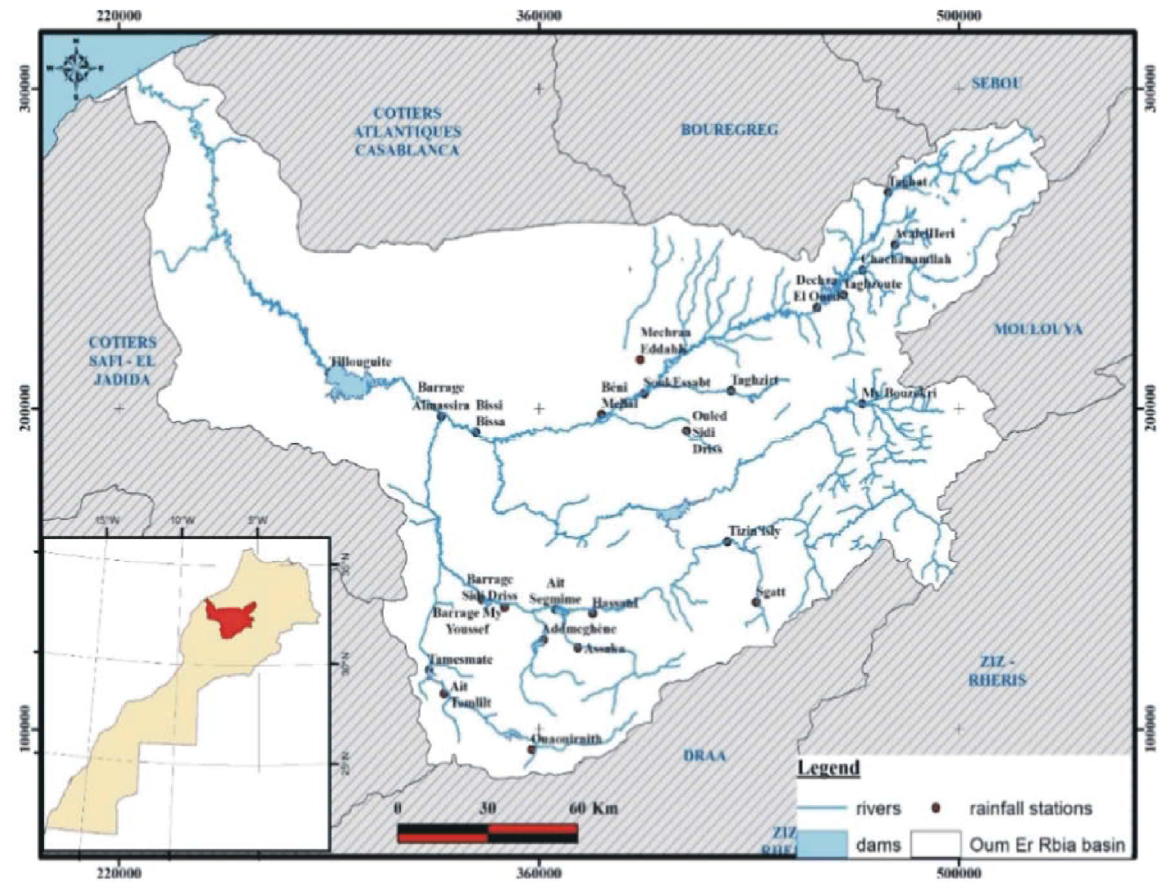


Fig. 8: Location of the OER study area and the rainfall stations

Table 5: percentage of SPI intensity for past and future periods

	Period	
Classification	1964-2013	2021-2070
Low wet	34.2%	30.25%
Moderate wet	8%	18%
Low dry	35%	34.6%
Moderate dry	7.8%	8.1%
Severe drought	6.4%	12%

period (1965-2014) (Table 5). Otherwise, the positive values of the SPI will be more frequent with a diminution of 4% for the moderate dry period.

Atlantic Hydraulic Basin

Case 1–OumEr-Rbia basin: The OumEr-Rbia basin is located in the western part of Morocco, it contains the longest stream in the country with a catchment area of 48,070 km2 (Figure 8). Elevations in the catchment range from 171 m to 4,071 m, but the quarter of the area lies below 500 m elevation. While half of the catchment is mountainous, the other half consists of plains and high lands, where agriculture activities are developed. The OumEr-Rbia's main tributary is Oued El Abid, with a mean annual discharge of 32 $m3s^{-1}$[9,10]. With rainfall ranging from 300 to 1100 mm, the OumEr-Rbia basin is subject to different climatic zones ranging from coastal climate on the Atlantic coast, an orographic climate in the Middle Atlas Mountains, passing through an arid climate in the plain of Rhamna and semi-arid in the plain of Tadla [5]. The mean annual precipitation is around 350 mm in the catchment. The precipitation decreases from east to west and from the Atlas chain towards the plain. The mean annual temperature in the catchment is 19ºC. The annual evapotranspiration is around 1,800 mm. Based on the available time series (1970-2011), the maximum of precipitation occurs in December and January and the minimum in August.

For 25 observed stations covering the OumEr-Rbia basin (Figure 9), monthly precipitation series for the period 1970- 2011 were obtained from the hydraulic basin

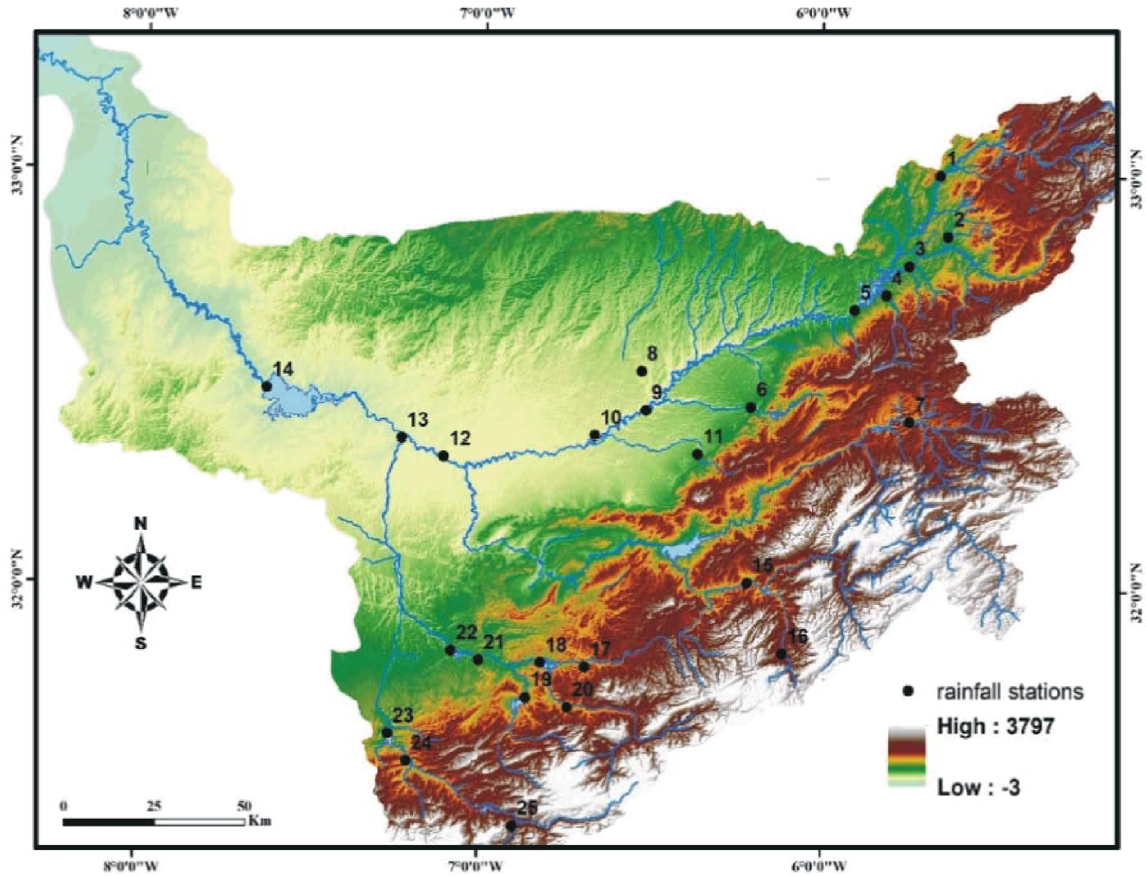


Fig. 9: DEM and Spatial distribution of the rainfall stations in the basin area

Table 6: Drought classification of SPI [7]

SPI	Class
2.0 or more	Extremely wet
1.5–1.99	Very wet
1.0–1.49	Moderately wet
0.99 to -0.99	Near normal
-1.0 to -1.49	Moderate drought
-1.5 to -1.99	Severe drought
-2.0 or less	Extreme drought

agency of OumEr-Rbia (ABHOR), which oversees the technical control of measurements and water resources management. The series were selected according to the length of the period of measurements, their availability and reliability. The geographical characteristics of the observed synoptic stations are presented in Figure 9.

Drought Occurrence and Analysis: Drought occurrences were investigated on the bases of frequency of the events for each drought category by taking the ratio of drought occurrences in each time step to the total drought occurrences in the same time step and drought category (Table 6).

Mapping Meteorogical Drought with SPI: One of the most frequently used deterministic interpolation methods in spatial interpolation is the inverse distance weighting method (IDW) [11], because of its relatively fast and easy computation and interpretation [12]. IDW sums the values of nearby points multiplied by a weighting factor. The weights are a decreasing function of distance. For this purpose, the ArcGis10 software was used as an infrastructure for making spatial distribution maps.

Drought Severity Temporal Dynamics: Figure 10 shows the temporal evolution of the SPI average of all rainfall stations in the basin. The analysis of the standardized precipitations index (SPI) indicates that during the period ranging from 1980 to 1993, the OumEr-Rbia basin knew a significant rainfall deficit, after the previous one recorded in 1975, with a minimum value in 1981 (-1,49) and in 1992 (-1,22). Indeed, these low values characterize moderate to severe types of droughts as shown by Figure 10.

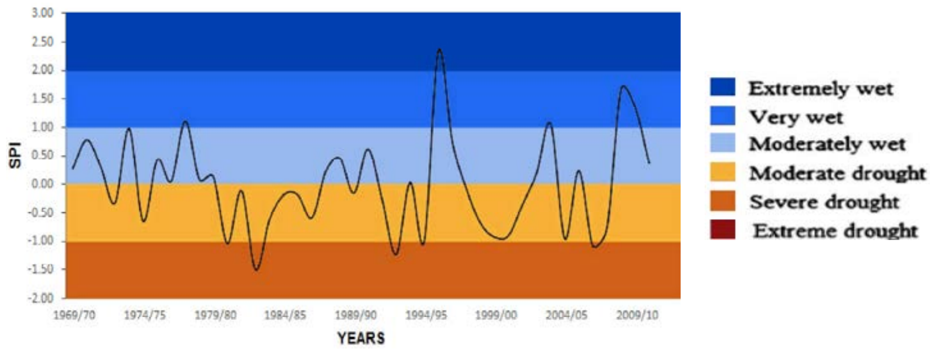


Fig. 10: Evolution of SPI in the OumEr-Rbia basin during the period 1970-2011

Table 7: Average annual values of Standardized Precipitations Index (SPI) for the period 1970 -2011 and showing wet and dry periods

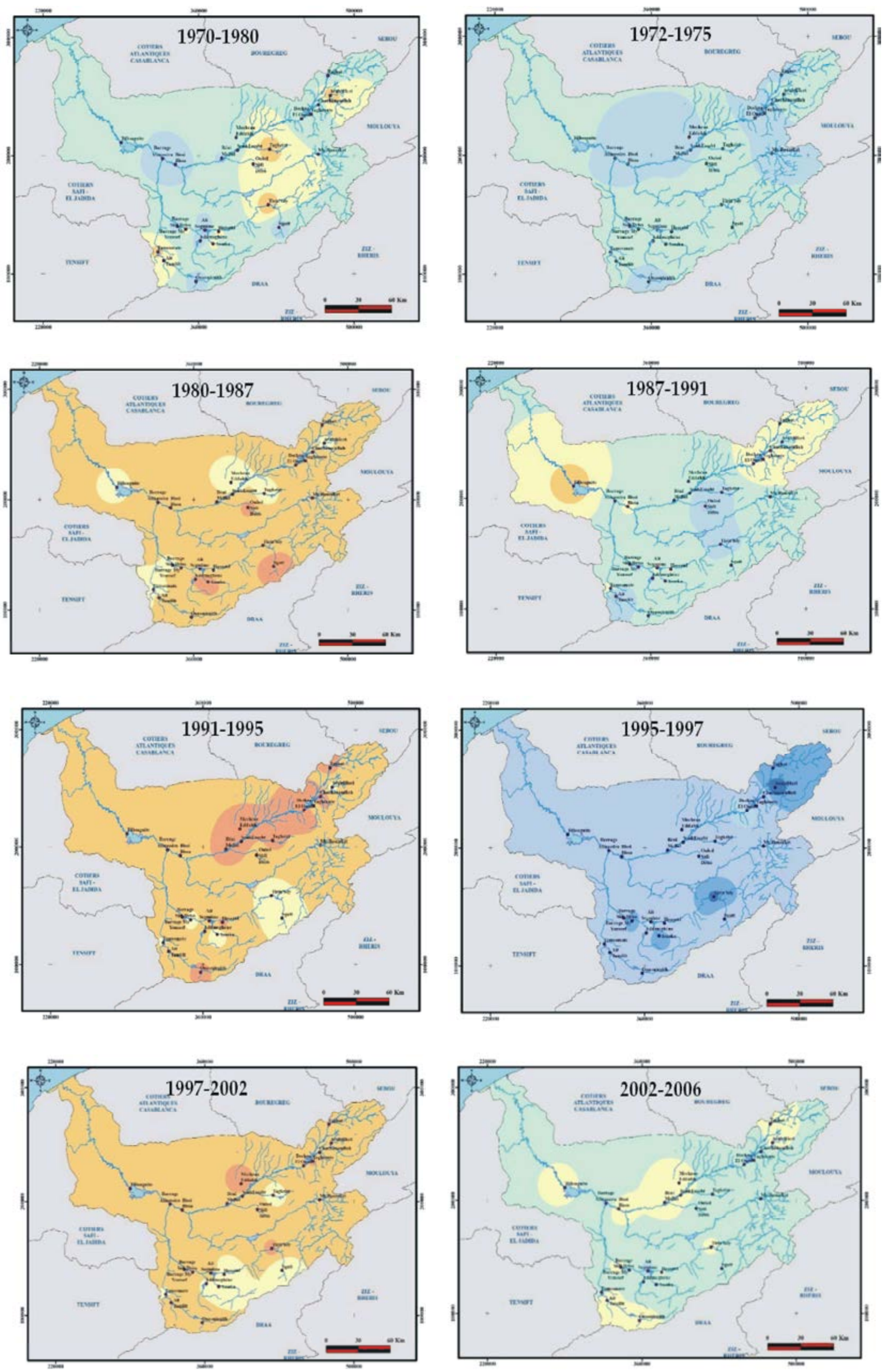
Descriptors	Wet period					Dry period					1969/2011
	1969-1980	1987-1991	1995-1997	2002-2006	2008-2011	1972-1975	1980-1987	1991-1995	1997-2002	2006-2008	
Average	0,46	0,44	1,54	0,50	1,13	-0,48	-0,60	-0,61	-0,58	-0,92	0,00
Maximum	1,11	0,62	3,98	1,05	1,67	-0,32	-0,10	0,74	-0,08	0,08	2,33
Minimum	0,06	0,23	-0,32	0,20	0,37	-0,64	-1,49	-1,65	-0,92	-1,84	-1,49
Standar deviation	0,40	0,20	1,00	0,48	0,68	0,23	0,51	0,66	0,36	0,41	0,82
Gap mean	0,33	0,14	0,83	0,37	0,50	0,16	0,38	0,56	0,30	0,32	0,64

Depending on the SPI values obtained during the period 1979-2011, the average values of the SPI are generally positive for the years 1969 to 1980 (SPI=0.46), from 1987 to 1991 (0.44), from 1995 to 1997 (1.54), from 2002 to 2006 (0.5) and from 2008 to 2011 (1.13); while it is negative on all the following five-year periods: 1972-1975, 1980-1987, 1991-1995, 1997-2002 and 2006-2008 with extreme SPI values reaching -1.49, -1.65 and -1.84 respectively for 1980-1997, 1991-1995 and 2006-2008 as illustrated in Table 7. Considering all rainfall stations and all years leading to 1050 cases in total, wet conditions prevail in 60% of cases which corresponds to the period 1969-1980 (Tab 5). High humidity or locally extreme occurs in 88% of cases over the 1995-1997 period and in 54% of cases in 2008-2011. From 1980 to 1987 drought far outweigh, accounting for 83% (1980-1987) to 100% (1991-1995 and 2006-2008) of the cases.

The period from 1972-1975 is dry and it is exceptionally distinguished by a relatively high humidity (18%) although the SPI average index is low and corresponds to -0.48. But, the excess of this humidity is compensated by a moderately low humidity. The Standardized Precipitation Index (SPI) is used to evaluate drought characteristics, frequency and duration. The spatial and temporal distribution of meteorological drought was also studied in the OumEr-Rbia basin over the last four decades, using Geographical Information System (GIS) to map the spatial extent of droughts within time steps. The obtained results show that during these last forty years the OumEr-Rbia basin experienced dry periods from 1980 to 1987, from 1991 to 1995, from 1997 to 2002 and from 2006 to 2008; and their intensity varies from moderate to severe. The examination of drought years reveals a relatively high frequency and large spatial extent of droughts which can take two to five consecutive dry years covering the entire basin area with very limited sectors. Generally, the OumEr-Rbia basin was affected by 53% of dry periods. The most dominant type of droughts is moderate.

Drought Severity Spatial Dynamics: The analysis of various droughts experienced at the 25 rainfall stations presented and illustrated in Figure 11 confirms once again the increased drying up trend of the OumEr-Rbia basin. The most persistent droughts occurred during the periods from 1980 to 1987, from 1991 to 1995, from 1997 to 2002 and from 2006 to 2008, they are remarkably composed of three, four and five consecutive dry years as shown in Figure 11 (maps 3, 5, 7 and 9). Based on the obtained results from the SPI mapping in the OER basin that the moderate and severe droughts occurred in the North East of the study area (Figure 11), characterized by topographic and geological conditions that are not in favor conditions, as for water storage for long time in the dam reservoirs of the basin.

We can then conclude that the climate change that occurs in the OumEr-Rbia basin has until now manifested by an increase in moderate to severe drought and not by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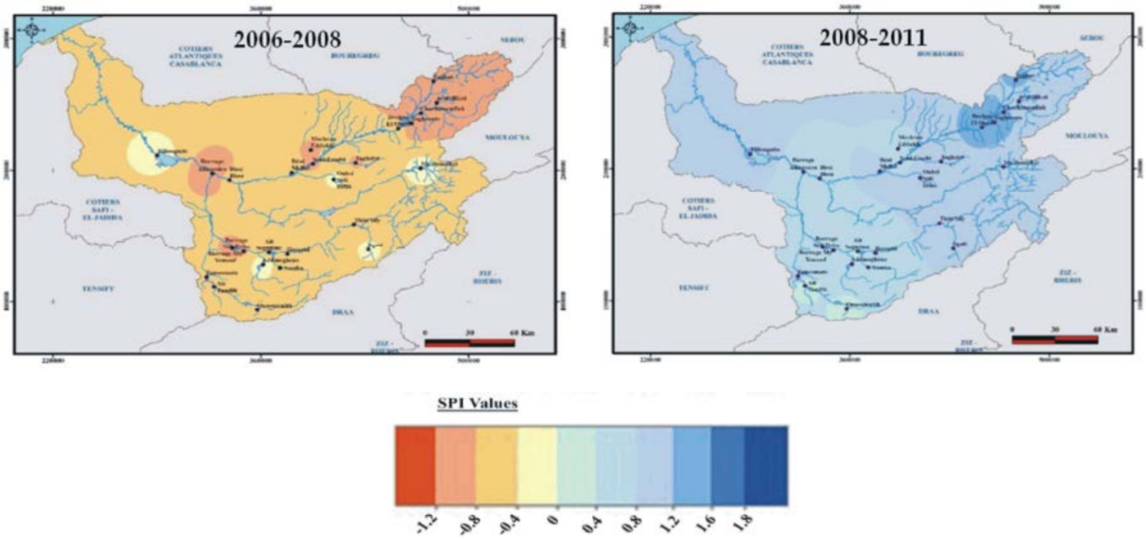

Fig. 11: Spatial distribution of SPI average values for different periods (10 maps where the SPI values are ranging between -1.2 and 1.8)

Table 8: Frequencies (% of stations / years) classes of Standardized Precipitations Index (SPI) for the period 1970-2011

Descriptors	Wet period					Dry period					1969/2011
	1969-1980	1987-1991	1995-1997	2002-2006	2008-2011	1972-1975	1980-1987	1991-1995	1997-2002	2006-2008	
Extremely wet	4%	0	16%	1%	15%	5%	0%	0%	0%	0%	4%
very wet	14%	16%	72%	14%	39%	13%	1%	0%	1%	0%	11%
Moderately wet	45%	49%	12%	52%	39%	23%	17%	0%	23%	0%	32%
Moderate drought	33%	32%	0%	18%	8%	51%	53%	96%	60%	56%	38%
Severe drought	3%	1%	0%	15%	0%	7%	29%	4%	16%	44%	15%
Extreme drought	1%	2%	0%	0%	0%	1%	1%	0%	0%	0%	1%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

extreme droughts. However, moderate droughts are largely dominant in almost all dry periods (40-60% of cases). In this study, the characterization of the meteorological drought using Standardized Precipitation Index (SPI) showed that during the 40 years of recorded rainfall, the OumEr-Rbia basin was affected by 53% of dry periods. The most dominant type of droughts is moderate (38%), while 15% is of severe droughts (Table 8), but the rest of the period types is distributed between moderately wet (32%), very wet (11%) and extremely wet (4%).

Case 2 - Rmel-O. Ogbane aquifer: The Rmel-O. Ogbane is unconfined coastal aquifer of the Loukkos hydraulic basin located near Larache city in the north of Morocco (Figure 12) and is generally very well known for their role in industrial, economic and social development of the area. Furthermore, in semi-arid areas of the country, GW is the only resource that supplies the urban and rural population for domestic consumption. The rain average decline due to the impacts of CC and causes the recurrent drought, decreases in recharge, which directly affects the GW level. This is coupled with EOP rates, ranging from 14.6 million (M) m^3 in 1961/62 to 21.52 Mm^3 in 2015/16 from the Rmel-O. Ogbane coastal aquifer that are used for industrial and drinking water supply for rural, urban areas and irrigation. This situation has led to a major decline in the GW levels and may eventually cause a deficit water balance of the aquifer as well as a degradation of the freshwater quality by SWI on the coastal plains, which poses serious threat to future water supply. Hence, effective management of GW resources in this aquifer system is necessary and taking into account the impacts of CC and Sea Level Rise (SLR). It can be made by developing a regional GW flow model that allows us to understand the conditions that govern the behaviour of freshwater/saltwater transition zone in the coastal aquifer subject to the various input conditions. These tools help the regional water resources authorities for planning economic and water resources development.

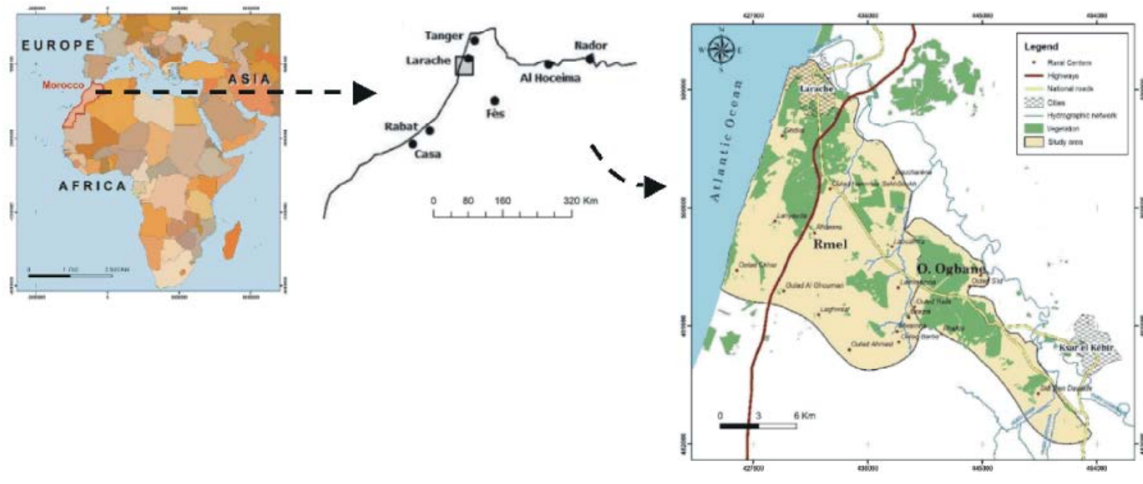

Fig. 12: Location map of the study area of the Loukkos basin

The methodology consists of three main steps: *(1) to begin with, analysing some climate data from weather stations and collect future predicted CC datasets with temperature and precipitation variables regarding Rmel-O. Ogbane area in Morocco from 2017 to 2050, (2) Secondly, based on this scenario and the present situation, evapotranspiration and rainfall are exploited to estimate recharge for the period 2017-2050 by using Thornthwaite method. (3) Finally, the monthly recharge outputs from Thornthwaite method is then used in a three-dimensional SEAWAT model to simulate variable-density GW flow and transport taking into account the impact of SLR. The developed model is capable to better understand the hydrodynamic functioning of the hydrogeological system by assessing the components of the GW mass balance, to determinate the spatial distribution of the hydrogeological parameters and to test planning management scenarios based on various economic assumptions.*

Tasks in the upper part of the chart (Figure 13) assemble several climate data sets for current and future predicted conditions, which are used to simulate recharge using Thornthwaite method [13]. This monthly recharge is then used in a three-dimensional SEAWAT model to simulate transient saturated variable-density GW flow to Assess and Predict the CC Impacts on Water Resources and Socio-Economic vulnerability.

Projected Trends of Some Time Series Data: The annual average measured rainfall in the Loukkos basin at Laouamra station shows a clear seasonal irregularity (Figure 14). Generally, these seasonal variations using 12-month moving average indicate an increase over the last six decades with the most important intensity during the 96s, 97s and 2010. The monthly values of the temperature in the Loukkos basin indicate an increase of temperature during the last four decades since the 1983's (Figure 15). Projected temperature and precipitation are obtained respectively from RACMO22T and HIRHAM5 Regional Climate Models (RCMs) under Representative Concentration Pathways (RCP) 4.5 scenario. Those projections show a reduction in precipitation of 16.7% (Figure 14) and an increase in temperature of about 0.45 °C (Figure 15). By examining these projections, we see that for about 20 years, between 2017 and 2035, the study area will be affected by an increase in rainfall. Then come the 40s of the 21st century, especially 2040, 2042 and 2043, a huge decrease in the amount of rain will affect the study area. Currently, the impact of CC in the Loukkos basin cause the recurrent droughts and decrease in recharge directly will affect the GW level in the aquifer and will lower more the water table which is already at present in a continuous GW level decrease (Figure 16).

Sea Level Rise: The evolution of global mean sea-level over the 20th and 21st centuries is shown in Figure 17 [14]. Since the end of the last deglaciation ~3000 years ago, the mean of sea level endured nearly stable. The red curve is plotted based on tide-gauge measurements available since the late 19th century and indicates that sea level has risen by an average of 1.7 ± 0.3 mm/year since 1950. Since the early 1990s, SLR has been routinely measured by high-precision altimeter satellites. The black curve represents the altimetry record zoomed over the 1993–2009 time span, the mean rate of SLR amounts to 3.3 ± 0.4 mm/year, suggesting that SLR is accelerating. Projections for the 21st century are also shown where the shaded light blue zone represents IPCC projections for the greenhouse gas

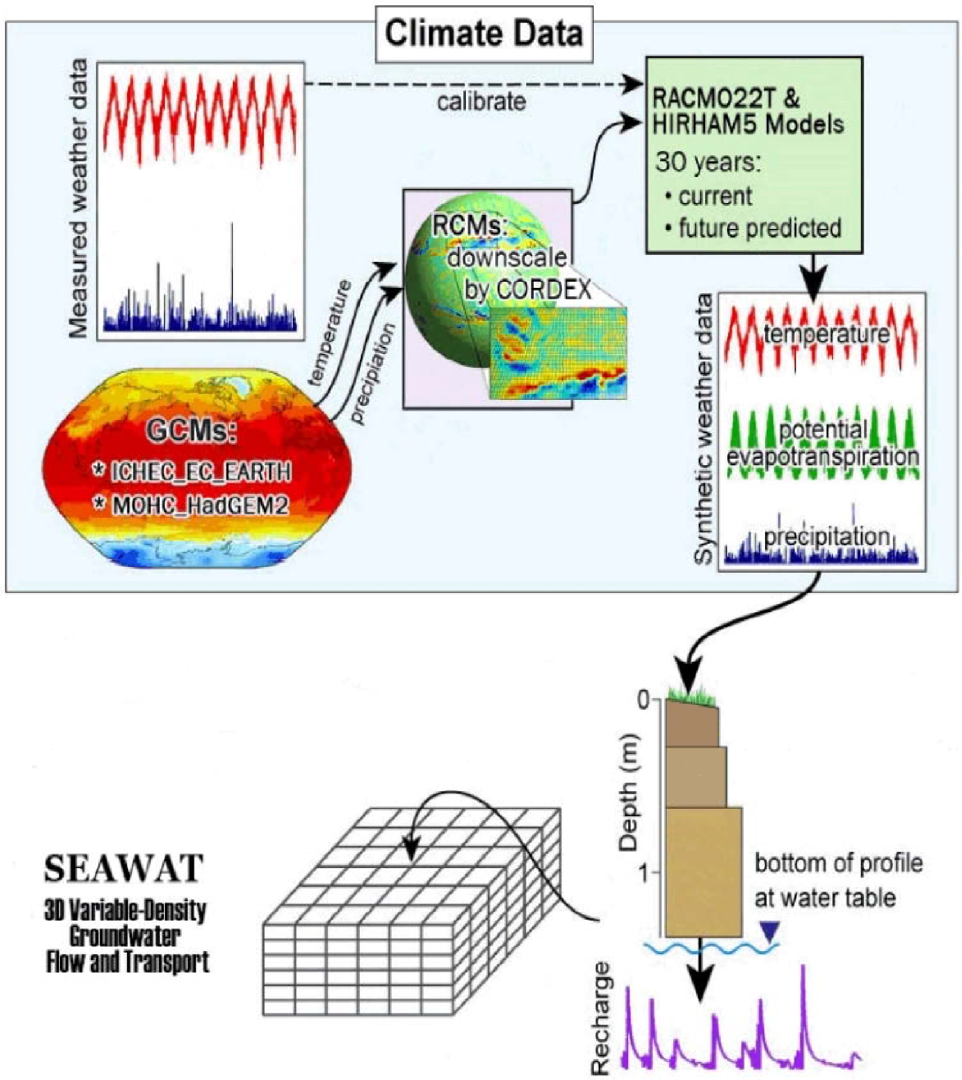

Fig. 13: Flow chart of tasks showing coupled Regional Climate Models and Groundwater Models

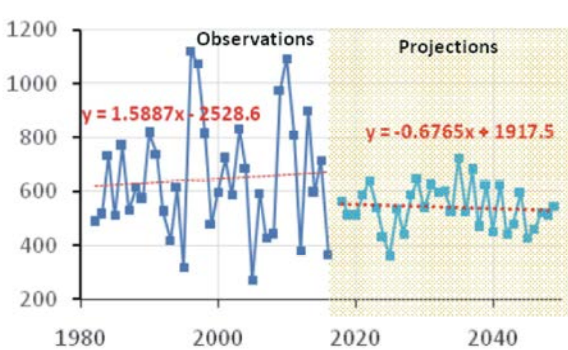

Fig. 14: Seasonal variation of precipitation (from 1982–2016 (measured) to 2017-2050 (predicted) at Laouamra station in the Loukkos basin.

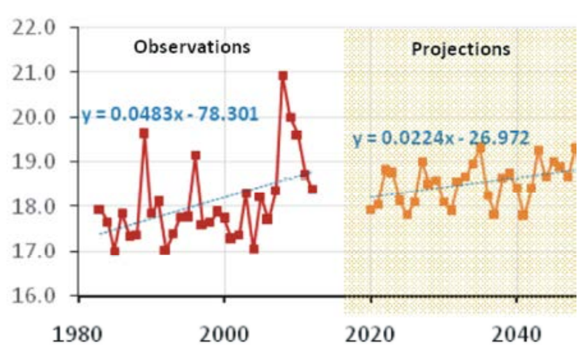

Fig. 15: Seasonal variation of temperature (1983- 2012 (measured) to 2017-2050 (predicted) at Laouamra station in the Loukkos basin.

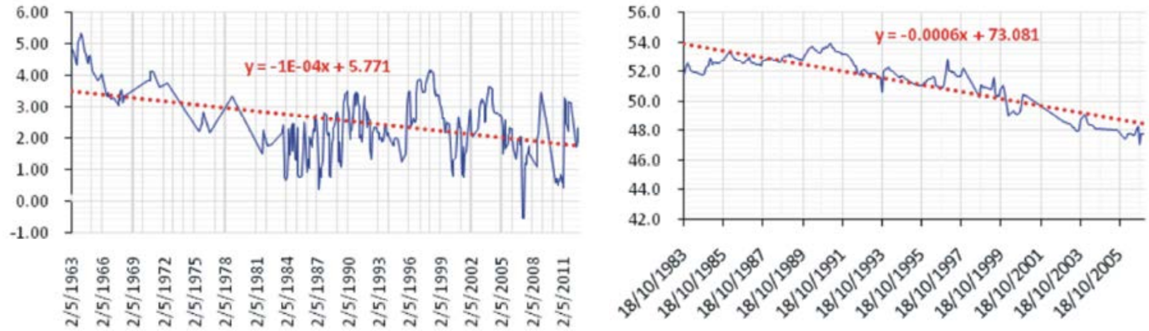

Fig. 16: Decrease in water table obtained from monitoring of 2 representative wells located in the centre (1407/3) and in the coast (342/3) of the Rmel-O. Ogbane aquifer.

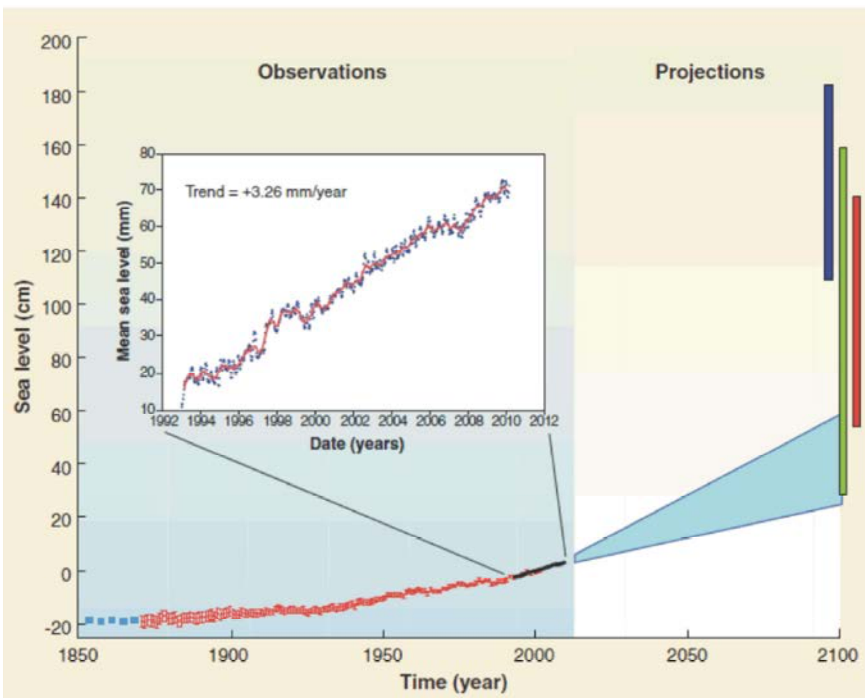

Fig. 17: Global mean of sea level evolution over the 20th, 21st and projections for the 21st centuries [14]

emission scenario. Global sea-level are controlled by two main factors that contribute to SLR. Firstly, *thermal expansion of sea water due to ocean warming*. Secondly, *input to water mass from land ice melt and land water reservoirs* [15].

The Assessment Report of the Intergovernmental Panel on CC (IPCC) projected that global sea level will rise by up to ~60 cm by 2100 in response to ocean warming and glaciers melting [15]. For our study area, we deduce that the sea level will rise linearly by up from ~6.45 cm by 2017 to ~21.3 cm by 2040. This change in the SLR in our study area is taken into account in our modelling step of groundwater flow and seawater intrusion into the aquifer.

Recharge: The predicted climatic parameters for the period 2017-2050 have been used to calculate the potential evapotranspiration by the Thornthwaite method. Potential recharge was defined as the difference between precipitation and potential evapotranspiration on a monthly basis. Recharge variation was computed considering the changes in precipitation (P) and potential evapotranspiration (ETP), where the ETP is computed by the Thornthwaite equation, as a function of temperature (T):

$$SPI = 16.k.\left(10.\frac{T}{I}\right)^{*}$$

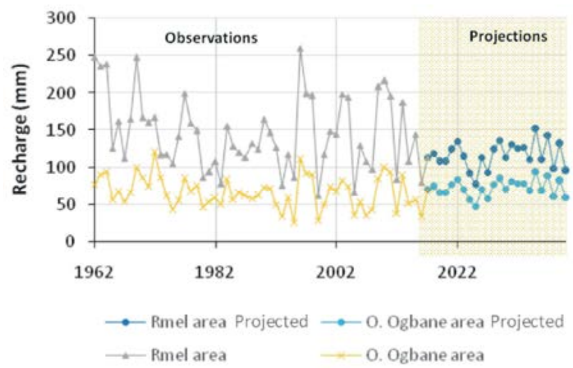

Fig. 18: Recharge calculated by Thornthwaite method in the Rmel-O. Ogbane area based on the observation and projection data

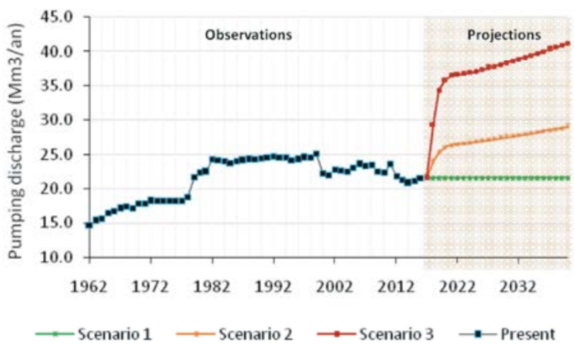

Fig. 19: Pumping discharge variation (1962-207) and projected scenarios (2017-2040) in the Rmel-O. Ogbane area

where T is the mean temperature for the month (in °C), I is the annual thermal index, i.e. the sum of monthly indices i[i = $(T/5)^{1.514}$], k is a correction factor which depends on latitude and month and a is

$$0.49 + 0.0179 * I – 0.0000771 * I^2 + 0.0000\ 00675 * I^3$$

Natural recharge of the Rmel aquifer by infiltration of rainfall is assumed to be uniform over the entire extension with an effective infiltration coefficient estimated at 21% on average (calculated by Thornthwaite method). In the O.Ogbane area, hydromorphic clay (known locally by Tirs) soils appear to be the least permeable. The natural recharge of the aquifer by rain infiltration is supposed to be uniform over the whole extension of the aquifer with an effective infiltration coefficient estimated at 13% [16]. Figure 18 shows that for about 20 years, from 2017 to 2035, the groundwater level of Rmel-O.Ogbane aquifer will be affected by an increase in natural recharge. Then come the 40s of the 21st century, especially 2040, 2042 and 2043, a large decrease in the amount of rain will affect the natural recharge of the groundwater level in the study area.

Pumping Discharge: Three planning scenario schemes were used to simulate the future changes in drawdown and salinity concentrations in a period of 24 years (Figure 19). The *first scenario* assumes that the same conditions are maintained and the pumping from the aquifer of about 21.52 Mm^3/y will continues constant until 2040. The future increased water demand will be provided by surface water or by a desalination plant. The evolution of the GW quality of the aquifer is also analysed in order to define the affected area by seawater intrusion. The *second scenario* consists of increasing pumping rates to satisfy the increasing water demand of the Larache population until 2040. The *third scenario* considers increases of more GW abstractions until 2040 to satisfy the water demand of both urban centres, Larache and Ksar El Kebir cities. Figure 19 shows the 3 pumping scenarios and their evolution until 2040.

Numerical modelling of seawater intrusion: A density dependent numerical model was built to simulate the flow and transport behaviour of the aquifer. It is used to study seawater intrusion in the Rmel-O. Ogbane coastal aquifer. A finite difference model was designed by means of the Visual Modflow using the SEAWAT code [17] resolving Equation (1) [18] for a period from 1962 to 2040, where flow and transport are coupled though the dependence of the density and dynamic viscosity on the salinity of the GW. The simulation period is based on various GW management scenarios established by ONEE at year 2016 [19] and ranging from 2017 to 2040. The numerical model considers three vertical layers to represent accurately the density variation within the aquifer depth. The model was extended one to two kilometers into the Atlantic Ocean, where a constant head and constant salinity boundary was imposed, taking into account the SLR. Figures 20 and 21 show the results of the predicted of drawdown and saltwater volumes intruded into the aquifer.

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(V_i C) - \frac{q_s C_s}{\theta} + \sum_{k=1}^{N} R_k \qquad (1)$$

Scenario 1, which considers that the current pumping is maintained and future water demand will be provided by surface water or by a desalination plant, show less impacts on the renewable resources and the water quality of the Rmel-O.Ogbane aquifer. Indeed, we will note decrease of the SWI volume in 2020 until 2040 (Figure 20.b), which is directly associated to the increase

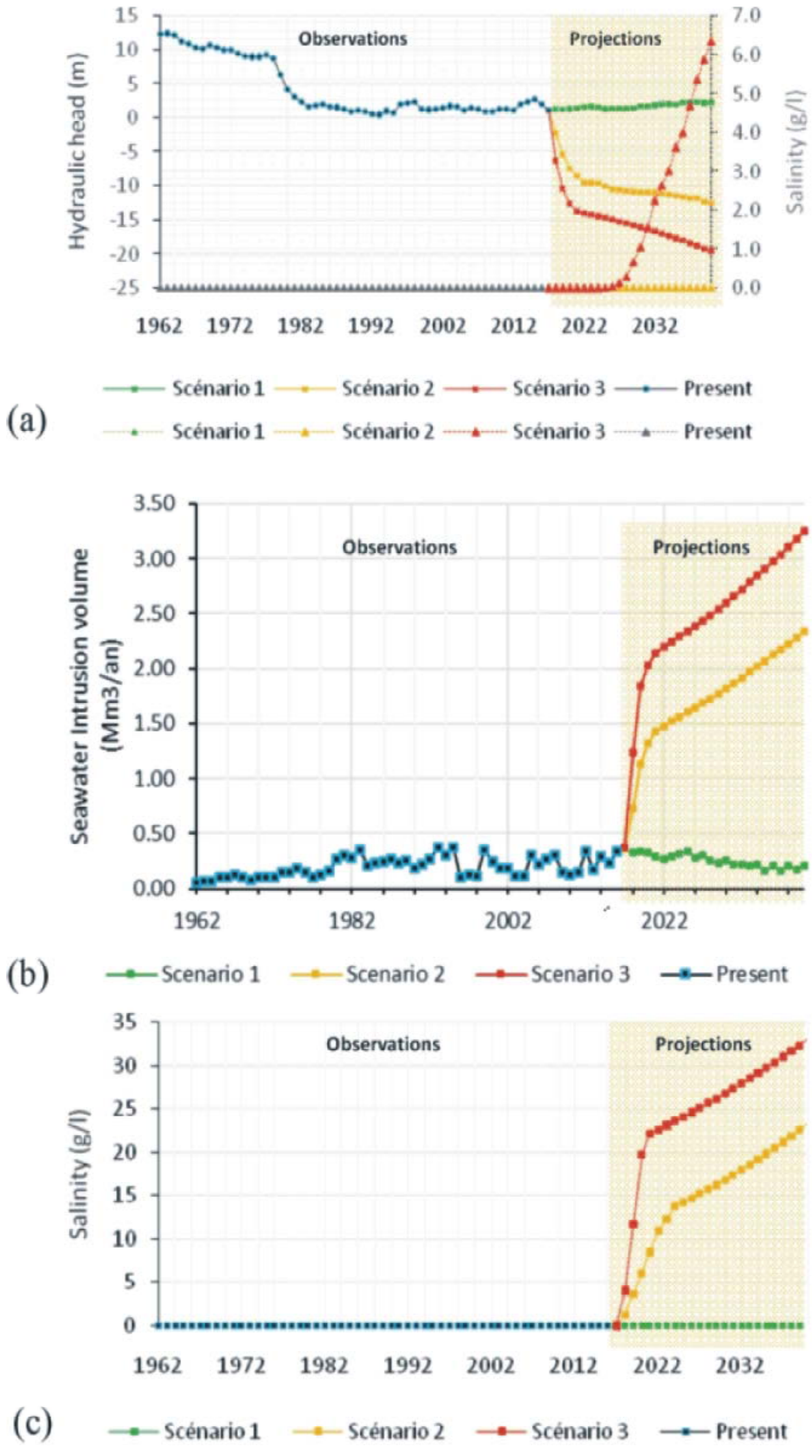

Fig. 20: a) Hydraulic head and salinity at piezometer 438/3 (located near the well field); b) Evolution of seawater intrusion in the Rmel-O.Ogbane aquifer; and c) Predicted salinityin the lower Layer at piezometer 1380/3 (located at 1.5 km far away from the coast).

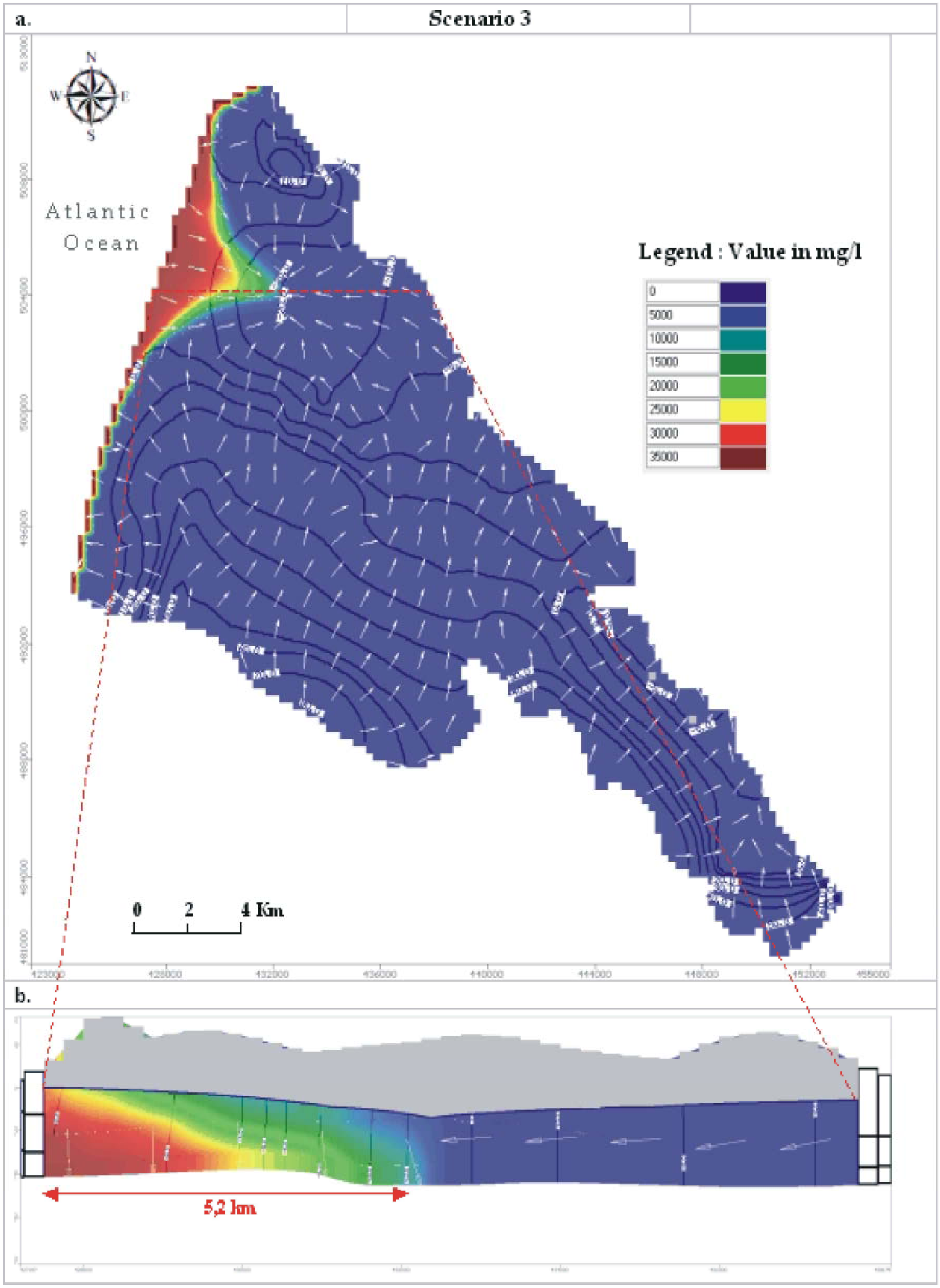

Fig. 21: Calculated piezometry and salinity for Scenario 3, a) Plan view of salinity simulated in 2040 for layer 3 and b) Transversal section of simulated salinity.

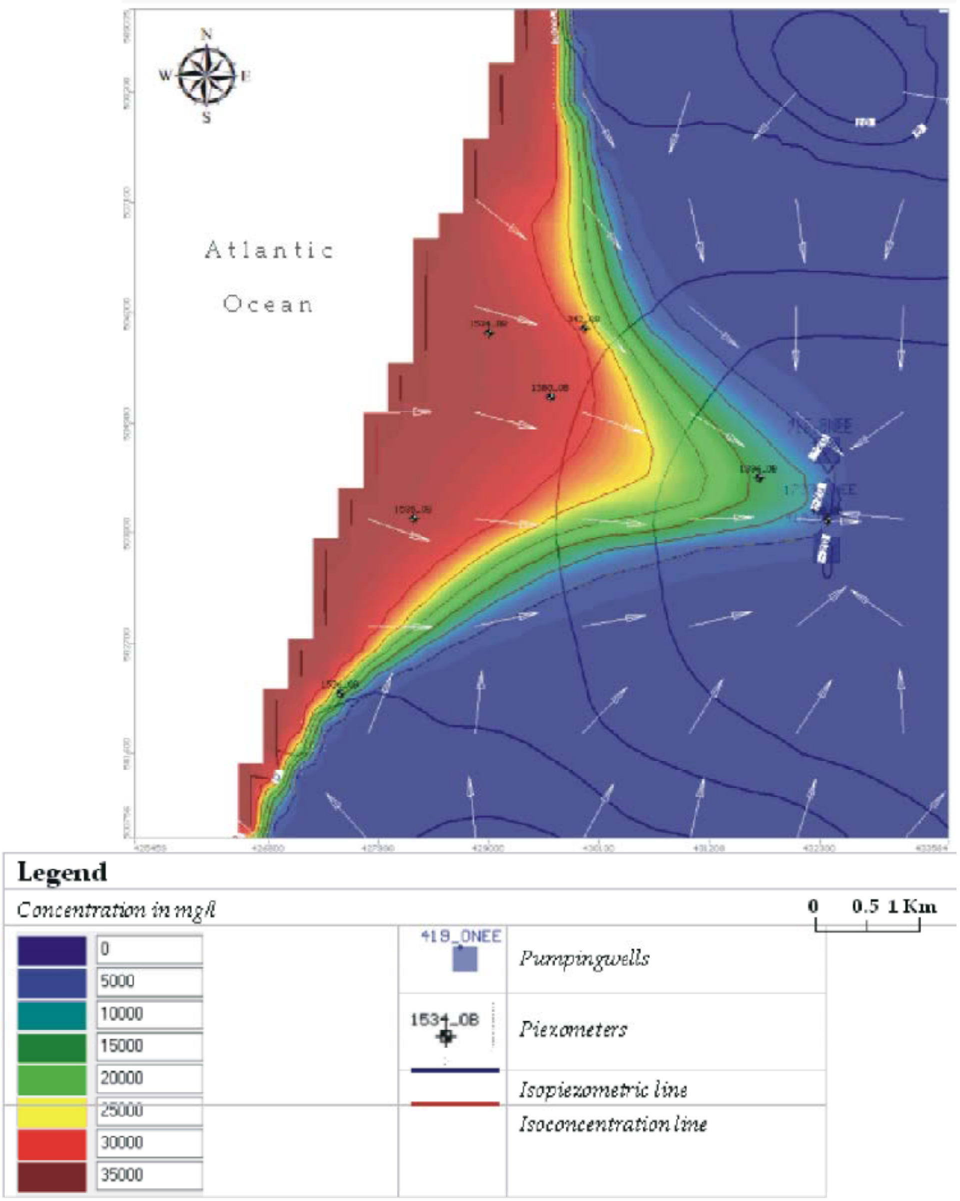

Fig. 22: Results from the 3rd scenario on seawater intrusion extent covering the northwestern sector of the study area and location of contaminated piezometers and pumping wells by 2040.

in hydraulic head (Figure 20.a) due to increased predicted recharge from 2017 to 2040 in the study area. Figure 20.c confirms also that the salinity concentration will be almost zero at piezometer 1380/3.

Scenario 2 shows that the salinity will increase sharply in the northwestern sector closer to the shoreline. The maximum extent of seawater intrusion will increase to 3.5 km deeper in the aquifer. The SWI volume intruded in the aquifer increases also steadily (Figure 20.b), while the GW level will continue to decline reaching maximum values around -10 m (Figure 20.a). However, the seawater would not reach the first group of well field in 2040. The salinity concentration is also expected to rise to reach values around 20 g/l at piezometer 1380/3 (Figure 20.c).

Scenario 3 is the pessimist one and also shows that by 2040 there will be more decrease in hydraulic heads due to intensive pumping discharge to satisfy the water demand of the two urban centres. Indeed, the hydraulic heads will reach negative values around -20 m at the main ONEE well field area (Figure 20.a), where the drawdown will increase by 25 m, which is highly significant. The aquifer is also contaminated by SWI in the NW sector of the coastal part, in which the toe would reach about 5.2 km inland with an invaded area of about 31 km^2 (Figure 21.a) and will be intruded with high salinity (15–25 g/l) in Layer 3 (Figure 21.b). As a consequence, seawater would reach seven observation wells (1534/3, 1535/3, 1536/3, 1380/3, 342/3, 1396/3 and 438/3) and four pumping wells (417/3, 419/3, 718/3 and 1737/3) gradually in 2040. Figure 22 shows clearly this seawater intrusion extend and the locations of the contaminated observation and ONNEE pumping wells. The expected salinity, greater than 2g/l, will be already reached in 2032 and will continue to increase up to 6 g/l by 2040 (Figure 20.a). A comparison between 2nd and 3rd scenarios, indicates that the salinity is expected to rise by 2040 from 20 to 30 g/l at piezometer 1380/3 located at 1.5 km far away from the coast (Figure 20.c).

CONCLUSIONS

For the Mediterranean study area (Ghis-Nekkor plain), the situation of increasing temperature and decreasing precipitation anticipate more droughts in the area as it has been shown through the values of the SPI. In this study, the outputs of the Hirham5 and Racmo22T RCMs have been employed for the estimation of future precipitation and temperature. The past and future projection of the latter parameters at the Ghis-Nekkor plain was used for the estimation of the SPI under the RCP 4.5 scenario. The analysis of drought intensity showed that the study area is more prone to both moderate and severe droughts but less prone to extreme drought. In fact, the rate predicted of drought is about 12% by 2070, which represents the double compared to the period (1982-2012). The results indicated that the climate change will affect drought frequency in the Ghis-Nekkor area and consequently its economy, social life, agriculture and environment. The increase of the frequency of drought would also impact the economy, in the Ghis-Nekkor plain. Thus, an impact study should be planned to anticipate the socio-economic strategies to be set-up and implemented.

For the Atlantic OumEr-Rbia hydraulic basin and based on the results of this research work, we can summarize that a drought study was investigated, using monthly precipitation time series from 25 rainfall stations during the period of 1970-2011. The Standardized Precipitation Index (SPI) is used to evaluate drought characteristics, frequency and duration. The spatial and temporal distribution of meteorological drought was also studied in the OumEr-Rbia basin over the last four decades, using Geographical Information System (GIS) to map the spatial extent of droughts within time steps. The obtained results show that during these last forty years, the OumEr-Rbia basin experienced dry periods from 1980 to 1987, from 1991 to 1995, from 1997 to 2002 and from 2006 to 2008; and their intensity varies from moderate to severe. The examination of drought years reveals a relatively high frequency and large spatial extent of droughts which can take two to five consecutive dry years covering the entire basin area with very limited sectors. Generally, the OumEr-Rbia basin was affected by 53% of dry periods. The most dominant type of droughts is moderate (38%), while 15% is of severe droughts and took place especially in North East of the study area. We can conclude that, based on the SPI values and their mapping, the OumEr-Rbia basin is highly vulnerable to drought for which the duration and intensity vary considerably. Drought is therefore a recurrent phenomenon but difficult to predict over time for its mitigation. When it occurs, it has negative impact on water resources with less water storage causing water scarcity in several areas of the catchment. However, the results obtained from this study, is of great importance for water resources management in the OumEr-Rbia basin, as it will assist the regional water managers for water resources planning, protection and rational management. Further research work in the catchment is going on to assess the impact of climate change on water resources using climate modelling projections.

For the Rmel coastal aquifer, a numerical model of the shallow unconfined aquifer was developed with the aim of studying the impacts of CC due to increasing of temperatures and sea level rise during the 21st century. Regional predictions under RCP 4.5 scenario of climatic parameters were used. The variation in recharge was determined by taking into account the anticipated variations in precipitation and in temperature. The numerical simulations were conducted for a period of approximately 78 years and dealt with seawater intrusion corresponding to various combinations of groundwater extraction, predicted climatic parameters and sea level rise. The results show that groundwater extraction associated to CC is the predominant driver of seawater intrusion in the study aquifer. Also, the decline in recharge and the rise in sea level due to the climate change accelerate the saltwater intrusion into the aquifers, which reduces the fresh groundwater resources. The main effect of this seawater intrusion in the Rmel-O. Ogbane aquifer will be the excessive over pumping that will decrease the renewable resources, which with the pessimist scenario may be increased by 30% of current values. The water quality will be affected mostly in the ONEE pumping area, immediately adjacent to the seashore. However, regular monitoring of the seven piezometers located at northwestern sector near the shoreline should be conducted frequently to control seawater intrusion. Improvement of the situation will be reinforced by the surface water use from irrigation, a desalination plant for drinking water supply and artificial recharge of the aquifer. This will improve significantly the groundwater quality in the coastal sectors of the aquifer and will protect freshwater from seawater intrusion.

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