Carpathian Journal of Earth and Environmental Sciences February 2024, Vol. 19, No. 1, p. 125 – 133; DOI:10.26471/cjees/2024/019/284

# WEIGHTING OF WATER RESOURCES VULNERABILITY INDICATORS USING ANALYTIC HIERARCHY PROCESS AND GIS IN THE FEZ-MEKNES BASIN, MOROCCO

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**Abstract:** This study analyzes and explores the associated problems with weighting, aggregating variables and combining groups of parameters that control the water resources vulnerability. The Fez-Meknes basin suffers from overexploitation and the groundwater level continue to decline. The assessment of territorial vulnerability to water scarcity and climate variability is a necessity to spatially delimit the areas likely to be affected. The vulnerability factors of water resources do not have equal impacts of vulnerability. The aim of this research is to identify, with experts in water resources management and the literature, a set of relevant factors and determine the relative contribution of each factor in the vulnerability assessment. To achieve this goal, we have developed a model that combines the Analytic Hierarchy Process (AHP) method, geographic information systems, and expert opinions to define and weigh the vulnerability factors of water resources in the Fez-Meknes basin. The study finding indicate that 21 indicators, categorized into 4 dimensions (Water Resources, Demographic-Socioeconomic, Infrastructure, and Environment), are likely to impact the state of water resources in the study area. The factor groups of Water Resources and Demographic-Socioeconomic have the highest values at 0.47 and 0.28, respectively. Meanwhile, the Infrastructure and Environment factors have the lowest values at 0.16 and 0.10, respectively.

**Keywords:** Water resource vulnerability, AHP, factorial weighting, water resource management, Morocco.

## 1. INTRODUCTION

The water resources in the Fez-Meknes basin have significantly declined over the past decade due to population growth, socioeconomic development, and climate change, as reported by ABHS (2006)**,** Dahan et al., (2017) and Kanga (2020). Protecting these water resources is a top priority in Morocco's water strategy because of their significance and the concerning state of the aquifers in the Saïss plain. A new strategy for groundwater administration and management is being planned by the Agence du Bassin Hydraulique du Sebou (ABHS, 2021). In fact, one of the problems to be solved to guarantee the availability of water resources is the reasonable development of industry, urbanization and agriculture (Berkani, 2023; Schilling et al., 2020). The population and the need for water resources are increasing. According to UNESCO (2015), the household and industrial sectors are the main drivers of the projected 20-30% increase in global water demand compared with the state of use in 2015. Therefore, rational and long-term management is considered crucial. Several studies have been conducted to better understand the nature of water resources and ensure their protection, effective management, and long-term development (Gain et al., 2012; Okpara et al., 2017; French et al., 2017; Aslam et al., 2018; Shabbir et al., 2018). The literature contains numerous definitions of vulnerability.

The IPCC (2001) defines vulnerability to climate change as the degree to which a system is susceptible and unable to cope with its adverse effects. However, a multidimensional analysis of water resource vulnerability is necessary when considering the concept of sustainable development. In order to provide appropriate indicators, numerous composite indices have been developed, which bring together various socio-economic and environmental aspects of the water sector to provide a measure of a complex, multidimensional problem (De Grosbois, 2015; Garriga, 2010; Shalamzari et al., 2018). Water stress has been measured at the regional and national levels using these indices. To determine the relative importance of index components in the vulnerability calculation, explicit weighting is required during the aggregation process. In this study, we used the Analytic Hierarchy Process (AHP) weighting approach to generate indicator and dimension weights.

The Analytical Hierarchy Process (AHP) is a multi-criteria decision-making method used to solve complex decision problems with competing and multiple objectives (Shabbir et al., 2018; Golfam et al., 2019; Gan et al., 2017). The AHP approach entails finding the hierarchies of correlated components. The factors are then weighed and compared to assess their relative relevance (Lua et al., 2017; Ferrando et al., 2021).

The study aims to evaluate water resource vulnerability in the Fez-Meknes basin using multicriteria analysis, the analytical hierarchy process (AHP), and the geographic information system (GIS). The assessment considers the complex and hierarchical nature of water resource vulnerability.

Using GIS techniques and the AHP approach, we analyzed the spatial relationships between the different indicators and obtained information on how they interact with each other. This is particularly useful in the case of complex decision-making problems where multiple factors need to be taken into account and combined, as is the case in our study. With GIS, we were able to represent the data on maps, allowing us to better understand patterns and trends within the data. This visual representation helped to identify areas of high or low vulnerability, potential hotspots or areas of concern. In addition, GIS is also used to identify the risks of potential vulnerabilities in order to develop more targeted and effective solutions.

## 2. MATERIAL AND METHOD

### 2.1. Study area

The Fez-Meknes basin is limited to the North by the pre-Riffian ridges, to the South by the Middle Atlas Causse, to the West by Oued Beht and it is limited to the East by the Oued Sebou valley. The location of the study area is depicted in Figure 1. The region covers 6 provinces and 55 municipalities and spans around 100 kilometers in length and 30 kilometers in width. The two largest cities, Meknes and Fez, are critical to the region's and country's socioeconomic development. They are regarded as one of the country's major cities due to its economic, agricultural, artisanal, tourism, and commercial potential.

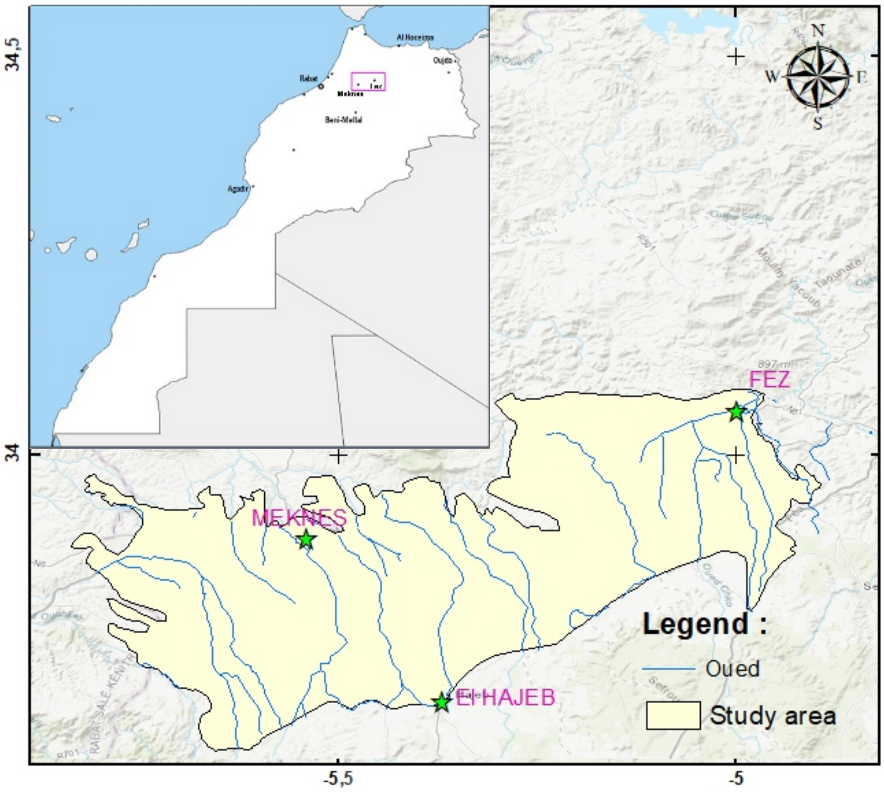


Figure 1. Location map of the study area

According to the 2014 census, the Fes-Meknes basin has more than 2.33 million inhabitants (HCP., 2014). The study area is one of the most important agricultural areas in Morocco. The useful agricultural area amounts to more than 265,000 ha (ABHS., 2021).

Groundwater recharge in the area is primarily facilitated through infiltration. Wells are utilized to extract groundwater. Annual rainfall exhibits high variability, with an average of 450 mm between 1975 and 2022. The study area's water inventory includes several Oueds (Beht, R'dom, Mikkes, and Fez) and two dams (El Gaada and Dhar Mehraz) (El Garouani et al., 2023a).

## 2.2. Methodology

Assessing water resource vulnerability poses a significant challenge due to data availability (El Garouani et al., 2023b, Hinkel, 2011; Zhang et al., 2023). Therefore, we selected dimensions and factors based on whether we could collect or calculate data for them during the study years. The number of factors considered is often limited by data availability and access.

It is crucial to remember that not all water resource vulnerability factors have the same impact. To establish their respective contributions, the discovered susceptibility factors must be ranked and weighted in a survey. The first step consists in structuring the data in a GIS database, crossing the layers information and spatially analyzing the different components and indicators of the vulnerability index.

The choice of criteria is based on the literature and the expert's opinion in the field. It consists in identifying the relevant factors, and then, on the basis of this identification, gathering all the data corresponding to these factors. Water management experts are requested to assign a weight to the different vulnerability factors based on their personal experience. The group of experts includes executives from the private or state water sector, university professors, hydraulic engineers from the Sebou Hydraulic Basin Agency. The developed methodology is shown in Figure 2.

The two primary tasks of the adopted methodology are as follows:

a- The AHP prosses, which consists of four stages:

- Multi-criteria formulation and expert evaluation.
- Standardization and classification of factors.
- Pairwise comparison of weightings and development of factor map.
- Verification of consistency and aggregation of criteria

b- GIS-based data processing techniques:

- Organization of descriptive and spatial data and production of factor maps.
- Integrating and analyzing data.
- Creation of thematic maps.

The identified criteria are those which have been recognized as representing essential characteristics in contributing to the vulnerability of water resources. The Fes-Meknes basin vulnerability index is composed of 21 indicators divided into 4 dimensions (Water resources, Demographic and Socio-economic, Infrastructure and Environment) likely to affect the state of water resources in the study area (Table 1).

Before using the AHP method, the required data were normalized using the min-max method. It allows meaningful comparison between variables with different scales and units. This also ensures that all values fall within the same range from 0 to 100. The formulas for calculating the normalized value of an observation for the positive and negative effect indices are respectively:

$$X_{ij} = \left(\frac{Xi - Xmin}{Xmax - Xmin}\right) * 100 \quad (1)$$

$$X_{ij} = \left(\frac{Xmax - Xi}{Xmax - Xmin}\right) * 100 \quad (2)$$

The AHP method follows a basic principle: identify relative problem factors, create a hierarchy, and assign weights to each factor after comparing them (Shabbir., 2015). To evaluate using the AHP method, start by determining the superiority of the criteria through pairwise comparisons. Pairwise comparison is conducted by assigning a priority value to each criterion based on the SAATY value scale (SAATY., 1977). The scale ranges from 1 (equal importance) to 9 (absolute importance).

Once the comparison matrix is constructed, the coherence of the matrix is checked by the coherence index (CI) and the Coherence Ratio (CR). CI and CR are respectively given by Saaty (1977):

$$CI = \frac{\lambda_{max} - N}{N - 1} \quad (3)$$

$$CR = \frac{CI}{RI} \quad (4)$$

The matrix is deemed sufficiently consistent if IC $< 0.1$ or CR $\leq 10\%$; if these values are more than 10%, the judgments might need to be revised. The random index given in table 2 is represented by the parameter (RI).

# 3. RESULTS

After conducting the hierarchical analysis and comparing the components and their respective indicators, we combined the combined weights of the criteria (Tables 3 to 7). The AHP approach's findings

Table1. Dimensions and indicators of territorial vulnerability to water scarcity and climate variability

| Dimensions | Indicators |
|---|---|
| **Resources (R)** | • Interannual cumulative precipitation (R1)<br>• Piezometric level (Useful depth) (R2)<br>• Precipitation variation coefficient (R3)<br>• Quality of water resources (R4)<br>• Hydrographic density ($km/km^2$) (R5) |
| **Environment (E)** | • Vegetation index (E1)<br>• Irrigated land/total cultivated land (E2)<br>• Potential Evapotranspiration (E3)<br>• Drought frequency (E4) |
| **Infrastructure (I)** | • Population access to drinking water (I1)<br>• Population access to electricity (I2)<br>• Population access to sanitation (I3)<br>• Distance to paved road (I4)<br>• Road density ($km/km^2$) (I5) |
| **Demographic and Socioeconomic (D)** | • Population density ($ha/km^2$) (D1)<br>• Population growth rate (D2)<br>• Literacy rate (D3)<br>• Unemployment rate (D4)<br>• Poverty rate (D5)<br>• Activity rate (D6)<br>• Population aged under 4 and over 65 (D7) |

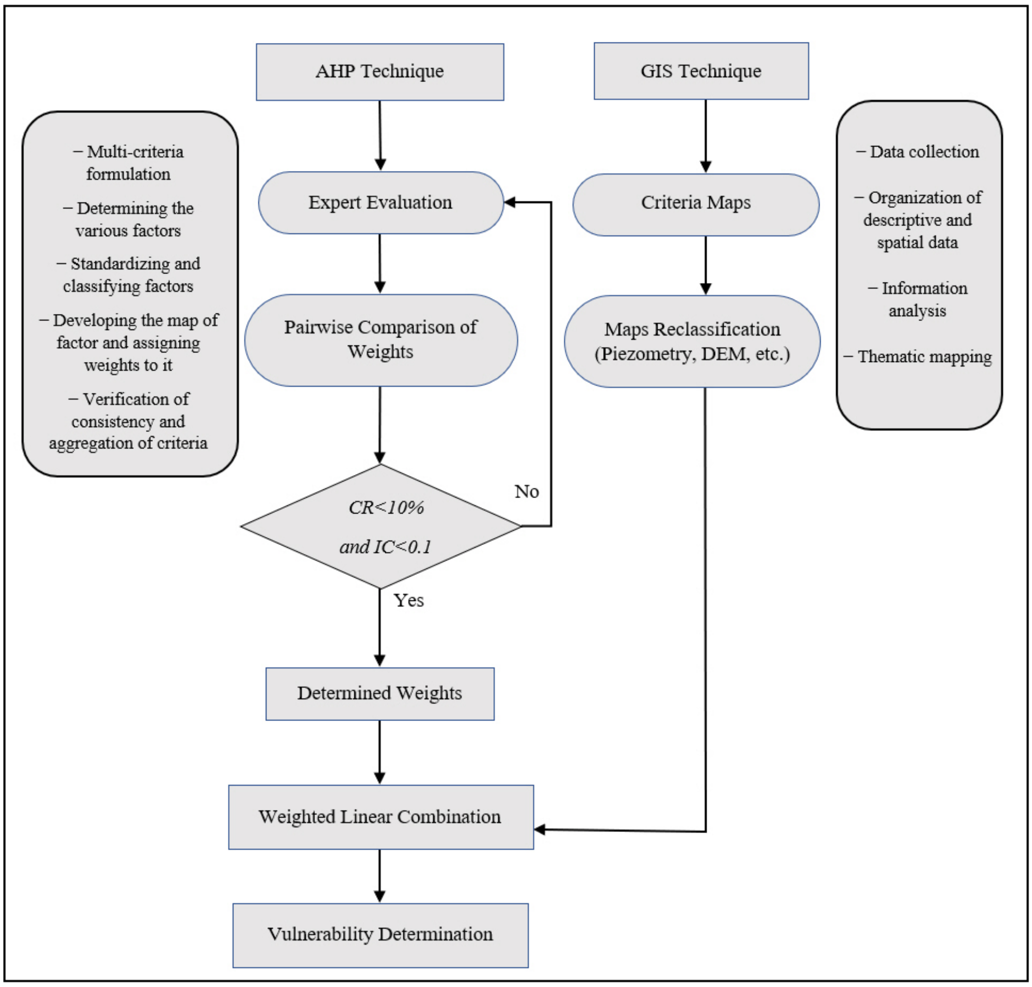


Figure 2. Flowchart

Table 2. RI random index (Saaty, 1977)

| Matrix dimension (N) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| **RI** | 0 | 0 | 0.5 | 0.9 | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 |

show that the two components with the greatest influence on decisions about the water resources management are the resource component (0.47) and the demographic and socioeconomic component (0.28) (Table 3).

Non-climatic factors, such as demographic and socio-economic variables, have also been found to contribute to the overall vulnerability of water resources. This amplifies the impact of climate change.

The resource component comparison matrix is shown in table 4. This table indicates that the interannual cumulative precipitation indicator (0.44) and the piezometric level indicator (Useful thickness) (0.26) have the highest weights. Therefore, they will contribute very significantly in the assessment of vulnerability.

From table 5, which concerns the indicators weighting of the demographic and socio-economic component, it can be seen that literacy rate (0.34), and unemployment rate (0.23) have the greatest weights, and consequently they are the most important and contributing indicators of influence in this component.

For the infrastructure component (table 6), the results indicate that indicators of the population access to drinking water (0.41), access to electricity (0.31) and sanitation (0.17) are the most important.

It is evident from table 7, which deals with the indicators weighting of the environment component, that the vegetation index (0.45) and the ratio of irrigated land to total farmed land (0.32) have the highest weights and are, thus, the most significant and contributing indicators of influence in this component.

Table 3. Pair-wise comparison matrix and weights of vulnerability dimensions

| Dimensions | R | D | I | E | Weight |
|---|---|---|---|---|---|
| **R** | 1 | 2 | 3 | 4 | 0,47 |
| **D** | 1/2 | 1 | 2 | 3 | 0,28 |
| **I** | 1/3 | 1/2 | 1 | 2 | 0,16 |
| **E** | 1/4 | 1/3 | 1/2 | 1 | 0,10 |
| **λmax** | **4,03** | **CI** | **0,01** | **RC** | **1,15** |

Table 4. Pair-wise comparison matrix and weights of Resources indicators

| Resources | R1 | R2 | R3 | R4 | R5 | Weight |
|---|---|---|---|---|---|---|
| **R1** | 1 | 2 | 3 | 5 | 7 | **0.44** |
| **R2** | 1/2 | 1 | 2 | 3 | 5 | **0.26** |
| **R3** | 1/3 | 1/2 | 1 | 2 | 3 | **0.15** |
| **R4** | 1/5 | 1/3 | 1/2 | 1 | 3 | **0.10** |
| **R5** | 1/7 | 1/5 | 1/3 | 1/3 | 1 | **0.05** |
| **λmax** | **5.08** | **CI** | **0.02** | **RC** | **1.7** | |

Table 5. Pair-wise comparison matrix and weights of demographic and socio-economic indicators

| Demographic / socio-economic | D1 | D2 | D3 | D4 | D5 | D6 | D7 | Weight |
|---|---|---|---|---|---|---|---|---|
| **D1** | 1 | 1/2 | 1/7 | 1/6 | 1/5 | 1/4 | 1/3 | 0,03 |
| **D2** | 2 | 1 | 1/6 | 1/5 | 1/4 | 1/3 | 1/2 | 0,04 |
| **D3** | 7 | 6 | 1 | 2 | 3 | 4 | 5 | 0,34 |
| **D4** | 6 | 5 | 1/2 | 1 | 2 | 3 | 4 | 0,23 |
| **D5** | 5 | 4 | 1/3 | 1/2 | 1 | 2 | 3 | 0,16 |
| **D6** | 4 | 3 | 1/4 | 1/3 | 1/2 | 1 | 2 | 0,12 |
| **D7** | 3 | 2 | 1/5 | 1/4 | 1/3 | 1/2 | 1 | 0,08 |
| **λmax** | **7.44** | **CI** | **0.07** | | **RC** | | **5.6** | |

Table 6. Pair-wise comparison matrix and weights of infrastructure indicators

| Infrastructure | I1 | I2 | I3 | I4 | I5 | Weight |
|---|---|---|---|---|---|---|
| **I1** | 1 | 2 | 3 | 5 | 6 | 0,41 |
| **I2** | 1/2 | 1 | 3 | 5 | 6 | 0,31 |
| **I3** | 1/3 | 1/3 | 1 | 3 | 5 | 0,17 |
| **I4** | 1/5 | 1/5 | 1/3 | 1 | 2 | 0,07 |
| **I5** | 1/6 | 1/6 | 1/5 | 1/2 | 1 | 0,05 |
| **λmax** | **5.18** | **IC** | **0,04** | **RC%** | **3,60** | |

Table 7. Pair-wise comparison matrix and weights of environment indicators

| Environment | E1 | E2 | E3 | E4 | Weight |
|---|---|---|---|---|---|
| **E1** | 1 | 2 | 3 | 4 | 0,45 |
| **E2** | 1/2 | 1 | 3 | 4 | 0,32 |
| **E3** | 1/3 | 1/3 | 1 | 2 | 0,14 |
| **E4** | 1/4 | 1/4 | 1/2 | 1 | 0,09 |
| **λmax** | **4,08** | **CI** | **0,03** | **RC%** | **2,42** |

Finally, the weighting of all dimensions and factors highlights the importance of combining all the criteria in a global index which will help in decision-making. In addition, the consistency index for all matrices is less than 10%, implying appropriate consistency in the experts' judgments. After normalizing the data on water factors, they were spatialized and integrated. The vulnerability of water resources for each factor was mapped and then aggregated into a single vulnerability map.

Kanga et al., (2019) and Babel et al., (2011) classified the final index of water resource vulnerability assessment on a scale of 0 to 1. Similarly, Borzì (2023) classified the final index into five degrees of vulnerability: very low, low, moderate, high, and very high.

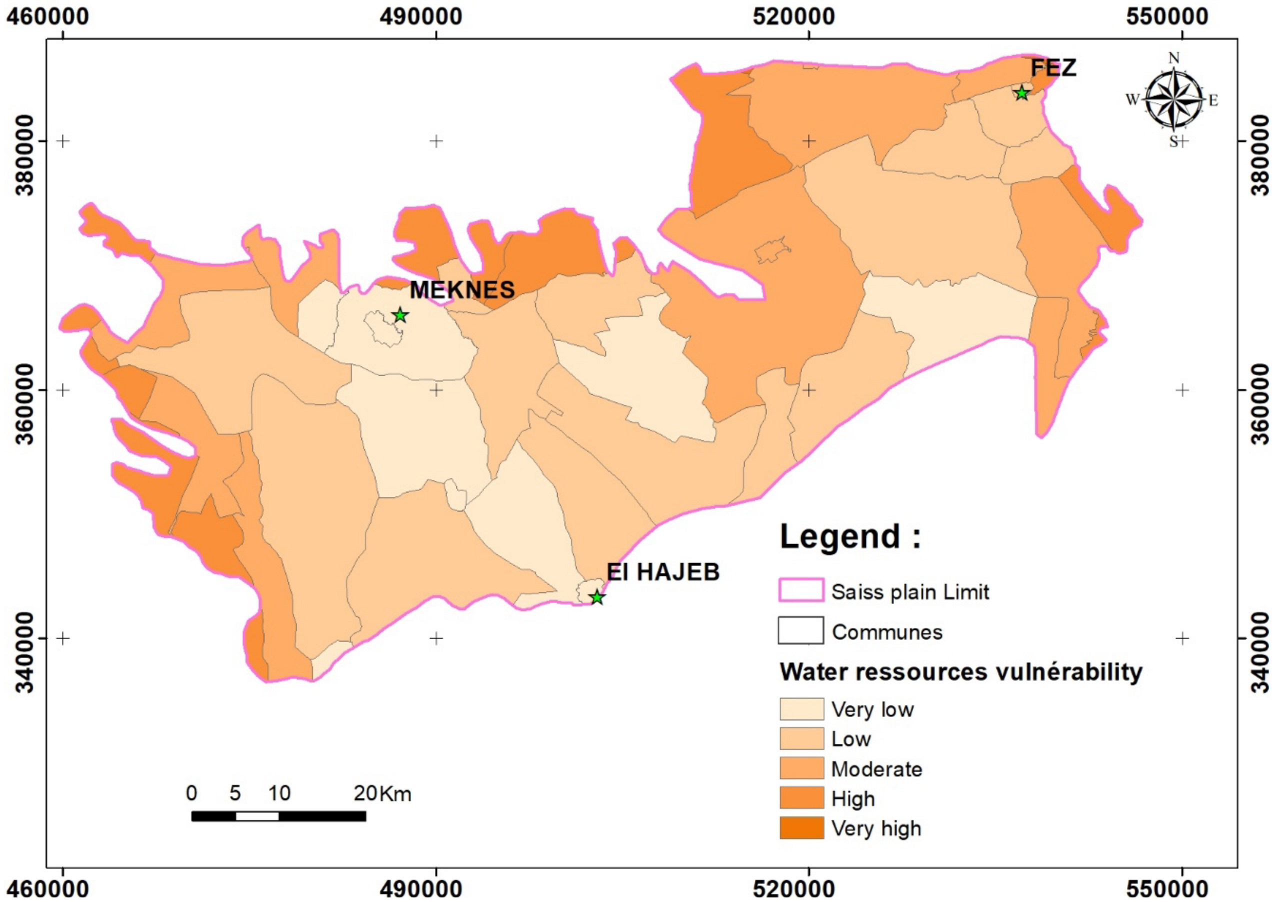


Figure 3. Map of the water resources vulnerability

To gain an overview of water resource vulnerability, it is necessary to aggregate several factors from different dimensions, including water resources, demographics, socio-economics, infrastructure, and environment. This approach enables the analysis of all factors interacting in the study area. Figure 3 depicts the final map of water resource vulnerability created by combining the 21 criteria.

The vulnerability map indicates that 70% of the study area has a low or moderate degree of water resource vulnerability. However, 30% of the area is classified as vulnerable to highly vulnerable. The northern and northwestern parts of the study area are particularly vulnerable.

Water vulnerability accuracy improves with higher resolution due to scale dependence on data (Robielos, 2020). The study uses data from various spatio-temporal scales, requiring both ascending and descending scales to obtain data at the target scales. Additionally, the reliability of all factors, and consequently the final value of the vulnerability index, depends on the quality and coverage of the data used.

## 4. DISCUSSION

The variation between the composite indices (dimensions) depending on the weightings assigned to the indicators from which they are constructed, the distribution of scores by commune is not systematically and radically different. This suggests that the indices are sensitive enough to highlight different aspects of vulnerability without being overly sensitive.

Figure 3 shows the spatial variation of vulnerability in the Saïss plain. It is the result of combining the 4 dimensions (Resources, Sociodemographic, Environment and Infrastructures). The findings indicate that most of the study area has moderate levels of vulnerability. Communes in the north and northwest, however, are particularly at risk.

Even though this research offers helpful information on the current condition of the water resources in the Saïss plain, it is vital to acknowledge its limits. Owing to data limitations and unavailability, certain indicators that could have yielded more precise results were excluded from the current analysis. However, efforts have been made to include indicators for every facet of the multidimensional territorial vulnerability index to climate change and water scarcity. To ensure conformity with the current literature, we have also relied on the indicators that have been recognized by experts and those that have been utilized in other articles.

Furthermore, by including additional contributing indicators and assigning more specific weights to indicators, it could be able to enhance the study methodology as a whole and provide precise vulnerability mapping. Despite these weaknesses, the vulnerability map obtained will help water resource managers and policymakers to develop appropriate mitigation plans that reduce water vulnerability in the Saïss plain. Additionally, the application of the theoretical framework proposed in this document at a local level could provide more precise results on local vulnerability circumstances and be more useful for policy makers, with customized modifications taking into account the specific characteristics of the study area.

Since the vulnerability indices are based on an intangible concept of vulnerability, their validation is inherently problematic (Vincent, 2007). Some studies validated vulnerability indicators using data on observed effects of climate variability, which assumed that these effects influence vulnerability. One form of indices validation involved expert judgment or peer review processes (Brooks et al., 2005). Validation of indicators and the relationships between vulnerability and different weight sets are studied using expert judgement data collected in a focus group. In most cases, this stage remained relatively underdeveloped and did not question the theoretical framework initially chosen.

Our next task will be to define more precisely the adaptation solutions to be mobilized, with flexible and reversible measures (governance, customary organization, regulation, etc.) or with actions requiring greater investments. To further increase the accuracy of this framework for our upcoming research, current data and machine learning approaches should be applied.

## 5. CONCLUSION

The study's results show that water resource vulnerability is affected by both natural and climatic factors, as well as non-climatic factors such as infrastructure and socio-economics. The water vulnerability index calculations assign different weights to indicators and dimensions based on expert consultations and specific contexts to emphasize their importance. According to the AHP method, the demographic and socioeconomic component has such a significant weight in relation to water resource and therefore acts as an obstacle to the sustainable development of the study region. The indicators and vulnerability components are weighted, revealing that the 'water resource' and 'demographic and socio-economic' components have the highest values at 0.47 and 0.28, respectively. Conversely, the 'Infrastructure' and 'Environmental' factors have the lowest values at

0.16 and 0.10, respectively. The study revealed that the concept of water resource vulnerability is relative, as the indicators' importance varies across different territories.

The vulnerability evaluation was completed with close expert participation. Data availability is one of the obstacles to assessing vulnerability, which significantly restricts the identification of indicators. Furthermore, the dependability, accuracy, and updating of indicators have their limitations. A comparative examination of 21 indices and 4 dimensions of vulnerability to water scarcity and climate variability, based on a multidimensional viewpoint, has demonstrated the diversity of quantified vulnerability assessments. This led to highly contrasting results regarding the location of the most vulnerable areas, linked to the choice of vulnerability indicators.

The zoning of risk areas and the assessment of territorial vulnerability to water scarcity and climate variability were made possible by the identification of components and their weightings. Water managers in the study region will be able to assess water resource vulnerability more precisely and successfully with the use of this cartographic representation of vulnerability as a decision-making tool.

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Received at: 10. 01. 2024
Revised at: 03. 02. 2024
Accepted for publication at: 04 02. 2024
Published online at: 08. 02. 2024