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Integrated Water Resources Vulnerability Assessment: A Multidimensional Approach and Geographic Information System Based in Fès, Meknès, and Ifrane Perimeters, Morocco

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Abstract

Water resources are disproportionately distributed, and more and more problems related to this precious resource are being reported around the world due to anthropogenic pressures and global environmental changes. This paper focuses on assessing the vulnerability of water resources in an integrated way, by taking into account hydrological, environmental, socio-economic and pollution factors, in order to delineate sensitive areas of water resources under a geographic information system. The framework for assessing the water resources vulnerability in the Fès, Meknès, and Ifrane perimeters was based on a participatory approach through a survey. The data collected on the identified factors are then processed under ArcGIS tool to aggregate the normalized value into a water resources vulnerability index. The result shows that the degree of vulnerability of water resources in most of the study area is considered to be at the "threshold" to "non-vulnerable". However, three (3) main areas were considered to be "moderately vulnerable" to "highly vulnerable" precisely in the South of the city of Meknes (Zone 1), from the

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West of the city of Fès (Zone 2), and finally the Dayet Ifrah area (Zone 3). The sensitivity analysis showed that five factors have more impact on the overall water resources vulnerability map: topography, poverty, water withdrawal, population density, and access to drinking water. The result of this study could help integrated water resources management planners take action to improve the overall water quantity and quality in the area, and it can be extended to a larger scale like regional, national or cross-country.

Keywords: Integrated water resource management, Morocco water resources, Water resource vulnerability factors, Tools of water vulnerability assessment, Water vulnerability

Introduction

Water resources are extremely distributed throughout the world. The natural supply of water remains the precipitation that is unevenly distributed in different parts of the world. In agreement with the study of Bhuvaneswaran and Ganesh (2019), 79% falls on the oceans and 21% on land out of the total annual precipitation that falls on Earth. In many areas, the variability of precipitation is increasingly intense resulting in physical water shortages in some areas and flooding in others. Sullivan (2011) reports that precipitation will increase in one part of the world, and it will decrease in other parts. In addition to this, significant changes are being observed in demographics, the environment, and the economic development around the world (Sullivan, 2011). The intensification of agriculture, urbanization, and industry are considered among the problems affecting the availability and quality of water resources worldwide (Alessa et al., 2018; Chande et al., 2019). The population is growing and the demand for water resources is increasing. According to the United Nations Educational, Scientific and Cultural Organization (UNESCO) (2019), water scarcity is increasing and will increase as population and climate change increase. Moreover, water demand will increase significantly in the next two decades (UNESCO, 2019). Several researchers (Shretha et al., 2017; Mirauda et al., 2011; Sullivan, 2011) believe that the problems faced by water resources, whether at the local level or on a large scale, are caused by human activities and extreme weather events induced by climate change. In Morocco, water stress is already being felt, and the latest report on the water resources valorization of the united nations (UNESCO, 2019) sounds the alarm and stipulates that water stress is between 25% and 75%, while it is 11% worldwide. The average temperature increase per decade is 0.16°C and precipitation modelling by 2100 shows a decrease in precipitation by up to 30% (Sbaa & Vanclooster, 2017). Therefore, these changes in climate factors will necessarily impact water availability. It should also be noted that the quality of water resources is seriously affected in some areas (Kanga et al., 2019a) due to human activities such as agriculture, industry, and domestic activities. The Moroccan government already has important laws on water resources management and action plans such as Law 10-95 adopted on August 16, 1995, repealed by Law 36-15 of October 16, 2016, and action plans such as the master plan for integrated water resources development, which has an action program to be implemented by 2050. Despite these efforts, Morocco is one of the countries that is most affected by pollution (El Ouali et al., 2011). Also, the quantity of water per capita per year, which was 3600 m^3 in 1960, was only 645 m^3 in 2015, which is below the water poverty level (Dahan et al., 2017). Due to the multiple disruptions of water resources, a multidimensional approach to assessing the vulnerability of the water system, such as the identification of vulnerable areas using socio-economic, hydrological, physical environmental factors and pollution, is essential to facilitate decision-makers' action plans. The main idea of this study is that the vulnerability of water resources system in the study area can be assessed based on components such as socio-economic, hydrological, potential sources of water pollution, biophysical characteristics, and eco-environment.

Vulnerability assessment approaches based on GIS-coupled indices such as DRASTIC (depth to groundwater, recharge, aquifer media, soil media, topography, impact to vadose zone, hydraulic conductivity), EPIK (epikarst, protective cover, infiltration, karst network), SI (susceptibility index), GOD (groundwater occurrence, overall class of aquifer, depth to groundwater table), PRK (topographic slope, fluctuations amplitude, permeability), and SINTACS (water table depth, net recharge, unsaturated condition, soil media, aquifer media, hydraulic conductivity, topographic slope) (Sadkhaoui et al., 2013; ElFarrak et al., 2014; Knouz et al., 2011; Sinan & Moumtaz, 2009; Amharref et al., 2007; Hamza et al., 2007) have been applied throughout the country, including the interest area. However, these researches only concern groundwater pollution and solely take into account physical factors (hydrological and environmental). The assessment of water resource vulnerability has been taken on a new dimension over the past decades (Kanga et al., 2019b), and it consists of analyzing water resources vulnerability in a holistic way by considering physical (hydrology, environment), socio-economic, governance, and institutional dimensions. Therefore, this paper focuses on assessing the vulnerability of water resources in an integrated way by taking into account hydrological, environmental and, above all, socio-economic factors, in order to identify sensitive areas of water resources under the environment of a geographic information system tool. The study was carried out in the Southern part of the Sebou river basin in Morocco between November 2019 and January 2020.

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Methodology

Study Area

The study area is located in the large Sebou catchment area and extends over two aquifers: the Fés-Meknès aquifer and the aquifer of the Barren limestone plateau. It spans over 7 provinces, including 64 municipalities, and covers an area of 5,849 Km^2. The economy is mainly based on agriculture and industry. Water resources are used for crop irrigation but also for drinking water supplied to nearby cities. The use of agri-inputs is very high in the study area and averaged 66.5% of farms. 51 potential sources of pollution are identified in the study area. Much of the study area has clayey textured soil, especially in the northwest, north, and northeast parts. The eastern and central parts are mainly made up of sandy-clayey textures. The western part of the study area consists of sandy-clay textured soils. The western part of the study area consists of sandy-silty textured soils and raw minerals. The deep aquifer of the Fés-Meknès aquifer includes the dolomitic limestone formations of the Lias and is highly fractured. The thickness of this aquifer varies from a few meters towards the center to 760 m north of the study area. However, the water level is on average 50 m deep in the captive part of the water table and 250 m deep in the non-captive part. The aquifer of the barren limestone plateau is juxtaposed with the Fés-Meknès water table and the basaltic aquifer of the Quaternary. The groundwater recharge is mainly provided by infiltration of rainfalls. Wells and boreholes are the means of exploiting groundwater in this area. Annual precipitation is highly variable. Average rainfall between 1988 and 2017 is 479 mm in the North and Northeast and 800 mm in the South. The inventory of waterbodies in the study area shows some natural rivers and lakes: Fés river, Guigou river (flow rate: 0 to 54 m^3/s), Boufekrane river, Tizguit river, Agay river, and lake of Dayet Ifrah. Figure 1 shows the location of the study area in Morocco and its land use.

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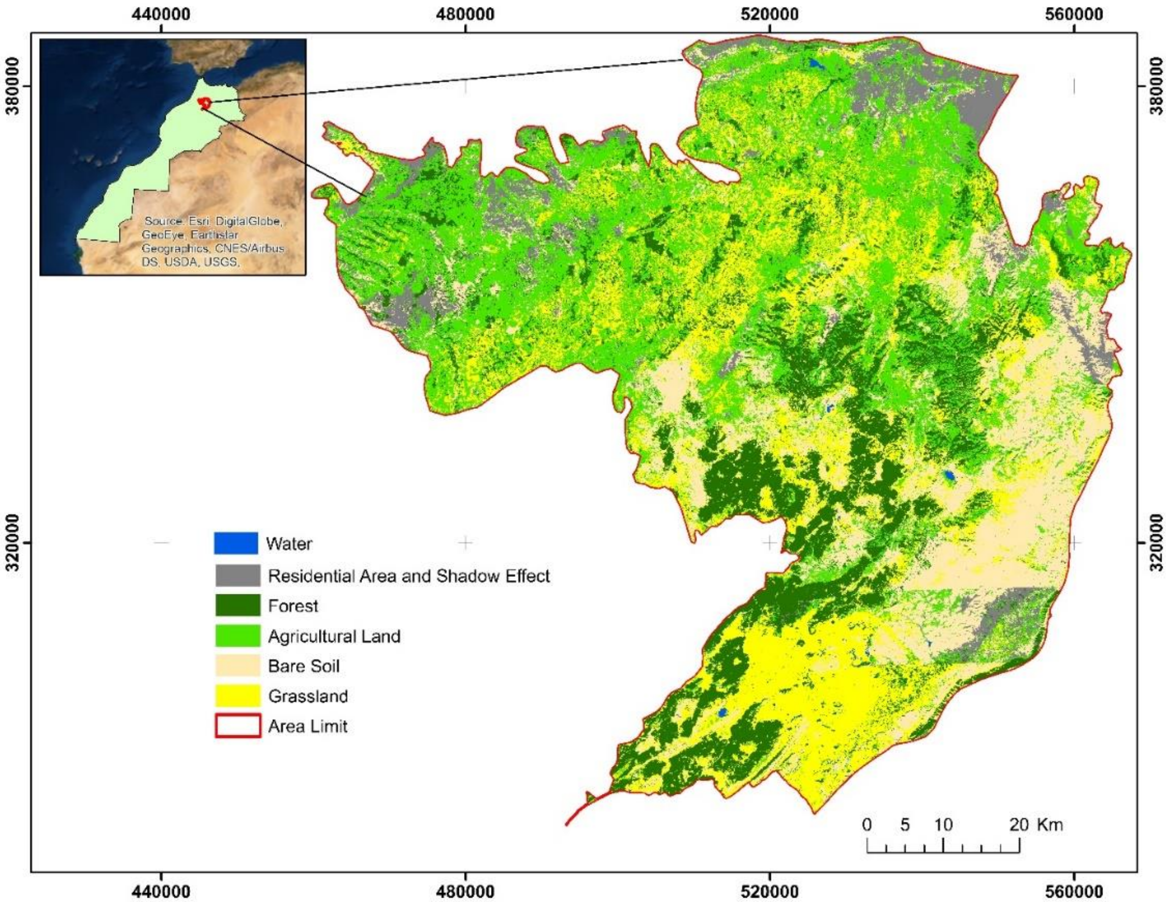

Figure 1. Land use in the study area (Kanga et al., 2019a)

Conceptualization of the Framework

The assessment of water resources vulnerability in this area was based on a participatory approach. The conceptual framework of the assessment involved water sector stakeholders through surveys on the water resources vulnerability factors. This survey was based on the following definition of water resources vulnerability: "the vulnerability of the water resources system represents the degree of fragility or susceptibility with which human activities and natural factors affect water quality and quantity while taking into account society's ability to address these threats to the system in a sustainable way". Figure 2 shows the process for assessing the vulnerability of water resources in the area of interest. The assessment was based on two important steps: the collection and selection of water resources vulnerability factors and the calculation of the final water resources vulnerability index.

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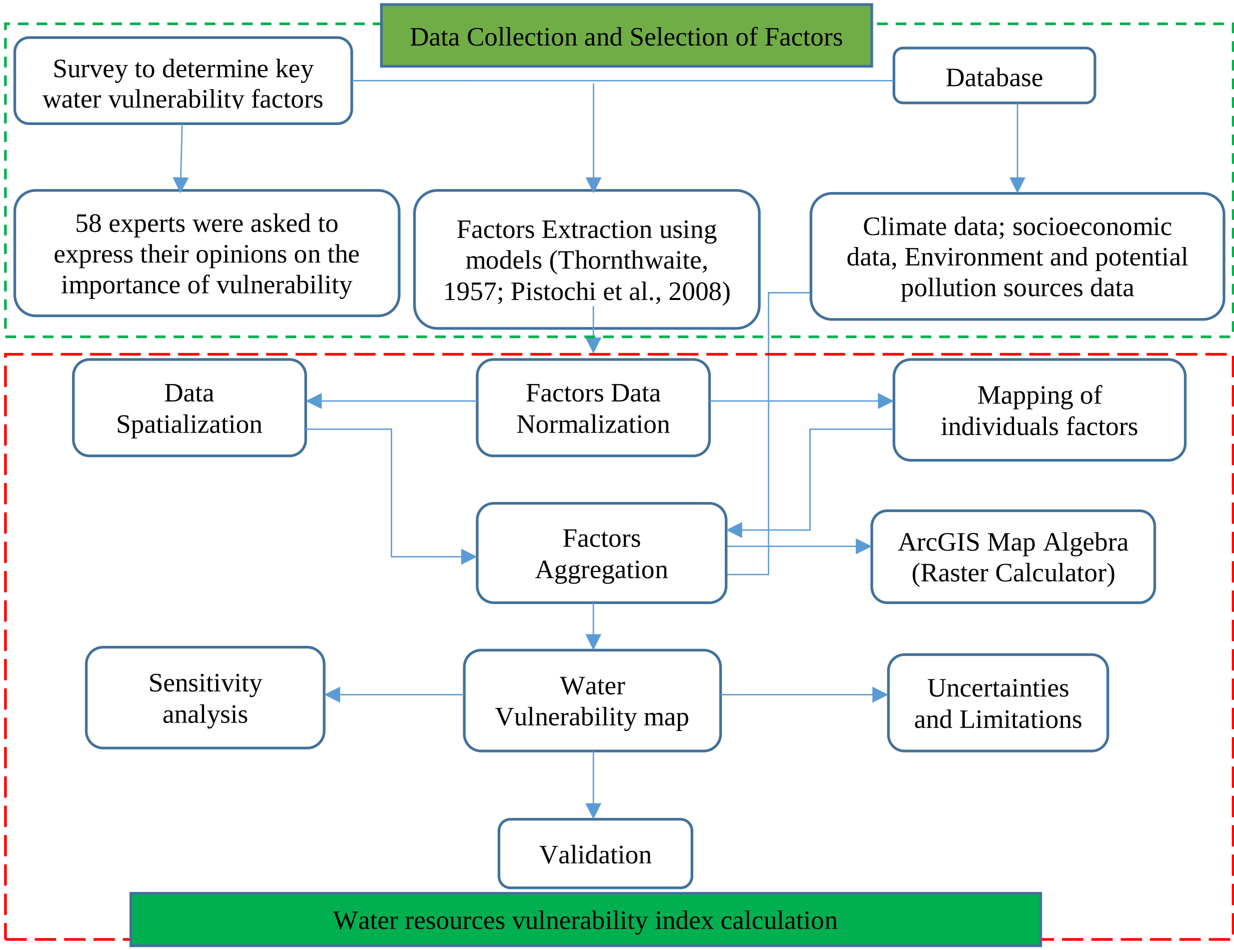

Figure 2. Conceptual framework of the water resources vulnerability assessment

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Selection of Factors and Data Collection

A total of 58 water resources management experts were asked to express their views on 25 factors categorized into five (5) components: Hydrological, Environmental physics, Socio-economic, Potential sources of pollution, and Eco-environment. Only 32 experts answered the questionnaire by distributing 200 points over 25 factors according to the relative importance of each water vulnerability factor. The survey sheets do not include the expert's surname, first name or function or the expert's affiliation, but consequently they are anonymous. After distributing the sheet to the expert, he has the right to fill it in or return it. Roughly 55 % completed the survey voluntarily. The collected data is then processed by applying multiple factor analysis to reduce dimensions under the FactoMine R software. Out of the 25 factors, 15 factors of vulnerability of water resources were well represented on the selected dimensions. However, due to the unavailability of data, only 13 factors were considered in this study. This survey and all the 25 factors are well-explained in Kanga et al. (2019c). Table 1 shows the different factors used to assess the vulnerability of water resources in the area of interest. Indeed, some factors can be collected directly from water bodies, while hydrological factors can be extracted by the Thornthwaite and Mather (1957) water balance model. The groundwater recharge factor was estimated by the model of Pistoschi et al. (2008) which poses:

$$R = P - Ro - AET \tag{1}$$

Where R, groundwater recharge; P, Precipitation; Ro, is the quantity of rainfall that runoff, and AET, is the actual evapotranspiration.

Socio-economic, eco-environmental, potential sources of pollution, and environmental data were collected from several sources, including the Moroccan high commission for the plan (HCP), the Secretariat of State for water, the Sebou Hydraulic Basin Agency (ABHS), National Institute of Agricultural Research (INRA), and the Division of Statistics of the Ministry of Agriculture, Fisheries, Rural Development, etc. (MAPM). Table 1 presents the data and models used to extract some factors.

Table 1. Data and models used to extract some factors

Component	Data set	Model	Source	Date	Scale
Hydrology	Precipitation (mm)	-	MAPMDREF[a]-Division of Statistics	1989-2018	Provincial
	Relative Annual Variability of Precipitation (mean/standard deviation)	-	MAPMDREF-Division of Statistics	1989-2018	Provincial

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	Temperature (Degree Celsius)	-	MAPMDREF-Division of Statistics	1989-2018	Provincial
	Evapotranspiration (mm)	Thornthwaite and Mather (1957)	Precipitation and temperature	1989-2018	Depending on land use/cover and soil type
	Actual Evapotranspiration (mm)	Thornthwaite and Mather (1957)	Precipitation and temperature	1989-2018	Depending on land use/cover and soil type
	Runoff (mm)	Thornthwaite and Mather (1957)	Precipitation and temperature and occupation map	1989-2018	Depending on land use/cover and soil type
	Groundwater recharge	Pistocchi et al. (2008)	Precipitation and temperature and occupation map	1989-2018	Depending on land use/cover and soil type
Biophysical Environment	Digital elevation model	-	https://geograchid.blogspot.com/	-	National (30 m x 30 m)
	Land use/cover map	Supervised classification	Area satellite image (Sentinel A2)	2018	Satellite (10 m x10 m)
	Soil texture map	Digitized from soil map (1/50 000)	National Institute of Agricultural Research (INRA)	1988	1/50 000
	Soil Water Retention Capacity (mm)	Thornthwaite and Mather (1957)	MAPMDREF-Division of Statistics	1989-2018	Depending on land use/cover and soil type
Socio-economic	Population Density (number per Km^2)	-	High commission for the plan (HCP)	2014	Communal
	Water Withdrawal for Industrial, Agricultural and Domestic Activities (ratio)	-	Sebou Hydraulic Basin Agency (ABHS)	2013-2018	Provincial
	Multidimensional Poverty Rate (%)	-	High Commission for the plan (HCP)	2014	Communal
	Percentage of Access to Tap Water (%)	-	High Commission for the plan (HCP)	2014	Communal
Potential pollution sources	Wastewater Evacuation by Septic Tank (%)	-	High Commission for the Plan (HCP)	2014	Communal

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	Percentage of the Population with Access to the Toilet (%)	-	High Commission for the plan (HCP)	2014	Communal
Eco-environment	Irrigated Area (%)	-	Sebou Hydraulic Basin Agency	2018	Communal

[a]MAPMDREF : Ministère de l'Agriculture, de la Pêche Maritime, du Développement Rural, des Eaux et Forêts.

Water Resources Vulnerability Index Calculation

The most common steps in water resources vulnerability assessment, specifically in a holistic way, are the selection of factors, weighting of factors, data normalization, and aggregation of factors into a composite vulnerability index. The assessment of the vulnerability of water resources is known as relative and subjective due, precisely, to certain steps in the assessment such as the choice of factors and their weightings. The identification of factors in this study was based on the weight assigned by experts to the different factors. To reduce the subjective of the vulnerability assessment, the relative weights of the factors resulting from the experts' judgement during the survey were not taken into account; these weights were used only to choose the most important factors regarding the water resources issue in the study area. For this reason, only three steps were considered in this evaluation: factor selection, data normalization, and aggregation of normalized values into a composite index. The data collected on the selected vulnerability factors were normalized, i.e., transformed between 0 and 1 to make them dimensionless, with the exception of factors with percentage values. In the literature, there are several methods for standardizing data. OECD (Organization for Economic Co-Operation and Development) (2008) reported some methods of normalizing values, which normalize between (-1) and (1), or between (0) and (1): Standardization at a point z, distance from a reference, logarithmic transformation, percentage of the mean, max-min operation, etc. In this case study, the method proposed by Aksoy and Haralich (2000) was used to normalize the values of all vulnerability factors.

$$X_{0-1} = \frac{\frac{x-\mu}{3\sigma}+1}{2} \tag{2}$$

Here X_{0-1} is the normalized value of the factor between 0 and 1; x, the dimensional value of the factor; μ, the mean of the series of values related to this factor; σ, the standard deviation of the series of values. Once the factor

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data transformed into values between (0) and (1), the normalization also takes into account the meaning of the factor with respect to the final classification of water resource vulnerability. This entails defining in advance a meaning for the composite index of final vulnerability, which, in this case of study, ranges from 0 (highly vulnerable) to 1 (Non vulnerable). To allow for the final classification of the composite vulnerability index, factors and their trends have been defined in terms of water vulnerability. Table 2 summarizes the factors, their definitions, and trends with regard to the water resource vulnerability.

Table 2. Definition of factors and their trends with regard to the vulnerability of water resources

Nb.[a]	Factors	Definition	Trend
1	Relative Annual Variability of Precipitation (mean/standard deviation) (RAVP)	Measures the stability of the system in terms of water supply by precipitation (RAVP= mean/standard deviation)	Higher value reflects a higher vulnerability due to instability of water system.
2	Groundwater recharge (mm)	Represents the amount of water reaching the groundwater table.	Higher value represents a lower vulnerability due to the important availability of water.
3	Soil Water Retention Capacity (mm)	Measures the potential ability of the soil thickness to retain water.	Higher value reflects a lower vulnerability due to the potential water retention capacity.
4	Runoff (mm)	Represents the amount of water flowing to surface water reservoirs (rivers, lakes, rivers, etc.)	Higher value reflects a lower vulnerability due to the availability of the surface water quantity.
5	Percentage of Access to Tap Water (%)	Represents the proportion of the population with access to drinking water, measures the sensitivity of the water supply system to the population.	A greater value represents a lower vulnerability.
6	Percentage of the Population with Access to the Toilet (%)	Measures potential pollution by faeces.	A higher value reflects a lower vulnerability due to the reduction of potential pollution of fecal coliform.
7	Population Density (number per Km^2)	Represents the number of inhabitants per unit area, measures the sensitivity of the water system to the water demand.	A higher value reflects a higher vulnerability due to the important water demand.
8	Water Withdrawal for Industrial, Agricultural and Domestic Activities (ratio)	Represents the amount of water removed from sources for agricultural, industrial and domestic activities. It measures the sensitivity of the system.	A higher value reflects a higher vulnerability due to the excessive water demand.
9	Wastewater Evacuation by Septic Tank (%)	Represents the proportion of wastewater discharged by septic tank, measures the control of potential water pollution.	A higher value represents a lower vulnerability due to the reduction of potentials pollution.
10	Illiteracy Rate (%)	Represents the proportion of the population unable to read and write, measures adaptive capacity, and the ability to cope with a water issue.	A higher value reflects a higher vulnerability.

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11	Irrigated Area (%)	Measures the share of land dependent on irrigation.	A higher value reflects a higher vulnerability due to the higher water demand.
12	Multidimensional Poverty Rate (%)	Measures the financial capacity, economic health of the population, and measures the adaptive capacity of the water system.	A higher value represents a higher vulnerability.
13	Topography	Controls runoff and water infiltration underground. In the high level of slope, water will runoff on low slopes and be stagnating or recharging.	A higher value reflects a higher vulnerability.

[a]Number

The values of each vulnerability factor have been classified into 5 degrees of vulnerabilities: 1. highly vulnerable, 2. moderately vulnerable, 3. threshold, 4. less vulnerable, and 5. non vulnerable. This classification of water resource vulnerability factors was based on literature for some factors following similar studies and on statistical distribution of values for other factors with the "histogram" option, which distributes the values in number of classes of choice (XLStat 2016). Table 3 presents the classification for each water resource vulnerability factor.

Table 3. Classification of vulnerability factors for water resources

Nb.[a]	Factors	Highly vulnerable	Moderately vulnerable	Threshold	Less vulnerable	Non vulnerable	Reference
1	Relative Annual Variability of Precipitation (standard deviation/ mean)	< 0.5	0.49–0.3	0.29–0.20	0.19–0.1	0.09–0	Alessa et al. (2008)
2	Groundwater recharge (mm)	0–5	0–25	25–100	100–250	>250	GIZ (2014)
	Normalized	0–0.15	0.15–0.27	0.27–0.38	0.38–0.56	>0.56	
3	Soil Water Retention Capacity (mm)	<102	102–204	204–306	306–408	>408	Statistical distribution
	Normalized	<0.27	0.27–0.30	0.30–0.38	0.38–0.59	>0.59	
4	Runoff (mm)	<33	33–83	83–166	166–250	>250	GIZ (2014)
	Normalized	0-0.13	0.13–0.26	0.26–0.48	0.48–0.70	>0.70	
5	Percentage of Access to Tap Water (%)	0 –20	20–40	40–60	60–80	>80	Statistical distribution
6	Percentage of the Population with Access to the Toilet (%)	0–36	36–52	52–68	68–85	>85	Statistical distribution
7	Population Density (number per Km^2)	>1000	1000–500	500–100	100–10	10–0	GIZ (2014)
	Normalized	>0.76	0.76–0.64	0.64–0.52	0.52–0.4	0.4–0	
8	Water Withdrawal for Industrial, Agricultural and Domestic Activities (ratio)	<0.5	0.5–0.2	0.2–0.15	0.15–0.1	0.1–0	Rakin et al. (1997)

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9	Wastewater Evacuation by Septic Tank (%)	0–20	20–39	39–59	59–79	>79	Statistical distribution
10	Illiteracy Rate (%)	0–11	11–22	22–33	33–44	>44	Statistical distribution
11	Irrigated Area (%)	>75	75–61	61–48	48–34	34–0	Statistical distribution
12	Multidimensional Poverty Rate (%)	>43	43–32	32–21	21–11	11–0	Statistical distribution
13	Topography (%)	<50	50–30	30–20	20–10	10–0	Statistical distribution

[a]Number

The final water resources vulnerability index was calculated by aggregating all the relative vulnerabilities of each factor under "ArcGIS 10.2.1, Map Algebra, Raster Calculator" tool. Geographic information systems (GIS) allow for assembling the criteria considered and aggregates a number of geoprocessing and spatial analysis (Rahman et al., 2008). The formula for aggregating the relative vulnerabilities of the factors is as follows:

$$WREVI = \prod_{i=1}^{n} (V_i)^{\frac{1}{n}} \tag{3}$$

With V_i, the vulnerability of water resources relative to the i^th factor and *n* the number of factors considered in the water resources vulnerability assessment; *WREVI*, the final water resources vulnerability index with values between 0 and 1, respectively "High vulnerable" and "Non vulnerable".

A sensitivity analysis was carried out to determine the contribution and the variation in the vulnerability of water resources at the spatial scale through the map removal sensitivity analysis. Many scientists (Pacheco et al., 2018; Neh et al., 2015; Hasan et al., 2019; Knouz et al., 2016) believe that models such as DRASTIC do not require the use of all parameters and sure enough, there are parameters that do not have significant contribution to the overall vulnerability. The sensitivity analysis index is formulated as follows:

$$S = \left[\frac{\left(\left| \frac{V}{n} - \frac{V'}{n'} \right| \right)}{V} \right] \times 100 \tag{4}$$

Here, S is the sensitivity measure expressed in terms of variation; V and V' are respectively the “undisrupted” and “disrupted” vulnerability index; n and n' are the number of factor layers used to calculate V and V' respectively. The undisrupted water vulnerability index is obtained by using all factors; the

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disrupted water vulnerability index was computed using a limited number of water vulnerability factors.

To validate the final map of water resource vulnerability in the area, Kappa index (Cohen, 1960) was estimated among water quality classes. The analysis of piezometric levels in vulnerable spots was used to validate the final water resource vulnerability map.

Result and Discussion

According to Adger (2006), the concept of vulnerability is complex and difficult to quantify; and he added that for decades, researchers have struggled to define metric factors to estimate vulnerability. It is now clear that there is not a set of water resources vulnerability factors that can be considered for all cases because the perception and the conceptualization of vulnerability depend on the problem encountered in the study area as well as the methodological approach in line with the objective pursued. In this case, as a reminder, 13 factors (Table 4) of 3 to 4 components were aggregated to assess the vulnerability of water resources and produce an overall water resources vulnerability map of the area of interest.

Water Resources Vulnerability Map by Factor

Once water factors vulnerability data are been normalized using equation 2, they are then integrated into ArcGIS to be spatialized. The vulnerability of water resources of each factor was mapped and categorized into 5 classes using ArcGIS quantile classification. After then, it is aggregated into a single vulnerability map by the raster calculator (ArcGIS) using equation 4. Figure 3a to 3m shows the water resource vulnerability map for each factor.

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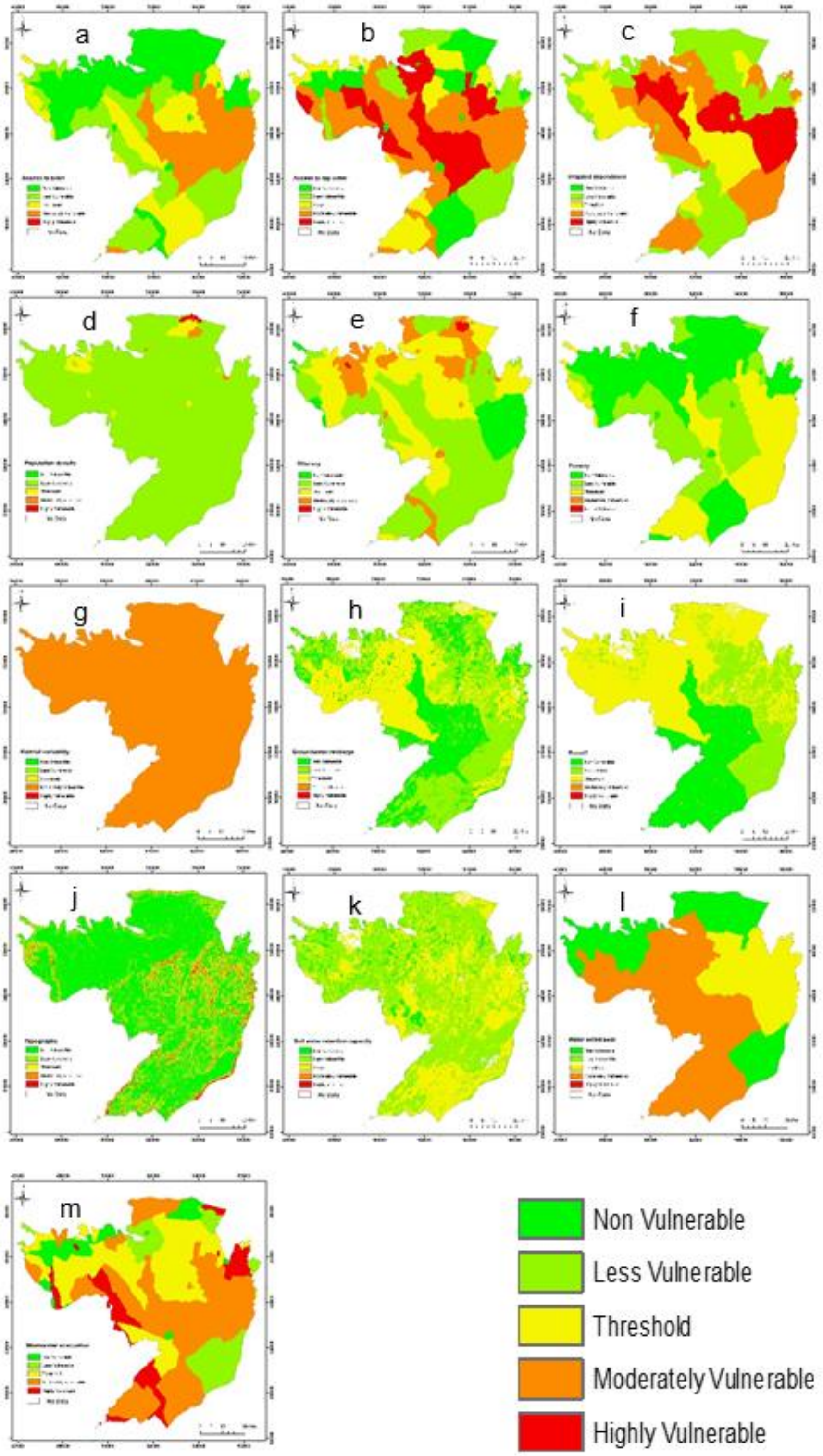

Figure 3. Water resources vulnerability map by factor

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Percentage of Population with Access to Toilets (Figure 3a)

This factor indicates the number of people with access to toilets. In another way, it indicates the proportion of population without access to basic sanitation facilities that prevent human excrement from coming into contact with water resources (Cai et al., 2016). The trend of this factor is that the higher the population's access rate, the less vulnerable the water resources are. This factor makes it possible to measure the potential pollution of water resources by fecal coliforms and waterborne diseases such as cholera, dysentery, diarrhea, etc. According to WHO and UNICEF (World Health Organization and United Nations Children’s Fund) (2017), the proportion of the world's population with access to sanitation facilities is 68% in 2015. The result shows that most of the Fés, Meknès, and Ifrane perimeters are considered as the "threshold" to "non-vulnerable". A small part south of the study area, in the commune of Oued Ifrane, from the East to the center of the communes of Tizguit, Dayet Ifrah, Laanoussar are considered moderately vulnerable.

Percentage of Access to Drinking Water (Figure 3b)

This factor represents the proportion of population with access to drinking water. It measures the sensitivity of the water supply system to the population. This factor is a demand indicator that measures water use efficiency (Winograd et al., 1989). Cai et al. (2016) stipulated that this indicator was developed to determine the adaptive capacity of water managers and how available technologies influence the withdrawal of water resources. According to WHO and UNICEF (2017), 71% of the world's population has access to safe drinking water. In Morocco, the percentage of access to drinking water is much higher, ranging from 76% to 90% at the national level (WHO and UNICEF, 2017). For this factor, a high value means a low vulnerability of water resources. Almost half of the study area is considered moderately to highly vulnerable. The remaining parts in the southeast, the north, and the northeast vary from the “threshold” to "non-vulnerable".

Irrigation Dependency (Figure 3c)

This factor indicates the share of land that depends on irrigation. Although irrigation is a water-saving activity, it remains a water resource extraction. In areas with intensive agriculture, irrigation can be one of the main sectors of water consumption. According to FAO data and the World Bank development indicators, the percentage of irrigated land in Morocco in 2011 is reported at 4.06 %. However, the perimeters of Fés, Ifrane, and Meknès represent an agricultural zone where cereals, legumes, and fodder are grown. Irrigation is therefore present in some parts of the perimeter throughout the year, except during winter. A high value of this factor indicates high

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vulnerability. Therefore, much of the study area is moderately to highly vulnerable towards the North and the East.

Population Density (Figure 3d)

Represents the number of inhabitants per unit area, measures the sensitivity of the water system to the water demand. Several researchers (Gain et al., 2012; Sullivan, 2011; Pandey et al., 2010; Wu et al., 2013) reported that population growth is one of the main causes of water resource disruptions. Indeed, when population increases, the demand for water for vital needs increases. With regard to the classification adopted, the study area is considered as "less vulnerable" with the exception of few small areas in the North, namely Fez medina considered as "highly vulnerable". Other municipalities such as Saiss and Sefrou present as "moderately vulnerable".

Illiteracy Rate (Figure 3e)

Represents the proportion of population unable to read and write. It measures adaptive capacity to cope with water issue. Illiteracy is the opposite of education, which gives the ability to analyze data (Alessa et al., 2008) and thus open up other knowledge to deal with water problems. When the illiteracy rate is high, the vulnerability of water resources increases. For this factor, most of the study area is depicted as being at the "threshold" to "non-vulnerable". However, in the northern part there are areas such as the municipalities of Al Machaour-Stinia, Sabaa Aiyoun, and Majjate which are considered as "Moderately vulnerable". Other areas in the North near the city of Fés such as the municipalities of Sais, Ain Cheggag, and Oulad Tayeb present themselves as "moderately vulnerable". In the south of the area of interest, the commune of Sidi El Makhfi is considered as "moderately vulnerable".

Multidimensional Poverty Rate (Figure 3f)

It measures the financial capacity, economic health of the population, and the adaptive capacity of the water system. For Gain et al. (2012), it measures the economic health of the population and its ability to cope with water problems. The link between environmental degradation and poverty rates has been highlighted by Satterthwaite (2003), who stated that urban poverty has an impact on environmental degradation in Africa, Asia, and Latin America. When the poverty rate is high, the vulnerability of water resources increases. Within this perimeter, the entire population lives above the poverty line. Therefore, water resources are considered from "threshold" to "non-vulnerable". Sullivan (2011) reported that the vulnerability of water resources in some South African municipalities is due to poverty.

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Rainfall Variability (Figure 3g)

All over the world, the main natural supply of water resources remains precipitation. When rainfall varies considerably in an area, the water system is affected because of this variability. The relative annual variability of precipitation measures the stability of the system in terms of water supply by precipitation. When the coefficient of variation is high, the water resources system can be very vulnerable. Within this perimeter, this coefficient was estimated with monthly rainfall from 1988 to 2018. According to Rakin's classification (1997), the water resource system is presented as "moderately vulnerable" due to the large variation in rainfall.

Groundwater Recharge (Figure 3h)

This factor represents the amount of water reaching groundwater or that infiltrates the subsoil. Groundwater recharge is one of the most important factors since the supply of drinking water and industries in urban and rural areas is provided by aquifers. When the recharge is important, water resources are less vulnerable. This perimeter has good potential for groundwater recharge due to precipitation and soil types (mostly clayey), and to its land use, which is mainly forested in the extreme South of the study area. The vulnerability of water resources related to recharge varies from "Threshold" to "non-vulnerable".

Annual Runoff (Figure 3i)

It represents the amount of water flowing to surface water reservoirs (rivers, lakes, etc.). Just as groundwater recharge, after precipitation, the amount of water that does not infiltrate the subsoil will run off depending on the biophysical characteristics such as soil type, land use and topography. When the amount of water flowing to water bodies is large, the vulnerability of water resources in relation to runoff is low. The result shows that water resource vulnerability varies from "non-vulnerable" in the extreme South of the study area and the center, to "less vulnerable" in the extreme East and “Threshold” in the extreme North.

Topography (Figure 3j)

Topography refers to the slope. Control the runoff and water infiltration underground. During precipitation, when water does not immediately infiltrate the ground, it flows to slight slopes to stagnate or infiltrate. Rahman (2008) states that areas with low slope tend to retain water for a longer period time, while water flows from steep slopes to low slopes. Within this study area, there is a significant variation in topography. From South to Southeast, the slopes are steep and do not favor local infiltration.

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Soil Water Retention Capacity (Figure 3k)

This factor measures the potential ability of the soil thickness to retain water. The potential capacity to retain soil water depends on the type of soil and land occupation. An area with clayey or silty soils and forest vegetation would retain much more water than other types and land uses. In the study area, the vulnerability of water resources related to the potential capacity to retain soil water varies from "threshold" to "non-vulnerable".

Water Withdrawal for Industrial, Agricultural and Domestic Activities (Figure 3l)

Represents the amount of water removed from sources for agricultural, industrial, and domestic activities. It measures the amount of water demand (Wu et al., 2013; Sullivan, 2011). In this area, the overexploitation of water resources is increasingly being felt. Agricultural intensification and industrial development are becoming increasingly important. The provinces of El Hajeb and Ifrane are considered as "moderately vulnerable". The rest of the study area ranges from "threshold" to "non-vulnerable".

Wastewater Evacuation by Septic Tank (Figure 3m)

Represents the proportion of wastewater discharged by septic tank, measures the control of potential water pollution. The evacuation of wastewater by septic tank allows to control the wastewater and to avoid a potential mixing with the drinking water. For this factor, nearly 50% of the study area has a low evacuation rate, which means that water resources are highly vulnerable. The vulnerability of water resources related to this factor varies from "highly vulnerable" in the south of the study area to "moderately vulnerable" towards the center of the study area. The rest of the perimeter varies from "threshold" to "non-vulnerable".

Overall Water Resources Vulnerability Map

The complexity of the water resources system makes vulnerability assessment a difficult task to undertake because of the complex interactions between the factors that influence vulnerability. To have an overview of water resources vulnerability, aggregate several factors of different dimensions, such as socio-economic, hydrological, pollution, eco-environmental, must be the simple way to undertake the assessment. This aggregation makes it possible to analyze the interaction of all factors in the study area using ArcGIS precisely and Raster Calculator, which studies the interactions between factors pixel-by-pixel. Figure 4 shows the result of aggregating the 13 factors into a final water resource vulnerability map. The overall vulnerability map shows that the degree of vulnerability of water resources in most of the study area is considered to be at the "threshold" to “non-vulnerable”. However, 3 mains

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areas stand out and range from "moderately vulnerable" to “highly vulnerable”. Zone 1 includes Lawija, Boufekrane, Ait Bourzouine in the northern part of the study area, from the South of the city of Meknes to the city of El Hajeb, where the degree of vulnerability of water resources from the “threshold” to “moderately vulnerable” is located forming an extension cluster with some points of "highly vulnerable". These small areas considered as “highly vulnerable” are present throughout the entire study area. Zone 2 in the northern part of the study area, spans from the West of the city of Fez to the areas of Sebaa Rouadi, Laqsir, and Ras El Ma, Bitit and Ain Chegag, as well as Oulad Tayed, where the degree of vulnerability of water resources varies from “moderately vulnerable” to "highly vulnerable". Zone 3 is within the commune of Dayet Ifrah towards the center-South. Although the area is forested with good hydrological potential, the degree of vulnerability of water resources varies from “moderately vulnerable” to “very vulnerable”. In addition to these three zones, a perimeter located in the commune of Oued Ifrane (O.Ifrane munic in Figure 4) to the South of the study area and the degree of vulnerability of water resources has been shown to be "highly vulnerable" although forested with significant hydrological potential. In the northeast of the city of Guigou, there are a few small areas where the degree of vulnerability of water resources is considered as “highly vulnerable”.

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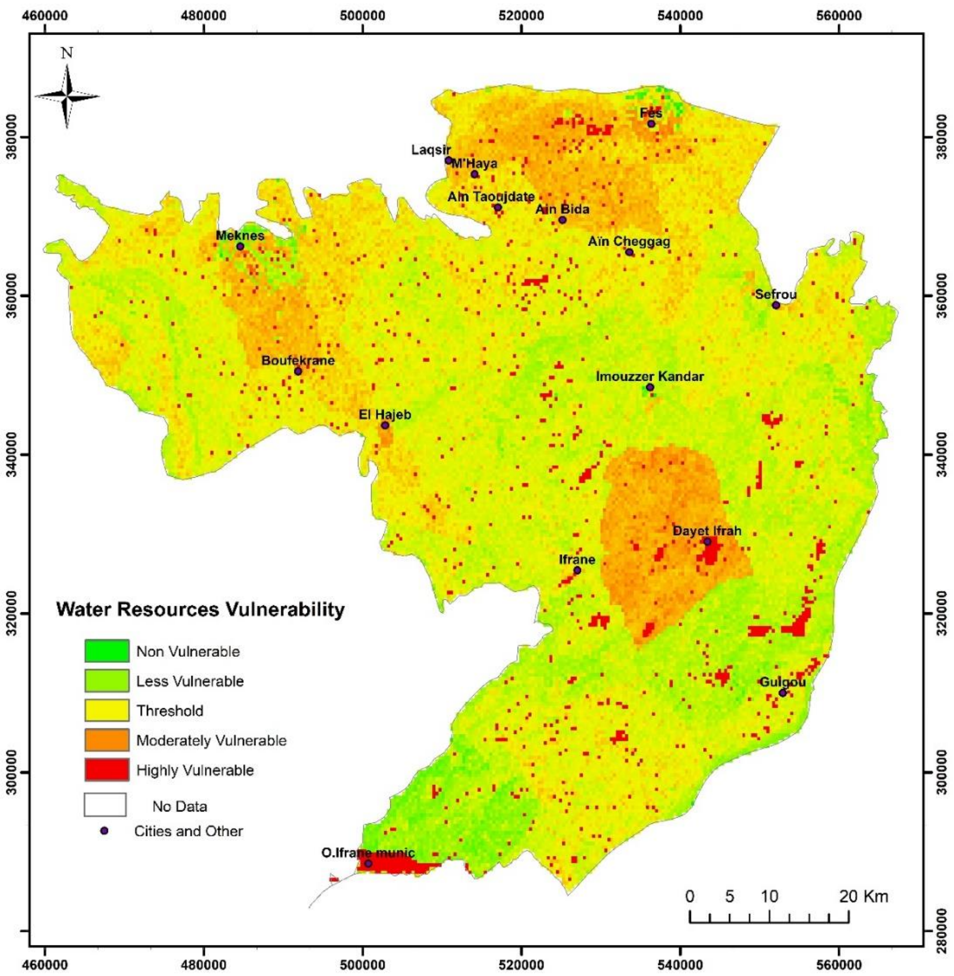

Figure 4. Overall water resources vulnerability map.

Sensitivity Analysis

A removal map sensitivity analysis was carried out to identify the factors that have the greatest contribution on the overall water resource vulnerability map. Each of the 13 factors was removed to assess its impact on the overall water resources vulnerability map by applying Equation 4. Table 4 presents the test result with the average sensitivity index for each vulnerability factor.

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Table 4. Descriptive statistics of the removal map sensitivity test

Vulnerability Factors	Mean	Max.	Min.	SD	CV (%)
Access to tap water	**0.75**	4.50	0.00	0.95	100
Access to the toilet	0.19	0.60	0.00	0.12	63
Rainfall variation	0.61	1.03	0.19	0.10	16
Illiteracy	0.61	1.20	0.11	0.20	33
Water withdrawal	**1.08**	2.51	0.13	0.53	49
Wastewater evacuation	0.54	3.86	0.00	0.32	59
Irrigated land	0.32	1.68	0.00	0.23	72
Population density	**0.64**	7.7	0.00	0.92	100
Poverty	**1.32**	8.73	0.00	0.93	70
Topography	**1.73**	4.05	0.00	0.70	40
Runoff	033	0.81	0.00	0.18	54
Groundwater recharge	0.36	1.45	0.00	0.21	58
Soil water retention capacity	0.30	3.09	0.00	0.23	76

The analysis of Table 4 shows that the "topography" factor showed the greatest impact on the final water resources vulnerability map since its influence on the removal of this factor was the highest and is 1.73. This is followed by the poverty factor with a sensitivity index of 1.32, the water withdrawal factor with a sensitivity index of 1.08, and finally the "access to tap water" and "population density" factors with sensitivity indices of 0.75 and 0.64 respectively. The topography controls two of the hydrological factors, namely “runoff” and “groundwater recharge”. The multidimensional poverty rate is a factor that influences many of the socio-economic factors directly or indirectly, namely the illiteracy rate, access to toilets, access to tap water, and even irrigation rate. Population density is also one of the most important factors, since it is what partly determines the demand for and use of water through abstraction for agricultural, domestic, and industrial activities. The observation of the coefficients of variation of the "access to tap water" and "population density" factors shows that they contribute significantly to the variation of the overall water resources vulnerability map with 100% each. The factors "irrigated land", "soil water retention capacity", and "access to the toilet" also contribute significantly to the variation in the overall map of water resource vulnerabilities with 76% and 63% respectively. Modest contributions to the variation of the final map are found in the factors of "groundwater recharge", "waste water evacuation", and "runoff" with 58%, 59%, and 54% respectively. The aggregation of the 5 factors (topography, poverty, water withdrawal, access to tap water and population density) that have the most significant impacts on the overall water resources vulnerability map shows that there is no much difference with the final map made with the 13 factors. Figure 5 shows the map produced with the 5 factors with the greatest impacts on the final map.

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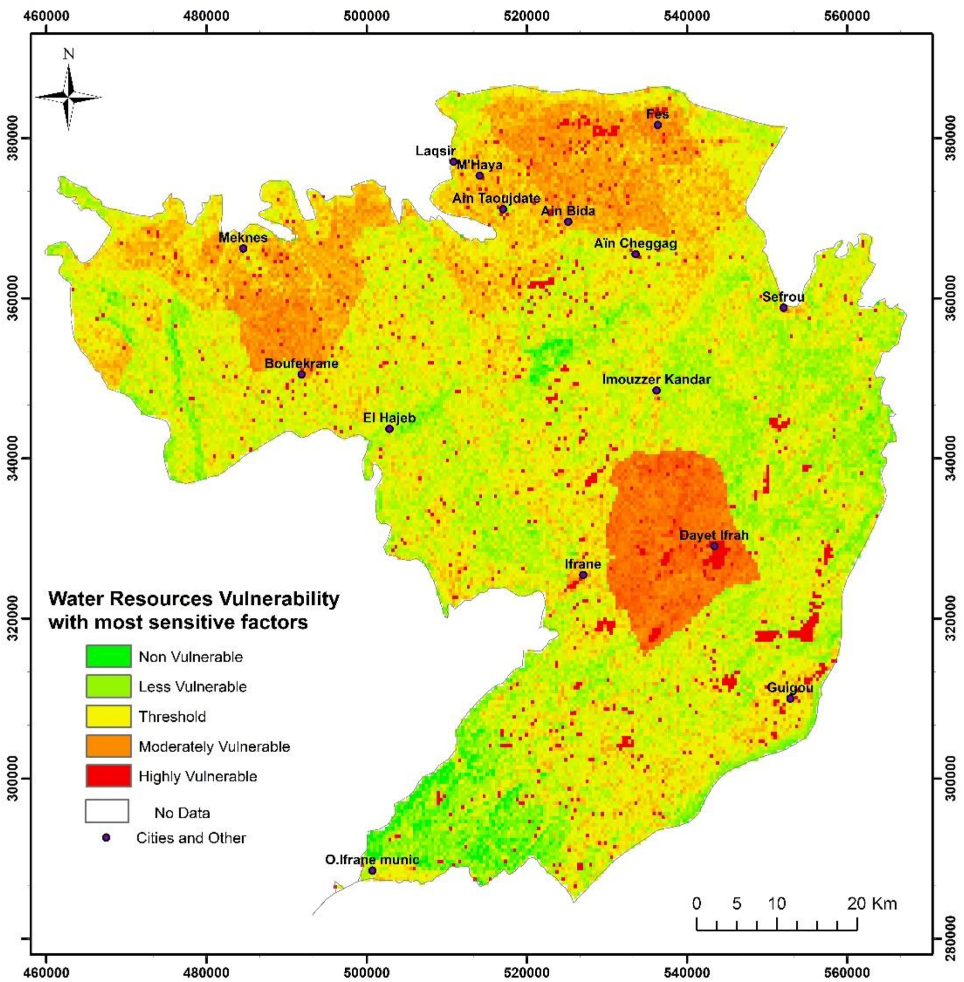

Figure 5. Water resources vulnerability with most sensitive factors

The vulnerability of zones 1 and 2 is mainly due to the interaction between the five factors below. The vulnerability of zone 3 is mainly due to the "access to tap water" and "water withdrawal" because the removal of these two maps has made these "moderately vulnerable" zones disappear. The removal of the "waste water evacuation" factor has also caused the "highly vulnerable" area in the southern part of the study area in the commune of Oued Ifrane to disappear. The removal of the "topography" factor removed the clusters of "highly vulnerable" present throughout the study area.

Validation

It is very difficult to validate a model based on an aggregation of several factors of different dimensions such as socio-economic, hydrological, potential sources of pollution, eco-environmental, etc. in this case. Several

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researchers who have assessed the vulnerability of water resources in an integrated way have not been able to present validation modules for their models, such as Plummer et al. (2013), Sullivan (2011), Gain et al. (2012), Alessa et al. (2008), Xia et al. (2012), and Pandey et al. (2010). On the other hand, Wu et al. (2013), whose integrated water resources vulnerability assessment model was based on a simulation, validated their result with observation data from 4 of the factors they considered important for their model. Moreover, some researchers (Hasan et al., 2019; Pacheco et al., 2018) who used the DRASTIC method to assess the vulnerability of water resources to pollution assumed that the observation of one or more physical and chemical water parameters would validate the final vulnerability map. The hypothesis of this research is that the vulnerability of water resources, i.e., the vulnerability related to the quantity and quality of groundwater and surface water in this area, could be assessed based on data from environmental components. Thus, to validate the final water resources vulnerability map in the study area, water resources quality data from 1988 to 2018 from 29 stations (Kanga et al., 2019a) were used. The analysis of piezometric data in vulnerable areas was used to validate the final water resource vulnerability map. The piezometric stations in zones 1 and 2 showed a significant decrease in the piezometric level from 1m in the 1970s to 60m in 2015. In zone 3 (the Dayet Ifrah zone), the course of the piezometric level of 3 boreholes from 1992 to 2008 showed a clear decrease in the water level, the most notable decrease being from 2.5 m to 14.4 m deep. In addition to the decrease in the piezometric level of the area, Dayets Aoua (localized in Zone 3) have experienced several dry spells in recent years, the most recent being on August 2019. The 30-year data from 29 water quality monitoring stations, including 3 surface water stations and 26 groundwater stations, were analyzed and classified into 5 classes: very poor, poor, medium, good, and excellent. A matrix of confusion was carried out between the 5 water quality classes and the 5 classes of the overall water resources vulnerability map. The resulting Kappa index (Cohen, 1960) is 0.26, which, according to Cohen's classification, is considered a poor agreement. However, it is difficult to draw a conclusion with only 29 stations. It is clear that increasing the number of stations will improve this agreement.

Uncertainties

The integrated water resources vulnerability assessment process inevitably contains some uncertainty. For example, the selection of vulnerability factors for water resources are based on a participatory approach involving water resource managers through a survey. Survey methods for data collection are subjective because of the subjective judgments of experts. In addition, the normalization method used is strongly related to the standard deviation of the data distribution. A large or small value could influence the

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normalized values of the different factors. The classification of hydrological factors comes from the bibliography and from the statistical distribution of data. The classification of socio-economic factors is mainly based on the statistical distribution of factor data. The existence of reliable data sources, and a classification of factors based on Moroccan legislation, can improve the reliability of the final water resources vulnerability map. It should also be noted that the lack of data on certain vulnerability factors has limited their use, and the secondary sources of data has been used for certain socioeconomic factors.

Conclusion

Integrated water resources assessment at the local level is increasingly being used. Indeed, water quality problems often associated with water stress should not be analyzed separately since these problems are induced by human activities generally, and rarely by natural factors. The result of this research makes it possible to refine water resources management policies in this area by influencing, not only the biophysical factors but also by investing in education, poverty reduction, and improving access to water for the population and sanitation in towns and villages. The method used to assess the vulnerability of water resources in this area is probably relative since the addition of other water resources vulnerability factors could give a different result with different areas of vulnerability. However, for the time being and with these 13 factors in mind (which may be reduced in 5), this result could be the closest state to the reality of the pressures on the water resources system in this area. This study could help integrated water resources management planners to take action to improve the overall state of water quantity and quality in the area. This research is not only assessed for the current water vulnerability using historical data, but would also provide information on the future state of water resources by creating scenarios that vary factors over time. Although this multi-dimensional assessment of the vulnerability of water resources is applied here at the local scale, its application can be extended to a larger scale like regional, national or cross-country.

Conflict of Interest

The authors declare that they have no conflicts of interest.

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