Frontiers in Science and Engineering
International Journal

Edited by The Hassan II Academy of Science and Technology of Morocco

Earth, Water and Oceans, Environmental Sciences

Climate variability, change and impact in southern Morocco: Evidence and understanding

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Volume 11 - Number 2 - 2021

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Frontiers in Science and Engineering
International Journal
Volume 11 - Number 2 - 2021
Edited by The Hassan II Academy of Science and Technology of Morocco

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December 2021

© Hassan II Academy Press

This special issue is carried out within the framework of CHARISMA project with the assistance of the Hassan II Academy of Science and Technology

Cover photo : Panoramic View of Ifni Lake, western High Atlas, Morocco

Dépôt légal : 2012 PE 0007
ISSN : 2028 - 7615

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Email : fse@academiesciences.ma
www.fsejournal.org

Layout by : AGRI-BYS S.A.R.L
Printed by : Imprimerie LAWNE,11, rue Dakar, 10040 - Rabat

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FORWORD

Thanks to its location, Morocco presents a great geographical, geological, and climatic diversity in several respects. However, in its southern part, the country is characterized by arid and semi-arid climatic conditions more or less severe. Environmental and biodiversity features are strongly impacted by the combination of climate variability and hydrologic stress. Drylands cover over 90% of the land area due to low and irregular rainfall and high potential evaporation that contribute to extremely high water deficits in this area. The climate of this large region is affected by global processes that are modified by regional and local factors. Changes in Atlantic Ocean conditions and land during the past caused changes in vegetation and human adaptations, especially during the Holocene and recent decades.

To anticipate the future behavior of dynamic drylands at the global scale, significantly impacted by global warming, studies of the past can yield insights into how climatic conditions evolved in response to global forcing. In addition, these looks into the prehistoric record can reveal how past changes have impacted continental and marine ecosystems and how wildlife and early human societies have adapted to these changes through the phenomena of relocation and migration.

However, instrumental records are scarce in these regions, and when available, they are not long enough to give a complete picture of natural climatic variability. Therefore, it is essential to examine pre-instrumental records of climatic variability through natural and historical paleoclimate archives to understand the amplitudes of climate changes, how these changes occurred, and the driving mechanisms on regional and global scales factors control them. These multiple evidence lines can inform about their impacts on natural resources and what former human populations have taken adaptation mechanisms. It could be valued today in a world subject to the effects of anthropogenic climate change that are especially significant in the hypersensitive arid zones.

In recent years, the international CHARISMA network has made a special effort to reconstruct past and recent climate and its variability and impacts using multi-proxy approaches to investigate paleoclimate archives of the last 2000 years with a focus on the last century that has had an accompanying instrumental record. Results from this program and those of other studies provide a rich interpretive background in the dry south of Morocco.

This special issue brings together reports of underlying current paleoclimate records, archeological evidence, and histories of human adaptation during the current epoch.

The emphasis of this special issue is to present the key information concerning some of the known changes and variations in arid zone ecosystems and address the influence of oceanic and atmosphere teleconnections on climate variations in southern Morocco and consequent societal adaptions. In addition, interlinked data between natural climate variations and their impacts allows addressing a new conceptual model that may prepare future climate-change scenarios in the Moroccan drylands.

The nine chapters of this special issue include contributions from different records ranging from natural archives to climate modeling to social analysis of behavior concerning climate change. As listed in the content, we have organized them as two introductory papers focused on the reconstruction of paleoclimate and the consequent paleoenvironmental changes inferred from speleothems and accompanying archeological evidence of human behavioral changes.

The first contribution promotes a better understanding of the roles of the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillations (AMO) on changes in the distribution of precipitation in southern Morocco. The second paper documents archaeological evidence for changes in the environment and human behavior during the Holocene. The results of both papers allow us to propose scenarios of adaptation to climate change that can be used as a model for structuring future human behavior to climate change. The special issue continues with more comprehensive papers and a transition into progressively more focused on specific locations and shorter time intervals. The next three of the nine articles deal with water resources management at different temporal and spatial scales. Compared to the first two, we can better understand the importance of observations on long scales for the management of resources. Likewise, for the management of water resources, papers dealing with desertification and land degradation make the transition towards the relation between climate change, biodiversity, and soils. Finally, we finish this special issue with articles that provide relevant analyses of the importance of preserving resources and biodiversity in the dynamics of emerging diseases.

This first compendium of papers from the same region allows us to trace scientific research's state of the art in southern Morocco. In addition, by their content, they motivate us to make an effort to propose a transdisciplinary and trans-sectoral synthesis for a sustainability science that is essential to develop solutions for the impacts of climate change in the future.

Lhoussaine BOUCHAOU & Abdelfettah SIFEDDINE
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Acknowledgments

Our deepest thanks go first to the Hassan II academy of science and Technology, to the Ibn Zohr University of Agadir, and to “L'Institut de Recherche pour le Développement (IRD)”, who encouraged and supported us within the International Network international CHARISMA. This Network involves the University of Ibn Zohr (Agadir); Sultan Moulay Slimane University (Beni Mellal); Mohammed V University of Rabat; Mohammed VI Polytechnic University, São Paulo University-Brazil; Instituto Potosino de Investigación Científica y Tecnológica (IPICYT), Mexico; Universidad Nacional Autónoma de México (UNAM). We also thank the Ibn Zohr-IRD cooperative projects CLIMPACTE (Changements climatiques passés, présents, futurs et impacts en Afrique de l’Ouest et du Nord: Observations et Modélisations).
This work is a production part of the consortium founded between Ibn zohr University of Agadir, l’Institut de Recherche pour le Développement (IRD), Mohammed VI Polytechnic University (UM6P), Mohamed V University of Rabat, Cadi Ayyad University of Marrakesh, Ibn Tofail University of Kénitra, and Sultan My Slimane university of Beni Mellal.

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Speleothem-based paleoclimate research in South Morocco: Interest and perspectives

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Abstract. Paleoclimate information is still lacking in key regions to understand the functioning of some of the main components of Earth's climate system. In NW Africa, the use of speleothems as a natural archive of past environmental and climate change gained considerable interest during recent years. From South Morocco, the published speleothem records constitute the only terrestrial paleoclimate information, which spans the Holocene with a high resolution. A multi-proxy speleothem record from Ifoulki cave in SW Morocco indicates relatively dry conditions during the Medieval Climate Anomaly (MCA), wetter conditions during the second part of the Little Ice Age (LIA), and a trend towards dry conditions during the current warm period. The local climate variability was modulated by the combined influence of both the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) and the interactions with the Sahara Low, which influenced the moisture flow from the Atlantic Ocean during the last 1000 years. Another multi-speleothem $\delta^{18}O$ from Wintimdouine cave in SW Morocco provides evidence of increased moisture during the mid-Holocene, coincident with the northernmost expansion of the West African Summer Monsoon (WASM) during the African Humid Period (AHP). The discrepancies with speleothem records from Northern Morocco indicate that the High-Atlas Mountains might have established a topographic barrier to the farther expansion of the WASM fringe. The paleoclimate information from South Morocco is still limited to the Holocene whereas speleothems from the region have a promising potential to span the past climate change throughout the Pleistocene with a high resolution.

Keywords: Speleothems, Paleoclimate, NAO, Monsoon, African Humid Period.

1. Introduction

North Africa is a key location to study the interactions between low-latitude African monsoon systems and high-latitude millennial-scale climate change (WELDEAB et al. 2007; TJALLINGII et al. 2008). However, information on climate variability in NW Africa remains however scarce due to the lack of long instrumental datasets that cover key periods in Earth's history. Moreover, the chronologies of most available reconstructions, which cover only parts of the Last Glacial Period, suffer from significant age uncertainties, as they are based on radiocarbon dating and tuning to the Greenland ice core records. High-resolution paleoclimate reconstructions in this region are thus essential to increase our understanding of hydroclimate variability on various timescales and discuss potential forcing mechanisms and related atmospheric circulation changes in the remote past beyond the industrial period. Thus, paleoclimate research based on speleothems in Morocco in recent years (WASSENBURG et al. 2013; WASSENBURG et al. 2016; AIT BRAHIM et al. 2017; 2018; 2019a; 2019b; SHA et al. 2019) is one way to explain this situation.

Indeed, NW Africa benefits from a wide range of carbonate formations, including karst systems (AIT BRAHIM et al. 2019b), which offer the opportunity to access a variety of speleothem forms that we can use in paleoclimate research. Speleothems can be

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DOI: https://doi.org/10.34874/IMIST.PRSM/fsejournal-v11i2.28990

precisely dated and provide high-resolution climate records of climate and environmental variability during the past (CHENG et al. 2016).

This article presents an overview of the speleothem-based paleoclimate research in South Morocco and the interest in developing this research field in NW Africa. We discuss the previously published high-resolution and well-dated records from speleothems collected from Ifoulki and Wintimdouine caves in SW Morocco (Fig. 1) (AIT BRAHIM et al. 2017; SHA et al. 2019). The South Moroccan speleothem records allow testing the presence of large-scale atmospheric teleconnections linking hydro-climate changes in sub-Saharan regions with the Northern Hemisphere cold events and the low-latitude African monsoon systems. However, the published work has been only focused on the Holocene and the last millennium.

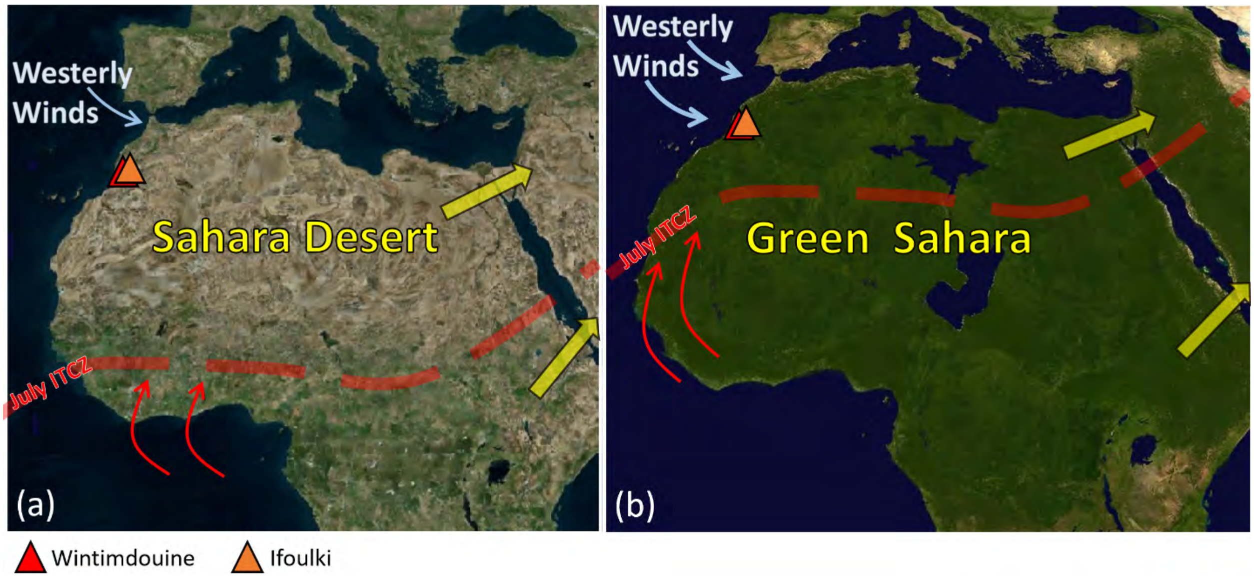

Figure 1. Conceptual model of the desert (a) and green (b) Sahara conditions, with their typical positions of the Westerly winds and July Inter-Tropical Convergence Zone (ITCZ). The concept of green Sahara (b) was modified after DEVIANTART (2020) and illustrates mega-lakes with no ecological barriers isolating NW Africa from the rest of the continent. The location of Wintimdouine and Ifoulki caves are indicated (red and oranges triangles). The yellow arrows indicate the most suggested routes for modern humans' migration out-of-Africa through the Nile valley and Bab Al Mandab (TIMMERMANN & FRIEDRICH 2016).

2. Discussion

2.1. Climate variability in SW Morocco during the last millennium

The IFK1 speleothem record from Ifoulki cave reveals substantial decadal to multidecadal oscillations between dry and humid periods, consistent with regional paleo-records with prevailing dry conditions during the Medieval Climate Anomaly (MCA) from 900 to 1350 AD and wetter conditions during the second part of the Little Ice Age (LIA) from 1500 to 1850 AD, and a trend towards dry conditions during the current warm period (Fig. 2) (AIT BRAHIM et al. 2017). The MCA-LIA transition is generally consistent with the North Atlantic Oscillation (NAO) phases, which were relatively more positive during the MCA than during the LIA. However, several discrepancies were observed in the detailed comparison between the reconstructed NAO index and the IFK1 record. These have been explained by other factors that also influenced the hydroclimate in SW Morocco during the last millennium.

The multi-decadal variability observed in the IFK1 record points to frequencies related to the Atlantic Multidecadal Oscillation (AMO) (DELWORTH et al. 2000, ENFIELD & CID-SERRANO 2010). Indeed, the MCA is dominated by warm sea surface temperature(SST) anomalies in the North Atlantic region (KEIGWIN 1996), which correspond to a positive phase of the AMO (FENG et al. 2008; MANN et al. 2009). The AMO potentially influences water $\delta^{18}O$ because changes in SST impact isotope fractionation taking place in the moisture source region. The SST in southwestern Morocco is not only dominated by the NAO (MC GREGOR et al. 2007) but also by the land-sea pressure contrast that affects upwelling along the coast of Northwest Africa. Such changes in the coastal SST certainly affected the regional southwest Moroccan climate. The potential link between IFK1 and the SST was explained by opposite signs between air temperature and the coastal SST. The relative increase (decrease) in surface air temperature over land relative to the ocean during the MCA (LIA) would accentuate (weaken) the low-pressure cell over land, whereas a high-pressure centre develops offshore. Thus, the land-sea pressure gradient co-varies with SST in the northwest African coast and warm (cold) surface air temperature over the Eurasian continent and the Sahara landmass strengthens (weakens) the Sahara Low (HAARSHMA et al. 2005).

2.2. The African Humid Period recorded by SW Moroccan speleothems

The South Moroccan Holocene paleoclimate record is described by a composite of $\delta^{18}O$ speleothem records from the Wintimdouine cave (hereafter the WIN record) (Fig. 3) (SHA et al. 2019). The WIN record shows a “heavy-light-heavy” pattern throughout the early, middle, and late Holocene. The early Holocene is marked with two abrupt and relatively short wet intervals around 10.5 and 9.8 kyr BP, revealing the moisture increase in NW Africa. The wet conditions became more persistent during the mid-Holocene (9 to 4 kyr BP), consistent with the timing of the Green Sahara and possibly reflecting overall humid conditions. In contrast, the late Holocene is marked by relatively dry conditions. Marine records from NW Africa, within the same latitude as Wintimdouine cave (31°N), also show a dry-wet-dry pattern during the Holocene (HOLZ et al. 2007; TIERNEY et al. 2017), consistent with the heavy-light-heavy pattern recorded by Wintimdouine speleothems. This supports the hypothesis that the West African Summer Monsoon (WASM) reached its northernmost expansion during the Early to Mid-Holocene African Humid Period (AHP) (SHA et al. 2019). A comparison of the WIN record with the Cariaco Basin Ti record (HAUG et al. 2001) suggests that the WASM did not reach 31°N from 11.5 to 9 kyr BP, as indicated by the $\delta^{18}O$ values that are slightly heavier than modern values in the WIN record. The persistent northward shift of the ITCZ from 9 to 4 kyr BP is consistent with the expansion of the WASM further northward during this period.

Interestingly, the speleothem records from North Morocco (~34°N) show a different $\delta^{18}O$ pattern during the Holocene (AIT BRAHIM et al. 2019a). The speleothem $\delta^{18}O$ records from North Morocco provide evidence of positive NAO-like conditions, which would result in dry conditions during the mid-Holocene. In contrast, the early Holocene was characterized by relatively negative NAO-like conditions (AIT BRAHIM et al. 2019a). The differences between North and South Morocco is related to the northward expansion of the WASM, which could only reach as far north as 31°N. This can be explained by the slackening of the WASM

at higher latitudes as well as the topographic barrier established by the High Atlas Mountains (AIT BRAHIM et al. 2016) which could block the WASM-related moisture flow towards North Morocco.

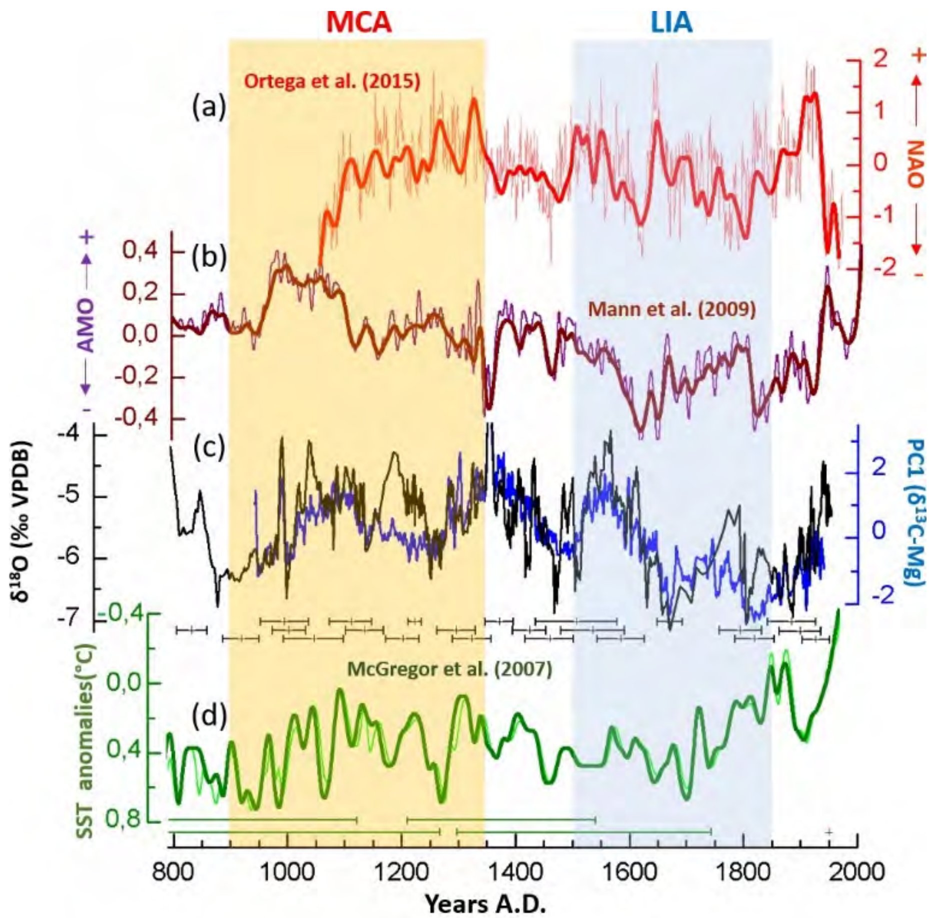

Figure 2. Comparison of the Ifoulki records ($\delta^{18}O$ and PC1 of $\delta^{13}C$ and Mg) (c) with the reconstructed NAO index (a) (ORTEGA et al. 2015), AMO index (b) and SST anomalies (inversed axis) (d) (MCGREGOR et al. 2007) including dating uncertainties. Bold curves correspond to the 10 yrs regular interpolation of each time series. Orange and blue shadings show the timing of the MCA and LIA periods as in Esper et al. (2007), WASSENBURG et al. (2013) and Ait Brahim et al. (2017). (modified after AIT BRAHIM et al. 2017).

2.3. Interest and perspectives for the Pleistocene

The Early to Mid-Holocene AHP is only one among many green Sahara periods, which might have influenced the pre-historic Hominin populations in NW Africa during the Pleistocene. Indeed, archaeological and genetic evidence reveals that anatomically modern humans (AMH) appeared during the Middle Pleistocene in Africa (CANN et al. 1987; MCBREATY & BROOKS 2000; HENSHILWOOD et al. 2001; WHITE et al. 2003; MC DOUGALL et al. 2005; MANICA et al. 2007).

Favourable climatic conditions and access to freshwater have always been major controls on the survival of human populations, which have been present in NW Africa since 300 ka PB (HUBLIN et al. 2017; RICHTER et al. 2017). In the past, changes in the orientation of the Earth's rotation axis resulted in significant hydroclimatic fluctuations in the subtropical Sahara belt of North Africa (DEMENOCAL et al.

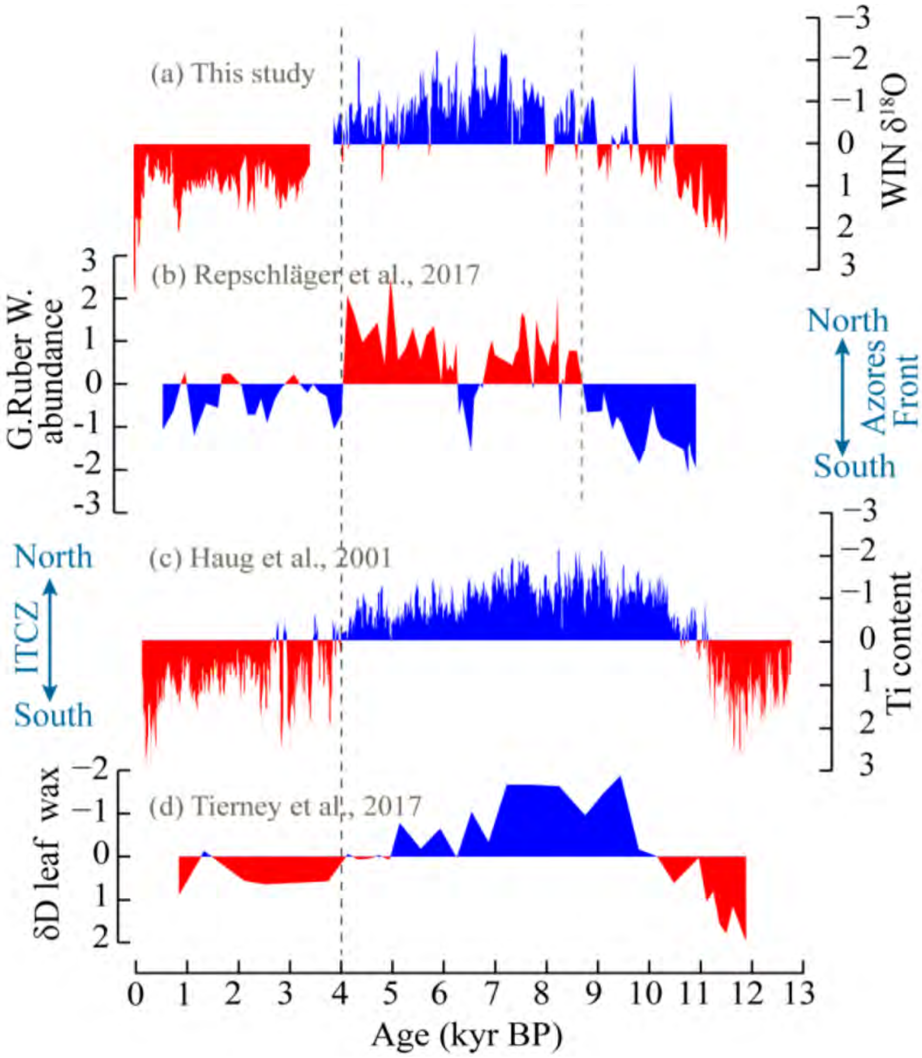

Figure 3. Comparison of the WIN record with other hydroclimate records. (a) The z-scored WIN $\delta^{18}O$ record (30.77°N, 9.49°W) (SHA et al. 2019). (b) Position of the Azores Front based on the abundance of the planktonic foraminifera *Globigerinoides ruber* in the sediment core in the vicinity of the Azores. The high value corresponds to a more northward shift of the Azores Front (REPSCHLÄGER et al. 2017). (c) The z-scored bulk Ti content of Cariaco Basin sediments from ODP site 1002 (10.71°N, 65.17°W). The low value corresponds to the high precipitation amount associated with a more northward mean latitude of the ITCZ (HAUG et al. 2001). (d) The z-scored leaf wax δD record from marine sediment core OCE437-7-GC27 (30.88°N, 10.63°W) (TIERNEY et al. 2017). The dash lines depict the start time of positive NAO-like states and the termination of the AHP (modified after SHA et al. 2019).

2000). Increased monsoonal rainfall and the resultant transformation of a desert into a green Sahara with abundant resources provided favourable conditions for the dispersal and associated genetic flow of early human populations across northern Africa into Eurasia. In contrast, the complex topography of northern Africa might have created refugia during desert Sahara periods or asynchronous wet periods and led to distinct evolutionary features between different populations. However, the exact timing and duration of these green and desert Sahara periods remain poorly documented in terrestrial paleoclimate

records, as most of them are fragmentary and poorly dated. Hence, further research about early human evolution and dispersals requires accurate climate reconstructions. Speleothems from south Morocco have a promising potential to correlate the cyclical greening of the Sahara with archaeological signs of human occupations and expansion within and out of Africa throughout the Middle Stone Age.

3. Conclusions

NW Africa is a key location to investigate the teleconnections between low-latitude monsoon systems and high-latitude abrupt climate change. Hence, climate reconstructions from this region are highly required. In South Morocco particularly, paleoclimate information is only limited to the Holocene, inferred from speleothems from Ifoulki cave and Wintimdouine cave. The high-resolution speleothem records revealed consistently dry and wet conditions during the MCA and the LIA, respectively, and a trend towards dry conditions during the 20th century. The local climate was influenced by the interplay between the NAO, AMO, and the Sahara Low during the last millennium. During the Holocene, the South Moroccan speleothems demonstrated that the WASM reached 31°N in NW Africa during the Early to Mid-Holocene AHP. Despite the overwhelming evidence in favour of previous Green Sahara periods, their spatial extent is still unclear. Hence, new paleoclimate records during periods beyond the Holocene can bring unprecedented insights into the past climate and environmental change and implications on pre-historic populations in the region since the Middle Pleistocene.

Acknowledgements

This work was carried out within the CHARISMA Project with the assistance of the Hassan II Academy of Science and Technology. The authors are grateful to IRD, France, and acknowledge especially support from RD representation in Morocco. We also thank ASA and ASS Associations of Speleologists for their help in the field.

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Potential Interactions between Climate and Prehistoric Populations in Southern Morocco: Insights from Archaeological and Paleoclimatic Evidence

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Abstract. Southern Morocco contains a rich archaeological record: engraving, painted rocks, and funerary monuments. This pre-historic and proto-historical heritage offers valuable information about the environmental context of pre-historic settlements. However, the Southern Moroccan archaeological record suffers from dating scarcity and hence, the difficulty in establishing a reliable chronology. Most archaeological sites date from 7000 to 1000 years BP and are marked by a transition period from a humid to dry climate during the late Holocene. The relatively drier conditions likely resulted in adopting a new lifestyle characterized by cattle ranching, agriculture, and animal domestication. Holocene's enormous climatic oscillations significantly influenced the development of human settlements in the region. The concentration of archaeological archives confirms the existence of sufficient water supply in an area today semi-desertic. Therefore, the sedentarization and the development of well-stylized rock art, in addition to the grouping of funerary monuments or tumuli with complex geometry, mark the wet and rainy periods. Meanwhile, unstable communities and long-distances migration are often the features that characterize the long dry periods.

Key words: Southern Morocco, archaeological record, rock art, tumulus, paleoclimate.

1. Introduction

Climatic variations have left their mark on various supports, such as carbonate concretions in caves and waterfalls, sedimentary deposits in lakes and terraces along ancient rivers. During the Holocene, which marks significant periods of prehistory, protohistory, and history, Southern Morocco went through different climatic periods. These periods are challenging to identify. The content of the numerous archaeological sites (engravings, paintings, and tumuli) illustrates the changes that human societies and animals have undergone in the natural environment and provides useful information to describe the main climatic periods (MANNING & TIMPSON 2014). This region also contains archives and information related to climate change, recorded in speleothems (stalagmites in the many caves in the region). To characterize the potential interactions between climate and human populations during the Holocene, we use the available archaeological evidence of Southern Morocco (rock art and funerary monuments) and the paleoclimatic data obtained from isotopic data ($\delta^{18}O$) recorded on the stalagmites in the caves within the area (AIT BRAHIM et al. 2017; 2019a; 2019b; SHA et al. 2019).

Based on the description of the region's archaeological heritage, through the characterization of different figures and monuments, the climatic change indices of the Holocene have allowed us to understand the climatic environment in which the prehistoric populations lived. Our approach is based on the description of the archeological heritage in the area to identify and characterize the different figures and monuments. After that, and because of the absence of absolute dating, we adopted a relative classification of the various inventoried

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DOI: https://doi.org/10.34874/IMIST.PRSM/fsejournal-v11i2.29015

art traces intending to make a chronology of the historical heritage and discuss its evolution along the covered period.

2. Description of the archaeological heritage in southern Morocco

The study focuses on Southern Morocco, represented by the Draa valley, the Jbel Saghro, and the Sahara (Tan-Tan, Smara and Awserd regions) (Fig. 1), the Anti-Atlas mountain. These pre-Saharan and Saharan regions knew a space heterogeneity occupied by the pre-historic human population and a complex topography from north to south. The archaeological heritage (e.g., engravings, cut stones, rock paintings, rock shelters, and various funerary monuments) is varied and abundant. Many caves content some archeological traces and speleothems.

a. Rock Engravings

Several sites of rock engravings are observed in the pre-Saharan region, along the large wadis and their tributaries (Figs. 1 and 2), which means that Man needs to express his knowledge and beliefs through these engravings (BERAAOUZ 2010).

Most rock engravings are made according to the Tazina style (PICHLER & RODRIGUE 2003; FALESCHINI 1998, GAUTHIER & GAUTHIER 1995). The engravings are polished and represent mainly animals, not exclusively wild since domestic cattle are engraved. Their presentation is often fanciful, with extremities exaggeratedly extended.

In the High Atlas, the main sites of Oukaimeden, Yagour, Azibn'Ikkis, and Jbel Rat are well known for the diversity of metal weapons, horsemen, and oxen representations (RODRIGUE 1999; HOARAU & EWAGUE 2008). However, the themes differ according to the sites. In the valley of Dades Wadi, discs and several Libyco-Berber inscriptions represent the engravings (PICHLER & RODRIGUE 2000). The Ouneine rock carving sites (CATTIN 2013) illustrate the same content as the Atlas sites with daggers, shields, horse hunting scenes, and chariots.

Some bovids engravings are well-preserved in the upstream part of the Massa Wadi, the right bank. Within the Jbel Tizelmi plateau and in the reliefs overhanging Aglou (Lgaada and Boutarigt), south of Tiznit, the engravings mainly depict riders (horsemen), a dromedary figure, and hunting and battle scenes (BRAVIN 2009). In Taouz, the three sites are best known for their hundreds of engraved chariots and diverse wildlife (GAUTHIER & GAUTHIER 2015). The Saghro region is rich in archaeological sites. The most important are those in Aït Ouazik, with a hundred engravings in "Tazina style" deep polished lines, Ikhf n'Ouaroun, and Tazarine (LHOTE 1982; MUZZOLINI 1989; PICHLER & RODRIGUE 2003). The Nkob station includes Libyco-Berber style engravings with several geometric representations, rider figures (horsemen), and animal representations. In Foum Chenna, Tibaskoutine, and Assif Wirgane…, the Draa Valley exhibits some exceptionally diverse engravings in fauna and Libyco-Berber inscriptions (PICHLER & RODRIGUE 2003).

From Foum Zguid to Foum El Hassane, several sites are present. These sites are located mainly both along the major tributaries of the Draa valley and Jbel Bani. For instance, we find Kebch, Mrimina, Wadis, Tissint, Akka, Tamanart, and south of Aït Ouabelli. Tiggane, Meskaou Wadis, Tiouaziouine, Imgradn'Tayali and Metgourine, Tahouast, Imin'Tart, Moumersal, and Ighir N'Ighnain are the main sites in the Tata region (RODRIGUE 2002).

In the Ighrem region (Ouaremdaz, Imaredn, Had Walkadi), the engravings represent cups, signs, domestic animals, Lybico-Berber letters, and daggers. In Tleta Tagmoute (Imaoun), there are several sites with domestic bovids, Libyco-Berber inscriptions, wild animals, and chariots (SIMONEAU 1977; SEARIGHT 1999; PICHLER 1999, 2000a).

In the Guelmim region, on the Noun Wadi and the EçÇayyad Wadi banks, the engravings are dominated by animal representations (wild fauna and domestic cattle), broadly linked to the Neolithic (BOKBOT et al. 2007).

At the engraving sites in the Noun Wadi basin, the dating of tests decorated with an antelope provided an uncalibrated radiocarbon age of 2790 ± 105 BP (GRÉBÉNART 1975).

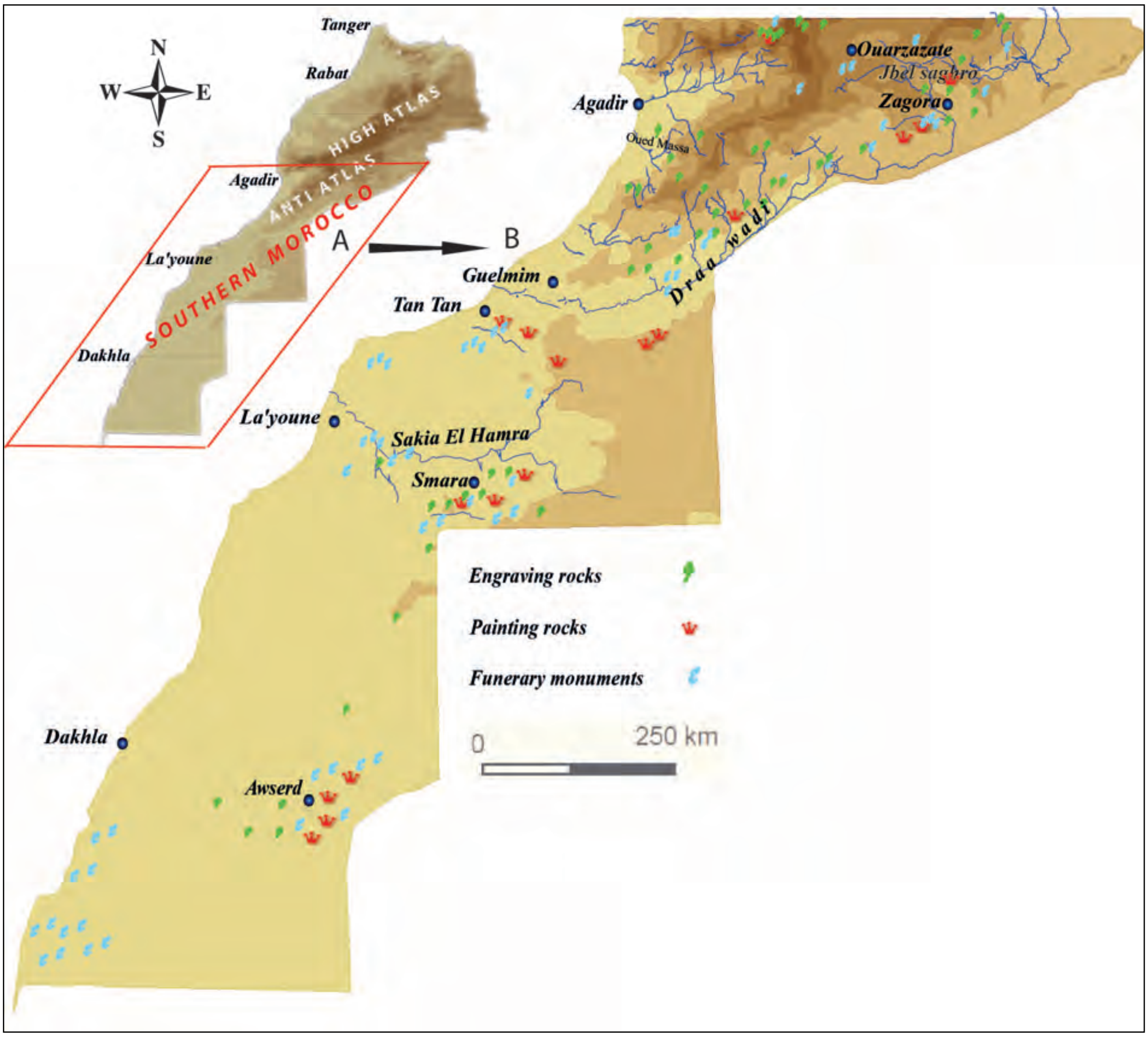


Figure 1. A- Location of the study area; B- Distribution of the main engraving rocks, painting rocks, and pre-Islamic funerary monuments in southern Morocco.

However, the presence of metallic weapons, chariots, and signs figurations, pleads in favor of art continuity until the Libyco-Berber period (SALIH & HECKENDORF 2002).

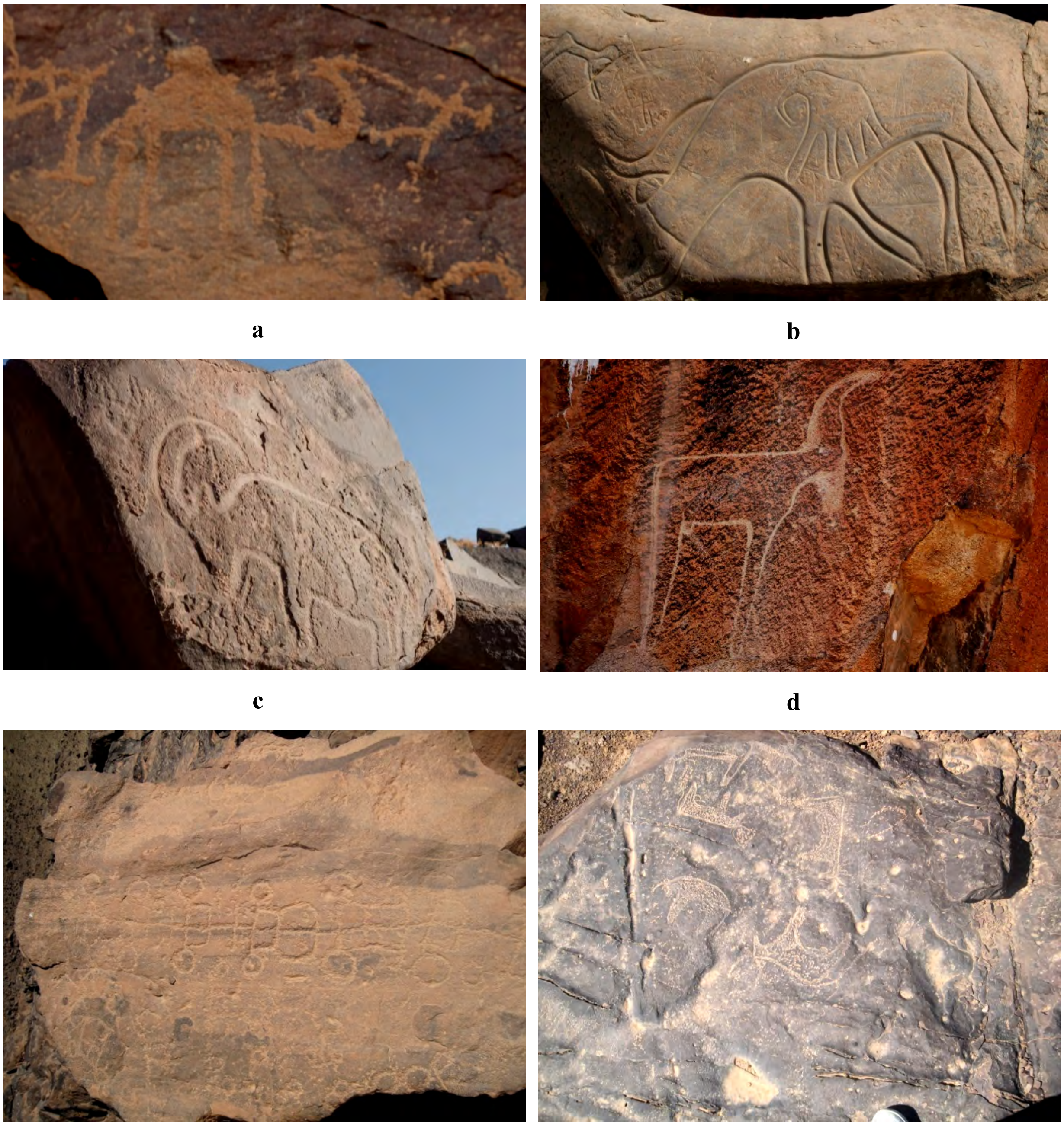
There are about a thousand engraved figures on the engraved slab of Azrou Klane located between Guelmim and Tan Tan. The oldest ones are Bovidian engravings belonging to the Libyco-Berber period represented by armed horsemen, involved in combat and hunting scenes (GRAFF 2016). The recent and contemporary engravings are numerous, such as a sailboat or a Bedouin tent.

In the Kerdous area, the main engraving sites are those of Ukas (the richest in wildlife), Tafraout (Tazeka, Jbel Mqorn, Ait Ben Said, Tagenza), and Ait Baha. In Assa Zag, at the entrance to the Ksar-Assa, a slab bear engraving of bovids, ostriches, quadrupeds, and a dromedary. Several cattle representations have been discovered at the Zag Wadi site (EWAGUE, 2018).

The Seguia el Hamra basin counts several rock sites (ALMAGRO BASCH 1944; 1946; MATEU 1948). The important ones are in the Smara area (Ras Lentareg, Mecaitab Wells, El Farsia, El AsleinBukart, Açli Bu Kerch, and Lumat de Asli). It is where we found many wild animal engravings (rhinos, elephants, giraffes, antelopes, bovines, and ostriches), geometric and anthropomorphic shapes, weapons and chariots, and Libyco-Berber inscriptions (RODRIGUE 2010). The Laghchiwat site, in the Seguia el Hamra area, includes several thousand

engravings, with a high proportion of giraffes. The Lajwad and Daraa Elquelba sites are in the vicinity of Awserd. Other notable localities are between Smara and Awserd.

Due to perceived similarities in subject matter, even across great distances, much rock art has been ascribed to pastors and hunter engravers, who have shared a set of cultural references. The large engraving sites illustrate the succession of wildlife representations, with firstly wild and secondary domestic. Libyco-Berber inscriptions and metallic weapons represent the most recent engravings.



a b c d e f

Figure 2. Selection of representations of engraving rocks: **a.** Dromedary held by an anthropomorphic shape (Amtoudi), **b**. Elephant inside a rhino (Ait Ouaaziz), **c**. Mouflon with curved horns (Tata), **d**. Bovid executed by a pecked technique on pink granite (Tazka, Tafraout), **e**. Alignment of seven chariots (Taouz) ,and **f**. Herd of cattle (Taouz).

b. Rock Paintings

The paintings found in caves and rock shelters (HECKENDORF & SALIH 1999) represent the life of Neolithic men and the surrounding fauna. There are few painting sites. The main ones are Aouin, Asguer, Oued Asleg, Jebel Aousnir, Oued Guelb, and Oued n'Thati (Fig. 1). Several compositions include spatial activities, such as dancing, hunting, and animal pictures (Fig. 3). The pigments used are often red, more rarely black or white. The patterns drawn in red, consisting of oval shapes with red dots, are observed in the rock shelters and some caves (such as the Zir Lbâaïr cave) around the Zaouia Sidi Abd En Nebi (HECKENDORF & SALIH 1999). On the edge of the Youmkat Assif tributary (Oukas site), the painted shelter shows a mounted bovine and an armed anthropomorphic painted in white.

In Tata province, there are about thirty rock shelters with cave paintings of different sizes and themes. These painted works probably date from the end of the 3rd millennium to the 1st millennium BC (SEARIGHT & MARTINET 2001).

At the level of the Laouinat shelter, located to the south-east of Tan-Tan, there is a representation of several small anthropomorphic shapes, three chariots similar to those engraved everywhere in southern Morocco, a varied fauna (sheep, bovines, antelope, ostrich, giraffe, and a ridden donkey) (SEARIGHT & MARTINET 2001). The Tifariti paintings in Saguiet el-Hamra, located about a hundred kilometers further south, show similar representations. Some painting sites from Asleg Wadi (MASY 2004) and another in Bou Dheir (BROOKS et al. 2003) depict a wild bestiary, often with large dimensions (up to 140 cm), and a remarkable ancient buffalo.

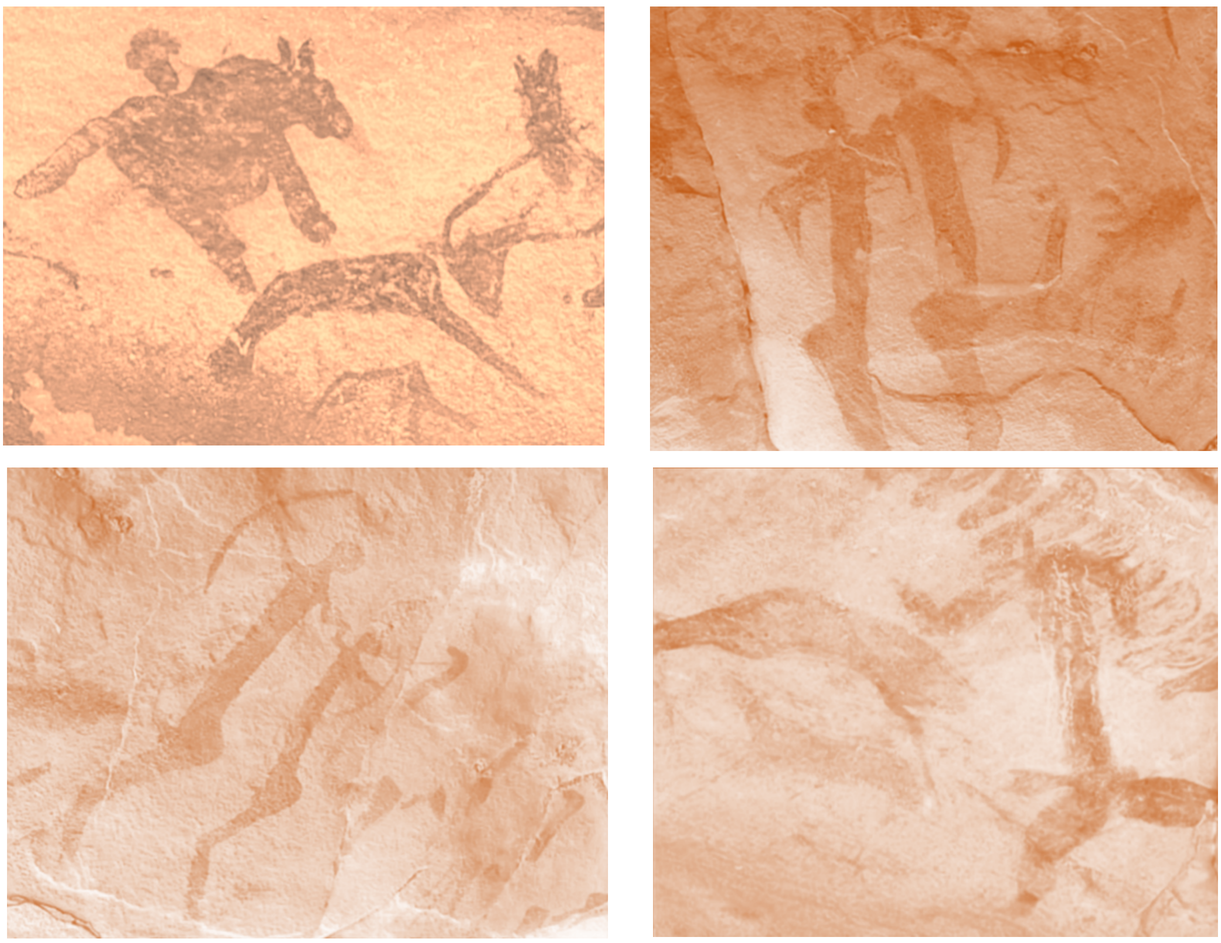


Figure 3. Rock paintings in the cave of Aouinet Azguer with inscriptions made in the flat areas. Anthropomorphs armed with bows are characterized by pronounced buttocks and broad thighs.

The cave paintings of Aouinet Azguer (Msied) are made in rock shelters located on the banks of the Azguer Wadi tributary. The painted figures, bovids, antelopes, lions, and anthropomorphic figures, are probably from different styles and periods (SEARIGHT & MARTINET 2002).

In the five painted shelters of Ifrann'Taska, the drawings are zoomorphic graphics (bovids), anthropomorphic illustrations, dotted lines, lines, geometric patterns, Libyco-Berber characters, and horsemen (HECKENDORF & SALIH 1999).

Several small caves (Cueva del Diablo, Cueva Pintada, Lajwad, Dáraa El Quelba, Legteitira) exist on the Jbel Lajwad's cliff of to the south-east of Aousserd in the Tiris desert. The main paintings are hand tracings, zoomorphic figures, quadrupeds, and Libyco-Berber characters.

The paintings of Zemmour are in several small shelters on rocky cliffs. Five pictorial styles are defined. The oldest is attributed to the Bronze Age (3800-3200 BP), as evidenced by halberds representations, and the most recent being between the 4^{th} century BC (2400 BP) and the beginning of the Christian era, according to the presence of Libyco-Berber texts and the absence of camels. A single inscription in Arabic could represent ages after the 15^{th} century AD. (SOLER SUBILS et al., 2005 & SOLER SUBILS 2006).

The paintings of Ifran-n-Taska (South-west of Zagora) are among the rare testimonies of non-engraved rock art in Morocco. The drawings have been made of red ochre, white, black, and yellow, on the inner sides of five shelters at the edge of a dry river (ZAMPETTI et al. 2013). The ages of these paintings are: 3794 ± 37 BP (shelter I); 4 1 00 ± 59 BP (shelter III) and 7062 ± 37 BP (shelter IV) (ZAMPETTI et al. 2013).

c. Protohistoric funerary monuments

The protohistoric funerary monuments of the pre-Islamic culture are tumuli of earth and/or stones of different shapes and sizes. The main sites of southern Morocco are in Figure 1. The most important groups are not far from pasture areas (HACHID 2000), and along the wadis: Draa, Noun, Ziz, Guir, Taouz, Chbika, Saquia El Hamra, Massa and their tributaries (SOUVILLE 1965; MILBURN 1974; BOKBOT 1991; BOKBOT 2000; BOKBOT et al. 2007; MATTINGLY et al., 2017; ABIOUI et al. 2019). There are several diverse forms of tumuli (Fig. 4). Along the Draa Wadi and its tributaries (Tazarine, Tamimoute, Tasminakhte, Oued El Myet, Tilougui, Bom Zwaguer, Mirdc, Foum Azlag, Rbat Lahjar, Tissergate, and Foum Larjam), we can distinguish simple stone lifting or in the form of spherical caps (MATTINGLY et al. 2017). The Foum Larjam site is the largest and the most spectacular burial ground in the entire Drâa valley (MEUNIÉ 1958).

Tumuli with monuments and chapels are common in Taouz. The antennae, crescent, and fly-wing tumuli are spectacular at the Garas' level hanging over the Oued Chbika (southwest of Tan-Tan). The tiered tumuli are found at Akhfnir and on the banks of the Noun Wadi. Tumuli with several branches are discovered in Awserd site. Other circular shapes with belts or antennae, heart shapes, crescent-shaped, or fly shapes, are also present in the region. The graves are either scattered or grouped in the necropolises form. Scattered graves indicate a nomadic state. Meanwhile, the necropolises form attest to the sedentary builders who practiced livestock and/or agriculture.

In Oued Chbika and Smara, funeral monuments show complex structures attesting to a significant investment in time and labor to create accurate geometric shapes and bring the appropriate construction material on site. These monuments are often associated with rock art sites and reflect the cultural and ethnic diversity of pre and protohistoric communities in the region. Their construction period is between the most remote Prehistory and the end of the Middle Ages.

Radiochronological ages of funerary monuments in southern Morocco are rare. EL GRAOUI et al. (2010) obtained an Age of 1430 ± 35 BP on a skeleton in a circular tumulus in Taghjijt. The grave traces are made up of metal objects (iron and bronze), ostrich eggs pieces, and shells.

Figure 4. Examples of pre-Islamic funerary monuments: **a.** Stone cairn (Foum El Hassane), the most common structure in south Morocco, **b.** skylight tumuli of Foum Larjam necropolis, **c.** circular tumulus (Azguigh, Agdz), **d.** complex monument with short antennae (Oued Chbika), e. chapel tumulus of Taouz, and **f.** tumulus with long antennae (Oued Chbika).

In the Tamrhalt-n-Zerzem (Oued Noun) graveyard, the funerary furniture consists of iron bracelets, iron earrings, necklaces made of copper and iron beads, tests of ostrich eggs, green rocks, seashells, and flint shards (BOKBOT et al. 2007). The most important tumulus of Foum Larjam necropolis was dated using radiocarbon: 2649 ± 28 BP, 1589 ± 30 BP, and 1344 ± 30 BP (MATTINGLY et al., 2017).

In the Saharan regions, the ages of the different types of monuments (keyhole, crescent, aligned and antennae) (MEUNIÉ 1958; GAUTHIER & GAUTHIER 2006, 2007, 2008, 2009; EL GRAOUI et al. 2010) show that the monuments keyhole (4280 to 5610 BP) and crescent (3310 to 4720

BP) are the oldest, and spread over the Lybico-Berber period. Monuments with antennas (1450 to 1870 BP) and alignment (1450 to 1870 BP) appear at the beginning of the Caballine period.

According to GAUTHIER & GAUTHIER (2009), these funerary monuments are probably the work of the same population existing there for more than 5000 years

3. Classification and chronology of rock art

The chronology of rock art is still relative due to the lack of geochronological data on rock carvings and paintings. However, several attempts have been tried for classification and chronology at local and regional scales, both locally and regionally (AUMASSIP 1993; CORNEVIN 1993). According to MORI (1970) and BARICH & GRUNERT (1991), the beginning of rock art dates to the Paleolithic end. Whereas for MUZZOLINI (1995) the oldest representations appear at the beginning of the Neolithic.

The archaeologists have defined the main periods by following stylistic criteria, analyzing the subjects represented, the superimpositions, and the patinas, and considering the succession of animal representations, first wild, then domestic. As a result, five main groups of engravings can be distinguished, based on the theme of representations.

a. Bubaline period

It is a period of the ancient buffalo (formerly called "Bubalus") and corresponding to the ancient Neolithic (7000 - 8000 years BP) (BERAAOUZ 2010). The ancient buffalo occupied the entire Northern part of the African continent during the Pleistocene. Representation of an example of *Synceruscaffer* (African buffalo) is in Smara. Four or five images are present in the banks of the Dra Wadi (RODRIGUE 2001). These images may be of ancient buffaloes. This period is closely related to the hunter-pastoral period characterized by wild animal representations (elephants, giraffes, hippos, rhinos, buffaloes, ostriches, antelopes, etc.) and the absence of domestic animal representation. The engravings of this period are sometimes associated with diverse symbols: spirals, labyrinths, and circles. SIMONEAU (1969) interpreted the engravings of cattle amid hunters as a hunter-pastoralists milieu. For the majority, this period would be before 3000 BC because from this date begins the Bovidian period. In other words, the beginning of the Neolithic in southern Morocco.

b. Bovidian period

The period of domestic cattle of the Middle Neolithic started about 6500 BP and lasted at least until around 4500 BP. The works show large herds of bovids and scenes from pastoral life (LE QUELLEC 1998; LHOTE 1989). The beef mounted in Adrar Metgourine (Akka, southern Morocco) is dated around 2000 BC (DU PUIGAUDEAU & SENONES 1964). According to (HECKENDORF 2008), the rock representations of Jbel Bani do not provide any clues of cultural changes caused by desertification linked to Neolithic cattle herding. The spatial distribution of the different engravings can be created as part of transhumance, from Saharan and pre-Saharan territories to the Atlas Mountains. In the absence of typical landmarks, the classification of rock art does not distinguish the Bubaline period (Tazina style) and the Bovidian period.

The presence of wildlife (elephants, rhinos, felines, antelopes, etc.) provides information on a climate similar to the current savannah. This relatively humid period is between the fourth and the third millennium BC (MUZZOLINI 1982). SEARIGHT (1999) dates the Bovidian from the Imaoun site, located north of Akka, to around 2000 BC. According to the author, this dating is justified by the fact that the pastures of the region continue to provide sufficient vegetation cover for the present cattle.

c. Chariot period and Caballo-Cameline period

The sites of chariot representations associated or not with humans are relatively rare. The most beautiful one is in Tamanart Wadi (Icht). The representations are sometimes associated with spear points and ornate discs (EZZIANI 2004). Chariots are engraved both in the High Atlas Mountains and in south Morocco. The chariot introduction from the Sahara into Morocco would date to around 700-600 BC (MUZZOLINI 1988) or

between 1000 and 500 BC (VERNET 1993). The schematic chariots of the Atlas could date back to the 7th / 6th centuries BC. And in this case, the term Atlas Bronze would be placed before this date and lasted until the 2nd / 3rd centuries (AUCLAIR et al. 2016). The chariots are engraved in a pastor to cattle milieu. The chariot episode in rock art, marked by the use of wheel couplings in daily life, is of great cultural significance (CAMPS 1982, 1989).

The Caballo-cameline period is subdivided into an early period of "horse" that extends from 3500 to 2000 BP and a recent period of "camel" (LHOTE 1984). In this period, the succession is domestic cattle, then horses and dromedaries. Horse engravings are rare. They are in Tamanart Wadi. Camel representations are exceedingly rare, as the dromedary would have been recently introduced in the region from the first millennium to medieval times (AUCLAIR et al. 2016). The dromedaries are introduced into Sahara since 250 ± 100 BC (MUZZOLINI 1995).

Saharan rock inscriptions, reflecting the period of chariot and horse, could be as old as the Maghreb Libyan alphabet. They could document one or rather several regional “Libyan Saharan alphabets” (HACHID 2007). The oldest Libyan inscriptions can be located between the Caballine and the Camel periods transition (PICHLER 2007). (MUZZOLINI 1995) assigning a date not earlier than the beginning of the 1st millennium BC for the ridden horse in the Saharan regions. However, the same author groups together the Libyco-Berber and horsemen who carry round shields and spears with camel engravings dated to around 200 BC in Morocco.

d. Libyco-Berber period and Metal Ages

This period is characterized by representations in the form of an alphabet that resembles Tifinagh (sites of Ouaremdaz, Ait Ouarzik, Foum Chenna, Wirgane, Tibaskoutine, etc.), which are protohistoric inscriptions, written in an old script that is difficult to decrypt (PICHLER 2000a; PICHLER & RODRIGUE 2003; PICHLER 2007). According to MONOD (1932), the “cameline” or even “equine” period largely corresponds to the “Libyco-Berber” group. The origin of this alphabet can be located between the end of the second millennium BC and the first millennium BC (HACHID 2007). The oldest inscriptions may have been dated to the 6th century BC (CAMPS 1977) and persisted in North Africa until the end of the ancient world (early 8th century) minimum. These inscriptions cover the period from protohistory to early history and even more recently (RODRIGUE 1989; RODRIGUE 1992).

The presence of camels and horses allows placing Foum Chenna engravings in the second half of the first millennium BC (PICHLER 2000b). Libyco-Berber alphabetic signs can only date back to the 7th - 8th centuries BC (PICHLER 2007). The beginning of the Libyco-Berber period is 1000 BC in North Africa and Sahara (Aumassip) or the first millennium BC (CHENORKIAN 1988).

The representations of the metal ages are tall male figures, accompanied by daggers and halberds, especially at the High Atlas sites, in Oukaimeden and Yagour (EZZIANI 2004; AUCLAIR et al. 2016). The metal weapons representations testify to contacts between Moroccan and European territories during the Bronze Age (RODRIGUE 2010). The thousands of engravings on the plateau of Jbel Tizelmi correspond to the late period during which the abundance of rifles is related to this weapon introduction in the region.

The High Atlas weapons had a close connection with the Bronze Age of the El-Argar civilization (south-eastern Spain, 1800 to 1200 BC) (HACHID 2007). The High Atlas engravings of Bronze Age metal weapons can be subdivided into Old Bronze (local weapons and/or imported from ancient Iberian) and relatively recent Bronze (integration of Mediterranean Bronze into the Atlas world) (CHENORKIAN 1988). The Bronze Age continued in the High Atlas until the 6th-5th centuries BC (early Antiquity). The arrival of metallurgy (copper, then iron) and the horse marked the end of prehistory (VERNET 2014). The engravings and paintings that depict metallic weapons and chariots associated with horse domestication are part of the prehistoric period (GAUTHIER & GAUTHIER 2008). The Bani region is unique when it comes to metal weapons. Engravings showing weapons have been

discovered on the Adrar Metgourine site (CHENORKIAN 1988), north of Akka, and on the Tazout N'dri site, located east of Assa (SIMONEAU 1969). The iron tools, weapons, and Arabic curved dagger entered North Africa at 700-1000 BC or the end of the 7th century AD.

e. The Islamic period and Powder Age

This period is represented by metal objects, such as fibulas, swords and scissors, and Muslim tombstones oriented towards Mecca. In recent centuries, images of rifles and symbols in the shape of stars have appeared in Yagour, Tizelmi, and Tainant (AUCLAIR et al. 2016; DURIEUX 2018). They are attributed to the Powder Age and are related to the emergence of patterns marked by the appearance of firearms at the turn of the colonization age.

4. Climate variability and potential impacts on prehistoric populations

Archaeological, pre-historic, or proto-historical archives provide valuable data to better understand past climate changes. But due to the lack of accurate dating, they are hard to decrypt in southern Morocco (CLARKE et al. 2016; SEARIGHT 2013). Nevertheless, it is possible to approach climatic variability in this region during the Holocene by combining the isotopic data recorded on the speleothems taken from the Win-timdouine cave (Fig. 5f) with those on the archaeological heritage of southern Morocco (Fig.5 a to d).

In southern Morocco, the Upper Paleolithic is relatively humid. The climate is dry from 11500 to 10800 BP, with a wet period around 10500 BP. It became relatively wetter only after 10000 years BP due to the shift of the African monsoon northward. During the called "Green Sahara", the climate remained relatively wetter until about 4000 years BP. This long period has observed three short periods (centennial-scale) of relative aridity: 9400 to 9000, 8200 to 8400, and 5200 to 5000 years BP, which could have created a favorable environment for human settlements in the region.

After 3800 years BP, the climate conditions were deteriorated significantly due to the increasing aridity and some of the humidity intervals that may have lasted for several centuries. Interestingly, most of the archaeological sites were dated from 7000 to 1000 years BP. This transition period from a wet to dry climate is favorable for pastoralism and hunting. The latter part of this period is dry, and cattle ranching, agriculture, and animal domestication have been developed. Hence, adopting a new lifestyle indicates the pre-historic society's resilience against a relatively unfavorable climate.

Wild or domestic animals' presence or absence is intimately linked to climatic features, particularly in southern Morocco. Accordingly, the presence or absence of animals is generally illustrated in rock art.

Livestock farming has been replaced by highly mobile pastoralism based on sheep and goats. It involved movement in both Saharan and mountainous pasturelands, where water could be available. The areas around the Anti-Atlas oases (Draa river, Massa river, and Tata valleys) and the High Atlas Mountains (Oukaimeden, Yagour, Azibn'Ikkis, Jbel Ratand, Ouneine) would have provided certainly refuge zones for species unable to survive in increasing aridity. This period is associated with sedentarism and the greater exploitation of available natural resources. The large wadis retain some humidity which attracts the fauna of the large dry Sahara. And this would explain why we have the rapid increase of rock art representations and funerary monuments throughout these wadis and their tributaries.

We propose that rock art may significantly contribute to understanding people's concentration in Southern Morocco and their relation to climate changes during the Holocene.

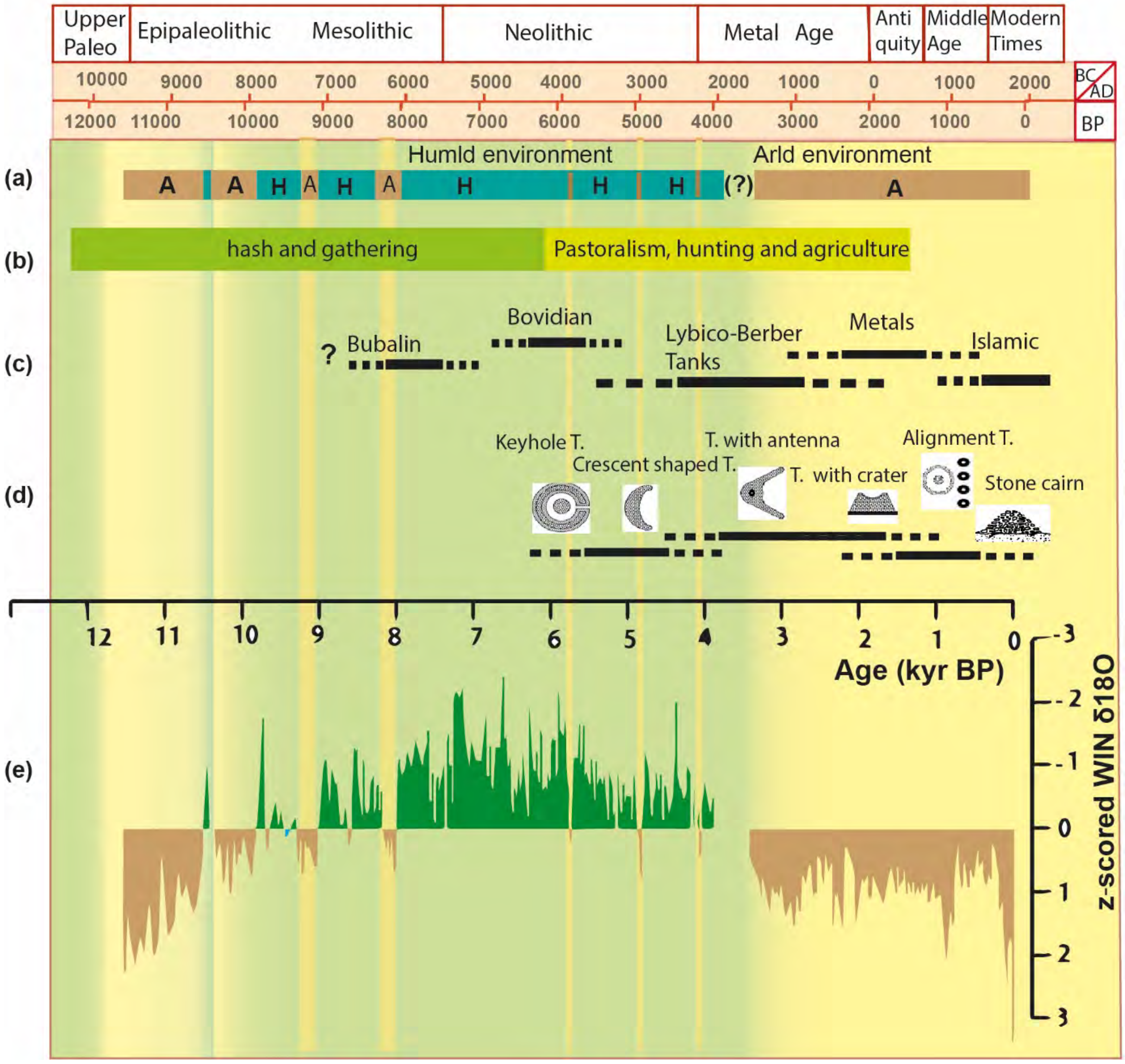


Figure 5. Holocene climate changes in the great south of Morocco as reconstructed based on the speleothem records discussed in the text; cultural changes are also reported. a. Alternating arid (A) and humid (H) periods, b. Human cultural change during Holocene times, c. Chronology of engraving rocks, d. Evolution of the shape of pre-Islamic funerary monuments (GAUTHIER & GAUTHIER 2009), and references therein] and e. Hydroclimate records in Win-Timdouine stalagmite (AIT BRAHIM et al. 2017, 2019a, 2019b, SHA et al. 2019).

5. Conclusion

This review of southern Moroccan rock art sites shows that several different modes of existence and climate variability had mainly influenced the populations and their artistic activities like painting and engraving rocks. Most of the wadis banks and their tributaries show rock art and funerary monuments, attesting to the local evolution of human occupation. From the oldest period (Bovidian) to the Caballine and Libyco-Berber periods, the figures testify to permanent human occupation in southern Morocco.

The difference in themes, style, and patination indicate that rock art is not all contemporary, plus many sites experienced several periods of occupation. In the north of the study area, the rock arts are sparse and less extended (Oued Massa, Yagour, Ounein), while the stations in the southern are substantial and variable. Additionally, in the South, the representations of abundant wild animals plead in favor of hunting in a steppe environment. While in the north, ruminants replace wild animals, show animals' domestication, and metals' use in artistic activities.

Climate change has undoubtedly played a major role in the evolution of human populations, their activities, migrations, and the future of civilizations. Indeed, the Holocene is characterized by a climate oscillating modestly on the regional scale. Nevertheless, these climatic oscillations have had a significant influence on the development of human civilization in the area, as highlighted elsewhere (ANDERSON et al. 2007; FOSTER 2012). Households concentration testifies to the existence of water points around which populations carried out their different activities. The drying up of water sources has likely caused the migration or disappearance of populations in these contexts. The dramatic climate change during the Holocene and the natural environment in which prehistoric populations lived have induced distinct cultural responses. In an arid climate, long dry periods are often characterized by unstable and conflicting societies, increased insecurity among human groups, and their migration over long distances (BROOKS 2006; ANDERSON et al. 2007; FOSTER 2012; CLARKE et al. 2016). On the other hand, during humid and rainy periods, sedentarization is dominant, and the development of well-stylized rock art, and the grouping of tumuli with complex geometries (ABIOUI et al. 2019; BERAAOUZ et al. 2014). On the boarding of palm areas, the concentration of rock art and funerary monuments attests that the geographical conditions might have remained unchanged during the last centuries.

Southern Morocco offers a wide range of rock art sites that have been identified extensively. Due to perceived similarities in the area and even across great distances, much of rock art has been attributed to hunter-gatherer painters and engravers who appear to have a shared set of cultural references. As is often the case with rock art, the accurate attribution of authorship, date, and motivation is difficult to establish. But the research on rock art in southern Morocco is still ongoing, along with the archaeological and paleoclimate records that could help better understand past human-climate interactions.

Acknowledgements

This work was carried out within the CHARISMA Project with the assistance of the Hassan 2 Academy of Sciences and techniques. The authors are grateful to IRD, France, we acknowledge specially the support from IRD representation in Morocco. We also thank Faouzi Vision for allowing us to use the pictures of the rock paintings.

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Towards more sustainable and climate-smart water and agricultural systems: Study case of the Souss Massa Basin in Morocco

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Abstract. Our study analyzes the vicious spiral between climate change impacts, agricultural practices, and adaptation choices to cope with the maladaptation residual risk. Therefore, the evolution of future agriculture will be shaped by its response to climate change. Our investigations argue for investment in ecosystem-based water management to increase the resilience of agricultural development and stimulate sustainable natural resource management. Furthermore, smart agricultural technologies are proposed to boost adaptive capacity, guarantee food security, and mitigate climate change in all agricultural systems. Finally, we consider the integrated and multidimensional to improve the security and the link between water, energy, and food. The analysis suggests that in order to achieve the resilience and adaptations against climate change, agricultural policies should shift from maximizing agricultural output to the consideration of the synergy between ecosystems, the promotion of the nexus food water energy and the concrete involvement of all concerned stakeholders.

Key words : Climate change, ecosystem services, water security, climate-smart agriculture

1. Introduction

Agriculture currently accounts for 70% of global water withdrawals, 30% of total global primary energy consumption, and 51% of aggregate global energy use (Godoy-Faúndez et al., 2021). Together, they increase pressure on ecosystems, produce considerable volumes of wastes, and impact local communities.

The world is currently facing significant challenges in its adaptation and mitigation of climate change to provide goods for the growing demand for food, water, and energy—key inputs into a modern society. Improving agricultural systems is a key response to both especialy for Morocco, where agriculture is a major sector for the national economy. By contributing to the national GDP by 15% to 20% , Moroccan agriculture is a key socioeconomic sector due to its strategic role in food security, employment, currency mobilization, and stabilization of rural populations (PCN30 2018).

Water scarcity raises significant concerns about the sustainable future of humanity and the conservation of ecosystem functions. Hence, water security is an emerging concept that researchers and policymakers have widely recognized in recent years. Aware of its dependence on water, Morocco has long adapted to the scarcity of this resource by implementing a policy of dams construction long before the problem of climate change arises and asserts itself on the international scale. However, the analysis of the evolution of water demand and energy needs for water shows the risk of a severe water shortage by 2050 (El BADRAOUI et al. 2011). Moreover, the importance of mobilization costs and the deterioration in the quality of surface and groundwater resources amplify the vulnerability of the water sector in Morocco.

The development of unconventional water resources (seawater desalination, demineralization of brackish water, reuse of treated wastewater, and rainwater harvest) is

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DOI: https://doi.org/10.34874/IMIST.PRSM/fsejournal-v11i2.29003

becoming necessary for Morocco. However, most of the strategies adopted are geared towards managing water supply while demand is constantly increasing.

Since almost no adaptation action can completely eliminate a climate change impact and the associated risk, the costs of the residual risk (the remaining impacts after the implementation of the adaptation action) also need to be accounted. Thus, while improved water management is a crucial element, a portfolio of synergistic interventions is the most promising approach to covering the full spectrum of climate risks that confront farmers and impede the investment needed to realize the potential benefits of water management. Several options are available for managing the risk that feasible water management strategies cannot cover.

Nowadays, significant advances in climate-smart technologies and practices create a critical opportunity to move agricultural systems in Morocco towards more productive and sustainable levels, while addressing climate change. However, there is also a considerable challenge in effectively using of these technologies. Gaps in knowledge of the synergies between climate, water and agriculture need to be addressed to adopt the right transformation pathways. In addition, only a few development plans and efforts elucidate the implementation of climate-smart agriculture (CSA) technologies. The FAO defines CSA as agriculture that sustainably increases productivity, resilience (adaptation), reduces/removes GHGs (mitigation), and enhances achievement of national food security and development goals (MANN et al. 2009). Thus, farmers need to be encouraged to adopt climate-smart practices and policy-makers should initiate an integrated approach in this field.

Our study includes a literature review on climate change mitigation and adaptation practices from Web-based publications, projects, and papers at regional, national and local levels. Hence, we propose several specific areas of investment that we consider timely, and promising.

By taking the Souss Massa Basin in Morocco as an example, this paper aims to analyze the challenges associated with the development, and discuss the opportunities for introducingnew innovations in agriculture and water resource management as a sustainable answer to climate change.

2. Climate change impact on agriculture and water resources

The predominant climate concern for the Souss Massa region is the impact on limited and declining water resources. With water demand expected to increase due to population growth, expanded irrigation schemes and tourism, and water resources projected to decrease under the increasing dryness conditions. Several studies have assessed the possible impacts of climate change on water resources and agricultural activity in the region of Souss Massa, which represents one of the agro-economic pillars in Morocco. This has indeed highlighted the problem of water scarcity in connection with intensive agriculture, which risks crippling socio-economic activity in the region (CHOUKR-ALLAH et al. 2017).

Seif-Ennasr et al. (2016) have indicated that the mean temperature should increase in both short and long term; from 3° C for the period 2030-2049 and from 4 to 5° C within the end of the century following most studies carried out on climate change, including in other similar regions of the world. On the other hand, precipitation will follow the opposite trend for all models in both scenarios, RCP4.5 and RCP8.5, to reduce -10% to -30% during the period 2030-2049 and up to -60% during the period 2080-2099. Moreover, the water balance would be affected by climate change and aggravated by the overuse of groundwater, mainly by agricultural activity.

Climate change is expected to intensify many of the challenges facing agriculture in the Souss Massa, but in ways that can only be partially anticipated. Climate change could affect land suitability for agriculture and the growth of crops, leading to a decrease in the agricultural area under cultivation and overall production. Furthermore, the period between planting and maturity of crops will be considerably shortened affecting crop production and water demand (Seif-Ennasr et al.

2020). Under this situation, mismanagement of soil, rangeland vegetation, and groundwater extraction will amplify the impacts of climate change (SCHILLING et al. 2012).

The alarming effects of climate change could reaffirm the urgency to immediately implement new policies and strategies to make the management of water resources more sustainable from an environmental, social, economic, and financial standpoint. The case of the aquifer contract, one of the national policy measures designed to tackle water scarcity and save water, and the use of desalination for irrigation of cash crops under a public-private partnership, are examples of measures implemented in the Souss Massa watershed. These measures represent a good indicator of the awareness of water stakeholders and actors of the alarming situation of water resources. , but their deployment must be coupled with practices for the conservation of ecosystem services and clean energies.

3. Integrated and multidimensional water security

Water resources are inherently linked to economic growth. Income generation and poverty alleviation heavily rely on water security for agriculture and other livelihood activities (LINDEN et al. 2005). The water security assessment is a powerful tool to understand a specific area's water-related issues and hazards. It combines the information provided by several sources into a grouped and standardized value (KHAN et al. 2020).

Recent studies have explored the links between economic growth and water security (KHAN 2020 ; LORENZO & KINZIG 2020).Water security is achieved when water resources are properly managed to satisfy drinking and sanitation needs. It helps sustain productive economies (agriculture, industry, and energy), preserve healthy ecosystems, and build resilient communities to cope with change (Fig. 1). Nonetheless, population growth, changing socio-economic, and ongoing climate change have been the major hurdles in achieving and maintaining water security. Thus, water security of a country is determined by its own unique set of physical, social, economic, political, and environmental circumstances.

We measure the water security based on the combination of five dimensions (Fig. 1): Household water security, Economic water security, Urban water security, Environmental water security and, Resilience to water-related disasters can help raise awareness at different scales, from citizens to policy-makers, and initiate the appropriate measures to improve the water situation.

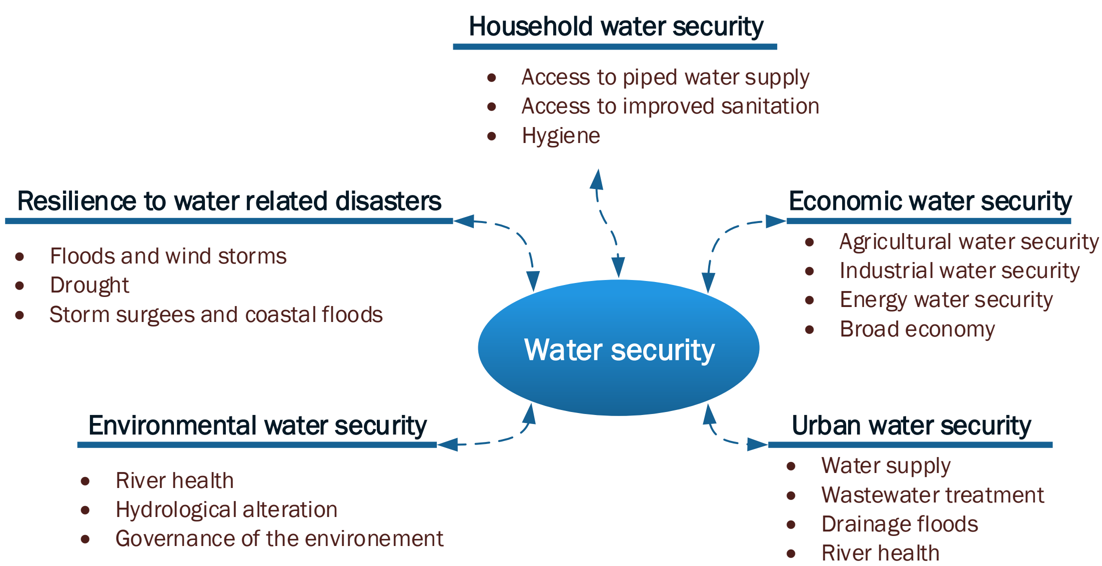

Figure 1: Water Security dimensions

A number of efforts have been made in the past to quantify Water Stress, Water Vulnerability or Water Security, leading to many approaches, indicators and paradigms. Among all of them, the 2016 AWDO's (Asian Water Development Outlook) Economic Water Security framework has been used in DMADFORWATER (Developdent and application of integrated technological and management solutions for wastewater treatment and efficient reuse in agriculture tailored to the needs of Mediterranean African Countries), to allow a more consistent comparison of information with previous and forthcoming international studies.
To measure the productive use of water to sustain economic growth in food production, Economical Water Security was estimated based on the subindexes detailed in the methodology (Table 1).

4. Methodology

Table 1 shows the sub-indicators of water security for Souss Massa Basin according to the adapted AWDO approach. Thus, the water security was calculated based on broaad economic index (water resource) and agricultural index.

The Water Resources Index is a compound out of the sub-indices resource reliability calculated based on grid information extracted and summarized at basin level. The hydrological catchments are extracted as vector data from the Global Drainage Basin Database (GDDB) and then were processed with the software R (MATLOFF 2011).

The Interannual Variability is calculated by the coefficient of variation from long-term time series on mean annual precipitation.

$$IV = \frac{\sigma}{\mu} \qquad (1)$$

Where: IV is the Interannual variability, σ is standard deviation and μ is the mean annual precipitation (mm) over the considered period.

The intra-annual variability is calculated by determining the variability between long-term average monthly precipitation data. The method as the inter-annual rainfall calculation. The major difference is that the intra-annual rainfall, the variation within the year is collected and not between the years.

Storage ratio - Storage capacity related to the Total Renewable Water Resources the storage ratio related to the total renewable water resources, SR is calculated as :

$$SR = \frac{\mathrm{Ct}}{\mathrm{TRWR}} \qquad (2)$$

Where Ct is the total storage capacity within a region of consideration (km^3) and TRWR is the total annual renewable freshwater resources within a region of consideration (km^3). A higher ratio of storage to total renewable water resources indicates that a country is more resilient to changes.

Storage – Drought (Duration) length index. The Storage-Drought duration length index SDL is calculated as:

$$SDL = \frac{Ct/Wm}{DDM} \qquad (3)$$

Where Ct is the Storage capacity in a country (km^3); Wm is the average monthly withdrawal (km^3/month) and DDM is the average hydrological drought duration (months).

The water productivity in agriculture (WPA) sector is calculated as:

$$WPA = \frac{\mathrm{GDPA}}{\mathrm{AgrWU}} \qquad (4)$$

Where: WPA is expressed in (\$ million/ km^3)

GDPA is the agricultural gross domestic product (million \$) and AgrWU is the agricultural water use (km^3).

In agriculture, we use the ratio between the water footprint of agricultural goods consumption and agricultural goods productions to calculate self-sufficiency.

The water security score calculated for the Souss Massa Basin is below the average, with a score of 4.9 over 10. This is due to two major factors : (1) high dependency on the water embedded in the agricultural products and (2) high water stress, with a water demand higher than the freshwater availability. The sub-indicator storage ratio indicates the reservoir capacity of the basins is

almost 100% of the TRWR (Total Renewable Water Resources). This large reservoir capacity allows the basin to surplus the required water during at least ten months without precipitation, giving a certain resilience to the water-dependent sectors.

Indeed, according to the Plan Bleu (EL BADRAOUI et al. 2011), the Souss-Massa basin presents a TRWR of around 901 Mm^3/year (382 Mm^3/year surface water and 425,3 Mm^3/year groundwater). In comparison, the water demand is estimated at 1068 Mm3/year, with around 993 Mm3/year (93%) is consumed by agriculture only (Figure 2). As could be derived from the data provided in figure 2, water demand exceeds the available water volume, translating into water stress of almost 0,33 Mm^3. That means that the Souss-Massa basin requires around 33% more water than renewable water resources. A more in-depth analysis reveals that these additional resources usually come from groundwater, creating an over-extraction of around 167 Mm3/year (AFC 2012). This over-extraction is translated into a constant decrease of all the aquifers' water tables in the basin.

Table 1: Sub indicators of Water Security of the adapted AWDO approach applied at Souss Massa basin scale(MIGUEL et al. 2020)

Sub Index	Total Weight*	Max. score**	Obtained score	Description
1. Broad Economy Index (water resources)	1/2	5		Describing the general water-related boundary conditions for the use of water for economic purposes
1.1 Resources reliability	1/6	1,6		Indicating the resilience to water availability fluctuations
1.1.1 Inter annual variability	1/18	0,55	0,11	Rainfall coefficient of variation between years
1.1.2 Intra annual variability	1/18	0,55	0,11	Rainfall coefficient of variation within the year
1.1.3 Storage ratio	1/18	0,55	0,55	Relation between storage capacity and the total renewable resources
1.2 Water Stress	1/6	1,6	0,33	Relation between freshwater withdrawal and total renewable resources
1.3 Storage Drought duration length index	1/6	1.6	1,33	Indicating the duration that the economic sectors could be supplied by the water stored in dams during a dry period
2. Agricultural Index	1/2	5		Indicating water productivity in agriculture and food security
2.1 Water productivity in Agriculture	1/4	2.5	2	Relation between the gross domestic value of agriculture and the water used by the sector
2.2 Self-sufficiency in Agriculture	1/4	2.5	0,5	Relation between the annual water footprint of agricultural goods consumption divided by the annual water footprint of agricultural goods production (net balance of imported virtual water)
Economic Water Security	1	10	4,9	

*Total weight over the 10 point score of the Key Dimension Economic Water Security

**Maximum score that could be reached per subindicator over the 10 point score of the Key Dimension Economic Water Security

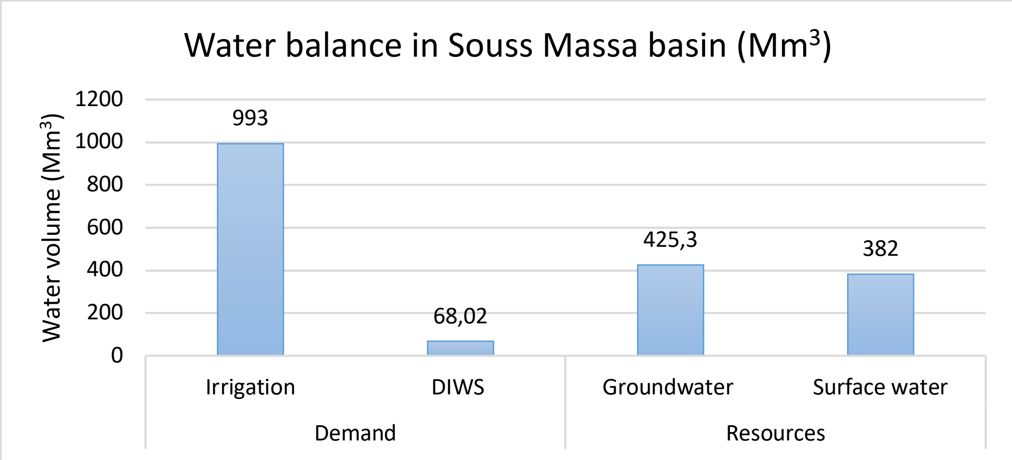

Figure 1: Water balance in Souss Massa Basin (Mm3) (ABHSMD 2019)

Hence, urgent measures to balance offer and demand are required to guarantee that enough water is available for all the economic activities in the basin. Among these strategies, the use of reclaimed water from the coastal city of Agadir to irrigate high added value products would give a significant contribution to alleviating water stress.

5. Ecosystem-based adaptation

Well-functioning ecosystems provide valuable services such as food, clean water, carbon sequestration, flood, and erosion control and habitat for wildlife. At the same time, they help promote resilience to the impacts of climate change.

In Chtouka Ait Baha district, an intensive growing area with the Souss Massa Basin, groundwater plays an integral role in all ecosystems, including the agro-ecosystem, forest, wetlands, etc... Thus, it is essential to maintain the ecological integrity of some key ecosystems. For example, Hirich et al., (2017) has shown that the agro-ecosystem is the most productive ecosystem contributing by more 74% in the Total Economic Value (TEV) of the whole ecosystem of Chtouka Aït Baha. Moreover, the forest ecosystem contributes by more than 13% to the TEV. It has more regulating services rather than provisioning services (compared to agro-ecosystems) as climate regulation, CO_2 sequestration, and erosion control services contribute by more than 43% of the TEV. On the other hand, the regulating services in agro-ecosystems contribute only by 3% in the TEV of the ecosystem.

The payment for ecosystem services (PES) is an innovative option that has emerged over the last years and figures among the most prominent innovations in conservation. (WERTZ et al. 2011). An Ecosystem-based Adaptation (EBA) to climate change approach relates to "the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change"(MIDGLEY & CHESTERMAN 2012). Ecosystem-based Adaptation restores, protects, and manages ecosystems to help human communities cope with the impacts of climate change (NYMAN et al. (2015). However, the willingness to pay for implementing an EBA remains limited because of lack of information, lack of financial resources, and institutional resistance.

Many experiences from around the world point out the major role of ecosystem management in the resilience of natural resources and human beings to climate change impacts and the protection against climate hazards in addition to the role is carbon sequestration (MUNANG et al. 2013). Therefore, the United Nations Framework Convention on Climate Change (UNFCCC) invites Parties to enhance action on adaptation by "building the resilience of socio-ecological systems, including through economic diversification and sustainable management of natural resources."

As ecosystems support diverse sectors and different social groups in multiple ways, implementing an EBA requires the involvement of many stakeholders and policymakers as described in figure 3.

6. Climate smart agriculture technologies

Energy management increases agricultural productivity, promotes access to water resources and their optimal management for private and industrial use. For example, a large amount of energy is required to extract, treat and distribute water. In addition, crops need energy and water to be grown. This cycle positions energy as a catalyst for food security, agricultural productivity, and improved water resource management.

We present, in table 2, an overview on the climate-smart agriculture (CSA) technologies as a vast array of solutions that enhance the Water-Energy-Food (WEF) nexus. It brings us back to the crucial issue of food security and its close link with clean energy production methods and the rational use of water resources. Therefore, we consider different scenarios depending on stakeholder interest, data and resource availability.

This flexible structure should allow stakeholders to generate several strategies according to different coupling technologies and practices options. In addition, the energy implications in the modes of water use are significant, including wastewater treatment and desalination. Thus, for efficient and prudent use of water and energy, these potential solutions provide insight into WEF-related issues that could be addressed.

To adapt to changing climate conditions and other challenges, farmers in the Souss Massa have been making changes to their agricultural practices, such as the wide adoption of the drip system and the use of desalinated water. However, these changes in farming practices target only the water economy and do not include soil and land management practices nor water conservation technologies. The technologies and approaches suggested in table 2 are expected to boost adaptive capacity, food security and contribute to climate change mitigation in farming systems in this region.

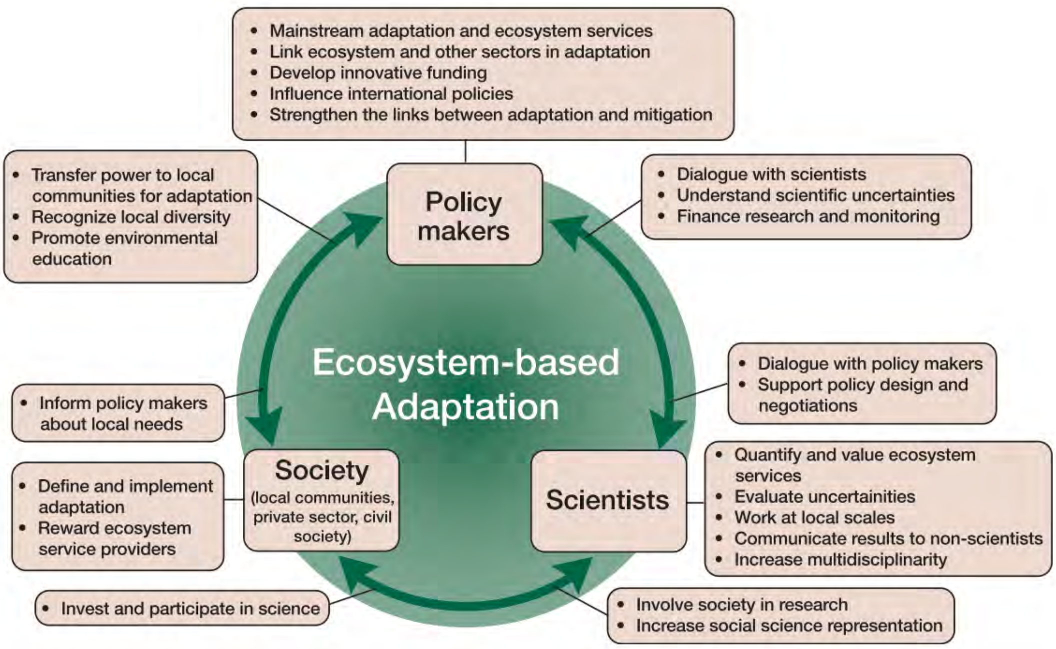

Figure 3: Roles of stakeholders in implementing EBA(NYMAN et al. 2015)

Table 2 :Inventory of climate-smart options

Potential Adaptation/ Mitigation technology	Type	Category	Adaptation/mitigation potential
1. Water-smart : Interventions improving water use efficiency			
Rainwater Harvesting	Sustainable Land Management	Technological	Collection of rainwater not allowing to run-off and use for agricultural in rainfed/dry areas and other purposes on-site.
Drip Irrigation, Smart's greenhouses and use of aquaponics / hydroponics techniques	Input use efficiency enhancing technologies	Technological	Application of water directly to the root zone of crops and minimize water loss
Laser Land Leveling	Sustainable Land Management	Technological	Leveling the field ensures uniform distribution of water in the field and reduces water loss (also improves nutrient use efficiency)
Furrow Irrigated Bed Planting	Sustainable Land Management	Technological	This method offers more effective control over irrigation and drainage as well as rainwater management during the monsoon (also improves nutrient use efficiency).
Drainage Management	Input use efficiency enhancing technologies	Technological	Removal of excess water (flood) through water control structure
Sea water desalination	Input use efficiency enhancing technologies	Technological	Reduction of pressure on underground resources and adaptation to the lack of surface water resources
Extension of wastewater reuse	Input use efficiency enhancing technologies	Institutional	Reduction of pressure on underground resources and adaptation to the lack of surface water resources
2. Energy-smart : Interventions improving energy use efficiency			
Zero Tillage/Minimum Tillage	Improved mitigation Reducing GHGs	Technological	Reduces amount of energy use in land preparation. In long-run, it also improves water infiltration and organic matter retention into the soil.
Increased production of energy from renewable energy sources	Changes in physical systems	Technological	Use of solar energy for multiple purposes (irrigation, desalination, etc.). Use of wind, waste energy and geothermal energy
3. Nutrient-smart : Interventions that improve nutrient use efficiency			
Site Specific Integrated Nutrient Management	Sustainable Land Management	Technological	Optimum supply of soil nutrients over time and space matching to the requirements of crops with right product, rate, time and place
Green Manuring	Input use efficiency management techniques	Managerial	Cultivation of legumes in a cropping system. This practice improves nitrogen supply and soil quality
Intercropping with Legumes	Input use efficiency management techniques	Managerial	Cultivation of legumes with other main crops in alternate rows or mixed. This practice improves nitrogensupply and soil quality.
4. Carbon-smart : Interventions that reduce GHG emissions			
Agroforestry	Sustainable Land Management	Technological	Promote carbon sequestration including sustainable land use management
Integrated Pest Management	Pest control	Technological	Reduces use of chemicals; use of mechanical and biological approaches that are environmentally friendly, cost-effective, easy to use, and efficacious.

Zero Tillage/Minimum Tillage	Improved mitigation ReducingGHGs	Technological	transition to no- or low-tillage practices is a major source of carbon sequestration
5. Weather-smart : Interventions that provide services related to income security and weather advisories to farmers.			
Weather based Crop Agro-advisory	Weather information distribution technologies	Technological	Climate information-based value added agro-advisories to the farmers
Crop Insurance	Innovative on-farm storage infrastructure	Institutional	Crop-specific insurance to compensate income loss due vagaries of weather
6. Knowledge-smart : Use of combination of science and local knowledge			
Contingent Crop Planning	InsuranceProducts	Managerial	Climatic risk management plan to cope with major weather-related contingencies like drought, flood, heat/cold stresses during the crop season
Improved Crop Varieties	Input use efficiency enhancing technologies	Technological	Crop varieties that are tolerant of drought, flood and heat/cold stresses
Seed and Fodder Banks	On-farm storage	Technological	Innovative on-farm storage infrastructure for the conservation of seeds of crops and fodders to manage climatic risks
Marketing & Education Program	“Climate Smart” extension programs	Institutional	Program of marketing and education is then needed to bring innovation to practitioners.
Aids & Trade	Aid distribution mechanisms	Institutional	Aid and trade could serve as substitutes for migration as a response to climate change.
Establishment of an incentive system	Farmer’s awareness	Institutional	Systems to support the switch to renewable technologies (Examle solar energy).
Effective implementation of laws	Law application	Institutional	Effective implementation of laws (Morrocan law N° 13-09 on renewable energies)

7. Conclusion

The evolution of agriculture in the future will be shaped by its response to climate change. Consequently, farmers need to adapt their practices to accommodate climatic conditions, and agricultural activities need to be modified to reduce greenhouse gas emission (GHG).

The adaptation to climate change cannot be achieved by one sector alone but rather—by considering adaptation priorities across all sectors. Therefore, it is not only a question of combating global warming that we argued the three solution types :ecosystem-based adaptation, climate-smart agriculture technologies, and integrated multidimensional water security, but also of completely changing the resource use paradigm.

The Souss Massa Basin in Morocco, the adopted example in this paper, represents a worrying example of most of the large basins in the MENA region with the high socioeconomic footprint, limited water resources, and fragile ecosystems. The unbalanced relationship between demand and supply of water in this region, worsened by the impact of climate change, makes integrated adaptation and mitigation efforts an urgent necessity.

Through this analysis, we have tried to convey the following key messages:

- Seawater desalination for agricultural purposes is a climate-smart solution, but it must be coupled with the use of renewable energies such as solar energy.
- Implementation of climate-smart agriculture can be a significant driver of sustainable agriculture and would fit appropriately in any national development plan for agriculture (i.e., the Green Generation strategy).
- Linking ecosystems-based adaptation with the climate change adaptation strategies is critical to achieving sustainable development.

- Concrete involvement in decision-making will promote sustainable ecosystem management and climate change adaptation measures.Climate smart agriculture is not a new agricultural system but a new approach that enhances the efficiente functioning of the water, energy and food security nexus.
- Efficiency and resilience have to be considered together, at every scale and from environmental, economic, and social perspectives.

Acknowledgements

This study was carried out within the context of the CHARISMA project with the assistance of the Hassan 2 Academy of Sciences and Techniques and MADFORWATER project. The authors express their gratitude to the Hydraulic Basin Agency of Souss–Massa and the agricultural department for access to their database. The authors are grateful to the French National Research Institute on Sustainable Development (IRD, France).

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Water resources status to global changes in the Taznakht plain, Draa basin, Morocco.

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Abstract. The Taznakht area, located in the central part of southeastern Morocco, belongs to an arid zone. It has an extreme scarcity of water resources. The water resources are mainly drawn from groundwater using wells and traditional irrigation systems (Khettara). This study analyzes how climate and anthropic factors have impacted the state of water resources in the Taznakht plain throughout the last decades (1985-2015). We conducted a statistical analysis using climate data to identify climate trends in the area. With remote sensing, we tracked the diachronic evolution of vegetation into the plain to observe the impact of the resulting trends. Then, we established Khettara distribution all over the plain, and their state of functioning was related to the evolution of agricultural fields. The results showed a clear impact of drought phases on vegetation throughout the 30-year study, implying a vulnerable water state. Taking one particular village as an example, we found that the disappearance of Khettaras due to climate change, extensive pumping, lack of maintenance by the inhabitants, and reliance on less environmentally friendly irrigation systems has contributed to the disappearance of agricultural fields. This situation indicates that global warming and climate change are severe problems for water management in Taznakht region. Therefore, we discussed that after 2005, due to the Green Morocco Plan (GMP), these climate and anthropic impacts did not affect vegetation as much as in previous years. Nevertheless, these impacts affect the Taznakht plain ecosystem, and the socio-economic situation of its population, so continuing with applying similar GMP strategies and encouraging the process of Khettaras renovation and recovery is the right path for a well-balanced lifestyle in the area.

Key words: global changes; water resources; gis & remote sensing; khettara system, taznakht plain

1. Introduction

Morocco is a semi-arid Mediterranean country with limited and irregular precipitation (SCHILLING et al. 2012). Surface water and groundwater are important for its socio-economic development, where 80% to 95% of water resources are used in agriculture, with at least 40% originating from groundwater (SCHILLING et al. 2020). Climate change has significantly impacted the water situation, inducing a dramatic decline (from 20 to 65m) in groundwater levels over the last 30 years (HSSAISOUNE et al. 2020). It creates a lingering imbalance between groundwater extraction and recharges in many basins (HEIDECKE & HECKELEI 2010; HSSAISOUNE et al. 2017; KLOSE et al. 2008; WARNER et al. 2013). The Draa basin was most affected and has been underwater stress in recent years (HSSAISOUNE et al. 2020; CARRILLO-RIVERA et al. 2013; OUYSSE et al. 2015). The groundwater resources in Drâa basin, located in the southern part of Morocco, are strongly impacted by climate variability and anthropogenic activity (HSSAISOUNE et al. 2020; CARRILLO-RIVERA et al. 2013). The low precipitations in the Draa basin have affected water resources highly and, therefore, socio-economic activities in the area (HEIDECKE & HECKELEI 2010; HEIDECKE & KUHN 2007; SCHULZ et al. 2007). Evapotranspiration increases

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DOI: https://doi.org/10.34874/IMIST.PRSM/fsejournal-v11i2.29008

and induces a decline in surface water resources (dropped and stored by dams) in different climate scenarios projected by TRAMBLAY et al. (2018). As predicted by MILANO et al. (2012), apart from the trends in water supply, an escalation in water stress did happen because of a sharp rise in water demand due to population growth and economic development.

In Ouarzazate province, the water demand increased from 2.3 million cubic meter (MCM) in 2010 and was expected to reach 4.1 MCM in 2030, which is a remarkable increase compared to Zagora and Agdez cities that is from 1.4 MCM to 2.5 MCM, and 0.3 MCM to 0.6 MCM, respectively in the same period (KARMAOUI et al. 2019; JOHANNSEN et al. 2016). Taznakht village, not far from Ouarzazate city, shows the same situation. It is a region containing Khettaras, which are subterranean channels draining perched shallow aquifers that helped favor agriculture crops which is one of the potentials generating income activities in the area (MESSOULI et al. 2008). However, since the decreasing economic role of agriculture, the collective maintenance of Khettaras systems has declined and turned useless due to different factors (LIGHTFOOT 1996; FAIZ & RUF 2009). Therefore, the degradation of the Khettaras network, among other impacts, could be a relevant indicator of global changes in the area. According to several authors (PENG et al. 2015; MORAWITZ et al. 2006; SEABROOK et al. 2007), geographical information system (GIS) and remote sensing are important tools to study the vegetation dynamics, change in plant cover, and the analysis of global changes impact on water resources.

This paper aims to assess the impact of human activities and climate change on water resource depletion in Taznakht and on Khettara's system degradation. The particular contribution of this study is to use the statistical trends, remote sensing, and geographic information systems to assess the impact of global change on groundwater resources in arid areas.

2. Study area

Taznakht is part of the Ouarzazate province, itself part of the large region of Draa-Tafilalt (Fig. 1). Administratively, Taznakht is subdivided into five communes: rural (Ouislsate, Iznaguene, Siroua, Khzama) and one urban (Taznakht). The latter is the center of the administrative complex (AIT ELHAJ, & BOUNAR 2016). The total area of Taznakht is 4,405 km² with an estimated population of 45,225 inhabitants, spread over 7,140 households (HAUT-COMMISSARIAT AU PLAN 2014).

Taznakht is an integral part of Drâa basin, characterized by an arid to semi-arid climate with a bimodal precipitation distribution (i.e., dry summers and winters with erratic precipitation events (DE JONG et al. 2008; SCHULZ & DE JONG 2004)). According to Köppen-Geiger climate system, the study area is classified as Arid Desert hot "BWh" climate type (see Table 1 in PEEL et al. 2007). This classification indicates a warm Mediterranean climate with a dry summer. The average temperature in Taznakht is 19.5 ° C, and the average rainfall is 161.9 mm. The high evaporation rate can exceed 3000 mm/yr (KLOSE et al. 2008; AIT LAMQADEM et al. 2019). The hydrological system depends to an extent on water runoff from the Anti-Atlas Mountains range surrounding the Tznakhte plain. However, the quasi-absence of surface water supplies in the area results in high dependence on groundwater extraction, which, increased in the last decade due to the Moroccan Green Plan.

The Taznakht area, part of the Precambrian Zenaga Buttonhole, is located about 80 km southeast of Ouarzazate in the central Anti-Atlas, on the northern edge of the West African Craton (WAC). This buttonhole consists of a Paleoproterozoic basement, composed of schists, micaschists, and granites (CHEVALLIER et al. 2001). The northern slope includes non-metamorphic sub-vertical outcrops of the Neoproterozoic age (Fig. 2). They are composed of quartzites and conglomerates, overlain unconformably by two slightly deformed Late Proterozoic and Terminal Proterozoic units (SAIDI et al. 2019). The first unit is a low-acid Precambrian III volcanic unit composed of an orogenic sequence of calc-alkaline affinity. The second unit corresponds to an upper Adoudounian carbonate sequence (SAIDI et al. 2019). Note finally that, IKENNE et al. (2017) noticed the presence of Mesoproterozoic overlying materials,

represented by limestones and quartzites that they attribute to the Taghdout group.

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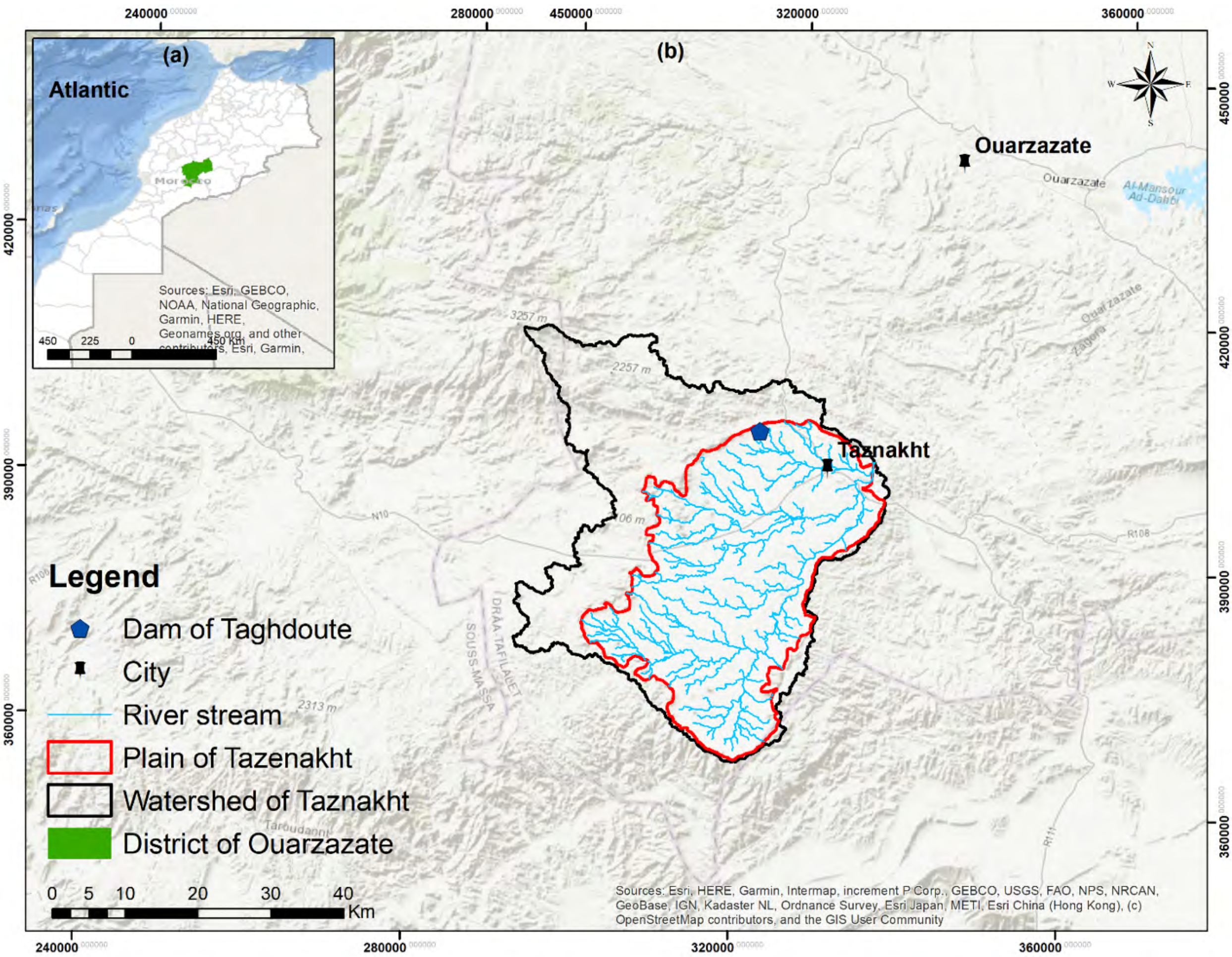

Figure 1: The geographic localization of Taznakht plain (a) localization at national and regional scale (b) localization at watershed scale

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In Taznakht, the useful agricultural area counts for 193400 ha where 2780 ha is dry and 1880 ha is irrigated, the rest (more than 97% of the total area) is mostly uncultivated spaces used as rangelands. The practice of Saffron cultivation spreads over an area of 80 ha in four rural communes: 30 ha in Siroua, 25 ha in Iznaguene, 15 ha in Ouisselsate, 10 ha in Khouzama. The total number of Saffron producers in Taznakht is estimated to be 1025, with an average area of 959 m² of saffron per producer. Water resources are limited and irrigation is practiced around water sources, Wadis, and private wells. Besides saffron, agriculture is based on cereals, horticulture, forage crops, and arboriculture. This plant production system is associated with extensive breeding of mainly sheep and goats (ABOUDRARE et al. 2014). The region of Taznakht is widely known for the quality of its Berber carpets, which usually require women of the area often weave several months of work. Subsistence farming, extensive breeding, and traditional carpet weaving crafts are the primary sources of income for the Taznakht people.

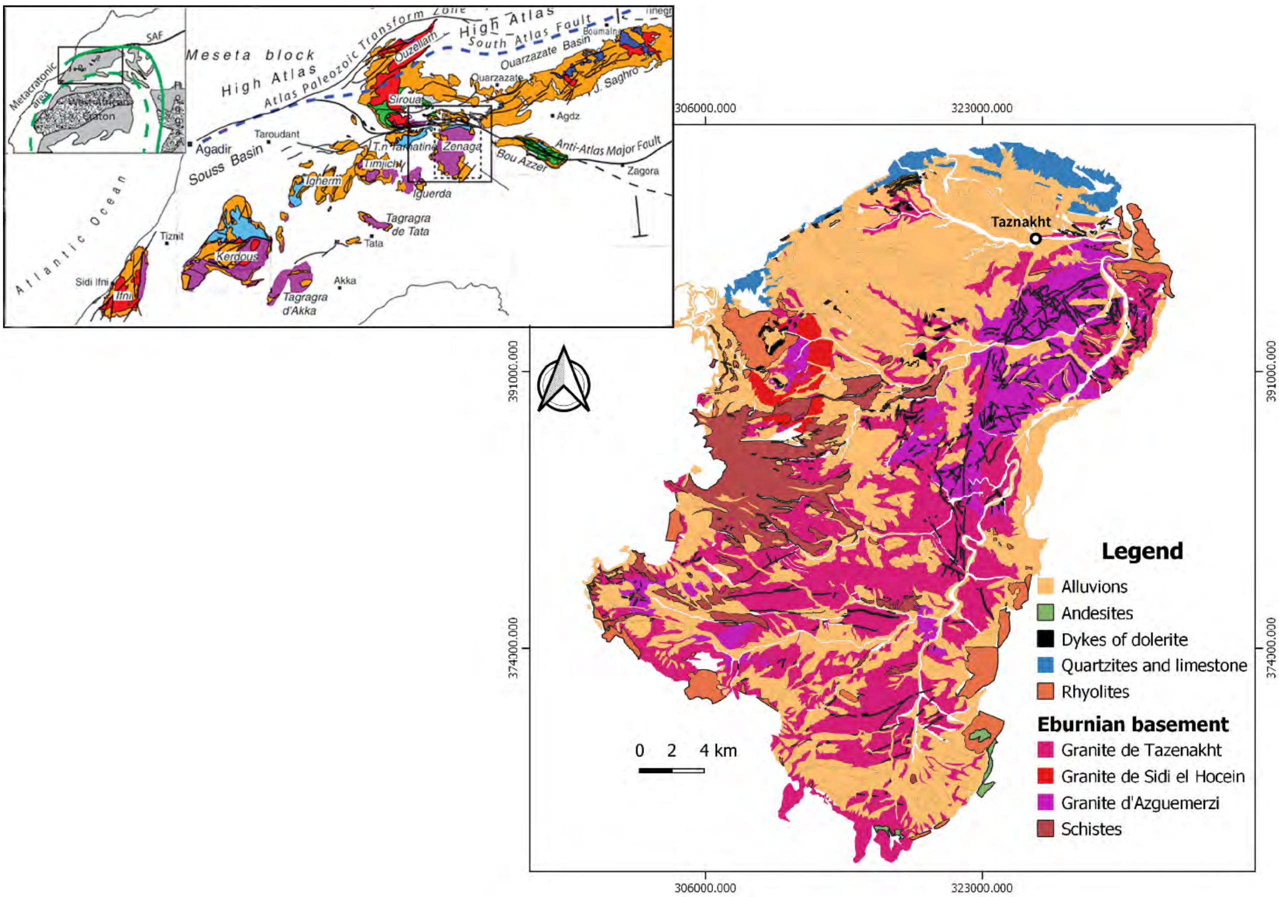


Figure 2: Schematic geological map, illustrating (a) the geological structures in Morocco and (b) the Anti-Atlas domain (THOMAS et al. 2002), and (c) the major rock materials in Zenaga inlier.

3. Data and Methodology

3.1. Data

This study used the rainfall and temperature data, remote sensing images and field trips investigations, and inventory and social survey of Khettara systems.

3.1.1. Rainfall and temperature data

Rainfall and temperature records from Assaka meteorological station, as outlet points of the Taznakht plain, were used in this study. Data series from Assaka station were provided by the Draa Oued Noun Hydraulic Basin Agency (ABHDON).

The meteorological data used in this study are annual precipitations, monthly precipitations, monthly average temperatures, monthly maximum temperatures, and monthly minimum temperatures, from the year 1985 to the year 2015, recorded in the station of Assaka.
In addition to in-situ measured temperatures, monthly average estimated temperatures are extracted from the "climate change knowledge world-bank" for 12 points into the plain.

3.1.2. Remote sensing data

Seven multispectral image sets from Landsat 4-5 Thematic Mapper (TM) and Landsat 8 Operational Land Imager (OLI) were downloaded freely online from the U.S. Geological Survey platform (https://earth explorer.usgs.gov/). The selected period is from the 20th of April to the end of May, except for 2020 where the most recent image was acquired on the 30th of March. We chose this period to avoid confusion with the annual vegetation and agricultural periods, using the radiometric resolutions for the Landsat MSS and TM sensors were 8 bits. In comparison, the radiometric resolution of the Landsat OLI sensor was 16 bits. Table 1 presents the main characteristics of the used images.

3.2. Methodology

The adopted methodology in this work is divided into three fundamental phases, as presented in Fig. 3. The first phase concerns the collection and statistical analysis of climate data. The second phase starts with the Landsat images collection and pre-processing and ends with the study of the vegetation evolution to evaluate the impact of climate and anthropic factors on the water resource condition and the vegetation change (Fig. 3). Finally, we dedicate the third phase to Khettaras inventory and spatiotemporal change detection of rural agricultural fields.

Therefore, we combined the data and results obtained with the change detection output into an integrated analysis and discussion, providing a better understanding of the spatiotemporal dynamics of vegetation and impacts on groundwater resources.

Table 1. Description of the used Landsat multispectral images

Satellite	Sensor	Spatial resolution	Acquired date
Landsat 4-5	Thematic Mapper (TM)	30 m	17-May-1985 15-May-1990 13-May-1995 26-May-2000 24-May-2005 20-April-2010
Landsat 8	Operational Land Imager (OLI)	30 m	20-May-2015

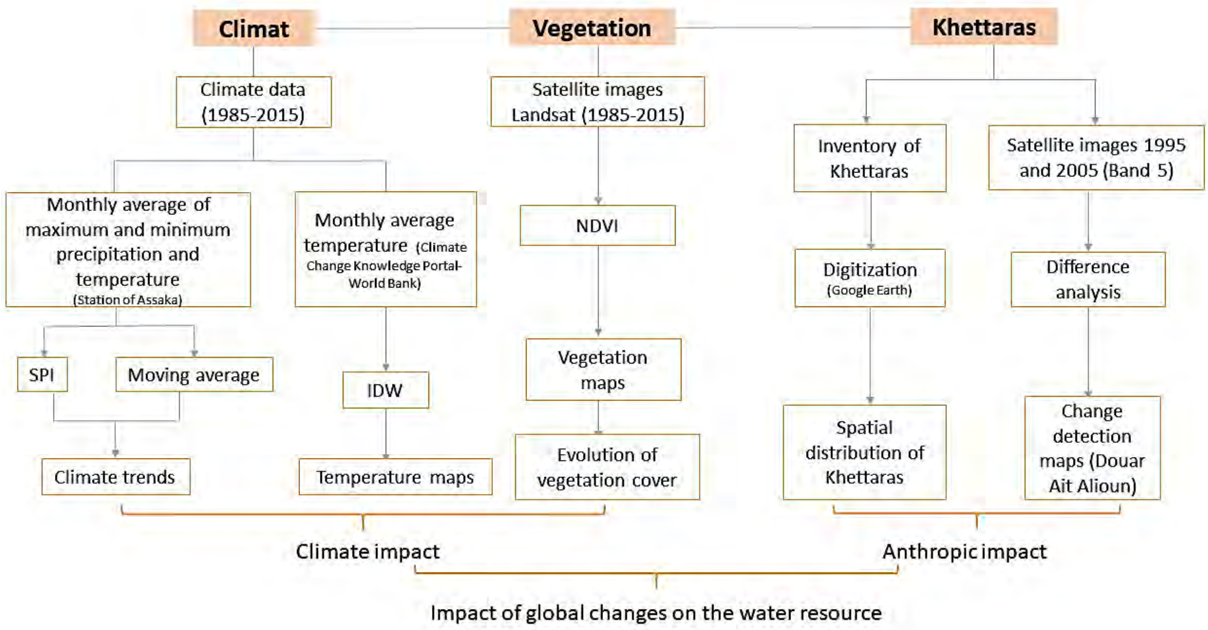


Figure 3. Methodological flowchart of this study

3.2.1. Statistical treatment of climate data

Two statistical methods were used in this study: The Standardized Precipitation Index (SPI) and the moving average.

The SPI, developed by MCKEE et al. (1993), is a powerful tool for drought studies and is classified as a green index thanks to its simplicity and ease of use. It is the standard index for tracking and monitoring meteorological drought. SPI is performed from the following equation (1):

$$SPI = (Pi - Pm)/s \qquad (1)$$

Where:
Pi: Total rainfall for the year i;
Pm: Mean annual rainfall of the time series;
σ: Standard rainfall deviation of the time series.
The moving average is the most apparent data smoothing over a specified period. It is a calculation that analyzes data points by creating a series of averages of different subsets of the full data set, which helps smooth out short-term fluctuations and highlight longer-term trends or cycles.

The monthly average temperature extracted from the climate change portal of the World Bank for 12 points within the plain is interpolated using inverse distance weight (IDW) to visualize the spatiotemporal distribution of temperature.

3.2.2. Vegetation index

The Normalized Difference Vegetation Index (NDVI) quantifies vegetation by measuring the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs) using the equation below (WEIER & HERRING 2000):

$$NDVI = \frac{(\text{Near infrared} - Red)}{(\text{Near infrared} + \text{Red})} \qquad (2)$$

This index varies from -1 to +1.

Varying between -1 and +1, NDVI was computed for all the plains extracted from the satellite images using the same remote sensing and image processing software. Then, they were reclassified into two classes: a vegetation cover, and a non-vegetation cover, using a geospatial processing program.

Finally, we converted each image into a percentage to define the vegetation cover and analyze its evolution over the years. We then deduce a graph to verify the existence of a trend.

3.2.3. Khettaras Inventory

Using Google earth and field trips inventory, Khettaras were digitized throughout the Taznakht plain and documented according to their number

and location in a GIS database. Some their characteristics are extracted such as wells number, length of every system, current status of in addition to the total length of all the Khettaras in the Taznakht plain.

4. Results

4.1. The Standardized Precipitation Index and rainfall trend

With equation (1), we calculate the SPI to determine the wet and dry phases in the climate of Taznakht plain, using the annual mean of rainfall data from 1985 to 2015. Figure 4a displays that the 30-year study starts with a lightly dry year heading for a moderately dry one by the end of 1986, and directly after 1987, an extremely wet phase started and kept going until the end of 1989. A variation of dry and wet steps began from 1990 to 1993, followed by a continuous wet phase until 1995. We divided this wet phase into a moderate one in 1994 and a light one in 1995.

From 1996, precipitation kept decreasing until the end of 2000, so this whole period was marked a lightly dry one but 2000, which was a moderately dry year. In 2001, precipitation went up again keeping an SPI of only 0.09 but making it at least a lightly wet year. However, it started falling again, marking a lightly dry phase from 2002 to 2007 with one moderate dry year; 2004. From 2008 to 2010, another wet phase started, followed by a dry one that lasted from 2011 to 2014, with the two years 2011 and 2013 moderately dry. The year 2014 increased directly after, marking the highest SPI since 1989. Finally, we noted that over the 30-year study period, we counted 17 dry years and 12 wet years.

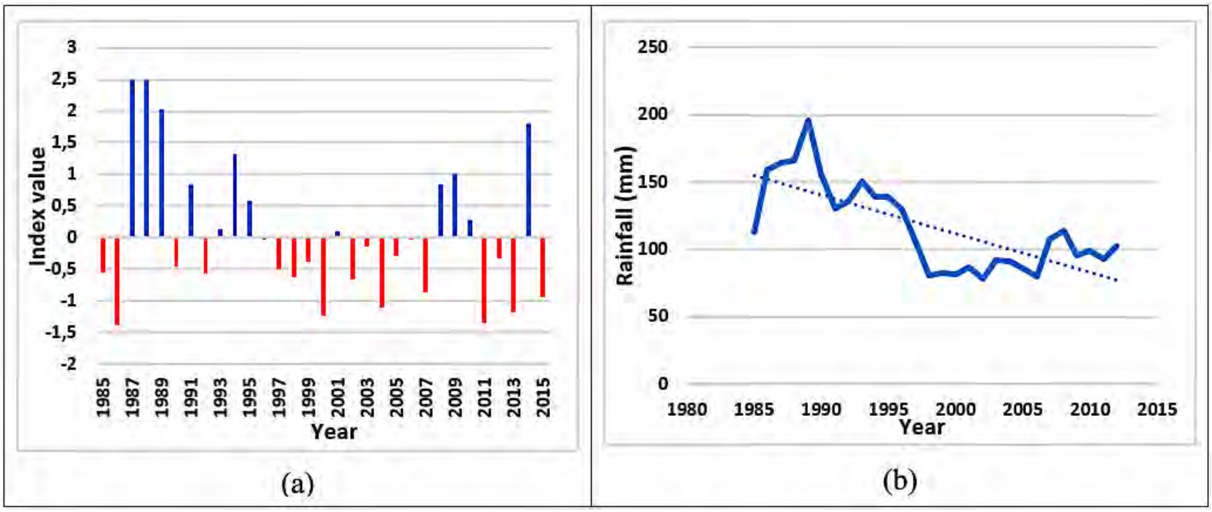


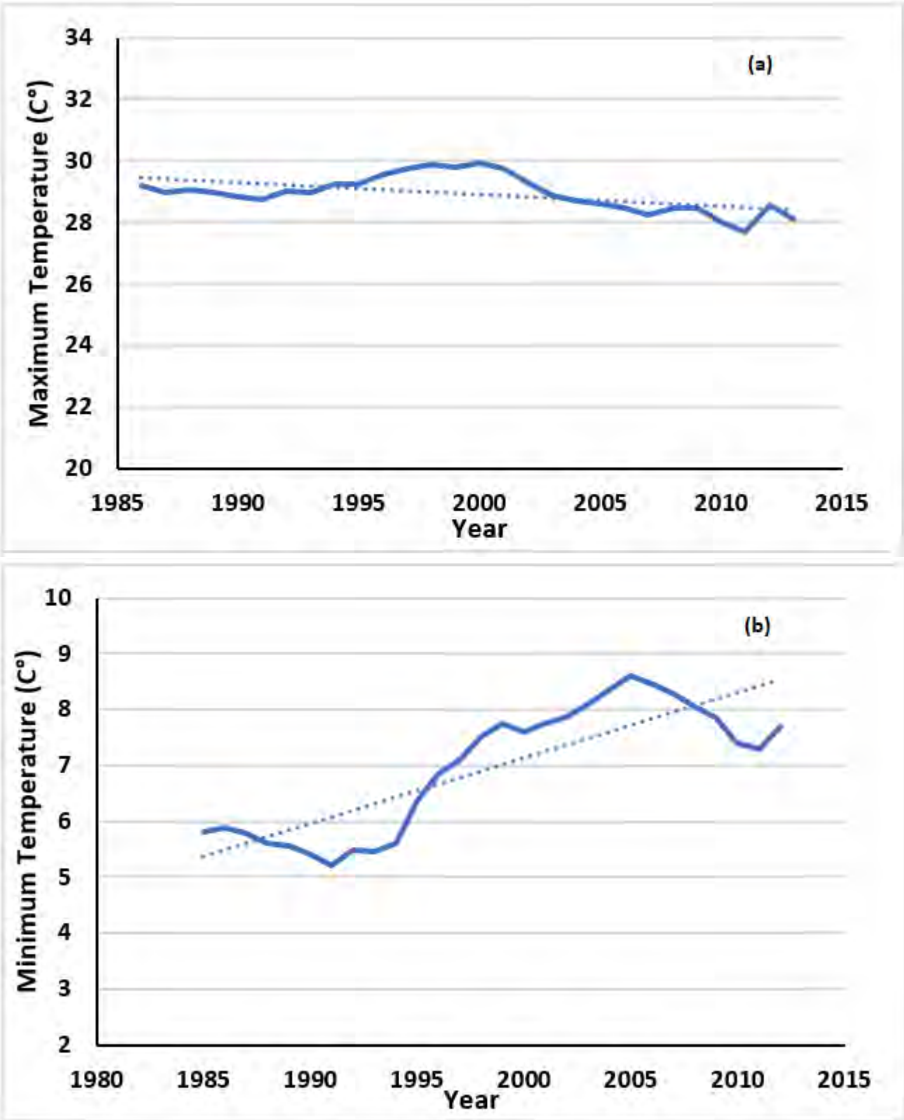
Figure 4. Statistical treatment of rainfall data, (a) SPI results for the period 1985-2015, (b)Moving average of annual rainfall (1985-2015)

We calculated the moving average of annual precipitation to confirm the predominance of dry phases throughout the years. For this purpose, we used groups of 5 years to see the precipitation trend during the global period 1985-2015. Figure 4b shows a remarkable decrease in rainfall throughout the years, with huge variations, especially from 1985 to 1998. This period witnessed the most substantial precipitation in 1989, with 198.58 mm of rain. Furthermore, we noted an evident decline in rainfall from 1995 - 2000 to the end of the time series. As a result, we demonstrated a widespread rain was decreasing trend in the area, reducing around 70 mm during the studied period.

4.2. Spatiotemporal evolution of temperatures in the Taznakht basin

Using groups of 5 years, we calculated the moving average of the maximum and minimum temperatures (Fig. 5) to understand better the impact of temperature on the plain of Taznakht.

In Figure 5a, the trend declines very softly throughout the years, as the first and last maximum temperatures are very close; they are both limited between 28 °C and 29 °C. On the other hand (Fig. 5b), an evident increasing trend in minimum temperatures with a variation of 3.36°C was noted. Therefore, we detected that temperature is building up in the new millennium as it exceeds 8°C, contrary to the decades before where it never passed 6°C, which influenced the trend to increase even more.



a

b

Figure 5. Moving average temperatures (a) Maximum temperatures (b) Minimum temperatures

In Figure 6, the elaborated maps using estimated satellite climate data and validated by in-situ measured data (Fig. 7) show that temperatures have increased over the Taznakht plain during the 30-years period.

The lowest temperatures are recorded in the northern part of the plain, while the highest temperatures are in the southern region and the same distribution list for the whole period. We noted that the temperature decreased in the upper half of the plain from 1980 to 1995. It rises again before the year 2000 and then decreases again from 2005 to 2010 and finally increases again until 2015.

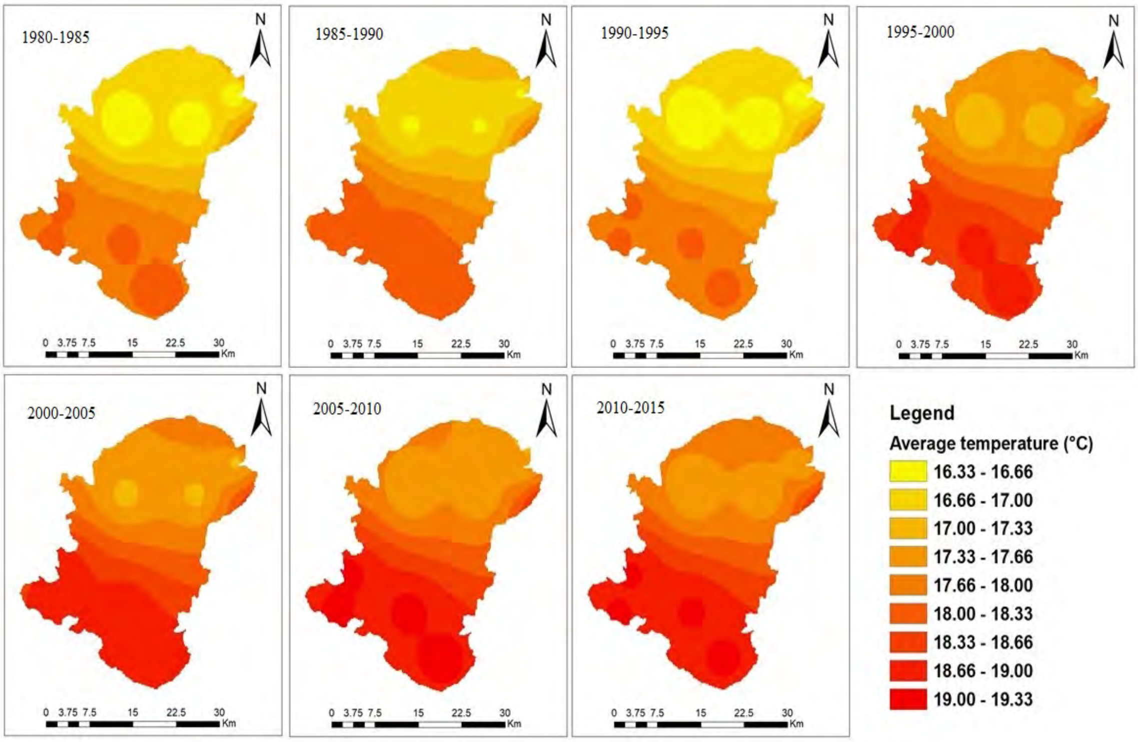


Figure 6. Spatiotemporal evolution of monthly average temperatures in the Zenaga Buttonhole.

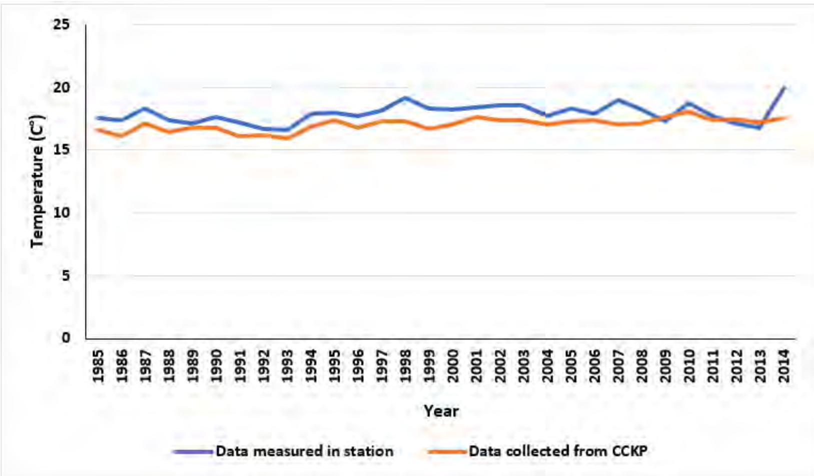


Figure 7. Validation of collected temperature data from CCKP by measured temperatures data

4.3. Evolution of plant cover

The application of the NDVI on every satellite image allowed us to obtain the vegetation maps that show the evolution of the plant cover from 1985 to 2015 (Fig. 8). In this studied period, there was a slight change in the plant cover in the NE of the plain where it has gotten stronger with the emergence of a green field in the SW. From 1985 to 2000, a general decline of the plant cover all over the plain was recognized where vegetation looks less strong, specifically mentioning the disappearance of two fields in the NE of the plain. From 2000 to 2015, a very remarkable vegetation growth was noted, as it appears stronger and more intense throughout the whole plain in 2015 compared to 2000, along with the emergence of many green fields in the north and in the south parts of the plain.

In the study of the evolution of vegetation in the plain of Taznakht, we calculated the percentage of vegetation cover and then compared it to the non-vegetation surface. We gathered our results in the

graph of Figure 9. From 1985 to 1995 we noticed that the percentage of plant cover growing by 0.77%, and then reduced until 2005 by 1.07%. After 2010, the plant cover exceeds 2%.

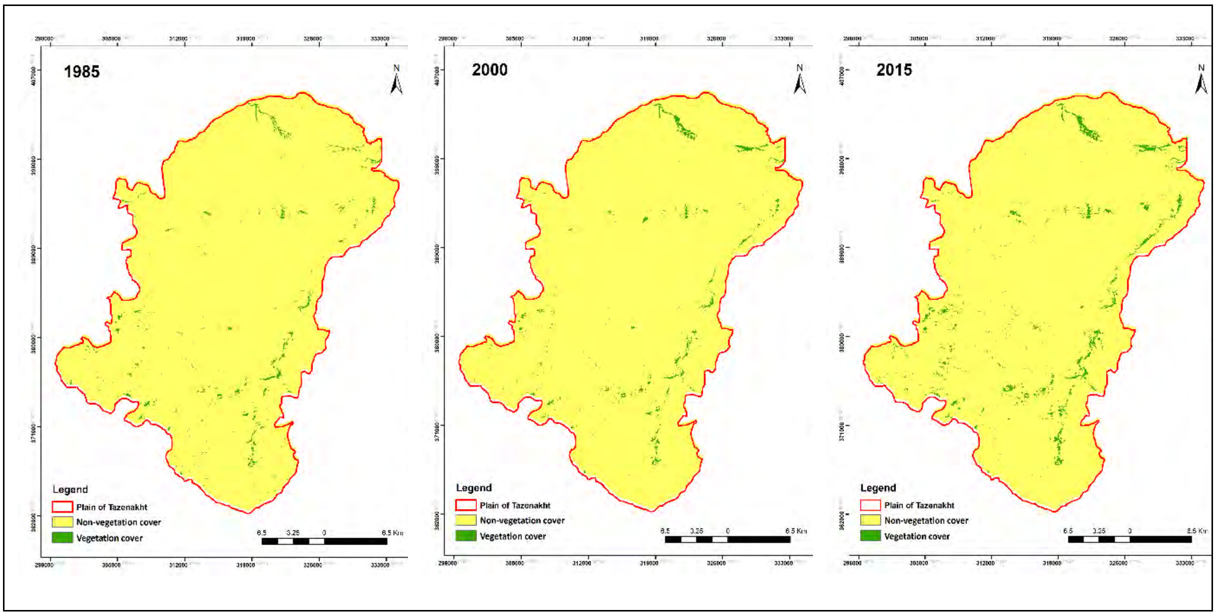


Figure 8. Spatiotemporal evolution of vegetation in the plain of Taznakht from 1985 to 2015

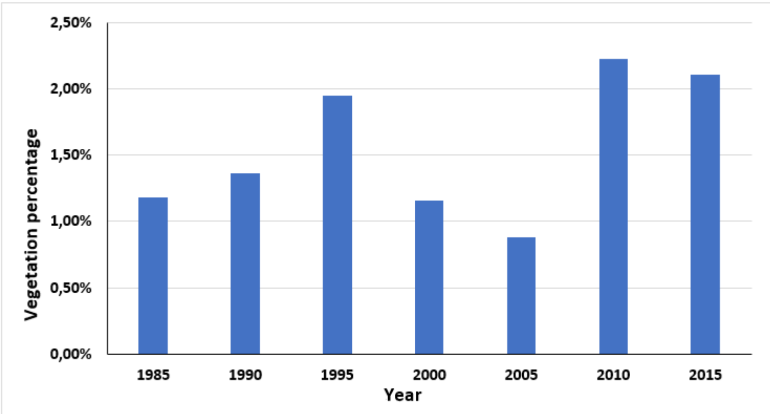


Figure 9. Vegetation percentage evolution during the period 1985 to 2015.

4.4. Agricultural field distribution according to the Khettaras conditions

After the field inventory and the digitizing of all the Khettaras around the plain of Taznakht using Google Earth, data were exported, then projected over a satellite image of the year 2020 as shown in the map below (Fig. 10). We noticed that Khettaras are distributed all over the plain and are mostly localized close to water streams. Almost every village or Douar has its own and sometimes multiple Khettara series, depending on the size of irrigated fields. There is 11.48 km of the Khettara series-across the whole plain.

Most of the Khettaras in the Taznakht plain are not functioning, which impacts vegetation reduction, proven in the example of the small Douar Ait Alioun. The NDVI results in figure 11 show the distribution of vegetation by green color. Generally, the surface occupied by irrigated fields is reduced from 1995 to 2005. According to field observations and social surveys, this reduction is quite remarkable. For example, in the 2005 map, an entire agricultural field disappeared compared to the 1995 map, rounded by the red circle in figure 11.

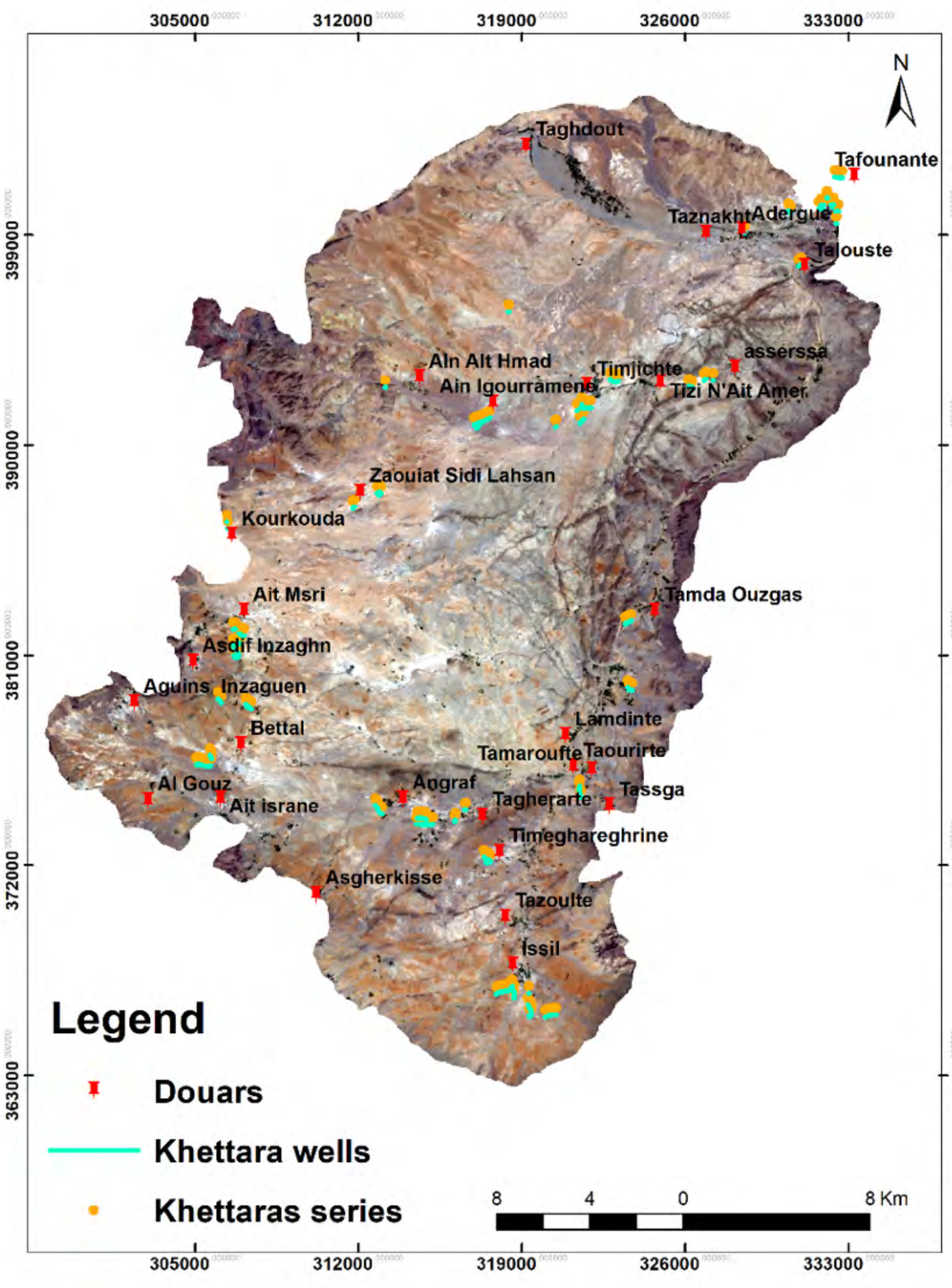


Figure 10. Spatial distribution of Khettaras systems on satellite image background of Taznakht plain

5. Discussion

We conducted the climate analysis using statistical and GIS interpolation methods that revealed that during the period 1985-2015, the climate of Taznakht experienced a variety of wet and dry phases. The results of the standard precipitation index allowed us to observe a variety of precipitation statuses in Taznakht, as they showed a climate that experiences different phases ranging

from extreme wetness to moderate drought over the 30 years (1985-2015). Taznakht experienced the last intense wet phase in 1987-1989, with the highest amounts of precipitation record, ranging from 185.4 mm to 281.3 mm. Indeed, after 1983, we never had such a high precipitation rate, but after a dry phase, an occasional increase occurred from time to time.

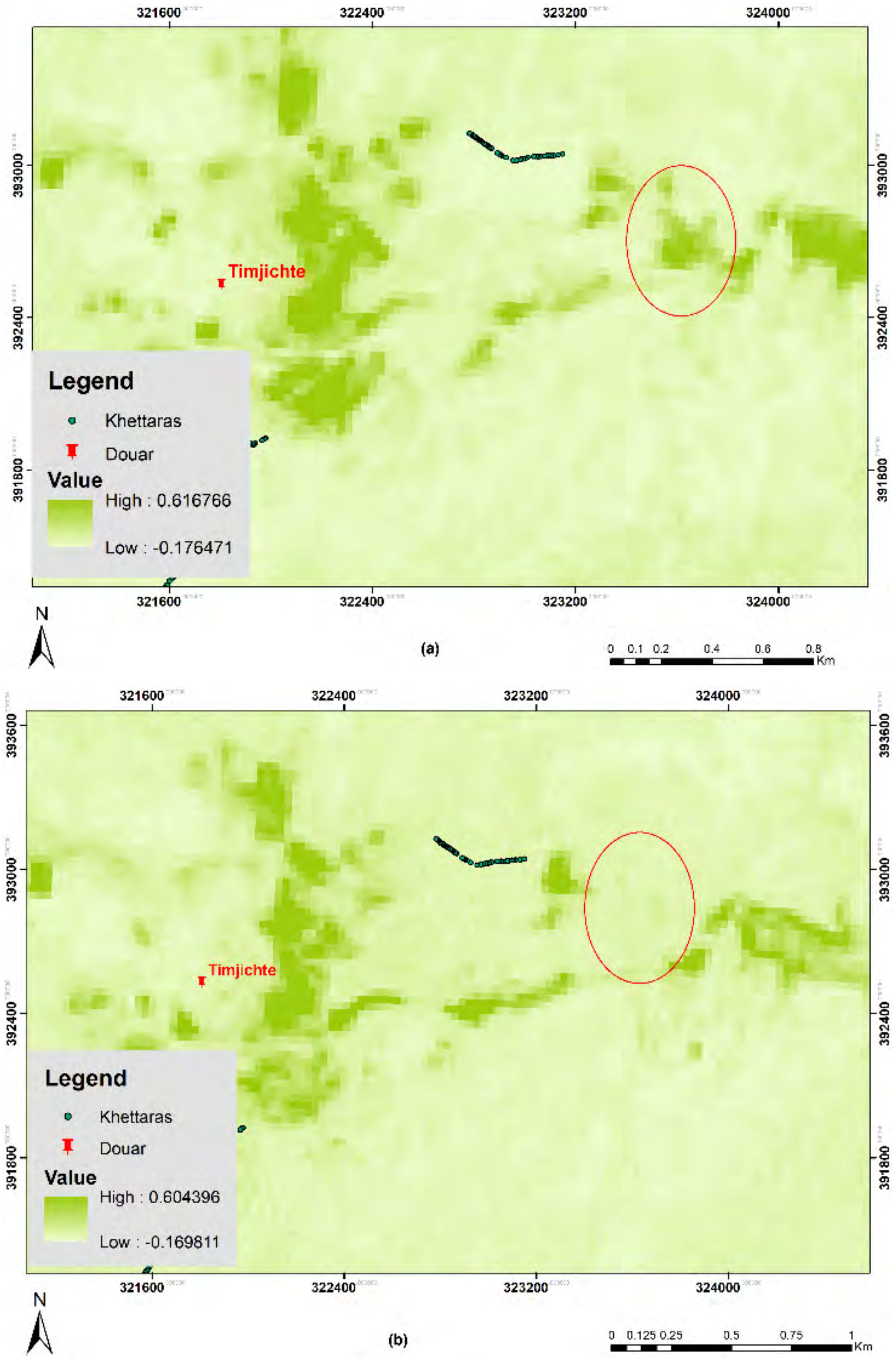


Figure 11. Example of agricultural field losing in the study area. NDVI maps of year 1995 (a) and year 2005 (b)

Comparing the period 2000-2015 to 1985-2000, we noticed that the precipitation rate decreased. The moving averages of precipitation and temperature showed correlative results. Precipitation showed, according to the standard index results, a decreasing trend. Maximum temperatures presented a decreasing trend, as the change is hardly recognizable. In contrast, minimum temperatures increased since 1985; this trend continued from the new millennium until the end of the time series. We can thus conclude that it was not as cold as before because the temperature is constantly increasing in Taznakht, especially since the decrease in precipitation did not help.

Furthermore, the increasing frequency and intensity of drought in Taznakht are related to global climate change. Therefore, the resulting trends will likely be more evident in the future. In this case, reduced precipitation and increased temperatures in the Taznakht plain will drastically reduce water resources. This reduction will impact the irrigation of agricultural fields, and only groundwater will be available to alleviate the water stress in this plain.

In 1985, the vegetation cover only counted for 1.18% of the whole area of Taznakht plain. The plain being can explain this small percentage at its early recovery from the light drought it experienced between 1982 and 1983. The vegetation cover in Taznakht plain kept going up until 2000. After that, it started declining drastically, especially in 2005, when it reached the lowest amount of vegetation cover during the whole time series of 30 years due to climate change's impact on the plain. However, 2005 had a modest amount of precipitation; for example, the Assaka station recorded only 108.3 mm, which we explain by unseasonal rainfall.

A notable increase in vegetation cover occurred in 2010 when it reached the highest percentage in the 30-year time series due to increased rainfall and the adoption in 2008 of the Green Morocco Plan, which aims to improve vegetation cover.

This plan has allowed a substantial increase in the production of saffron, in parallel with market demands. Subsequently, thanks to this plan, the vegetation remained abundant, despite the 50% decrease in rainfall compared to 2010.

Furthermore, analysis of the NDVI maps of Douar Ait Alioun shows that the change in vegetation cover appears negative due to the decrease in agricultural fields between 1995 and 2005. According to our survey, it seems that the series of Khettaras in this Douar was inactive after the year 1995, which caused the disappearance of some fields, usually directly irrigated by this system.

Therefore, it is clear that the disappearance of the Khettara system has impacted the distribution of agricultural fields and has led to erosion and a decrease in vegetation cover.

Finally, we noted that the decline in the performance of this system is mainly due to the orientation of the inhabitants towards more modern irrigation systems through boreholes, even if they are more expensive. Unfortunately, a prolonged period of intense drilling and pumping will undoubtedly lead to a general disturbance of the aquifer, sometimes resulting in a lowering of the water table and drying up of the Khettaras.

6. Conclusion

The plain of Taznakht experiences severe drought proven by rainfall reduction (with almost 50%) during the observed 30-years (1985-2015) with more dry phases than wet ones, increasing temperatures accompanied by high evapotranspiration rates, and dry inactive Khettaras; which impacts the economic and social situation of its population. The evolution of vegetation cover was studied using Landsat images and the vegetation index to clarify the impact of climate change on water resources in the plain.

This study demonstrated a reduction in vegetation cover of 45% since the beginning of the new millennium, showing a correlation with the climate tendency. However, after 2005 the state of vegetation reached the highest area in 2010 (2894 ha). This cover extension coincides with Green Morocco Plan, launched in 2008 and supported an agriculture process in the country including the Taznakht area. During 2015, the vegetation cover observes a similar extension of 2738 ha than 2010, despite the high temperature and low rainfall. The main water supply was from groundwater, causing overexploitation of the aquifer. We highlighted

this human impact by distributing agricultural fields and Khettaras state over the plain using the NDVI results. These Traditional techniques used to collect water for drinking and agriculture purposes are in continuous degradation, in the area, letting place to the boreholes which the government supports. This local turning from traditional Khettara systems to more modern techniques of drillings because they need a high cost of maintenance to exacerbate the water crisis in the area.

Acknowledgements

The authors express their gratitude to Hydraulic Basin Agency of Draa-Oued Noun for providing the in-situ climate data. This work was carried out within the CHARISMA Project with the assistance of Hassan II Academy of Science and Technology, the support of Ibn Zohr University and WASA project. The authors are grateful to the "Institut de Recherche pour le Développement" (IRD, France). We acknowledge specially support from IRD representation in Morocco.

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Projections of extreme soil moisture drought in southern Moroccan watersheds under anthropogenic climate warming

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Abstract. The intensification of drought conditions across North-Western Africa is one of the most expected consequences of anthropogenic global warming. However, the effects of 1.5-3°C policy-relevant global warming on soil moisture drought events remain unknown at the catchment scale. This study provides a comprehensive assessment of these events across four semi-arid catchments in Southern Morocco. We use soil moisture simulation from an ensemble of four Land Surface Models (LSMs) forced with bias-adjusted climate projections from four Global Climate Models (GCMs) under three Representative Concentration Pathways (RCPs 2.6, 6.0, and 8.5). The ensemble projects an unprecedented increase in drought events duration, persistence, and severity, driven by global warming intensification, across all catchments. Under 3°C global warming, which is the current track, these catchments are projected to experience decades-long (up to 20 years) mega-droughts compared to a maximum drought duration of 7 years under 1.5°C and 11 months in the historical period (1971-2000). This intensification is accompanied by an increase in drought persistence and order of magnitude (12-16x) of historical drought severity. Under these conditions, a strong increase in aridity, especially in winter and spring, from 9-11 mm under 1.5°C to 17-22 mm is projected under 3°C global warming. Given these large changes, historical drought extremes might be considered the new normal conditions in the future. For these reasons, further assessments are needed more urgently than ever to investigate the impact of these extreme events on society and evaluate possible mitigation strategies in the context of uncertainty to provide reliable information to minimize the negative effects of these events.

Key words: drought, soil moisture, global warming, watershed, Morocco

1. Introduction

North-Western Africa is regularly affected by severe drought episodes because of the strong inter-annual variability of precipitation (DRIOUECH et al. 2013; ESPER et al. 2007; KNIPPERTZ et al. 2003; LIONELLO 2012; TOUCHAN et al. 2008; TRAMBLAY et al. 2013). These climatic extremes affect ecosystems, the economy, and more importantly human livelihood. The heavy reliance on rainfed agriculture, particularly for rural populations which are mostly poor, leads to the pronounced vulnerability to drought events in the region (BYERS et al. 2018; LERNER-LAM 2007; SCHILLING et al. 2012; SCHILLING et al. 2020; WAHA et al. 2017). For example, about 90% of agricultural land in Morocco depends on precipitation regimes and mainly consists of small traditional farms that produce 70% of agricultural GDP, employ 75% of the rural population, and are responsible for the bulk of the country's basic food supplies (BAZZA et al. 2018). Severe drought, therefore, can be extremely costly and lead to devastating impacts in the country. For example, drought episodes of 1994-1995 resulted in a 7.6% GDP loss reducing rural employment by 60% (BAZZA et al. 2018; VERNER et al. 2018). The 1999 drought affected more than one million hectares of crops with an estimated cost of

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DOI: https://doi.org/10.34874/IMIST.PRSM/fsejournal-v11i2.28993

900 million $ US, at minimum, reported by the insurance sector (http://www.emdat.be/) as a large number of farmers lacked insurance and only received little compensation for their losses (VERNER et al. 2018). Recent drought episodes caused a decrease in agriculture production which adversely affected more than 700,000 people in 2006-2007 and resulted in a devastating 3% drop in economic growth in 2015-2016 (BAZZA et al. 2018; VERNER et al. 2018).

Society as a whole, and poor populations, in particular, will likely pay the heaviest price for the warming and drying trend across Morocco (ALEXANDER 2016; DRIOUECH et al. 2020b; TRAMBLAY et al. 2013; TRAMBLAY et al. 2020). In upcoming decades, a likely increase in dry spell length and frequency is found in terms of precipitation, soil moisture, and evapotranspiration in the Mediterranean basin due to anthropogenic global warming (DRIOUECH et al. 2020a; GREVE & SENEVIRATNE 2015; GREVE et al. 2014; HOEGH-GULDBERG et al. 2018; HUANG et al. 2016; IPCC 2012; ORLOWSKY & SENEVIRATNE 2013; POLADE et al. 2017; TRAMBLAY et al. 2018; TRENBERTH et al. 2014).However, the effects of global warming on the characteristics of soil moisture-related drought events are still unknown at the local scale (*e.g.,* drought duration and area). In particular, stakeholders and water managers need solid information about future changes in drought and soil moisture characteristics in the south Moroccan watersheds.

Droughts start with a precipitation deficit which propagates into a reduction in soil moisture and surface and subsurface water depletion (WMO 2018). However, the translation from precipitation deficit into soil moisture is not linear and depends on several processes that control the surface water balance (BERG & SHEFFIELD 2018; KONAPALA & MISHRA 2017). Therefore, soil moisture is considered an integrative indicator for drought because it reflects the balance between rainfall, evapotranspiration, and total runoff (surface and subsurface) (KEYANTASH & DRACUP 2002). In addition, soil moisture persistence was found to be an important driver of projected changes in droughts due to the carry-over effect of soil moisture deficit from one season to the next, which can cause year-round drought events (IPCC 2012; WANG 2005). Soil moisture drying can directly impact crop development and yield, cause vegetation stress, enhance the risk of wildfires, affect biodiversity, and pose great threats to food security and livestock farming (PEICHL et al. 2019; XU et al. 2019a).

Soil moisture drought can be monitored through various metrics that consider precipitation (atmospheric supply) and potential evapotranspiration (atmospheric demand) (BERG & SHEFFIELD 2018). The Palmer Drought Severity Index (PDSI) uses a simple water balance model to measure moisture deficit (DAI 2011). Even though these metrics are appealing and may be accepted for present and past conditions, they come with many shortcomings when applied to analyze future drought trends (BERG & SHEFFIELD 2018; GREVE et al. 2019). The parameterization of potential evapotranspiration in such measurements often depends on temperature. This has been criticized, and we have found that future drought and aridity have been overestimated (SHEFFIELD et al. 2012; TRAMBLAY et al. 2018; TRENBERTH et al. 2014). Furthermore, these metrics are essentially a lumping of many hydrological processes, important to drought development, into a greatly simplified model (BERG & SHEFFIELD 2018). These measurements use potential evapotranspiration as an approximation of actual evapotranspiration. Nevertheless, it neglects soil moisture and vegetation control on evapotranspiration(IPCC 2014). For example, these metrics do not account for the future increases in atmospheric CO_2 on stomatal conductance which was shown to reduce the projected increase in potential evapotranspiration leading to wetter soils, thereby fundamentally changing drought projections (GREVE et al. 2019; MILLY & DUNNE 2016; SWANN et al. 2016; TRAMBLAY et al. 2020; YANG et al. 2019).

Using simulated soil moisture from the recent and more sophisticated land-surface and hydrological models (offline or coupled to climate models) is less problematic for drought analysis than these simplistic metrics. However, there is considerable

variability in future soil moisture projections due to uncertainty in climate projections and hydrologic model parameterizations (BOSSHARD et al. 2013; DONNELLY et al. 2017; GOSLING et al. 2017; LU et al. 2019; MARX et al. 2018; SAMANIEGO et al. 2013; SAMANIEGO et al. 2017; THOBER et al. 2018). Hence, multi-model ensembles are fundamentally required to provide a comprehensive assessment of soil moisture drought. In this study, we assess the impact of global warming on soil moisture drought events using a large multi-model ensemble of 4 general circulation models (GCMs), four land-surface models (LSMs), and three representative concentration pathway scenarios (RCPs). This analysis answers the following research questions:

- What is the magnitude of changes in the characteristics of extreme soil moisture drought events across the southern catchments of Morocco under three policy-relevant global warming levels of 1.5, 2, and 3°C compared to historical conditions?
- What is the implication of future drought extremes in terms of changes in soil water content availability (aridity) over these catchments?

2. Methods

2.1. Study area

The study area covers four semi-arid catchments in southern Morocco, shown in Figure 1. They encompass all rainfed agriculture areas of significant importance for Morocco's economy and are considered the backbone of rural populations. We delineated nine catchments based on the HydroBASINS polygon layers from the HydroSHEDS database(LEHNER & GRILL 2013; LEHNER et al. 2008).

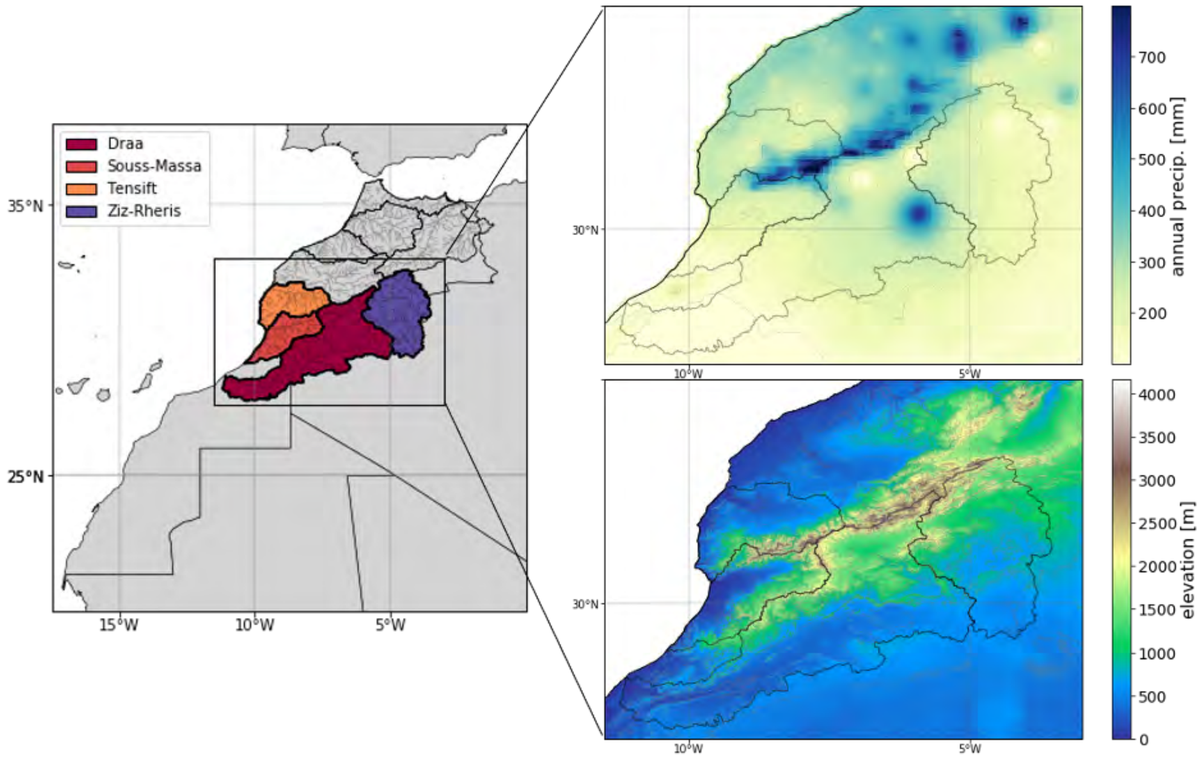

Figure 1: Geographical location, elevation, and precipitation across the four southern Moroccan catchments. The catchments are delineated based on the HydroBASINS polygon layers from the HydroSHEDS database (LEHNER & GRILL 2013; LEHNER et al. 2008). The elevation map is provided by http://www.ngdc.noaa.gov/mgg/topo/globe.html. Precipitation map presents the annual average during the period 1981-2008 computed from the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) time-series (FUNK et al. 2015).

Mountainous areas of the Atlas Mountains dominate catchment topography. The pronounced orography strongly influences the distribution of precipitation and separates the hyper-arid conditions of the Sahara Desert in the south from more temperate northern areas. Winter months are the most prevalent wet season with substantial inter-annual rainfall variability in these parts. Climate variability in these areas is connected to large-scale atmospheric circulations, the Atlantic Ocean's influence, and the local impacts of orography and the Sahara Desert (DRIOUECH et al. 2013; KNIPPERTZ et al. 2003).

2.2. Datasets

This study used an ensemble of monthly soil moisture simulations from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) phase 2b experiment (WARSZAWSKI et al. 2014). The ensemble consists of four state-of-the-art LSMs, presented in Table 1, driven by downscaled and bias-adjusted climate forcing data from four GCMs (GFDL-ESM2M, IPSL-CM5A-LR, HadGEM2-ES, and MIROC5) under historical conditions during 1850-2005 and three RCPs (2.6, 6.0, and 8.5) during 2006-2100 at 0.5° by 0.5°(~50 km at the equator) gridded spatial resolution. Soil moisture is simulated for different depths across LSMs which we integrate into depths of 1 m for the drought analysis.

To evaluate the performance of the different LSMs, we compared simulated soil moisture to observations from the European Space Agency (ESA) Climate Change Initiative (CCI) project (DORIGO et al. 2017; GRUBER et al. 2017; GRUBER et al. 2019). ESA CCI is the first satellite-based soil moisture time-series spanning over 40 years and is currently available globally on a daily basis at 0.25° by 0.25° resolution (~25 km at the equator). ESA CCI dataset is derived by merging active and passive microwave-based soil moisture of the first centimeters of the soil from multiple satellite missions (LIU et al. 2011; WAGNER et al. 2012).

Table 1 : Information on the LSMs used in this study

Model	Institution	Soil	Evaporation Scheme	Runoff scheme	References
Community Land Model version 4.5 (CLM45)	National Center for Atmospheric Research, USA	15 soil layers	Monin-Obukhov Similarity Theory	Saturation-excess	(THIERY et al. 2017)
Joint UK Land Environment Simulator (JULES)	Met Office, United Kingdom	4 soil layers	Penman-Monteith	Infiltration-excess, Saturation-excess	(BEST et al. 2011)
Lund Potsdam Jena managed Land (LPJML)	Potsdam Institute for Climate Impact Research, Germany	5 soil layers	Priestley-Taylor Method	Saturation-excess	(SITCH et al. 2003)
Organizing Carbon and Hydrology In Dynamic Ecosystems (ORCHIDEE)	Institut Pierre Simon Laplace (IPSL), France	11 soil layers	Penman-Monteith Method	Saturation-excess	(GUIMBERTEAU et al. 2018)

The ESA CCI product offers several quality flags and only soil moisture values considered reliable are taken into account (LOEW 2008; PARINUSSA et al. 2011). A comprehensive validation of the ESA CCI soil moisture using in situ observations was done in many parts of the world and shows a close agreement with observations (DORIGO et al. 2015; PASIK 2019). We used The ESA CCI soil moisture in hundreds of hydrological and meteorological studies worldwide. A list of papers using ESA CCI soil moisture is available over https://www.esa-soilmoisture-cci.org/node/137. For example, the ESA CCI dataset is used to evaluate soil moisture from multiple LSMs, hydrological models,

GCMs, and the Coupled Model Intercomparison Project phase 5 (CMIP5) outputs (DU et al. 2016; LAUER et al. 2017; PREIMESBERGER & PASIK 2020; SCHELLEKENS et al. 2017). The ESA CCI product was used to successfully detect large scale droughts in East Africa to support humanitarian aid organizations (ENENKEL et al. 2016; MCNALLY et al. 2016; PREIMESBERGER & PASIK 2020).

ESA CCI only accounts for volumetric soil moisture in the first centimeters of the soil, representing a somewhat different quantity than LSMs simulated soil moisture. LSMs provide soil moisture content in water stored in different soil layers at given depths due to the other soil representations across LSMs. These differences translate to varying temporal soil moisture dynamics between LSMs, making inter-comparing them challenging. We only considered soil moisture content in the upper soil layer of ≤10 cm(DORIGO et al. 2015; LAUER et al. 2017) to overcome this issue. Even though the upper soil layer in LPJML equals 20 cm, we decided to keep it in the analysis to avoid reducing the ensemble size. We converted LSMs soil moisture content of the upper soil layer to the volumetric unit (m^3 m^{-3}) to match ESA CCI by dividing by the layer thickness and water density 998.2 kg m^{-3} (20°C). The evaluation period of 1988-2005 is chosen because ESA CCI has poorer observational density before this date (Fig.5 in DORIGO et al. 2015).

2.3. Time sampling

In this study, the period 1971-2000 T_0 is selected to represent historical climate conditions. For future conditions, we followed the sampling approach in JAMES et al. (2017) to define global warming periods. First, the offset of global mean temperature between the pre-industrial period of 1881-1910 and 1971-2000 is assumed to equal 0.46°C (VAUTARD et al. 2014). Then, 30-year periods (T_Δ, presented in Table 2) are estimated, per GCM and RCP combination, when global warming reaches or exceeds one of the three policy-relevant warming levels of 1.5, 2, or 3°C minus 0.46°C. This approach provides a large ensemble which is essential for a robust analysis of drought events under different warming levels (SAMANIEGO et al. 2018).

Table 2: The 30-year periods T_Δ estimated, per GCM and RCP combination, when global warming reaches or exceeds a warming level of 1.5, 2, or 3°C relative to 1971-2000

Warming level	RCP	GFDL-ESM2M	HADGEM2-ES	IPSL-CM5A-LR	MIROC5
1.5°C	2.6	-	2007-2036	2008-2037	2020-2049
	6.0	2040-2069	2011-2040	2009-2038	2027-2056
	8.5	2021-2050	2004-2033	2006-2035	2012-2041
2°C	2.6	-	2029-2058	2060-2089	-
	6.0	2060-2089	2026-2055	2028-2057	2050-2079
	8.5	2038-2067	2016-2045	2018-2047	2028-2057
3°C	2.6	-	-	-	-
	6.0	-	2056-2085	2066-2095	-
	8.5	2067-2096	2035-2064	2038-2067	2052-2081

2.4. Soil Moisture Drought Identification and Characteristics

Similar to previous assessments (SAMANIEGO et al. 2013; SAMANIEGO et al. 2018), a grid cell is considered under drought if the soil moisture index (SMI) is less than the value corresponding to the 20th percentile of the historical conditions T_0. This threshold reflects moderate drought conditions or even worse according to the US Drought Monitor classification (USDM, http://droughtmonitor.unl.edu/). The SMI is derived from soil moisture x_t of each month t in a given period T (warning T_Δ or historical T_0) as:

$$SMI_t = F_{T_0}\,(x_t)\;\forall t \in T \qquad (1)$$

F_{T_0} is the cumulative distribution function estimated using the kernel density estimate F_{T_0} of

simulated soil moisture during the historical period T_0. f is defined as:

$$f_{T_0}(x) = \frac{1}{nh}\sum_{k=1}^{n} K\left(\frac{x-x_k}{h}\right) \qquad (2)$$

$x - x_k$ are soil moisture values of a given calendar month *n* during the period T_0. *K* is a Gaussian kernel function with a smoothing parameter h which was estimated following Silverman's rule of thumb for each calendar month, grid cell, and GCM-LSM combinations. Drought events are identified in space and time using a clustering algorithm previously developed and applied to study soil moisture drought in Germany and Europe (SAMANIEGO et al. 2013; SAMANIEGO et al. 2018). In space, all cells below the 20th percentile threshold are consolidated into drought clusters. In time, overlapping drought clusters at consecutive time steps are grouped into spatiotemporal drought events. It is worth noting that we chose to calculate the persistence of moderate (<20th percentile) instead of severe (<10th percentile) drought conditions because they both can have extreme impacts as a result of the high vulnerability and low to absent coping capacity in the study domain.

A drought event can be characterized in terms of its duration and severity (MASIH et al. 2014; SHEFFIELD & WOOD 2008). Duration is the time from the onset until the end of an event and equals the average number of months estimated over all the cells within a drought event. Severity (or magnitude) equals the sum of soil moisture deficit below the threshold value (20th percentile) from the onset until the end of an event. In this study, we only focused on the analysis of the most extreme drought events (that is, the longest, largest, and most severe) per period T and GCM-LSM combinations.

In addition to the characteristics discussed above, we also computed drought persistence which characterizes the level to which an area is prone to remain under drought when it already suffers one (SAMANIEGO et al. 2013). Drought persistence is estimated using a two-state Markov chain ($SMI_t \leq 0.2$ and $0.2 < SMI_t \leq 1 \forall t \in T$) as the probability π_{00} :

$$\pi_{00} = Pr[SMI(x_{t+1}) \leq 0.2 | SMI(x_t) \leq 0.2]\ \forall t \in T \quad (3)$$

π_{00} is computed at a monthly time step for each grid cell, period, RCP, and GCM-LSM combinations.

Finally, due to its relevance for water planners, we also estimate the change in available soil water content (aridity) under drought condition as:

$$\Delta x_{T_\Delta} = F_{T_\Delta}^{-1}(0.2) - F_{T_0}^{-1}(0.2) \qquad (4)$$

$F^{-1}(0.2)$ is the soil moisture value corresponding to the 20th percentile during a given period (warming T_Δ or historical T_0 for each cell, RCP, and LSM-GCM combinations. Δx is reported as seasonal averages of the estimated values for each month. The results are represented by the average over all the cells within a given catchment.

3. Results

3.1. Model Verification

The Multi-model ensemble skill in reproducing multi-year annual means of observed soil moisture across the four catchments is assessed during the period 1988-2005. The ensemble mean shows reasonably good skill in simulating the observed annual soil moisture (Fig. 2) with a correlation value of 0.76 and a mean relative bias of -24%. Similarly, GCM-LSM individual combinations underestimate the observed annual means (by 25-45%), except LPJML showing a positive bias of 13%. These differences are higher approaching desert regions, which is of minor importance due to the small soil moisture content in such environments. We note that the verification performed here is quite rigorous as the layer thickness considered is not consistent across LSMs and between LSMs and satellite observations, which in turn are associated with significant uncertainties. Therefore, this verification can mostly be used as a qualitative assessment of these models.

3.2. Changes in Drought Events Characteristics

From Table 3, a large increase in drought event duration is projected as global warming intensifies. The ensemble median duration of the longest events is estimated at a maximum of 11 months (IQR 6-15 months) in Tensift catchment

under the historical period (1971-2000). These events become many folds longer at around 87 months (IQR 50-132), or 7 years, as soon as global warming reaches the 1.5°C Paris Agreement target. All the southern catchments are expected to experience mega-droughts that last more than 10 years (120 months) under 2°C global warming and approaches 20 years (240 months) under 3°C warming (Table 3).

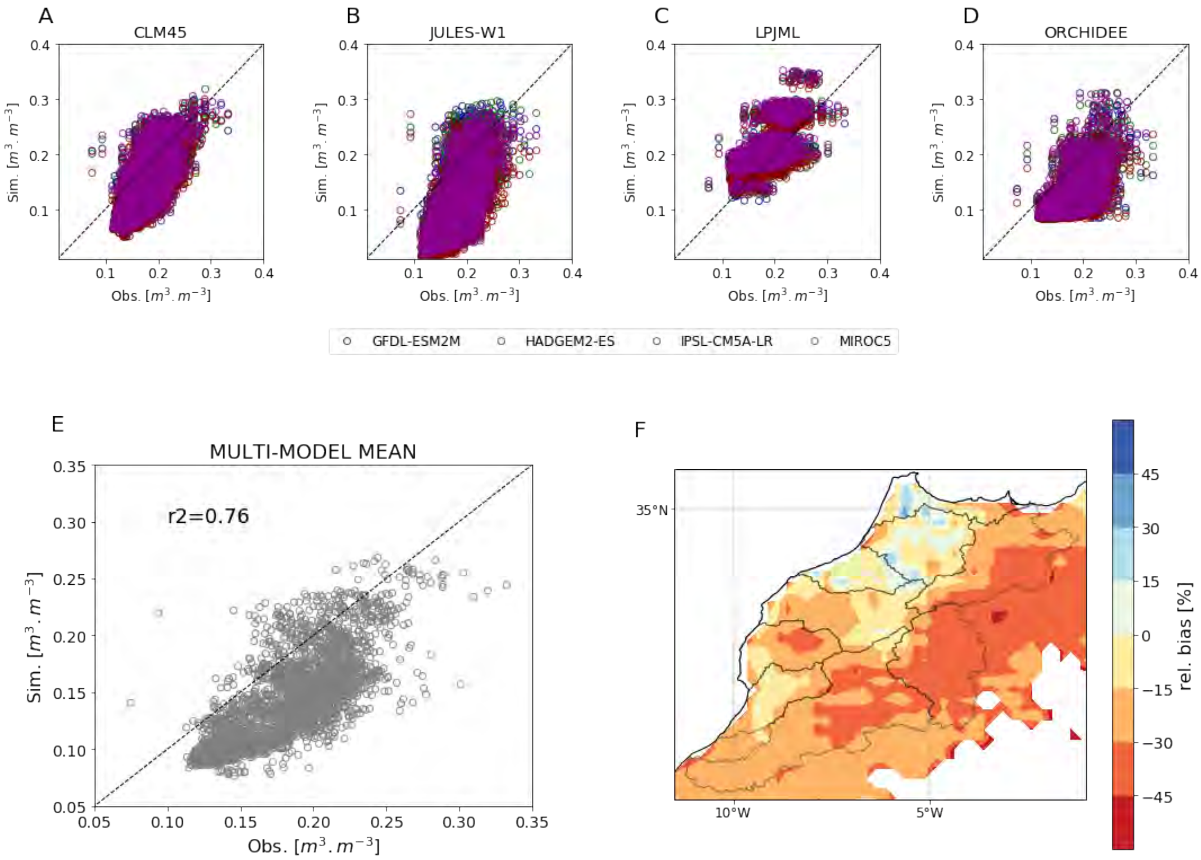

Figure 2 : Evaluation of simulated soil moisture of the upper soil layer. (A-E) Scatter plots of multi-year annual means of observed and simulated volumetric soil moisture for all LSM-GCM combinations (A-D) and the multi-model ensemble mean (E). Each circle in the scatter plots corresponds to the annual mean soil moisture in a given year during the period 1988-2005 and a grid cell located within the nine catchments. (F) Relative bias between simulated and observed soil moisture.

Under these decade long events, drought persistence, estimated as the likelihood of drought-prone areas to remain under drought when already suffering one (SAMANIEGO et al. 2017), is greater or equal 0.8 (80% of the time) across all catchments even under the 1.5°C climate mitigation future (Table 3). As global warming intensifies, the catchments are projected to experience high persistent drought extremes, with an average value of π_{00} equals 0.9 (Table 3). Additionally, the exacerbation of these events is accompanied by many folds of their historical severity as global warming intensifies (Table 3). Under the lowest warming level of 1.5°C, the ensemble median severity increases by around 6 folds over the drier catchments of Draa and Ziz-Rheris and around 3.8 folds across Souss-Massa and Tensift compared to the historical period (Table 3). As global warming gets more intense, the increase in drought severity continues and highlights the sensitivity of these catchments as they experience a 5-10x (12-16x) order of magnitude of historical events severity under 2°C (3°C).

Table 3: Results for drought duration, persistence, and severity averaged over the four catchments under historical (1971-2000) and different global warming conditions. The multi-model ensemble median of drought characteristics is shown along with the interquartile range (25th-75th percentile) as a measure of uncertainty. Drought persistence is expressed as the likelihood (0-1) of drought-prone areas to remain under drought. Drought severity is shown as the ratio of events severity under a warming level to their historical severity.

	Draa	Souss-Massa	Tensift	Ziz-Rheris
Drought Duration [months]				
1971-2000	**13** 9-17	**10** 6-16	**11** 6-15	**16** 8-21
1.5°C	**162** 74-210	**90** 50-159	**87** 50-132	**135** 74-188
2°C	**182** 92-235	**110** 49-209	**124** 57-191	**170** 96-223
3°C	**251** 195-299	**221** 104-284	**217** 122-269	**261** 174-293
Drought Persistence [-]				
1971-2000	**0.66** 0.51-0.76	**0.59** 0.42-0.69	**0.57** 0.45-0.67	**0.69** 0.52-0.73
1.5°C	**0.84** 0.76-0.89	**0.81** 0.51-0.86	**0.78** 0.59-0.85	**0.82** 0.74-0.87
2°C	**0.84** 0.77-0.92	**0.82** 0.6-0.89	**0.83** 0.63-0.86	**0.85** 0.76-0.91
3°C	**0.90** 0.85-0.94	**0.91** 0.68-0.94	**0.89** 0.74-0.92	**0.89** 0.83-0.94
Drought Severity [-]				
1971-2000	**1.0** -	**1.0** -	**1.0** -	**1.0** -
1.5°C	**6.0** 5.7-9.6	**3.8** 2.8-7.2	**3.7** 2.9-5.7	**6.1** 4.5-8.3
2°C	**10.0** 6.8-13.5	**4.7** 4.2-9.7	**5.4** 2.5-7.9	**8.5** 6.1-12.9
3°C	**13.5** 15.4-23.4	**13.7** 8.7-15.9	**12.5** 8.1-16.4	**15.9** 11.7-19.9

3.3. Changes in Available Soil Water Content under Drought

Given this large exacerbation of future drought extremes, historical events "may no longer be classified as extremes" (SAMANIEGO et al. 2018), but rather as the new normal conditions. This points to the crucial question for water managers on what these new droughts imply for adaptation policies across the nine catchments. Similar to previous studies (SAMANIEGO et al. 2018), we answer this important question by calculating the absolute change in available soil water content corresponding to the 20th percentile drought threshold between historical and future conditions. This quantity indicates the change in available soil water content, and thereby aridity, under drought conditions. The absolute change in soil water content is calculated for each season (DJF, MAM, JJA, and SON) and averaged over each catchment.

From the analysis of the ensemble projections, presented in Figure 3, all catchments experience a decrease in soil water content in all seasons and under all global warming levels. Overall, the highest decrease in available soil water content is projected for the winter and spring seasons (Fig. 3). This increase in aridity intensifies with increasing global warming and goes from 12±7 mm (1.5°C) to 15±9 mm (2 °C) to 24±8 mm (3°C) soil water content shortage across Morocco. The Souss-Massa and Tensift catchments generally show a higher increase in aridity compared to the drier catchments of Draa and Ziz-Rheris (Fig. 3). Under 3°C warming, winter available soil water content in the Souss-Massa catchment is projected to decrease by 17±9 mm, corresponds to 17,000 m^3 km^{-2} water shortage. This large decrease is cut by approximately half at 9±7 mm if global warming is limited to the 1.5°C level. Likewise, a

higher increase of aridity of 22±11 mm at 3°C is projected during winter across the Tensift catchment compared to 11±8 mm under 1.5°C. Catchments of Draa and Ziz-Rheris show a lower decrease in soil water content (Fig. 3) due to lower water supply in these areas. In general, the increase in aridity in all catchments under all warming levels further highlights these environments' large sensitivity to global warming, regardless of its level.

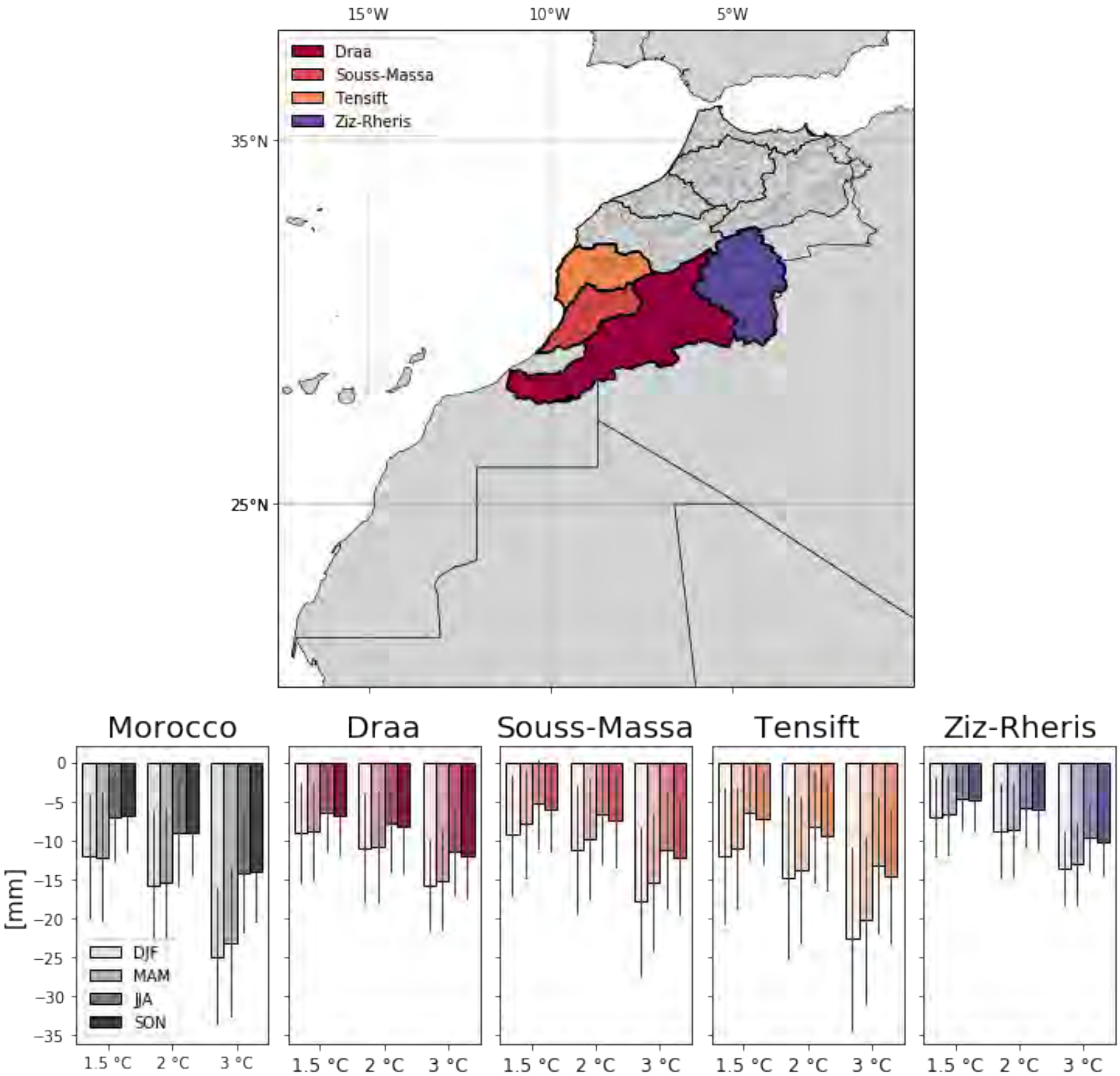

Figure 3 : Absolute change in available soil water content (aridity) between different global warming levels and the historical period. Map (top panel) shows the geographical location of the four catchments. Bar plots present the multi-model ensemble mean absolute change (bars) and standard deviation (whiskers) of soil water content during drought events averaged over each catchment for the four seasons (from left to right: DJF, MAM, JJA, and SON). The first bar plot panel (titled Morocco) shows the average across the whole country.

4. Discussion

Moroccan catchments are projected to experience drought extremes of unprecedented duration, persistence, and severity due to increasing global warming. Under low climate mitigation, corresponding to 3°C global warming, drought extremes are projected to spread over all catchments, last for decades (10-20 years), with extreme persistence (π_{00} >0.8), and many folds (>10x) more severe compared to the historical

conditions. This increase in dry spells extremeness appears across generations of climate models based on different scenarios and metrics over the Mediterranean basin. It is deemed very likely with rising global temperature (DAI 2013; DALIAKOPOULOS et al. 2017; DRIOUECH et al. 2020a; DUBROVSKÝ et al. 2014; GREVE & SENEVIRATNE 2015; IPCC 2012; 2013; ORLOWSKY & SENEVIRATNE 2012; ORLOWSKY & SENEVIRATNE 2013; OZTURK et al. 2015; TRENBERTH et al. 2014; WANG 2005; XU et al. 2019b; ZHAO & DAI 2015). Consistent with these projections, reconstructions of past droughts in North-Western Africa also demonstrated that the second half of the twentieth century stands out as the driest among the last nine centuries (TOUCHAN et al. 2011).

This exacerbation of drought extremes is due to the large decrease in soil water availability projected in all seasons, especially in winter and spring, which is mainly a result of the projected decline in precipitation and increase in atmospheric evaporative demand due to high increases in maximum daily temperatures over the Mediterranean (POLADE et al. 2017; SENEVIRATNE et al. 2016). By the end of the 21st century, the projected rainfall reduction is estimated at 38% in Northwestern Africa based on 30 CMIP5 GCMs (POLADE et al. 2017) which is similar to what is projected by the four GCMs used to drive LSMs (Fig. 4). This reduction is deemed very likely and is consistent with the widening of the Hadley Circulation (IPCC 2013). For all catchments, this increase in aridity can be reduced substantially with strong climate mitigation and adaptation, corresponding to the Paris Agreement 1.5°C warming target. Nonetheless, the impact from 1.5°C is still substantial for these southern catchments and highlight their sensitivity to global warming regardless of its degree.

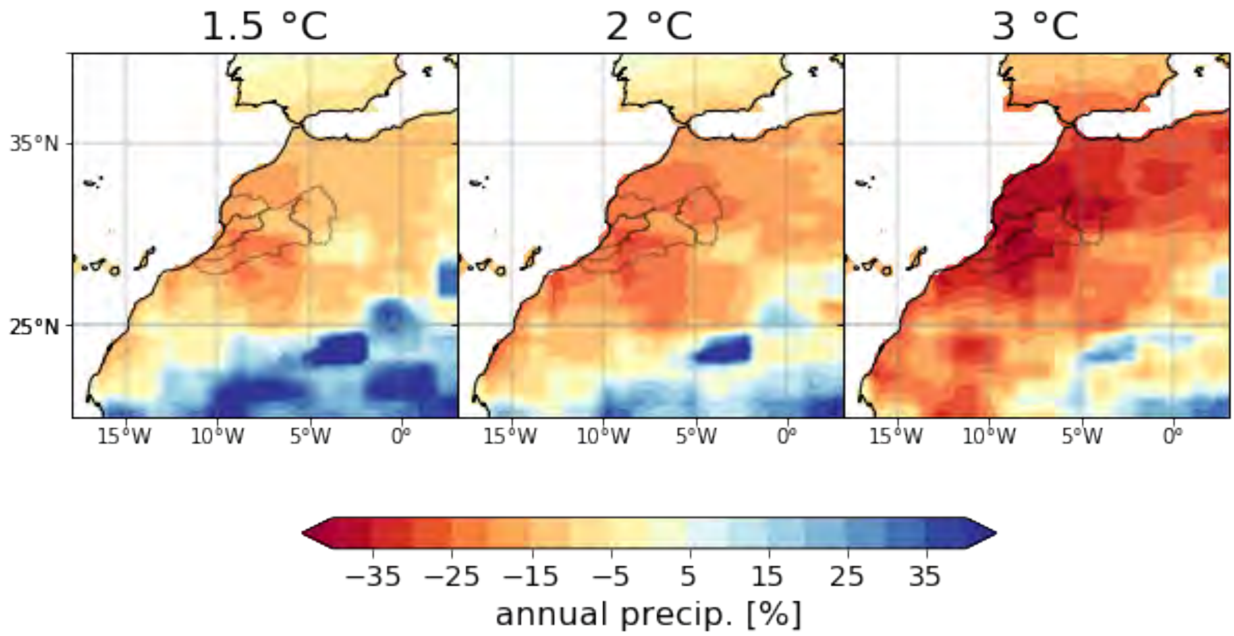

Figure 4 : Relative changes of the 4 GCMs (bias-adjusted) average projections of annual precipitation anomalies for different warming levels relative to the historical period 1971-2000.

With current policies, the latest data from Climate Tracker (www.climateactiontracker.org) show that the world is on track to warm by 3°C in this century. For the study domain, this comes with a large exacerbation of drought events to a degree that historical extremes may be considered as normal conditions in the future, which was also suggested for the Mediterranean region (NAUMANN et al. 2018; SAMANIEGO et al. 2018). Moreover, the strong decrease in soil water content in all seasons indicates an alteration of the hydrologic regimes toward more arid and hyper-

arid conditions across all catchments, confirming previous works (KOUTROULIS et al. 2019; OZTURK et al. 2018; TRAMBLAY et al. 2018). This change will severely affect vegetation and biodiversity, threaten food security, and increase water abstraction. As a result, it could become increasingly challenging to satisfy the basic needs of a growing population potentially leading to a food crisis, higher inequality levels, social instability, and conflict (GLEICK 2014; GODFRAY et al. 2010; GROLLE 2015; MAHARATNA 2014; SCHILLING et al. 2020; VON UEXKULL et al. 2016).

The socioeconomic factors, including population growth, intensive agriculture, and land-use change, were more significant than climate change in North Africa (NIANG 2014). DROOGERS et al. (2012) showed that by 2050, socioeconomic development in Morocco can be responsible for 81% of projected water scarcity leaving 19 % attributed to climate change. This emphasized the crucial importance of including land cover and land-use change based on socio-economic scenarios in future projections (TRAMBLAY et al. 2020). Unfortunately, due to the lack of such information in the time of the ISIMIP2b project, human influence (e.g. Dams, reservoirs, irrigation, domestic water use, manufacturing and livestock production) is either absent (ORCHIDEE and JULES) or held fixed at the 2005 level (LPJML and CLM) in LSMs-based projections. Future studies therefore should include socioeconomic-based gridded projections of such influences.

Nonetheless, the consideration of multiple LSMs enables to consider a wide range of process representation, a fundamental requirement to capture the uncertainties originating from the differences across LSMs (DONNELLY et al. 2017; GOSLING et al. 2017; MARX et al. 2018; THOBER et al. 2018). The catchments investigated in this study are characterized by a transitional climate regime, under which soil moisture is limited and strongly constrains evapotranspiration (SENEVIRATNE et al. 2010). Thereby, the representation of soil moisture dynamics, which differ between LSMs, can significantly impact the simulation results. This impact will potentially increase as the catchments transition into drier conditions. For example, the different implementations of vegetation (*e.g.,* dynamics and response to atmospheric CO_2) and evaporation (*e.g.,* temperature-based, Penman-Monteith, or solving the energy balance) would lead to different evaporative response leaving a wetter or a drier soil and thus can fundamentally change the impact of global warming on droughts (GREVE et al. 2019; MILLY & DUNNE 2016; PRUDHOMME et al. 2014; YANG et al. 2019). Therefore further studies should investigate the merit of these different modeling decisions on drought assessment to reduce uncertainty in future projections of these events.

In summary, the results of this investigation highlight the need to adapt to unprecedented drought extremes in the future. Adaptation measures must be taken to minimize the impact of future droughts even if the national pledge under the Paris Agreement succeeds in limiting global warming to the ambitious target of 1.5°C. These measures, however, need to take into account a substantially higher exacerbation of drought extremes under the current track of 3°C global warming. Therefore, further assessments are urgently needed to investigate the impact of these events on society and evaluate possible mitigation strategies in the context of uncertainty in climate projections, land surface and hydrological models, downscaling methods, internal climate variability, and socioeconomic scenarios.

5. Conclusion

Moroccan Southern catchments are projected to face future soil moisture drought extremes with unprecedented duration, persistence, and severity compared to historical conditions (1971-2000). The level of global warming intensification drives the worsening of these extremes. Current policies put the world on track to warm by around 3°C by the end of the century. Under this condition, Southern Moroccan catchments are expected to experience the transformation of historically 11 months lasting events into decades-long (up to 20 years) mega-droughts under 3°C compared to 7 years under 1.5°C. This intensification is accompanied by an increase in drought events persistence and order of magnitude (12-16x) of their historical severity. Given these large

changes, historical drought extremes can be considered as the new normal conditions in the future. A strong increase in aridity drives these new conditions during all seasons with a soil moisture deficit of up to 17-22 mm under 3°C global warming compared to 9-11 mm under 1.5°C. Even though the intensification of drought conditions is reduced significantly under the ambitious 1.5°C Paris target, it is still substantial further highlighting the high sensitivity of these catchments to global warming regardless of its level. Therefore, adaptation measures must be implemented and must consider the substantially higher exacerbation of drought extremes under the current track to 3°C global warming. Further assessments are needed more urgently than ever to investigate the impact of these events on society and evaluate possible mitigation strategies that consider all uncertainty sources to provide reliable information to minimize the negative effects of these climatic extremes.

Acknowledgements

This study was carried out within the context of the CHARISMA project with the assistance of the Hassan II Academy of Sciences and Technology and Ibn Zohr University of Agadir. The authors are grateful to the Inter-Sectoral Impact Model Intercomparison Project modeling groups and the cross-sectoral science team for their roles in producing, coordinating, and making available the ISIMIP models output. AE acknowledges support from Centre National pour la Recherche Scientifique et Technique (CNRST), Programme de Bourses d'Excellence de Recherche scholarship N°10UIZ2019.

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Assessing land degradation and sensitivity to desertification using MEDALUS model and Google Earth Engine in a semi-arid area in Southern Morocco: Case of Draa watershed

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Abstract. In Morocco, desertification affects a large area. It is more pronounced as the climate is arid with increasingly a long drought and poor soils that are highly vulnerable to erosion. In addition, the precarious living conditions of rural populations grow to overuse natural resources to meet their growing needs, which amplifies further environmental degradation. In this study, we have used the MEDALUS model to develop the sensitivity map of the Draa watershed. It is very characterized by its topographic, geomorphologic, and hydrological aspects and bioecological qualities. The MEDALUS approach has allowed us to identify the different parameters and to calculate the four indexes needed for this algorithm. The sensitivity of desertification depends on the quality of soil, climate, vegetation, and management system. An aridity index featured the climate was established by using eight climate stations' data. The soil quality is determined by the texture maps, depth, slope, and parental materials from the geological maps of the investigated region. The quality of vegetation to combat desertification is performed by its resistance to drought, fire risk, ability to soil erosion, and plant cover calculated from the Sentibel-2 imagery and performed in Google Earth Engine (GEE). Finally, we had approached the last indicator by land-use intensity and poverty rate from the Census data. The sensitivity map was established by combining the four indexes. The results indicate that the most part of the Drâa watershed is threatened by desertification and represent low resistance to drought and low protection against erosion. Aridity affects more than 63% and this conditions make the area very vulnerable to desertification. These results could be help the decision-makers and policy to better manage and mitigate desertification impacts under global changes.

Key words: Morocco, desertification, MEDALUS, Draa watershed.

1. Introduction

The fight against desertification is at the crossroads of the issues of climate change, preservation of biodiversity, conservation of water and soil, but also the fight against poverty and food security.

In Morocco, 93% of the territory is affected by the phenomenon of desertification, activated by the random aspect of rainfall, the general trend of which is downward with an uneven and irregular distribution over nearly a century of observation (HCEFLCD, 2016).This natural constraint is aggravated by human pressure expressed through the water supply-demand deficit, the vulnerability and overexploitation of forest and rangeland ecosystems, and already limited soil resources, whose useful agricultural area per capita is in continuous decline. The cost of the degradation of natural resources in the forest, cropland and rangeland sectors and following siltation of dams is estimated at 2.9 billion DH/year (HCEFLCD, 2016).

Monitoring the progress of desertification requires, on the one hand, a description of the biophysical and socio-economic conditions of the environments affecting these phenomena, and on the other hand an understanding of the mechanisms and processes resulting from these conditions.

Indicators are traditionally used in evaluation, and monitoring in forecasting. They can be attached to two main groups:

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DOI: https://doi.org/10.34874/IMIST.PRSM/fsejournal-v11i2.29049

(i) That of the causes of desertification that are both natural (e.g. evolution of climatic factors) or induced (Human pressure);

(ii) That of the effects of desertification on biological environments (mainly flora and fauna), physical environments (soils and water resources) and socio-economic environments (famines, migrations, changes in practices, etc.).

The development of methods for assessing and monitoring the state of the environment and the impact of actions to combat land degradation is based on the establishment of long-term observation networks using compatible data collection and transfer methodologies.

The interest of these observatories is to collect the necessary data, on a harmonized basis, to monitor over time the evolution of processes and to allow the definition of reference situations. They make it possible to develop indicators and test them, to develop decision support tools integrating these indicators. They are also privileged sites for research on the study of mechanisms and processes, as well as on the factors determining evolutions.

Thus, mapping and monitoring the spatial extent of degradation constitute one of the bases of knowledge of the phenomenon of desertification. It is essential for the establishment of control plans and programs for the sustainable use of natural resources in arid and semi-arid areas.

Techniques for observing, measuring and exchanging information are now evolving. There are many sources of assessment and monitoring ranging from global surveys and satellite data analysis, to studies of environmental change at the local level. They are valuable decision-making tools. In this respect, remote sensing seems to be a tool of privilege, as it makes it possible to draw more accurate maps on the progress of desertification.

The Draa watershed reaching from the southern declivity of the High Atlas to the Saharan foreland in the Southern part of Morocco, is one of the biggest basin with a surface of 92,500 km². Its upstream part corresponds to the High Atlas and Anti-Atlas reliefs including Jbel Toubkal (alt. 4165 m.a.s.l.) in the North-West, M'Goun (alt. 4071 m.a.s.l.) and Saghrou (alt. 2712 m.a.s.l.) in the North-East of the basin. The watershed is limited by Ziz-Rhris basin to the east, and Souss-Guelmim to the West. To the south, the study area borders the basin of Sahara (Fig. 1).

The basin is characterized by a temperate climate in its Mountainous part (High Atlas) and arid to hyper-arid the middle and downstream part (KLOSE 2009). The basin is highly vulnerable towards Global Change concerning hydrology and soil degradation (REICHERT & JAEGER 2009). The vegetation is sparse through the basin with a high density in the oases along the Draa river in its middle part and some tributaries. Precipitation events are extremely variable in time and space. Snow storage and rain in the High Atlas Mountains are main supply for reservoir filling and groundwater in alluvial part mainly. The watershed ecosystem is extremely sensitive to Climate Change. Hydrological processes are controlled by shallow soils and low vegetation cover. The aridity, soil erosion and water scarcity are the main issues faced during the last decades. Scenarios of climate change based on the downscaled and socio-economic development highlighted the impact of Global Change on water resources, desertification and soil degradation (CHRISTOPH et al. 2010). The main objective of our study is to more identify the significant indicators of the desertification process in the basin.

Morocco has signed the UNCCD and developed a national program to combat desertification. However, the available knowledge of desertification and land degradation, notably by water and wind erosion, sand dune, salinization, and waterlogging, are insufficient and sketchy. Therefore, many diagnostic processes are necessary to reach this objective.

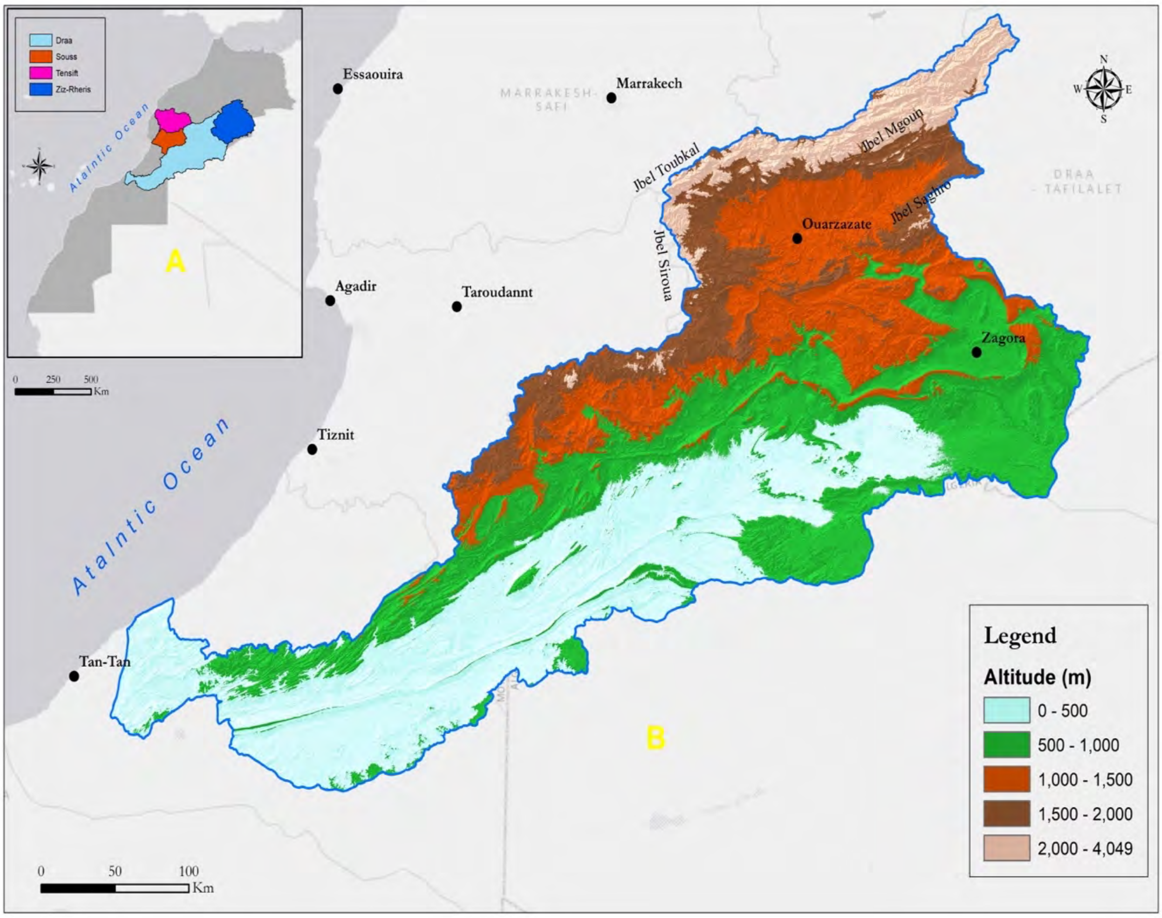

Figure 1: A. Geographic location of the Draa Watershed in Morocco ; B. Map showing watershed boundaries (blue line) and elevation model.

2. Methods

Our methodology is based mainly on GIS and remote sensing technologies. To map the sensitivity of the Draa watershed to desertification, we have considered four indicators: climate, soil, vegetation, and management quality (Fig. 2). Each of these indexes, determined by a specific methodology, allows us to build a GIS model to define the critical area of desertification impact.

Mediterranean Desertification and Land Use (MEDALUS)) is an approach to assess, model, and understand the desertification phenomena that increasingly affect the Mediterranean area(EUROPEAN COMMISSION, 1999). It includes the European Union because of agricultural and land-use practices and because of climate change.

The methodology adopted in this study is based on the MEDALUS approach which has been adapted by OSS within the framework of the DISMED (2003a, 2003b). This approach is used in the Arab Maghreb Union (AMU) countries and Egypt to elaborate the desertification sensitivity map on a scale of 1/1000000 (LJOUAD et al. 2003).

According to the figure 2, the system is based on the calculation of the Desertification Sensitivity Index (DSI), obtained by superimposing four other indexes (LABBACI et al. 2018).

We determined the sensitivity of the Draa basin to desertification by mapping the quality of soil, climate, vegetation, and management system (QARRO & SABIR 2004). The climate quality is featured by the aridity index, precipitation and aspect. To determine the soil quality, we have used the texture maps, depth, slope, and parental materials.

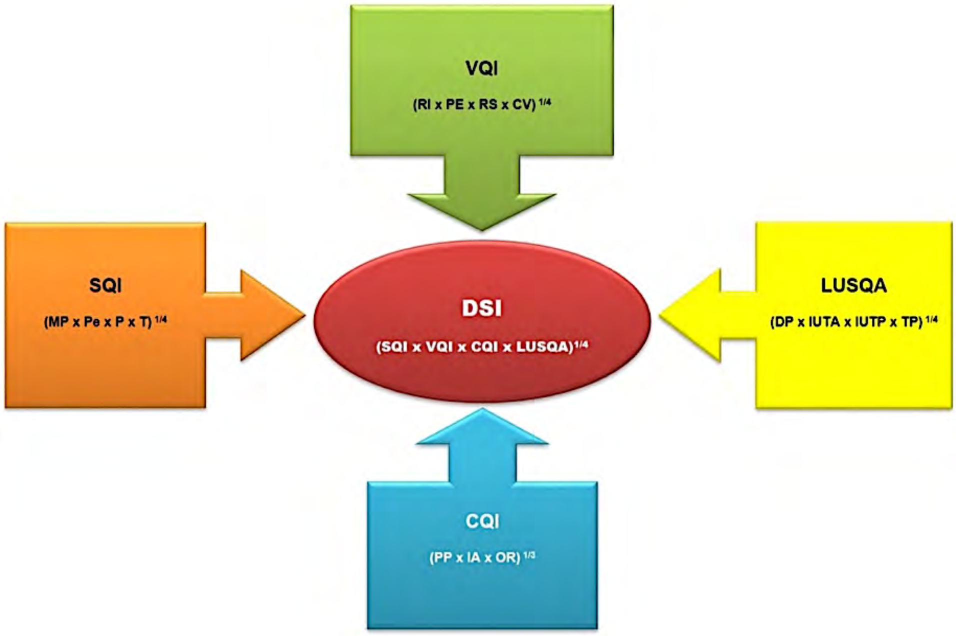

Figure 2 : Evaluation of the desertification sensitivity index according to the MEDALUS approach

Furthermore, the vegetation quality index takes in consideration the resistance to fire forest and drought, protection of the soil from erosion, and vegetation cover. We approached the management quality index by assessing land-use intensity and the poverty rate.

2.1. Soil quality

The soil quality is determined using the map of parental materials, texture, depth, and slope based on the geological and pedology studies undertaken over the investigated area.

2.1.1. Parent Material index (PMi)

The PMi information is established from the geological map. Therefore, the used classification is given by three classes: coherent materials, medium Coherent materials, and Soft materials (Table 1).

Table 1: Range of the parental material index (PMi)

Ranges	Parental Material	Index
Coherent parental material	Limestone, dolomite, non-friable sandstone, hard limestone crust, granite, quartzite.	1
medium Coherent materials	marl-limestone, friable sandstone, flyschs containing sandstone banks.	1,5
Soft material	Marl, clay, flyschs, shale, sandy formations, alluvium and colluvium	2

2.1.2. Depth index (Di)

Soil depth in the Mediterranean environment (North Africa and Middle East) does not have the same meaning as humid climates. This index ranges depend on the depth of the substratum (Table 2).

Table 2: Range of the depth index (Di)

Ranges	Description	Index
Very thick	Soil of thickness greater than 1.5 m with a substrate not penetrable by the roots or of thickness greater than 1 m on a loose substrate.	1
Medium to thick	Depth of 0.75 to 1.5 m with a coherent substrate or 0.5 to 1 m with a loose substrate	1,33
Not very thick	Depth ranging from 0.25 to 0.75 m	1,66
Very thin	Depth less than 0.25 m	2

2.1.3. Texture index (Ti)

The textures were estimated from the Morocco's SOTER project database (2012). The coefficients were assigned to the units according to table 3.

2.1.4. Slope index (Si)

The slope was determined from the digital elevation model with a resolution of 20 m (Table 4) .

Table 3: Range of the texture index (Ti)

Ranges	Description	Index
Light to medium texture	Limono-sandy, sandy-silty, balanced.	1
Fine to medium texture	Limono-clay, clay-sandy, sandy-clayey.	1,33
Fine texture	Clayey, clay-silty.	1,66
Rough texture	Sandy to very sandy.	2

Table 4: Range of the Sol Quality Index (SQi)

Ranges (%)	Description	Index
< 5	Low	1
5 - 15	Medium low	1,33
15 - 35	Stiff	1,66
> 35	Very steep	2

2.1.5. Soil Quality Index (SQi)

The SQi map was developed by cross-referencing parent materials, slopes, texture and depth indexes according to the formula below and considering the following standards (Table 5):

$$SQi = (PMi \times Di \times Ti \times Si)^{1/4} \quad (1)$$

Where:

PMi is the Parent Material index
Di is the Depth index
Ti is the Texture index
Si is the Slope index

Table 5: Range of the Sol Quality Index (SQi)

Ranges	Soil quality	SQI
1	Good	< 1,13
2	Medium	1,13 à 1,45
3	Low	>= 1,45

2.2. Vegetal quality

Vegetation is at the same time the expression and the index of the natural balance of the ecosystems. The vegetal cover is the first component enduring anthropogenic impacts, and its state is related to the process of desertification as natural degradation. It shows indications related to resistance to drought, fire risk and ability to mitigate erosion and, Plant cover degradation.

These data were developed by the DISMED team, which was responsible for drawing up the vegetation and climate quality index maps. The data, the description of the classes and the indexes used are explained in tables 6, 7, 8 and 9.

2.2.1. Fire risk index (Fri)

Table 6: Range of the fire risk Index (FRi)

Ranges	Description	Index
Weak	Bare soils, multiannual crops, annual crops such as Tobacco, Maize, Sunflower	1
Moderate	Annual crops such as cereals and meadows, deciduous oaks, mixture of Mediterranean vegetation, maquis. Very clear argan forest	1,33
High	Mediterranean scrubland, holm oak or cork oak forests, dense argan forests	1,66
Very high	Coniferous forest, dense irrigated arboriculture	2

2.2.2. Resistance to drought index (RDi)

Table 7: Range of the resistance to drought index (RDi)

Ranges	Description	Index
Very high	Dense pine forests and maquis with mixed Mediterranean vegetation, argan grove, cedar	1
High	matorral of pine, sparse cedar, degraded argan grove, olive grove	1,33
Moderate	Arboriculture based on almond and vine, barley	1,66
Weak	Annual crops such as cereals, annual meadows, apple trees	2

2.2.3. Protection against erosionindex (PEi)

Table 8: Range of the Protection against Erosion index (Pei)

Ranges	Description	Index
Very high	Dense pine and/or cedar forests and scrub with mixed Mediterranean vegetation	1
High	Mixture of Mediterranean vegetation in maquis, dense Argan grove, dense matorral of pine and / or cedar	1,33
Moderate	Deciduous tree forests, almond-based arboriculture, very clear argan grove, degraded matorral	1,66
Weak	Bare soils, annual crops such as cereals, annual meadows, vines	2

2.2.4. Plant coverindex (Pei)

Table 9: Range of the Plant coverindex (Pei)

Ranges	Description	Index
High	> 50 %	1
Medium	30 à 50 %	1,33
Low	10 à 30 %	1,66
Very low	< 10 %	2

2.2.5. Vegetal quality Index (VQi)

The vegetal quality index is a combination of four other indexes: Fire risk (FRi), Resistance to drought (RDi), Protection against erosion (PEi), Plant cover (PCi):

$$VQi = (FRi \times RDi \times PEi \times PCi)^{1/4} \quad (2)$$

Where:
Fri: Fire risk
RDi: Resistance to drought
Pei: Protection against erosion
PCi: Plant cover

The map of vegetal quality was made up using the following classification (Table 10):

Table 10: Range of the Vegetation Quality Index (VQi)

Ranges	Vegetal quality	VQI
1	Good	< 1,13
2	Medium	1,13 à 1,38
3	Low	≥1,38

2.3. Climate quality

The climate can be considered as the major cause of land degradation. In fact, soil erosion is due to heavy and concentrated rainfall in space and time, affecting primarily the vegetal cover.

The result was made on the base of the index of aridity, rainfall, and aspect.

2.3.1. Aridity index (Ai)

The aridity index was calculated by the following formula:

$$Ai = \sum_{i=1}^{n} (2Ti - Pi) \times Ki \quad (3)$$

where:

Ti is the average temperature of month i in °C;
Pi is total rainfall of month i in mm;
Ki is the proportion of months with 2Ti > Pi.

Table 11: Range of the aridityindex (Ai)

Ranges	Description	Index
1	< 50	1
2	50 à 100	1,15
3	100 à 150	1,6
4	>150	2

2.3.2 Rainfall index (Ri)

The rainfall index was fixed as mentioned by the table below. The period of yearly average rainfall data is 1977-2020:

Table 12: Range of the rainfallindex (Ri)

Ranges	Description	Index
1	> 400 mm	1
2	200 à 400 mm	2
3	< 200 mm	4

2.3.3. Aspect index (Asi)

The aspect index was determined from a digital elevation model at a resolution of 20 m like the slope index.

Table 13: Range of the Aspect index (Asi)

Ranges	Description	Index
1	Aspect NW to NE	1
2	Aspect SW to SE	2

2.3.4. Climate quality Index (CQi)

The climate quality index is a combination of the three cited indexes: aridity, rainfall, and aspect:

$$CQi = (Ai \times Ri \times Asi)^{1/3} \quad (4)$$

To map the climate quality index, the CQi was ranged as below:

Table 14: Range of the Climate Quality Index (CQi)

Ranges	Climate quality	CQi
1	Good	< 1,13
2	Medium	1,13 à 1,38
3	Low	≥ 1,38

2.4. Management quality

The definition of desertification requires both key indicators related to the physical environment and the human-induced stress. The use of land is associated with a given type of management which is dictated by and changes under the influence of environmental, social, economic, technological, and political factors. To map the

management quality index (MQi), we have used two indexes: The Land Use Intensity index, and the Poverty index.

2.4.1. Land Use Intensity index(LUi)

The LUi map was obtained from on the land cover map as explained in the table 15 below:

Table 15: Range of the Land Use Intensity index (LUi)

Ranges	Description	Index
1	Low: non-agricultural or extensive agriculture	1
2	Medium: semi-intensive agriculture	1,5
3	Strong: intensive agriculture	2

2.4.2. Poverty index (Pi)

To better assess the management quality index, the poverty rate was used. To derive the poverty index, we have used the Census data of 2014 (RGPH, 2014).

Table 16: Range of the poverty index (Pi)

Classes	Description	Valeur
1	< 12,3	1
2	12,3 à 18,6	1,33
3	18,6 à 27,7	1,66
4	> 27,7	2

2.4.3. The management quality index (MQi)

The management quality index (MQi) is assessed as the product of land use intensity and poverty index using the following algorithm:

$$MQi = (LUi \times Pi)^{1/2} \quad (5)$$

Then the management quality is defined using table 17:

Table 17: Range of the Management Quality Index (MQi)

Ranges	Climate quality	CQi
1	Good	1 to 1,25
2	Medium	1,26 to 1,5
3	Low	≥ 1,5

2.5. Desertification Sensitivity Index (DSi)

After obtaining the four indexes (SQi, VQi, CQi and MQi), the Desertification Sensitivity Index (DSi) is determined by the intersection of the multiplicative maps according to the following equation:

$$SDi = (SQi \times VQi \times CQi \times MQi)\ ¼ \quad (6)$$

The classification used to comprehensively assess the sensitivity of soils to desertification is presented in table 18.

Table 18: Range of the Desertification Sensitivity Index (DSi)

Ranges	Description	DSi classes
1	Unaffected areas	≤ 1,20
2	Less sensitive areas	1,20 – 1,26
3	Moderately sensitive areas	1,26 – 1,36
4	Very sensitive areas	1,36 – 1,46
5	Critical areas	> 1,46

3. Results

3.1. Soil Quality Index (SQi)

3.1.1. Parent Material index (PMi)

The results in the table 19 indicate that the coherent materials cover more than 31 % of the watershed area. On the other hand, the medium and soft materials represent 24 and 44,5 % successively.

Table 19: Range of Parental Materials index

PMi	Description	Area (Ha)	%
1	Coherent materials	2832373,43	31,35
1,5	Medium coherent materials	2180972,72	24,14
2	Soft materials	4021337,85	44,51

3.1.2. Slope index (Si)

More than 80 % of the territory has a slope less than 15 % represented by the rangeland andagricultural land. About 17 % of the area has a slope ranged between 15 and 30 %, and 3,24 % has a slope under 30 %. Those results show that the watershed can generate important runoff if nothing is done to control erosion and protect vegetation (Table 20).

3.1.3. Depth index (Di)

Soils with more than 1,5 m cover only 3,08 % mostly located in the East of the site. More than half of the area represents little deep soils located in the mountains (Table 21).

3.1.4. Texture index Ti

Soils with thin texture cover about 67 % of the whole site. Soils with slight to medium texture are less represented. On the contrary, soils with rough texture cover about 18,16 % (Table 22).

3.1.5. Map of Soil Quality Index

According to the criteria used, about 4 % of the territory of the watershed is slightly sensitive to desertification. More than 89 % has medium sensitivity, and 7 % is extremely sensitive. This means that all soils of the Draa watershed are vulnerable to desertification ; even the other factors, vegetal cover, climate, and management, are favorable (Fig. 3, Table 23).

Table 20: Range of Slope index

Ranges	Description	Si	Area (Ha)	%
< 5 %	Slight	1	3509363,93	38,84
5 to 15 %	Little slight	1,33	3698053,86	40,93
15 to 30 %	Steep	1,66	1535894,78	16,99
> 30 %	Very steep	2	291371,43	3,24

Table 21: Range of Depth index

Ranges	Description	Di	Area (Ha)	%
> 1,5 m	Very deep	1	278268,27	3,08
0,75 to 1,5 m	Moderately deep	1,33	6154426,74	68,12
0,25 to 0,75 m	Little deep	1,66	1240462,11	13,73
< 0,25 m	Very little deep	2	1361526,88	15,07

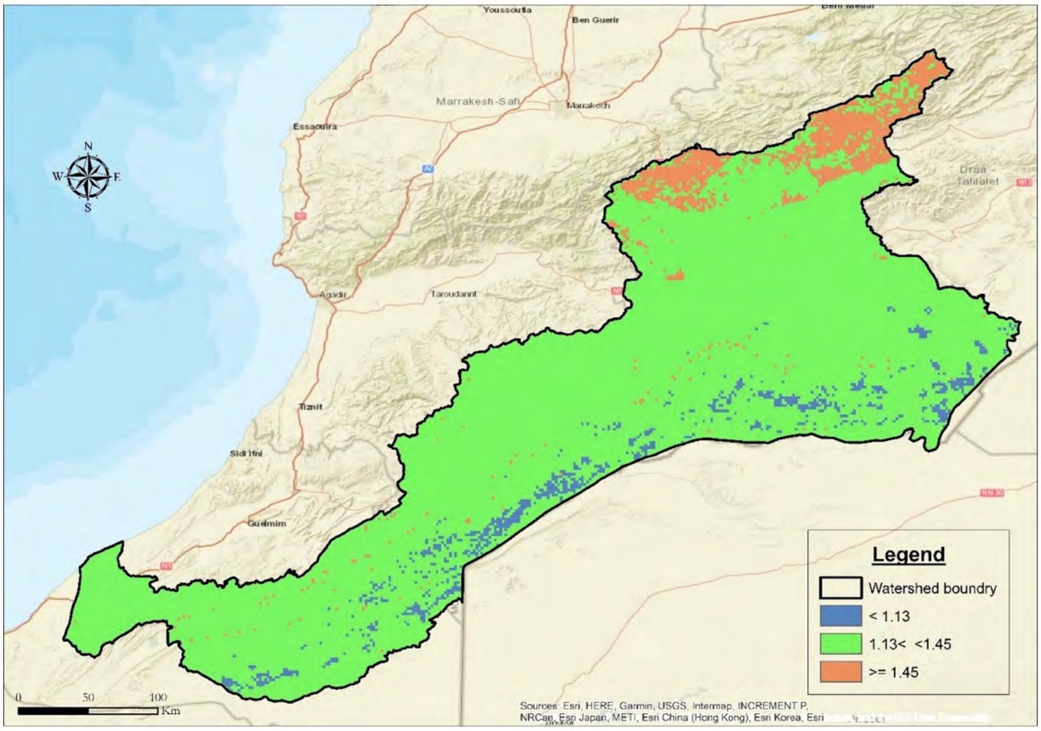

Figure 3: Map of Soil Quality Index of Draa watershed

Table 22: Range of Texture index

Ranges	Ti	Area (Ha)	%
Slight to medium texture	1	425533,61	4,71
Thin to medium	1,33	945027,95	10,46
Thin	1,66	6023423,82	66,67
Rough	2	1640689,62	18,16

Table 23: Range of SQI

Ranges	Description	SQI	Area (Ha)	%
1	Good	< 1,13	376566,8	4,17
2	Medium	1,13 to 1,45	8036709,01	88,95
3	Low	>1,45	621408,19	6,88

3.2. Vegetal Quality Index (VQi)

3.2.1. Fire Risk index (Fri)

Zones with a fire high risk to very high representing 99 %, it's covered by forests, crop lands, grasslands and barren (Table 24).

3.2.2. Drought Resistance index (DRi)

The obtained values show that approximately 80 % of the watershed cover presents a low to medium resistance to drought because the nature of the underwood and the presence of cultural lands which support little the hydric stress (Table 25).

3.2.3. Protection against Erosion (PEi)

The results show that approximately 20 % of the site surface is protected well by the vegetal cover against erosion (Table 26). The rest of the area is vulnerable because of the low plant cover.

3.2.4. Plant Cover index (PCi)

More than 16 % of the SBEI's plant cover represents low to medium protection against erosion. However, a most part of the surface shows a good cover protecting the site against the degradation with 84 %. (Table 27).

3.2.5. Map of Vegetal Quality Index

Allowing to the results obtained, the zones with low and medium vegetal quality represent the totality of the watershed area (Fig. 4, Table 28).

Table 24: Range of Fire Risk index (Fri)

FRi	Description	Type of vegetation	Area (Ha)	%
1	Low risk	Uncultivated lands	1914,1	0,02
1,33	Moderate risk	Crop lands	2368,75	0,04
1,66	High risk	Grasslands	7230177,47	80,02
		Barren		
2	Very high risk	Forests and shrubs	1800226,68	19,92

Table 25: Range of Drought resistance index (DRi)

DRi	Description	Type of vegetation	Area (Ha)	%
1	Very high resistance	Uncultivated lands	1914,1	0,02
1,33	High resistance	Forests and shrubs	1800226,68	19,92
1,66	Medium resistance	Grasslands	7230177,47	80,02
		Barren		
2	Low resistance	Crop lands	2368,75	0,04

Table 26: Range of Protection against Erosion (PEi)

PEi	Description	Type of vegetation	Area (Ha)	%
1	Very high protection	Forests and shrubs	1800226,68	19,92
1,33	High protection	Crop lands	2368,75	0,04
1,66	Medium protection	Grasslands	3632054,1	40,2
		Uncultivated lands		
2	Low protection	Barren	3600034,47	39,84

Table 27: Range of Plant Cover index (PCi)

PCi	Description	Type of vegetation	Area (ha)	%
1	Very high	Forests and shrubs	1800226,68	19,92
1,33	High	Grasslands	3632508,75	40,22
		Crop lands		
1,66	Medium	Barren	3600034,47	39,84
2	Low	Uncultivated lands	1914,1	0,02

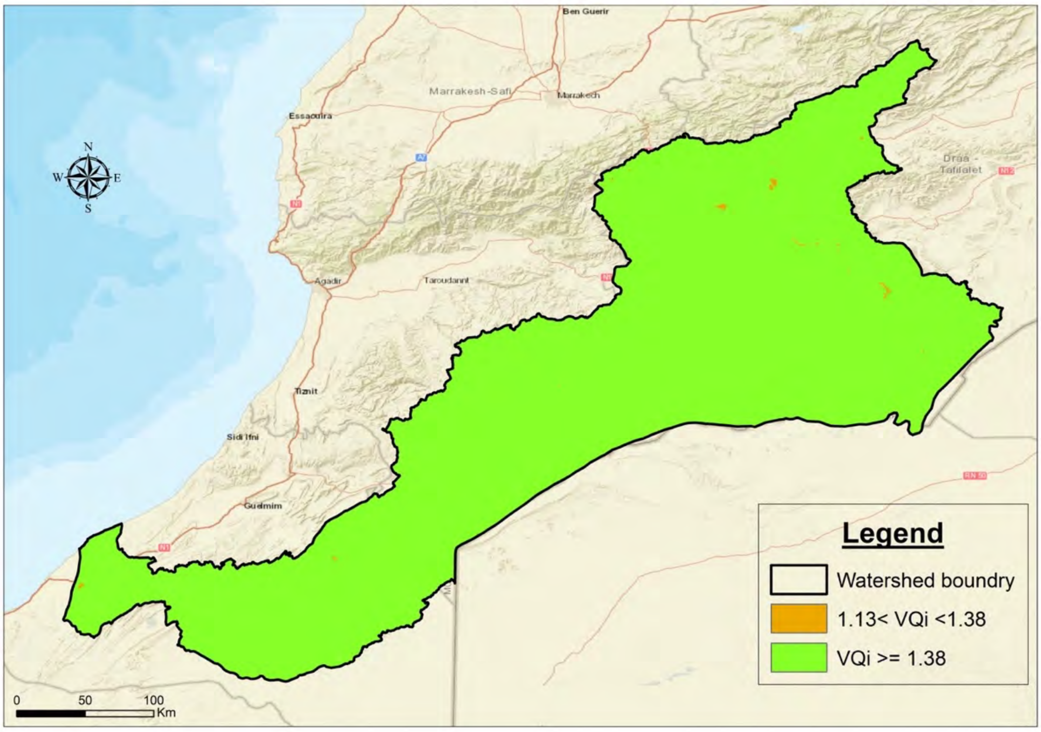

Figure 4: Map of Vegetal Quality Index of Draa watershed

Table 28: Range of Vegetal Quality Index (VQi)

Ranges	Description	VQI	Area (Ha)	%
1	Good	< 1,13	0	0
2	Medium	1,13 to 1,38	12753,53	0,14
3	Low	>1,38	9021930,47	99,86

3.3. Climate Quality Index (CQI)

3.3.1. Aridity index (Ai)

Regions with low aridity degree, corresponding to favorite climates, are slightly represented. Regions with high aridity degree represent 14,59 % and correspond to arid areas. The intermediary zones represent45 % of the territory of the Draa watershed (Table 29).

3.3.2. Rainfall index (Ri)

The range of rainfall “200 to 400 mm” is the most important, it is related to the arid climate dominating the whole Draa watershed (Table 30).

3.3.3. Aspect index Asi

The range of SW-SE’s aspect is the most dominant at the watershed, it represents 53 % of the total area of the site. This aspect is drier and more arid (Table 31).

3.3.4. Map of Climate Quality Index (CQI)

The climate quality index is a combination of the three cited indexes, aridity, rainfall and aspect, Table 31 gives the importance in term of surfaces of 3 classes corresponding to this indication.

Contrary to both indices previously calculated, we notice that zones with medium climate quality are dominant (89 %) while the zones with low climate quality represent only 11,1 % (Table 40). According to this result, the Draa watershed has an arid to semi-arid climate convenient to the desertification (Fig. 5).

3.4. Management Quality Index (MQi)

To map the management quality index (MQi), we have used two indexes (Table 33 and 34). We note that the intensive farming is bordering the conglomerations inside the watershed (only 0,12 %). The two other classes concern the medium and

the low land use intensity are most represented seen that the rest of the site is occupied by dense forest and agroforestry's practice associated with grasslands.

3.4.1. Map of Management Quality Index

The management quality index (MQi) is assessed as the product of land use intensity index (LUIi) and poverty index (Pi), (Table 35).

Table 29: Range of Aridity index (Ai)

Ranges	Description	Ai	Area (Ha)	%
1	< 50 days	1	3700695,97	40,96
2	50 to 100 days	1,15	2368273,49	26,21
3	100 to 150 days	1,6	1648335,54	18,24
4	>150 days	2	1317379	14,59

Table 30: Range of Rainfall index (Ri)

Ranges	Description	Ri	Area (Ha)	%
1	> 400 mm	1	0	0
2	200 à 400 mm	2	8437242,96	93,38
3	< 200 mm	4	597441,04	6,62

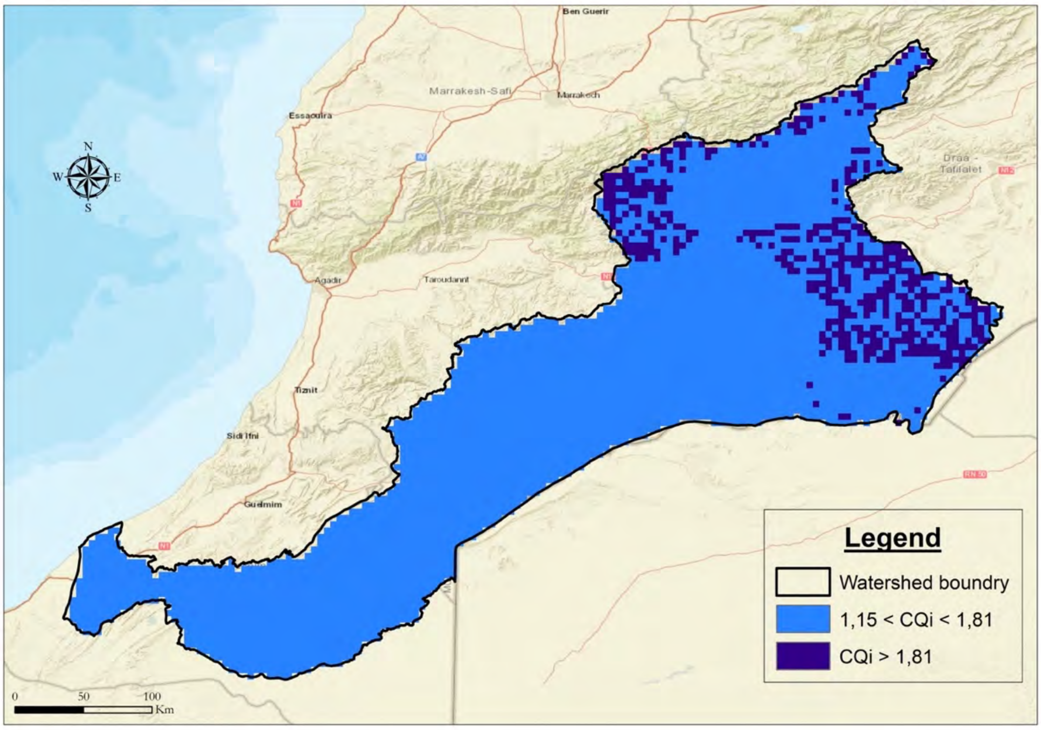

Figure 5: Map of Climate Quality Index of Draa watershed

Table 31: Range of Aspect index (Asi)

Ranges	Description	Asi	Area (Ha)	%
1	NW et NE	1	4219197,43	46,7
2	SW et SE	2	4815486,57	53,3

Table 32: Range of the Climate Quality Index (CQi)

Ranges	Description	CQI	Area (Ha)	%
1	Good	< 1,15	0	0
2	Medium	1,15 to 1,81	8031834,08	88,9
3	Low	>1,81	1002849,92	11,1

Table 33: Range of Land Use Intensity index

Ranges	Description	LUIi	Area (Ha)	%
1	Low land use intensity	1	6731743,05	74,51
2	Medium land use intensity	1,5	2292099,33	25,37
3	High land use intensity	2	10841,62	0,12

Table 34: Range of Poverty index

Classes	Description	Pi	Area (Ha)	%
1	< 12,3	1	3543403,06	39,22
2	12,3 à 18,6	1,33	3010356,71	33,32
3	18,6 à 27,7	1,66	2480924,23	27,46
4	> 27,7	2	0	0

The MQi index so established shows that the majority of the watershed (67 %) present a good quality of management. On the other hand, the low management's range is represented with 7,3 % of site's area in particular because of the intensification of the agricultural practices and the pressure of the population on natural resources (Fig. 6).

3.5. Desertification Sensitivity index (DSI)

The table 36 gives the importance in terms of area for the 4 classes of sensitivity todesertification in the Draa watershed. These values show that the area of the site is classified as sensitive to very sensitive. The mountain area is classified rather fragile, partly because of their cover. This grade is largely due to the influence of climate which is more aggressive (arid to semi-arid) south from the north and from west to east.In addition to this phenomenon, especially in mountainous areas, erosion is still an important factor of degradation, particularly in areas where the vegetation has undergone significant degradation due to the combined impact of a harsh climate and samples as well as for grazing for the various needs of the rural population, including fuel wood and firewood (Fig. 7).

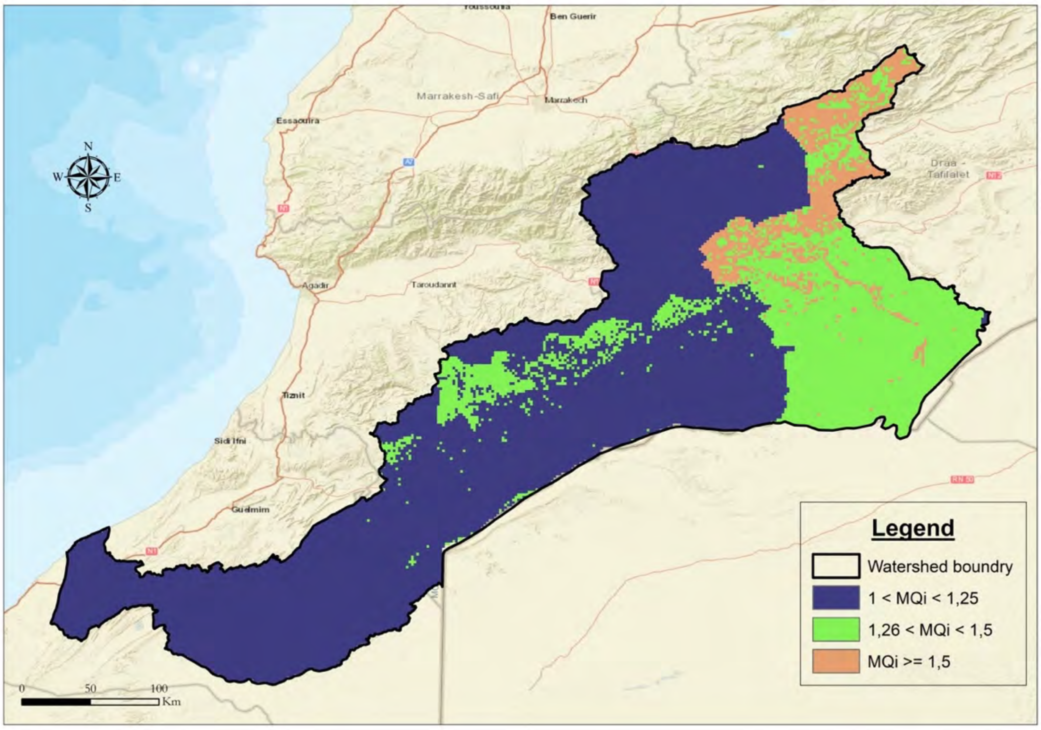

Figure 6: Map of Management Quality Index of Draa watershed

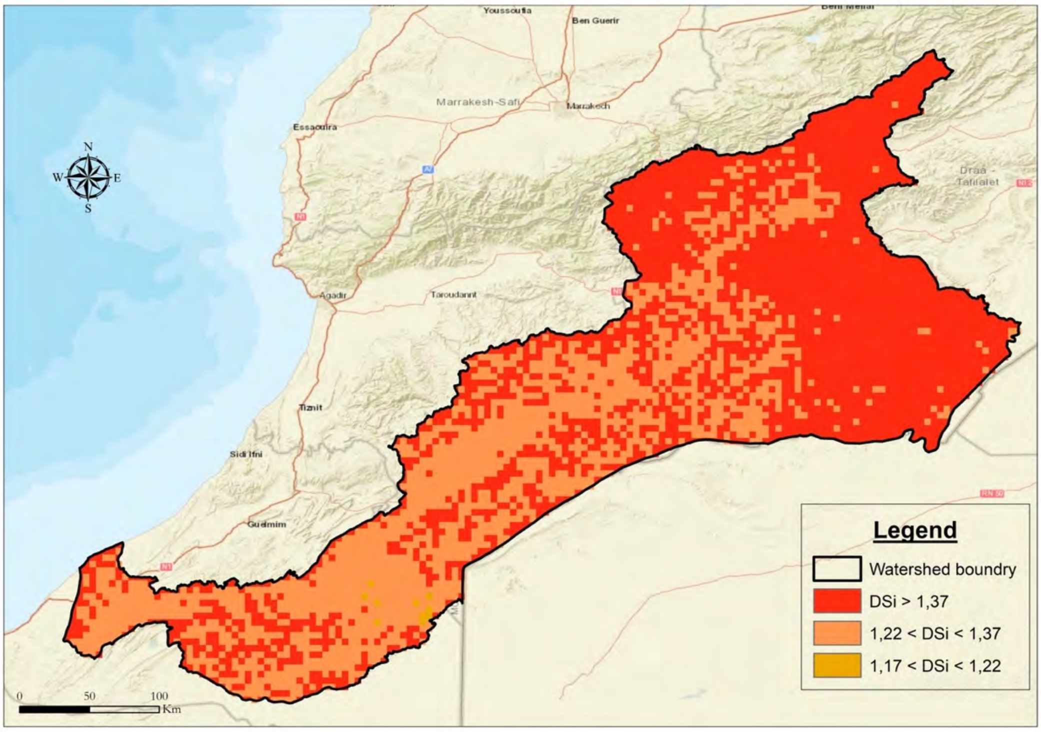

Figure 7: Map of the Desertification Sensitivity Index of Draa watershed

Table 35: Range of management quality index (MQi)

Ranges	Description	MQI	Area (Ha)	%
1	Good	1 à 1,25	6111963,73	67,65
2	Medium	1,25 à 1,50	2263188,34	25,05
3	Low	>1,50	659531,93	7,3

Table 36: Range of Sensitivity Desertification index

Ranges	Description	ISD	Area (Ha)	%
1	Very sensitive areas to Desertification	> 1,37	5101886,05	56,47
2	Sensitive areas to Desertification	1,22 à 1,37	3916535,51	43,35
3	Medium sensitivity areas to Desertification	1,17 à 1,22	16262,44	0,18
4	Low sensitivity areas to Desertification	< 1,17	0	0

4. Conclusion

Desertification becomes more and more threatening. In our study, we have used a methodology to develop the desertification sensitivity map of the Draa watershed based on the collection of a considerable amount of textual and graphical information. The data were used in a model combining GIS and remote sensing technologies.

The interpretation of the satellite images and the ground data made it possible to complete the available spatial and thematic data analysis, especially the land use map.Two major areas of sensitivity to desertification were identified:

- The southern and western zones of the site are considered as a critical area;
- The Northern and Eastern zones are represented by the fragile areas;

This work presents a coherent and objective scientific approach with indicators to assess the sensitivity to desertification of the Draa watershed. These indicators provide a planning framework that allows national and international agencies to assess the overall extent of erosion or

other risk factors, and to allocate resources for more detailed investigation.

The nature of the indicators is that they provide only a general overview. Secondary scale indicators should be used to define areas where more detailed studies are needed. They are therefore seen as the outer shell of an explicitly nested approach to risk identification and mitigation.

The value of desertification modelling is to be able to look at the current situation and remedy it while there is still time. In addition to the cartographic illustration and visualization aspect, the interest of the present study lies in the practical recommendations that can be drawn from linking sensitive areas (SDIs) with the factors considered responsible for the phenomenon of desertification. For example, exploration of the indicator maps and the sensitivity map (SDI) reveals that good quality soils occupied by annual crops are very sensitive to desertification compared to soils of less good quality but occupied by natural vegetation (forest).

Acknowledgements

The authors of this article would like to thank all the staff of the Laboratory of the Geosciences and Geo-Environment at the Faculty of Sciences of Agadir (Morocco). Thanks to CHARISMA Project with the assistance of the Hassan II Academy of Science and Technology and the support of Ibn Zohr University, Agadir. The authors thank the editor of the journal for his valuable efforts to enhance the quality of this paper.

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The last glaciation genesis and heritage of Ifni Lake, Western High Atlas, Morocco

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Abstract. Glaciers covered the reliefs overlooking the valleys of the Western High Atlas at the level of cirques. The footprints of the glacier activities are characterized in this region by moraines, boulders and ridges. The geomorphological observations show that the Ifni lake, located east of Toubkal Mountain, is formed by a natural dam that we interpret as glacial activity with low involvement of the left flank landslide. We studied the mixed volcanic lithologies of the moraine at various points of the valley. They are consistent with the erosion and transport of a suite of lavas formed by rhyolites, ignimbrites, andesites, and basalts. During part of the Holocene and the little ice age, the glacier has built a moraine of over 130 m in height, made in the form of three main ridges separated by depressions. The amalgamation of the moved unities and their steps could lead their interpretation as marks of the succession ofthree main stages of glacier advance and retreat during short-duration pulses.

Key words: Glaciation genesis, Glaciation heritage, Ifni Lake, Western High Atlas

1. Introduction

The reliefs of the High Atlas have been successively covered by glaciers whose tongues reached the surrounding valleys (DE MARTONNE 1924; DRESCH 1941; DRESCH ET AL. 1953; MENSCHING 1953; AWAD 1963; BEAUDET 1971; FINK et al. 2014; HANNAH 2014; HUGHES et al. 2004; 2011a; 2011b ; FLETCHER 2017). The Holocene period (the last 10 000 years) has shown major glacial oscillations. Glaciers have varied over the last millennia, and the Atlas landscapes have been marked by rich glacial legacies along the major valleys or in altitude.

Many mountain cirques and valleys in the Western High Atlas old Massif present glaciation evidence (MENSCHING 1953; HUGHES 2020; WICHE 1953). Geomorphological observations made by AWAD (1963) distinguished three periods of glacier activity (HUGHES et al. 2011b). This author presented complete geomorphological maps for eight valleys in the southern slope of the western High The southern slope of the western High Atlas has been little studied (CÉLERIER et al. 1922; DUMONT et al. 1973) and the genesis of Ifni Lake remains controversial. The dam of the lake was linked to glacial activity without evidence (CÉLERIER et al. 1922; DUMONT et al. 1973) affirmed that this lake is fed by glaciers in modern times with a glacier filling the valley between Jebel Toubkal and Tizi n'Ouanoumns. HUGHES et al. (2018) and HUGHES (2020) express doubt on the glaciations of this valley. They also note the lack of evidence of Pleistocene moraines in this region. The Ifni natural dam is associated with a large landslide (EL FELLAH 1994; DAKKI et al. 2020).

The main purposes of this study are to suggest a model of the genesis of Ifni Lake linked to glacial activity and discuss its expansion in the late Holocene based on the description of the frontal moraine of Ifni Lake.

2. Location and description of Ifni Lake

Ifni Lake is located on the southern slope of the western High Atlas in the Ouzalagh massif (Fig. 1). It is situated in the rainiest and coldest area of the upstream portion of Wadi Tifnout, the upper branch of the Souss River. Access to this lake is from the national road no. 10 to Aoulouz, then by

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DOI: https://doi.org/10.34874/IMIST.PRSM/fsejournal-v11i2.29010

the RP 1737 to the Mokhtar Soussi dam, then by a 55 km developed road runs along the Tifnoute valley. Then by walking a path of 4 .5 Km. Through angular blocks of different sizes, this arduous climb took about 1 hour 15 minutes.

The annual average rainfall is 532 mm (Aghbar station), and the annual temperature average is 22°C.

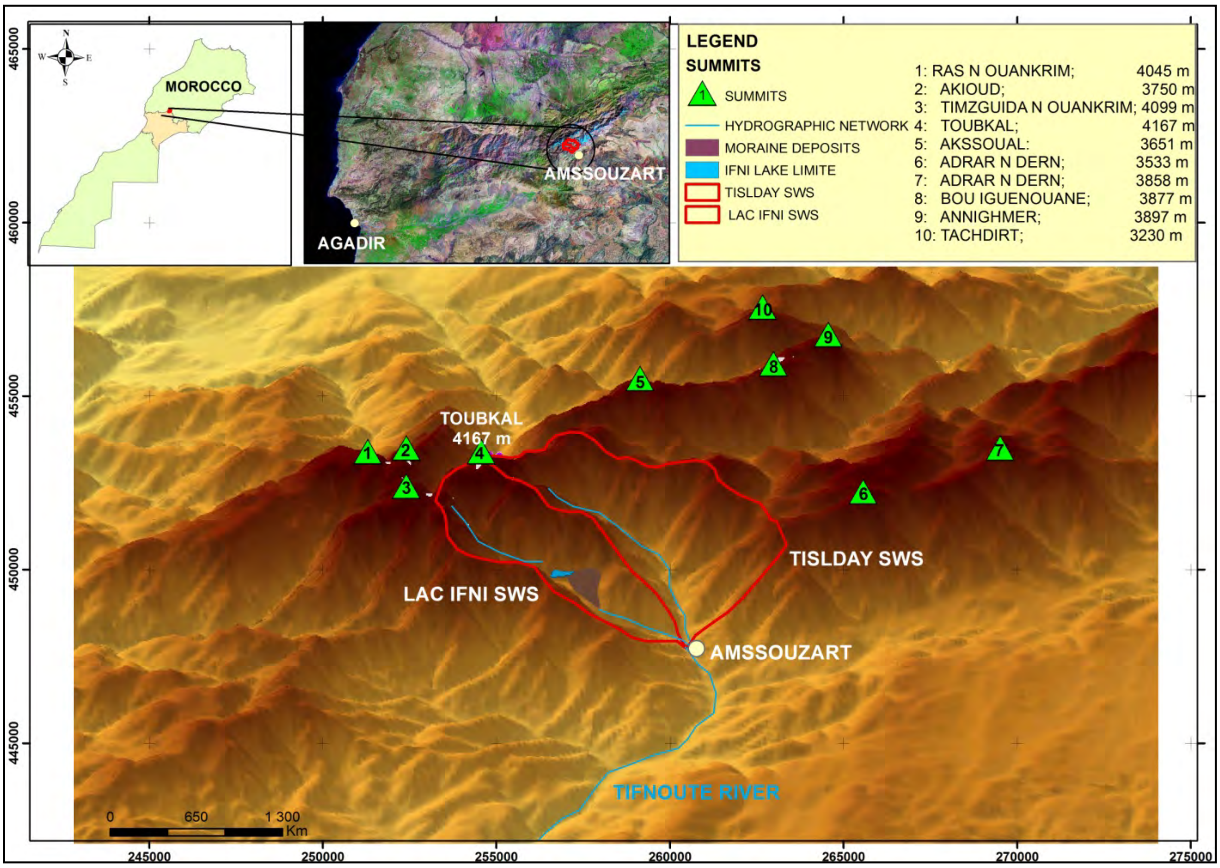

Figure 1 : 3D map showing the sub-watersheds of Ifni lake and Tislday (SWS) with altitudes of the main snow-capped peaks. In cartridge a sketch of situation.

This mountain, where the lake is situated, is one of the highest in Morocco (altitude of 2295 m). It has an elongated axis shape along the valley of the Assif n'Moursaine (Fig. 1). Its surface is about 30 hectares (770m/350m). It is located at the bottom of a valley, framed by Jebel Toubkal, Ouanoukrim and Ifni Dome (photos a & b in Fig. 2). Its surrounding basin is constituted of Precambrian igneous rocks (granites, rhyolites, andesites, basalts) and bordered at the bottom of a valley by the peaks of the Toubkal mountains (4167 m) to the north, Ouimekssane (4089 m) to the East and Adrar Bou Ouzzal (3650 m) to the West. Its banks are made up of steep slopes except for the West, where narrow stony plain borders it along the Assif. It is fed by the ravines' floods that lead to it but especially by the waters of the snowmelt drained by the main ravine Assif n'Moursaine. The Tizi N'Ouanoumss pass (3664 m) is located at the head of this valley between Toubkal (4167 m) and Igger n'Abdeli (3815 m). A natural dam bars Assif n'Moursaine, which flows for about three kilometers to the lake. It is a huge break in the slope of rock debris of varying nature and size.

3. Description and interpretations of the natural dam deposits

We used satellite imagery (Google Earth) and DTM (Global Mapper) beforehand to identify moraines and other glacial landforms in the study area, which allowed us to establish a more accurate classification and positioning during our

field investigations landforms. Therefore, we carried out three field missions to map the study area, describe the petrography of the materials of the natural dam, and note the direction and dip of the striations.

Ifni Lake is dammed by an impressive accumulation of centimeter-scale debris and boulders of several meters in height (Fig. 3), the most impressive can reach hundreds of tons' weight. However, their nature is variable and composed of: rhyolites, andesites, basalts, volcanic breccia, sandstones and volcano-detrital rocks of the Late Precambrian (Upper Neoproterozoic) (Fig. 3). The elements' size and nature depend mainly on the petrographic composition of the rock and the degree of fracturing of the rocky massif from which they originate. The large blocks, mainly volcanic, are packed in a mass of smaller debris, also angular and of the same nature. The debris appeared as a chaotic.

a b

Figure 2 : Panoramic View of Ifni Lake (a) in summer view toward natural dam (frontal moraine) and (b) in winter view toward Jbel Toubkal.

The total width of these deposits is 550 meters and their length is 1890 meters. The area occupied by the deposits is 1.63 km2 (approximately 163 hectares). These impressive piles represent around 100,000 cubic meters of material, i.e., the equivalent of five 10-ton trucks per day for 12 years.

We interpret these spectacular debris deposits as a glacial moraine. Glacial deposits originate from debris from the glacier bed or flanks and are moved by the glacier (Benn et al. 2010; Schomaker 2011; Trenhaile 2013). Because of their low transporting capacity, the streams leave the coarser components of the debris mass on the glacier. Accordingly, the vertical alteration in texture of the moraine debris reflects the changing influx of sediments, which is coupled to processes acting in the debris source area such as ablation, rainwater slide and flow because of heavy rainfalls in this area. In the middle part of the moraine we identified blocks with streaks on their faces (photos c & d in Fig. 4). However, it is sometimes difficult to distinguish the glacial striations from fault mirrors, especially since the outcrops in the study area are affected by several strike-slip faults.

The azimuth of the glacial striations measured in the different places of Assif n'Moursaine varies between N55 and N140. Also the quantity witch domain is the interval N120-N140 which means the glacier direction movement (Fig. 3) and (photos a and b in Fig. 4).

Erratic boulders that appear in large debris can reach up to several meters in diameter, scattered and of a different geological nature from adjacent outcrops. These are mixed volcanic lithologies like basalt, ignimbrite, rhyolite and andesite (photos a, b, c & d in Fig. 5), whose source is to be sought in the upstream part between Jbel Toubkal and Lake Ifni. That debris is a valuable signs of old expansions of the glacier tongue.

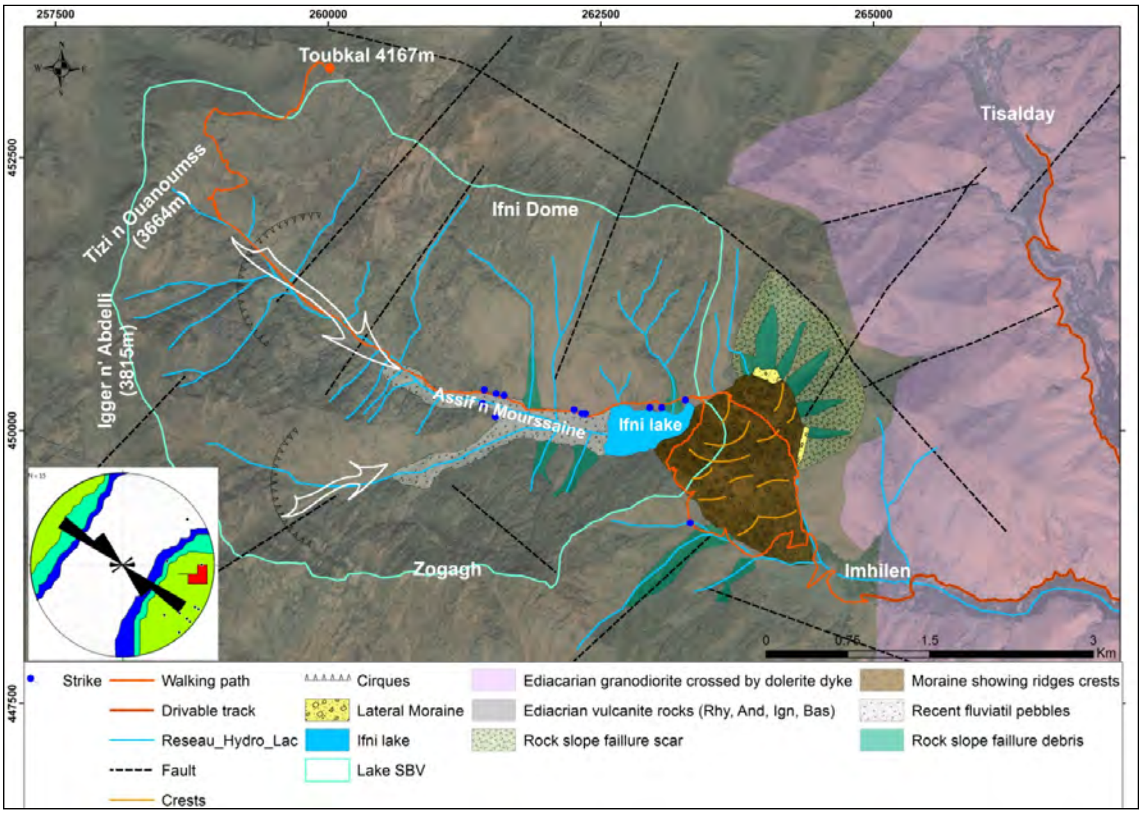

Figure 3: (a) Sketch geological map of Ifni area (Rhy; Rhyolite, And; Andesite, Ign; Ignimbrite, Bas; Basalt) and (b) stereographic rosette showing azimuth of the main glaciation striations.

(a)

(b)

(c)

(d)

Figure 4: Glacial striations: (a & b) left bank of Assif n'Moursaine (c) in the top of frontal moraine and (d) Large erratic volcanic boulder in Assif n'Moursaine.

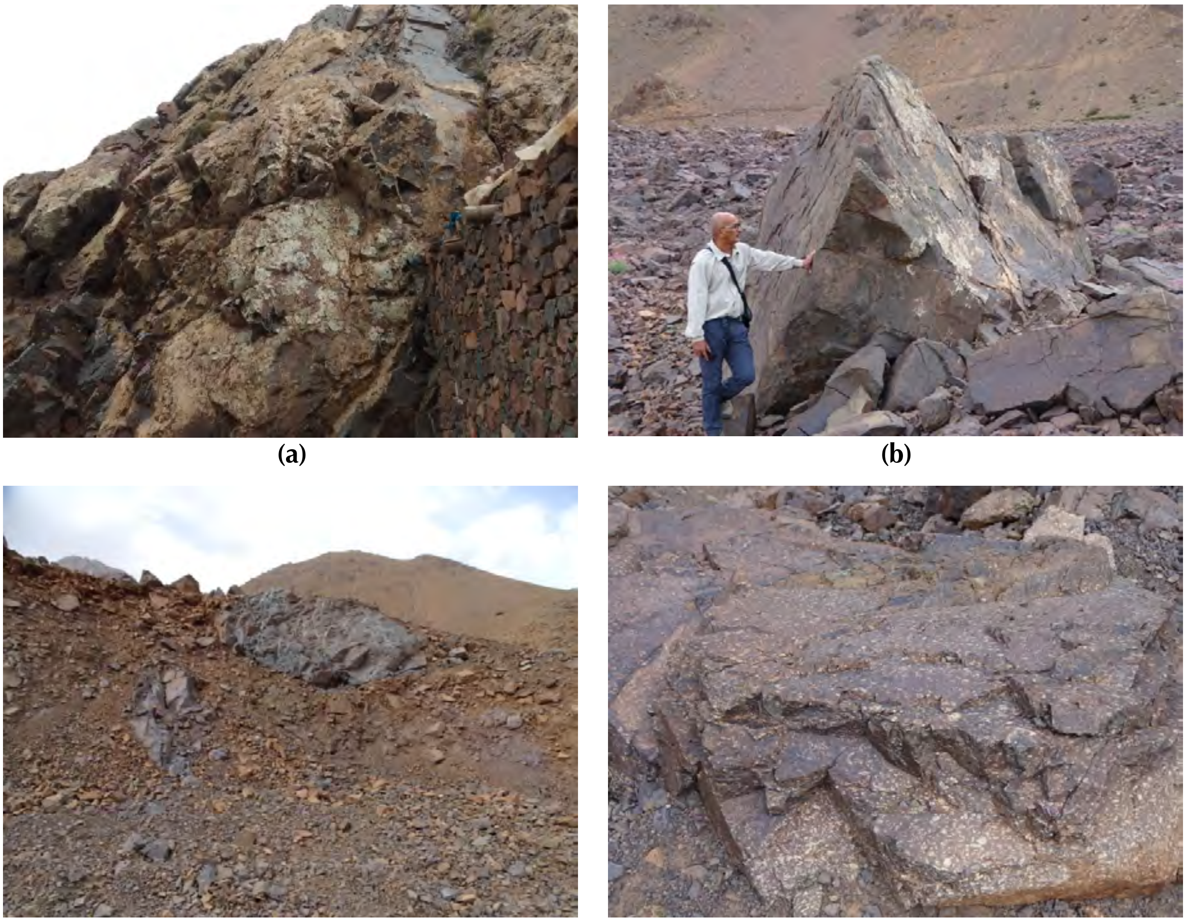
(a) (b) (c) (d)

Figure 5: Large boulders of various petrographic nature: (a) several-ton block in the upstream part of the moraine with numerous lichen patches, (b) boulder of rhyolite in the middle part of the moraine, (c) boulder like a dropstone in the upper part of the gravels and pebbles deposits, (d) andesitic boulder derived from the upper catchment.

They cannot be explained by river transportation (no rounded forms) or by solifluction processes. Instead, their presence miles from the parent rock attests to their transport through the glacier. The transported debris was deposited on the surface or into the ice mass after the ice melted.

We note the absence of stratification of deposits and grading of debris (photos a, b, c & d in Fig. 6). The distribution of large blocks does not happen randomly. They generally occupy the base of successive beads. The mapping of the moraine deposits (Fig. 7) shows that it was formed by the stacking, in steps, of three main arched cords separated by depressions. Their interlocking suggests that the glacier retreated in several stages.

Part of the old glacial deposits is now terraced and covered with vegetation. This succession of moraine "amphitheaters" makes it possible to locate the advance of the front of a glacier at different times, with a minimum of three main stages of the rise and recede of the glacial tongue.

Moraine constructions have a palaeo-geographic interest because they mark stages of stagnation or even glacial progression long enough for the glacier to have had time to build sedimentary constructions of a fairly large scale.

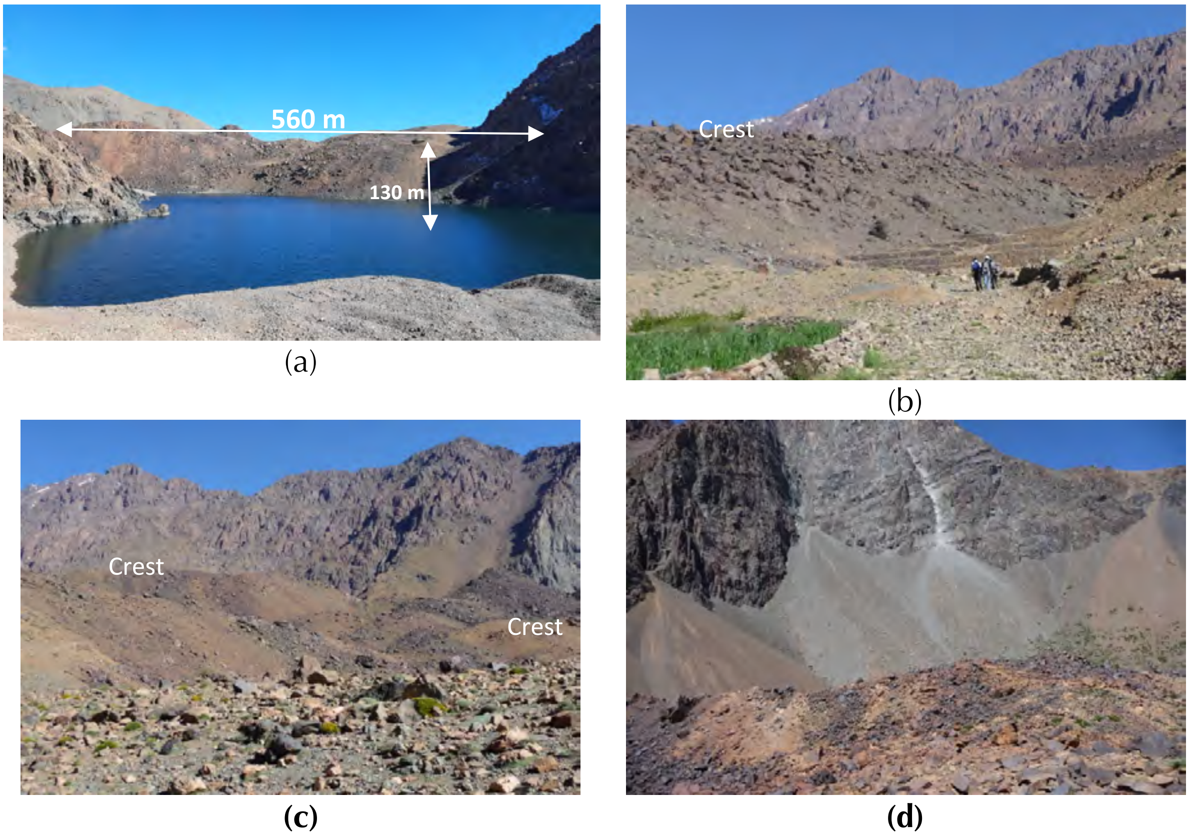

Figure 6: Glacial deposits (a) in front of the lake width and height of the natural dam, (b) in the upstream part, (c) in the middle part with crests of the composite moraine ridge (d) rocky slope failure debris in the left border of the moraine.

The highlighting of glacial stages has been used in most studies applied to the Late Glacial (PENCK et al. 1893-94). It has been applied particularly in the Swiss Alps. This method is based on the geomorphological characteristics and the depression values of the ice equilibrium line (SCHOENEICH 1998a, 1998b). According to this last author, the moraines are often more or less mixed or close to those of the Little Ice Age. They undoubtedly constitute distinct stages. Based on the proximity of the moraines, the risk is to group in a single stage, several fluctuations that have been spread over several centuries or even thousands of years. On the other hand, there is a risk of dissociating chronologically very close events.

4. Formation model of Ifni lake

The main geological processes that contribute to the formation of mountain lakes are:

- Following the collapse of land due to a tectonic activity at the origin of a basin filled with water ,
- During a landslide that obstructs a high altitude river, thus forming natural dams (560 m wide and more than 130 m high) and consequently lakes (photo a in Fig. 6)
- In a very large sinkhole or karstic polje in carbonate massifs ,
- Following the accumulation of water in a volcano crater or that of a meteorite impact,
- In a caldera or behind a lava flow,
- Behind a natural morainic dam or in a depression of a glacial umbilicus, retained by a rock lock.

High mountain lakes are found in both the High Atlas and the Middle Atlas (BOULHOL 1941). Their formation remains controversial.

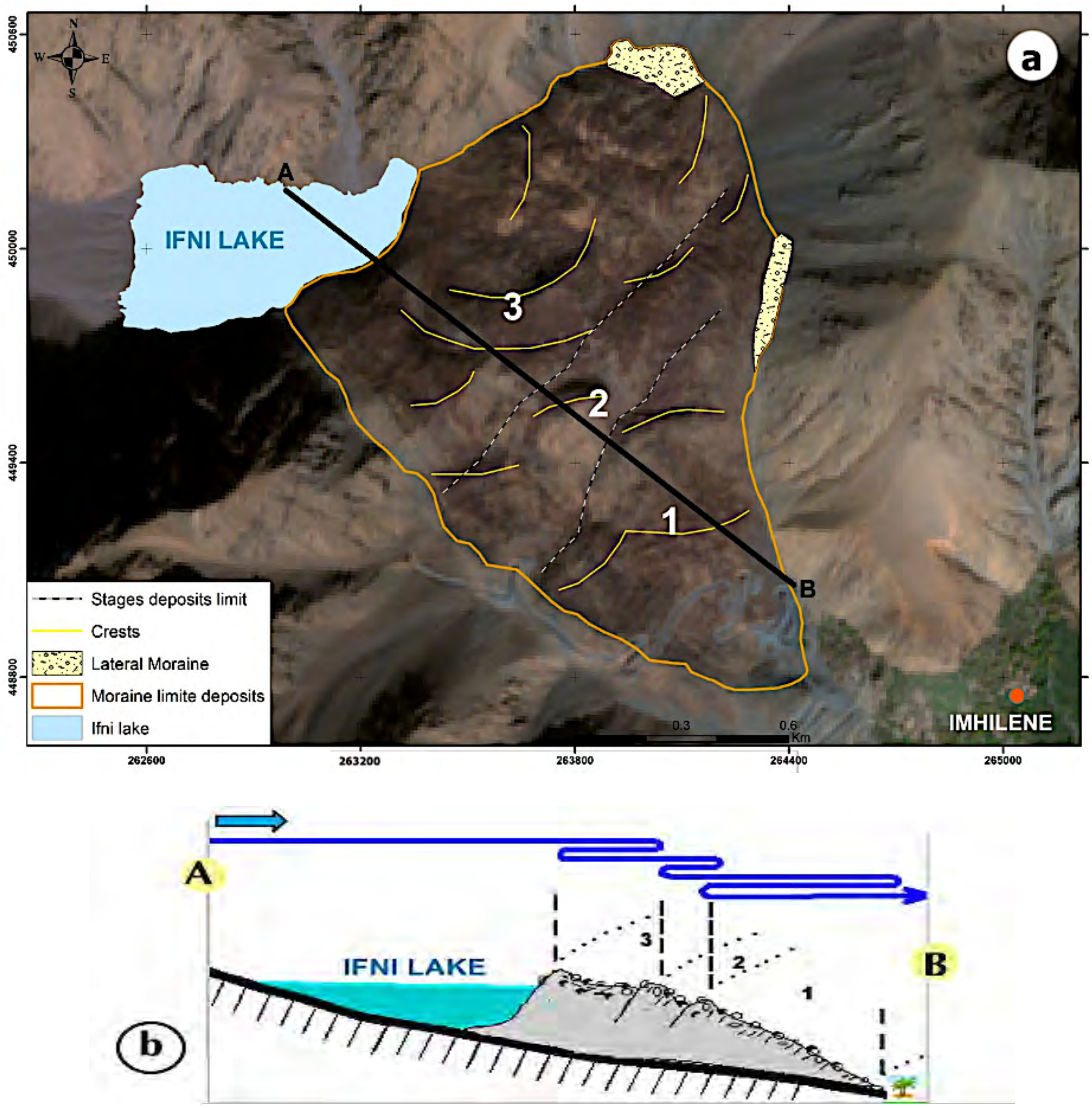

Figure 7: (a) Satellite image (Google Earth) showing the frontal moraine complex with crests and (b) Scheme of the morainic complex showing three main arched cords separated by depressions and the diagram showing the retreat stages with three oscillations in place.

DAKKI et al. (2020) considers Ifni lake, Tamda Anghomer (or n'Ounaghmar), Izourar lake and Tamda Tametrocht as lakes formed by landslides. For IBHI et al. (2013) the Tisslit and Isli lakes in the Imilchil region, central High Atlas, are interpreted as impact craters from a meteorite that split in two, while but CHARRIÈRE et al. (2014) locate these two lakes in a tectono-karst depression. For COUVREUR (1981), Lake Anghomer located on the southern slope of the central High Atlas, and Izourar lake in the region of Aït Bou Guemmaz are landslide lakes. Tametrocht lake, located in the Eastern Middle Atlas, on Oued Ighrane, is linked to tectonic activity (EL FELLAH 1994).

Ifni Lake, situated on the southern slope of Toubkal, is believed to be of glacial origin (CÉLERIER et al. 1922; BOULHOL 1941). The late-Quaternary glaciations are the origin of the most high mountain lakes. These glacial lakes can result from ablation actions by glaciers, or due to moraine dams (frontal moraine). Due to ablation actions, the lakes are located behind the locks, in the umbilics dug by the valley apparatus or at the bottom of the circuses.

Considering account the description of the deposits of the frontal dam of the lake, striations on the banks of Assif n'Moursaine, striations and grooves in the moraine deposits and the presence of erratic boulders, we consider that Ifni Lake is formed by glacial activity. It is a high mountain lake blocked by an accumulation of frontal moraines from the glacis during the wet Holocene enriched by massive landslides (Fig. 6d). The main stages in the formation of this lake are (Fig. 7):

- -Two small mountain glaciers were formed below the ridgeline (Fig. 8), in two cirques surrounded by reliefs of Tizi n'Ouagane (3750 m), Azrou Bou Krenaine (3650 m) and the Ifni Dome (3875 m).
- A little valley is identified in the current Assif n'Moursaine wadi oriented NE-SW. It slopes slowly towards the valley Tifnout, much shallower than it is today.
- Beyond the two cirques begins the glacial tongue when it exists, which flows into the Assif n'Moursaine to a lock overlooking the valley of Tifnoute.
- The glacial carried off fragments of fractured volcanic rocks, which present different, gravel and boulders.
- The glacial tongue transported pebbles and large blocks (several tons) fallen from the slopes or torn from the cliffs.
- The accumulation of this large volume of moraine deposits has been formed by at least three major glacial rises and retreated, and their age can extend over thousands of years.
- The frontal moraine was fed by debris from rock slope failure on both sides of the valley. As a result, the left bank exhibits a recent slip scar (Fig. 8).
- The glacial tongue was short (less than 5 km), Due both to the configuration of the relief, fragmented upstream, but above all, to the weak snow supply, due to the geographical location and the rapid melting of the ice exposed to the southwest.

The moraine sequences allow some correlations, although no radiometric age has been realized on the Ifni Lake Moraine. These sequences are located in the neighbouring Toubkal valleys, Aksoual area; HUGHES et al. (2011, 2012), and other regions of the High Atlas (FINK et al. 2012, 2014). HUGHES et al. (2011a and b) have provided the first radiometric ages of the region using analyses of terrestrial cosmogenic ^{10}Be isotopes. These ages indicated at least three periods:

- **Phase 1** (lower moraines): from 31.1 ± 3.8 to 76.0 ± 9.4 kyrs for the oldest and most extensive moraines, which implies that these were deposited during the glacial time before the global LGM and suggesting a local **LGM** here at the start of the last glacial cycle (Soltanian stage), The precise age of these moraines is not clear, but they certainly predate the last glacial maximum (27–23 kyrs, HUGHES et al. 2015).
- **Phase 2** (high moraines) has been dated from 19 to25 kyrs and correspond to the last glacial maximum.
- **Phase 3** (moraines deposited during a third phase of glaciation) indicate very similar ages of 11.1 ± 1.4, 12.2 ± 1.5 and 12.4 ± 1.6 kyrs, corresponding with the younger Dryas period (12.9-11.7 kyrs). These moraines belong to the last glacial cycle, known as the “Soltanien” stage in Moroccan stratigraphy (LEFÈVRE et al. 2002).

5. Extension of the last glaciation in the western High Atlas

Glacial formations have been highlighted in the central High Atlas (COUVREUR 1966, 1981). At mountain peaks, such as Jbel Toubkal (4165 m altitude), Ouanoukrim (4067 m), Igger n'Abdeli (about 3815 m), Aksoual (3651) and Bou Iguenouane (3730) in Arroumd, from tizi n'Ouagane (3750 m), Azrou Bou Krenaine (3650 m) and the Dôme d'Ifni (3875 m), there are glacial evidences such as cirques, troughs, rock mutton, erratic boulders and moraines and streaks (DRESCH (1941, 1949); HEYBROCK 1953); MENSCHING 1953; AWAD 1963; BEAUDET 1971).

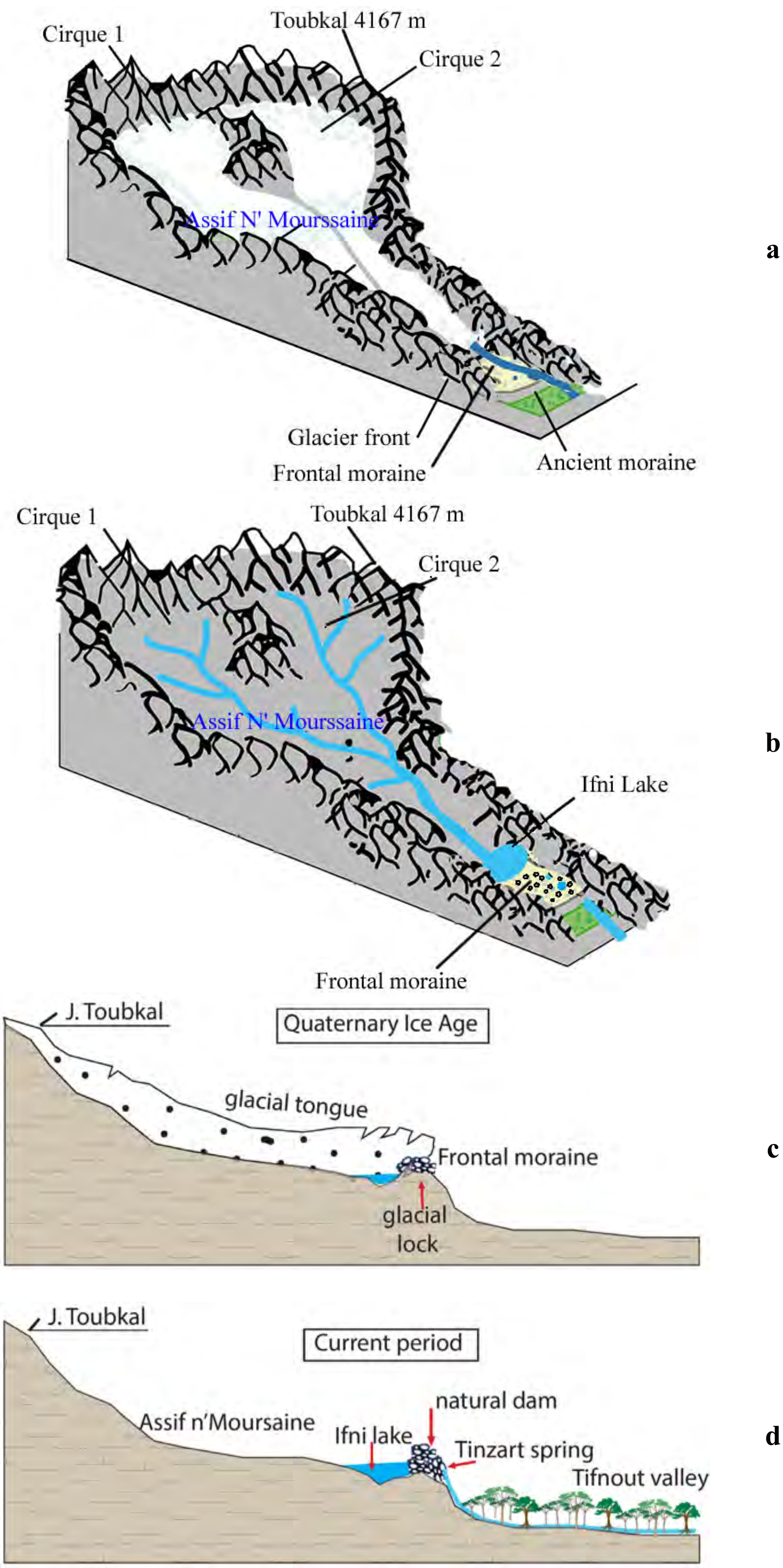

Figure 8: 3D model of the formation of Ifni Lake (a, b) and sections (c, d) in the ancient ice age and the present period.

One of the largest glaciers was that of the Toubkal massif. The northern flank of the western High Atlas has been the subject of several studies (CHARDON et al. 1981; HUGHES et al. 2011a, 2011b). It shows the traces of the glacier activity, which extended northward, almost 10 km up to an altitude of about 2000 m (Sidi Chamarouch) with cirques with moraines and valleys with erratic boulders (Fig. 9).

Climate change would explain the gradual retreat, then the glacier's disappearance.

In the recent Quaternary, a local glacial occupied the summits of the Atlas. These regional and mountain ice sheets have left a large expansion of pleniglacial, cataglacial and finiglacial deposits. However, current periglacial processes only existed on the high slopes. At the end of the Late Glacial period, a small glacial mountain reoccupied certain cirques. Periglacial actions were then more widely distributed but limited in their effects. The various mountain and periglacial glacial heritages indicate climatic influences during the last cold periods.

The periods of Pleistocene and Holocene have been characterized by the advances and retreats of ice reflecting significant climatic variations.

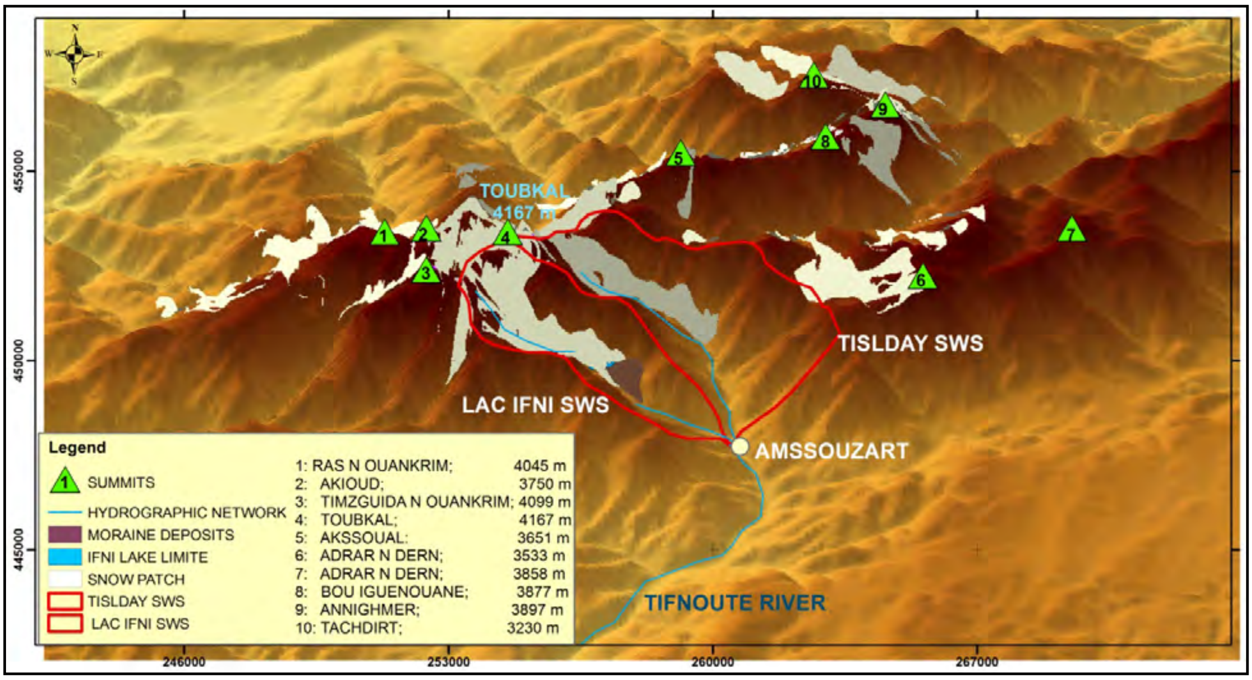

Figure 9: Situation of the main glaciers during the last glaciations period around Ifni Lake (digital elevation model based on a 30 m grid with Global Mapper).

The current interglacial period, from 10,000 years, called the Holocene, first rather warmer, is then colder around 6000 BP. It is marked by numerous small-scale climatic variations, which have caused significant glaciers fluctuations (GROVE 2004; WANNER ET AL. 2008; LE ROY 2012; MATTHEWS et al. 2005). Among these periods, the latest and well documented is the glacial advance period of the Little Ice Age that extends from the beginning of the 14th to the mid 19th century (GROVE 2004) which follows the warmer Medieval Period (*Medieval warm Period* ; ~ 900-1300). During the last millennium, alpine glaciers have fluctuated over a fairly large amplitude, with advances (rise) following retreats. A great advance is reflected just after the relatively warm period of the Medieval Optimum (10th-13th century) and continues, with ups and downs, until the strong downturn started in the 19th century. The Little Ice Age is characterized by a colder climate than the

current one, marked by a substantial drop in worldwide temperatures. It lasted five to six centuries. The Little Ice Age, which is characterized by two peeks dated around 1570-1650 and 1780-1830 is considered to be one of the most spectacular phases of progression that glaciers have known on the scale of our interglacial cycle.

Evidence of glacial activity during the Holocene period has been documented for the Atlas Mountains. However, small glaciers on the peaks of the study area were probably present during the Little Ice Age (HUGHES et al. 2011a). However, paleoclimatic data were obtained from isotopic variations of stalagmites. The latter, collected in the western High Atlas at Ifoulki and Win-Timdouine cave (AIT BRAHIM et al. 2017, 2019a, 2019b), have indicators that give information on the amount of rainfall. They show that the Upper Paleolithic is relatively humid. From 11,500 to 10,800 years **BP**, the climate was characterized by dry conditions with a wet period around 10,500 years BP. It is only from 10,000 years **BP** that the climate becomes relatively wetter due to the displacement of the African monsoon towards the North. The climate remained relatively the same during Green Sahara until about 3,800 years BP. This long period saw three short periods of relative aridity "centennial-scale climate variability": 9,400 to 9,000, 8,200 to 8,400 and 5,200 to 5,000 years **BP**. After 3,800 years, it was followed by a marked climate deterioration to more arid conditions, with some periods of humidity that could last a few centuries "centennial-scale climate variability". The last two periods before the current warming are the Medieval Warm Period and the Little Ice Age, which date back to around 950 AD to 1,400 AD and 1,400 AD to 1,850 AD respectively (DESPART et al. 2003).

6. Conclusion

Knowing the evolution of glaciers is more than ever necessary to analyze the change of the climate and prevent some of the consequences that their massive melt could have on the environment, water resources, and therefore on the future of our societies.

The moraine of the natural dam is associated with a climatic stage during the last glaciation because its formation requires specific glacial stability. A stationary front for debris and boulders to accumulate on the same site. The extended glacial equilibrium being challenging to maintain, it is likely that the moraines will build up in several stages. The glacier fluctuates slightly around the current position of the moraine front. This was built in the form of three ridges separated by small depressions. These coalescing moraine ridges can correspond to glacial deposits during three phases of rising (advance of the glacial tongue) and recede (withdrawal of the tongue).The glacier age behind this spectacular moraine is not yet known. The lichens of the moraine blocks have been sampled and are in the process of age determination. However, correlations can be made with radiometric ages (10Be) of moraine in regional valleys (HUGHES et al. 2011, 2012) and in other regions of the High Atlas (FINK et al. 2012, 2014). HUGHES et al. (2011a, 2011b). The youngest moraines have ages that fit into the Younger Drya calendar (12,900-11,700 BP).

Acknowledgements

This study was carried out within the context of the CHARISMA project with the assistance of the Hassan II Academy of Science and Technology and Ibn Zohr University of Agadir. Thanks to the “Institut de Recherche pour le Développement » (IRD, France and its local representation in Morocco) for their support.

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Participatory management of rangeland hydrology – a new socio-ecological technology to effectively adapt to and mitigate climate change: case from Morocco

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Abstract. Morocco's drylands cover over 90% of the land area; low and irregular rainfall and high potential evaporation contribute to extremely high-water deficits in this area. These phenomena have significantly impacted rangeland hydrology and nomadic and transhumant pastoralism. To adapt to this predominant water deficit, the inhabitants of these areas have developed two forms of lifestyles, which include household and livestock mobility: (i) a pendulum movement for seasonal transhumance between the mountains and their bordering plains; and (ii) random nomadic mobility regulated by the sporadic frequency of rains and thus water availability. In both cases, this mobility is controlled by the degree of the routes development ~~of~~, but also derives also from participatory governance of water access to livestock. For example, pastoral communities first use routes with ephemeral waters, while saving perennial or semi-perennial water sources for long lasting drought periods. To mitigate water scarcity, nomads and transhumant often reduce herd size, and switch temporarily to complementary activities such as trade, crafts, wage labor, and engagement in public services. However, the conservative practices of rangeland and water management have progressively declined following regional and global trends of sedentarism, urban extension, and the emergence of new activities such as intensive irrigation, industry, and tourism. Faced with this situation, various development organizations aim to recover local traditional conservation and participatory water management practices. Rainwater harvesting as well as hydraulic facilities, storage and tank services for isolated populations are being implemented at several points along nomadic routes. Besides, new schooling Opportunities have opened employment opportunities and additional income from farming activities. In this context, transdisciplinary monitoring of rangeland development through remote sensing in addition to biophysical and socio-economic indicators have been installed. In this work, we present an integrated analysis of hydrological management systems of Moroccan drylands in relation to pastoral adaptation to climate change.

Key words: Rangeland, arid zones, Climate change, water management, pastoralism, sustainability

1. Introduction

Morocco is one of the Mediterranean countries with a significant pastoral vocation. The agro-sylvo-pastoral, pastoral and oasis lands cover more than 90% of Moroccan territory (Ministry of Agriculture, 2015). These lands offer necessary land support dedicated to extensive livestock farming, which plays a significant role in the income generation for peasant society and the rural economy's functioning. Its production is about 1/3 of added-value in the agricultural sector, contributing to 30% of jobs. More importantly, it represents a source of income for 80% of rural households (Qarro et al. 2010).

Most of the rangelands, which represent 97% of the total (oasis 7 %), are located in arid and semi-arid environments where the chances of success of rain-fed cereal crops are closely related to the

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DOI: https://doi.org/10.34874/IMIST.PRSM/fsejournal-v11i2.28994

frequency of droughts (ARABA & BOUGHALMI, 2016; REED & DOUGILL, 2002). The North Africa drylands, including Moroccan ones, will face increasing temperatures with climate change. More importantly, they will experience disruptions to their hydrological cycles characterized by an increase of extreme events with a pronounced tendency of reduction of precipitation . This will exacerbate the already critical state of water scarcity and conflicts over water allocation and will have direct consequences for society (HSSAISOUNE et al, 2020; THOMAS, 2008).

Over centuries and decades, pastoralism in arid areas has been considered a crucial economic activity and a method of land exploitation. Under these conditions, the possession of even a small flock becomes a strategic way of ensuring the subsistence of human communities.

Nowadays, these large arid and semi-arid territories and their pastoral communities, after forming a civilization based on the management and control of natural resources scarcity, mainly water resources, are facing serious constraints related to the context of climate variability.

In this work, we will address the characterization of the socio-ecological frameworks for the exploitation of Moroccan pastoral territories. The objective is to re-examine the systems of mobilization and management of water resources related to traditional pastoral activities and analyze the technical ways for better mitigation and adaptation to climate change and variability.

2. Materials and method

The methodology used in this work focused on transdisciplinary, even multidisciplinary, collective action. We based our study mainly on the literature review of existing academic research and field observations, as well as various experiences of different researchers, including the different teams of authors involved in this paper through different research actions and projects. We focused on the scientific research carried out with the objectives of sustainable development but also of safeguarding and conserving the fragile ecosystems in situ. Therefore, we refer to : i) studies on the exploration and development of water supply systems for rural populations and their livestock, ii) establishment of National Parks and Biosphere Reserves for the conservation and rehabilitation of declining ecosystems, and iii) delimitation and characterization of pastoral and agro-sylvo-pastoral zones.

We also performed a qualitative analysis of available documents such as unpublished reports, books, and different research papers that constitute an added value to our contribution [AHLAFI 1999 ; FAO 2002, 2006 ; NEGGAR 2018 ; QARRO et al. 2010].

This theme is relevant for the sustainable development and exploitation of rangelands, as it constitutes a natural laboratory for observation and participatory analysis of socio-ecological systems. Therefore, it contributes to the monitoring of mitigation and adaptation aspects of climate change effects, particularly in:

- the amplification of the decrease tendencies of the production capacities in the arid and semi-arid ecosystems,

- the degradation, under the effect of massive migrations of young people, and the old systems of governance of scarce resources, thus producing a transmission break in the expertise between the different generations,

- the increasing actors' expression and partners interested in this theme, through the conciliation between development and the safeguard of the balance of arid and semi-arid ecosystems.

3.Results

Concerning its spatial spread between the Mediterranean and Saharan latitudes and its predominantly mountainous orographic character, Morocco is considered a territory with a pastoral vocation par excellence. The pastoral lands cover more than 87% of the national territory covering more than 71 million Ha (Fig. 1). Forest and scrub (matorral) areas constitute only 10%. In opposition, land classified as rangeland and uncultivated land covers more than 55 million Ha or 90% of the pastoral area. Without the forest rangeland, these grazing lands consist mainly of steppes at the rate of 94%; the rest concerns land covered with Alfa formations..

There are four main pastoral zones (Fig. 1):

3.1. The nomadic pastoral system:

It occupies the great Moroccan South, constituting the predominantly Saharan bioclimatic national territory with limited pastoral potential in terms of fern resources and watering water. This area is the seat of an exclusively nomadic pastoral system based on camel and goat breeding. Due to the geopolitical context with blocked borders and the modernization of pastoral activity, this system is in further declining.

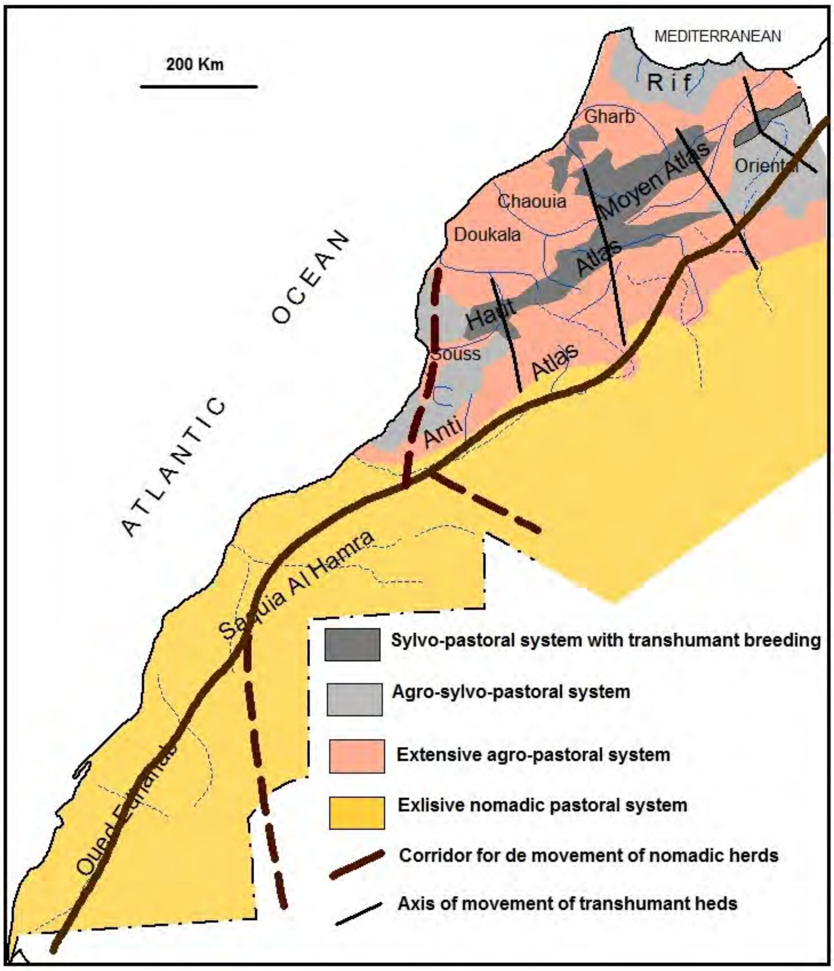

Figure 1 : Major pastoral zones and movement of pastoralism in Morocco

3.2.The extensive agro-pastoral system:

This system combines rain-fed cereal agriculture and extensive breeding with a local transhumant variant. This system is based on breeding mainly goats and sheep, and sometimes cattle. We distinguish two agro-pastoral sub-systems: first, the pre-Saharan zone, located between the Saharan area and the South Atlas Fault; second, the Atlantic plateaus and plains and Eastern Morocco..

3.3.The agro-sylvo-pastoral system:

Unlike the last system, goat-based cattle generally take advantage of the forest fodder resources offered by mountainous areas such as the Rif, the High Atlas and the Anti Atlas on their fronts open to the Atlantic Ocean, well as the Oriental Highlands.

3.4.The sylvo-pastoral system:

This system mainly concerns the high-altitude mountains represented by the High Atlas and the Middle Atlas and a few islets in the Central Plateau and the Oriental Highlands. These areas, characterized by their low temperatures and snowy accumulations in winter, offer precious pastures for the cattle of the transhumant tribes of

the pre-Saharan regions and the Atlantic and Oriental plains and plains (Fig. 1).

4. Discussion

4.1. Pastoral area and socio-ecological framework of exploitation

Most of the rangelands, located in areas with extreme edapho-climatic conditions, have a water deficit due to a high seasonal and inter-annual frequency of drought periods (Table 1 & Fig. 2):

- **Saharan rangelands**: mainly cover the provinces of southern Morocco with an area of around 50 million ha, more than 4/5 of national rangelands. The hyperaridity of the environment contributes to the reduction of the rates of floristic richness and recovery of vegetation, and the regression of water resources. The possibilities of using the rangelands can only be sporadic during irregular rainfall events;
- **Pre-Saharan rangelands:** located further north where the improved bioclimatic conditions allow the development of steppe plant formations dominated by Saharan strains. This area is a modest extension of 10% of all rangelands, but it remains strategic for the maintenance of pastoral activity through its forage supply of perennial xerophyte shrubs and its potential for livestock watering;
- **Eastern rangelands:** these are steppe lands representing 8% of the total rangelands. These lands are dominated by a plant formation of alfa representing a species adapted to arid or semi-arid bioclimatic conditions.

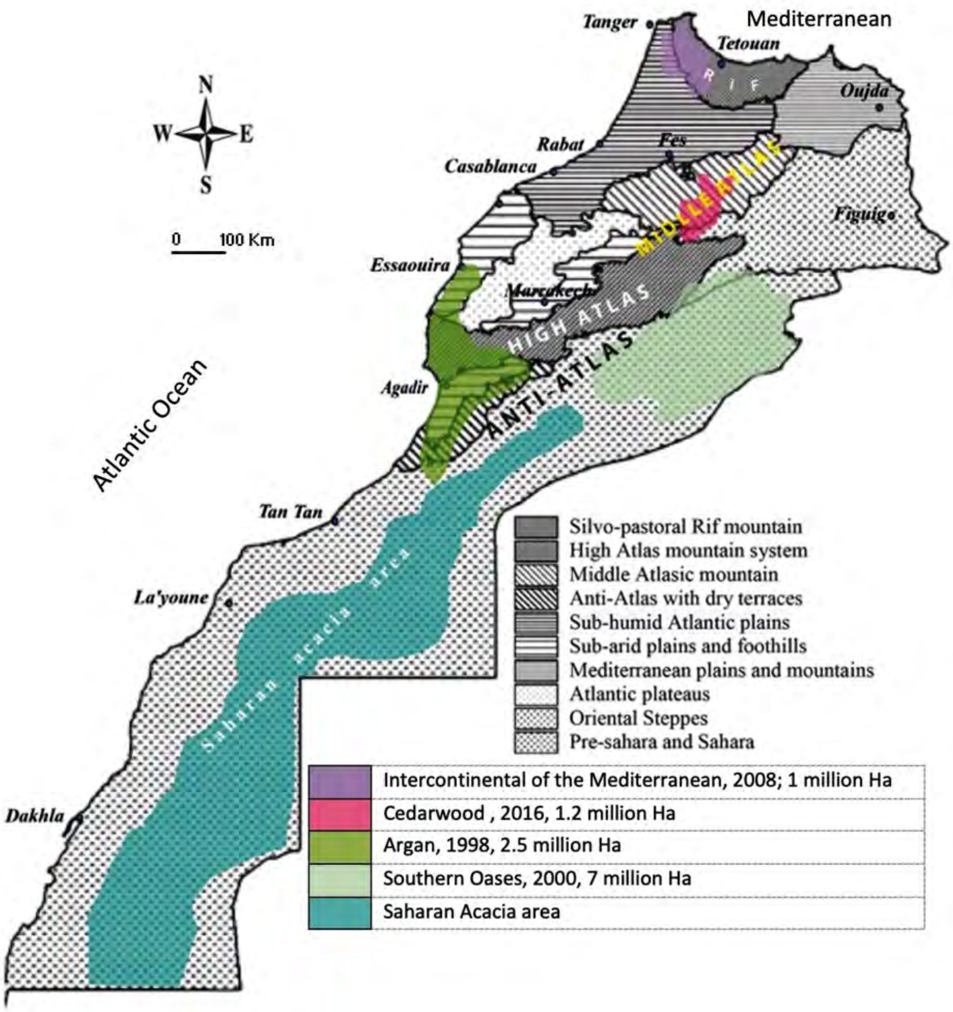

Figure 2 : Map of the regional systems of water and soil conservation (WSC) and biosphere reserves in Morocco (KOUBA et al. 2018, modified).

Table 1: Characterization of ecological zones in pastoral areas (QARRO et al. 2010)

Types	Extension (%)	Plant formations	Water potential
Saharan area	82	• Saharan formations ; • Very low floristic richness; • Very low recovery rate ; • Occasional herbaceous plant.	• Occasional surface water ; • Non-perennial groundwater; • Deep aquifers with limited potential; • Degraded water quality
Pre-Saharan area	10	• Saharan Steppe ; • Xerophytic shrub formations ; • Seasonal herbaceous plant.	• Seasonal surface flows; • Non-perennial groundwater; • Moderate water quality.
Eastern area	8	• Arid Steppe ; • Alfa formations and floristic community; • Seasonal herbaceous plant.	• Seasonal surface flows; • Semi-perennial groundwater; • Deep aquifers with moderate potential; • Moderate water quality.

4.2. Socio-ecological systems of rangelands and water governance

Human presence in drylands has only become possible through the shaping of ingenious socio-ecological systems for the mobilization and management of natural resources. For example, in the case of nomads and transhumant, the guarantee of the livestock's watering needs was based on the movements of the herds and their owning households to the water points (Table 2).

Generally, pastoral activity was practiced outside any significant hydraulic development. As a result, the most widely used surface waters are those of isolated ponds (Dayat, Graara) and receding ponds of wadis (Gueltas). At the same time, groundwater is limited to resurgences of underflows of wadis (Aayn). More often than not, to quench their thirst, livestock use the same water resources used by wild animals.

When the mobilization of more volumes of water becomes unavoidable to increase the duration of exploitation of the pastures, the communities pass to collective hydraulic installations mainly of dewatering and storage. The most adopted technique is the digging of wells (Bir, Hassi) for the extraction of water from the shallow aquifers generally attached to infra-flows of permeable alluvium. In pre-Saharan areas where the potential of underground resources becomes relatively scare, pastoral communities may have the possibility of benefiting from spring waters (Ayn) and underground drains with accumulation basins (Khettaras and Charij). On the other hand, for surface water, the most frequent developments consist in collecting rainwater and runoff: reservoirs covered with impluvium (Matfias) and open excavations (Ghdir).

The mobilization and use of water resources are subject to a rigorous and collective management system with the rights and obligations of individuals.

Table 2: Livestock watering mobilization

Planning types	Water resources	Techniques of mobilization
Exploitation without planning	• Ponds with acceptable quality : • Underflows resurgences:	• Dayat, graara, gueltas. • Aayne, Aayoune.
Traditional planning	• Storage of rainwater and runoff : • Exhaure of water from local aquifers : • Use of underground oasis drains:	• Ghdir, notfias . • Wells, Hassi . • Khettaras, charij.
Stakeholders intervention	• Wadi with perennial or semi-perennial flows • Exploitation of deep aquifers: • Water transfer to places of consumption:	• Dams, Small dams. • Boreholes. • Towed citterns.

4.3. Rehabilitation attempts and experiences of stakeholder participation

The pastoral areas in Morocco are more than ever subject to pronounced stresses due to overexploitation of rangelands combined with water shortage (DEL BARRIO et al. 2016; KOUBA et al. 2018).

In the face of declining dynamics, these areas are underway to rehabilitate the pastoral socio-ecological framework. They include various decisions, such as national range development strategies; emergency drought response programs; the range and livestock development project, biodiversity conservation project through transhumance in the High Atlas, projects to install national parks and biosphere reserves (Fig. 2). Currently, the ministry in charge has just launched a study of differentiation, inventory, and characterization of the rangelands to create pastoral and sylvo-pastoral spaces in the twelve regions of the country. The figure 3 shows an example of pastoral and transhumance within Southeastern Morocco including the movement axes between plain and Mountains in one hand and between water points and feeds areas in other hand. These movements are done according the different seasons.

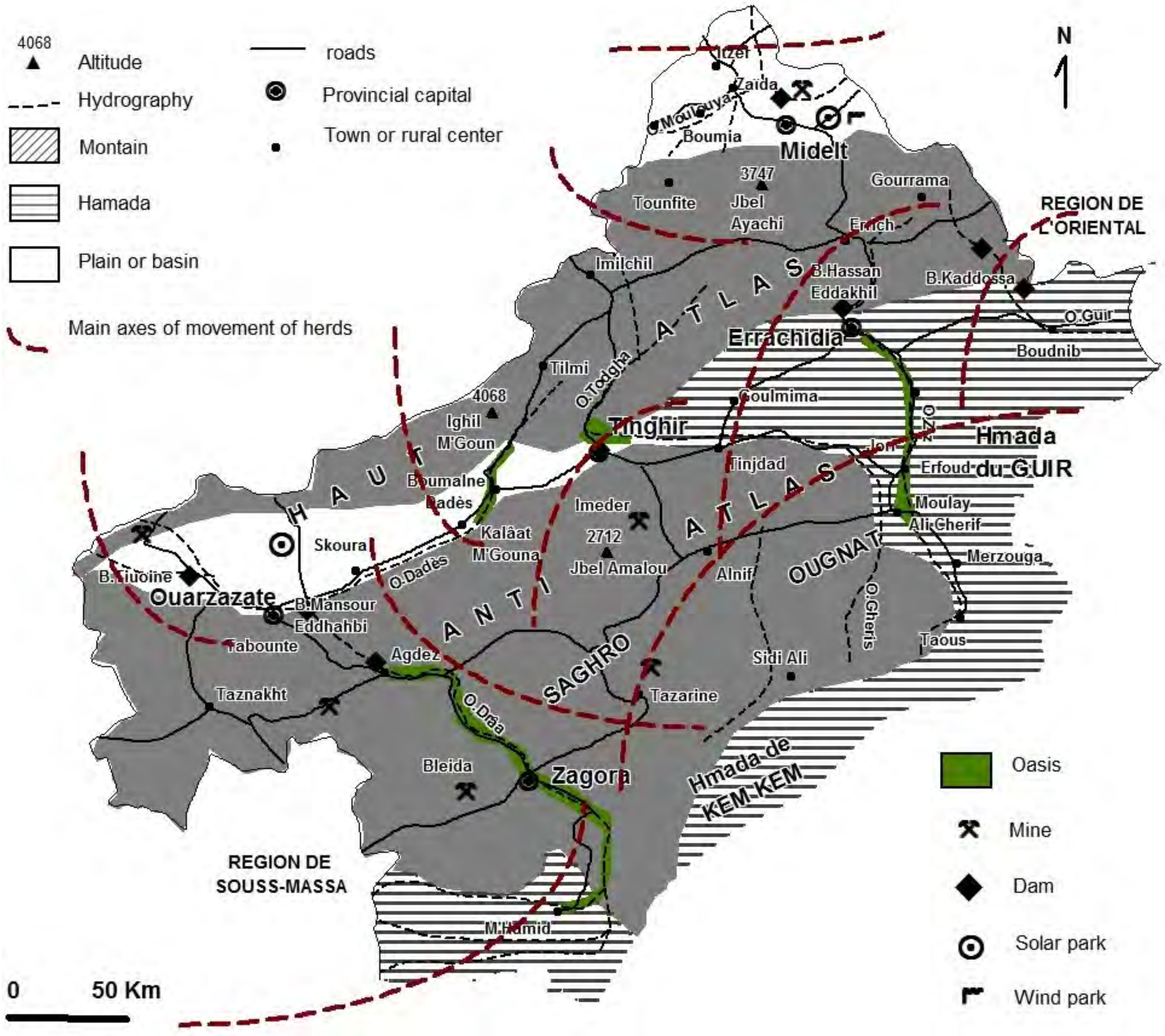

Figure 3: Case of pastoral and transhumance from Southeastern Morocco

The development and implementation processes of the various programs and projects have provided precious opportunities for adopting horizontal approaches favoring the principles of

consultation and citizen participation and all stakeholders. This new approach places the people concerned at the center of the development process. It has been relatively successful in improving pastoralists' living conditions and supporting their activities. To this end, more efficient hydraulic equipment has been installed, but this has not been able to halt the trend towards the disappearance of nomadic and transhumant lifestyles.

5. Conclusion

Even though the water supply systems used for livestock may appear to have poor to moderate yields, they are recognized by their high capacity to adapt to the fragility and irregularities of local water potential. For the community of scientists engaged in the processes of finding the best practices facing mitigation and adaptation to the effects of climate change, the traditional pastoral systems developed in the past by nomadic and transhumant societies in arid and semi-arid environments turn out to have a vital interest.

However, these legacy systems seem to be in a phase of regression and loss of expertise expressed by an increasingly intense settlement. Complex factors have contributed to this trend towards spatial fixation, and intensification of this mobile pastoral activity.

Far away from the ecological characteristics, the factors of change in these pastoral systems have economic, social and even political dimensions. This includes the closure of international borders, the urbanization spread, the desire to improve livestock farmers' standards, the growth of the population and food needs, and finally, the shift to intensifying livestock farming.

In this context, we remind that all the development activities of arid and semi-arid pastoral areas, carried out by the State and pastoral partners, are mainly oriented towards pastoral hydraulics to improve the water supply. However, such actions only facilitate the fixation of nomadic and transhumant societies, which ends in the exhaustion of the regeneration capacities of pastures and consequently by increasing the risk of speeding up the desertification process.

This includes the closure of international borders, the urbanization spread, the desire to improve livestock farmers' standards, the growth of the population and food needs, and finally, the shift to intensifying livestock farming.

Acknowledgements

Special thanks to the CHARISMA project with the assistance of the Science and Technology Hassan II Academy-Morocco. The authors greatly appreciate interactions and support provided by the international network RISZA (Network supported by CONACYT-Mexico) and the Agadir Platform (Ibn-Zohr University). Thanks for IRd institute in Morocco for his help for supporting fieldtrip.

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Dépôt légal : 2012 PE 0007
ISSN : 2028 - 7615

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