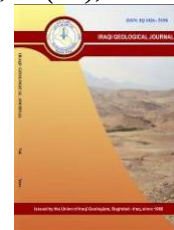




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Mapping of the Vulnerability to Water Contamination of the Kharroub River Dam (Northern Morocco) by Application of the SW Method

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Abstract

Pollution and contamination pose a permanent risk of limiting water resources. Urbanization and economic development contribute to the degradation of water quality. The preservation of this natural resource is a major necessity, especially in arid and semi-arid areas where surface water is very scarce. This work constitutes part of this environmental concern. It aims at mapping the vulnerability to contamination of the surface water of the Kharroub River dam (Morocco) and protecting its water resources. The method applied is the SW (Surface Water) method, which consists in elaborating thematic maps of three parameters: the hydric functioning of soils, the density of the hydrographic network and the importance of agricultural drainage. The realization and superposition of these maps allowed us to obtain the vulnerability map to surface water contamination of the Kharroub river watershed. The results obtained show that the low and medium vulnerability classes, representing 41.91% and 32.49% respectively, occupy most of the study area and are distributed throughout the basin. The areas presenting a high and a very high degree of vulnerability occupy respectively 24.65% and 0.95% of the surface of the watershed; they are located principally in the northern and the southern parts of the basin.

Keywords: Kharroub river dam; Watershed; Surface water; Vulnerability mapping; Contamination; SW method

1. Introduction

Globally, population growth, drought, water scarcity and the water need for important sectors (such as agriculture), as well as climate change, make water management imperative (FAO, 2020; Morgera et al., 2020). The global crisis of climate change is inextricably related to water. Climate change increases the variability of the hydrological cycle and, therefore, causes extreme weather consequences, reduces the availability of water resources, degrades water quality, and threatens, on a global scale, sustainable development, biodiversity and the people's right to safe drinking water and sanitation (UNESCO, 2020). In recent decades in Morocco, water has been characterized by temporal instability, spatial rainfall heterogeneity, and high vulnerability both to climate change and to the damaging effects of human activities (extractions, discharges of pollutants, etc.). In this respect, Morocco has, for a long time, been engaged in an active and dynamic policy to provide the country with important hydraulic infrastructure, improve access to drinking water, satisfy the needs of industry and tourism, and to develop irrigation systems to an important scale (CESE, 2014). For this purpose, Morocco has chosen, since the 1980s, the

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policy of building dams, which are used for irrigation, livestock watering, flood protection and drinking water supply in rural areas which lack groundwater resources (Eddahmouny et al., 2019; El Ghazali et al., 2021).

Improving and preserving the quality of water resources require the implementation of a policy based primarily on precaution measures, taking the environment into account in land use planning policy, and reducing pollution at the source by adopting appropriate methodologies (Bouslihim and Torra, 2020).

Our study is part of this environmental concern. We have developed surface water contamination vulnerability maps for the Kharroub river dam, which is under construction, using the SW method proposed by Grappe (2006). This method has been applied in several Mediterranean watersheds, such as the Martil river watershed and April the 9th, 1947 watershed (Herhar et al., 2014; Hilal et al., 2015). It is based on three parameters: the soil functioning hydric, the hydrographic network density, and the agricultural drainage. This method hypothesizes that one of the main factors of vulnerability is the proximity of the hydrographic network to the areas of the existence of the polluting products. This factor will be aggravated by the dominant mode of water circulation in the soil and by the importance of agricultural drainage.

This work is a diagnosis of water quality in the Kharroub river dam watershed; it is, therefore, a document of assistance for future decision-making. Furthermore, it can provide some water protection options. In this respect, this document intends to minimize water treatment expenses before their use and provide managers of water resources with methodologies which shall reduce the possible damage that can reach these resources.

2. Study Area Description

Located over the Kharroub river, this dam will reinforce the drinking and industrial water supply for the Tangier-Tetouan-Alhoceima region, with the regulation of an annual volume of 40 million m³ of water which will contribute to consolidating water facilities in northern Morocco with the aim of meeting the increasing drinking and industrial water needs and mobilize newly available resources, mainly surface water (HBAL, 2014).

The Kharroub river watershed is in the Rif mountains chain in the northwest of Morocco (Fig.1). It forms a surface delimited by the following Lambert coordinates: $x_1 = 461667.183767$ m, $y_1 = 523597.977912$ m, $x_2 = 481924.181158$ m, and $y_2 = 539307.515370$ m. Its total area is about 191 km² and its perimeter reaches 72.08 km, its Gravelius compactness index is equal to 1.46, which means that our watershed has an elongated shape. It is characterised by a more or less uneven topography and an altitude that varies between 16 m (at the level of Kharroub dam) and 1054 m at the level of the crest line (HBAL, 2014).

The hydrographic network of the Kharroub river basin is marked by the presence of the El Kerrouk river, which crosses the basin over approximately 13 km. Other watercourses also cross the basin but are not as active as the main river (Fig.2). There is no water table linked to the Kharroub river basin. Underground resources are constituted by small, local and non-perennial alluvial reserves. The Kharroub river watershed is characterized by a temperate Mediterranean climate with high precipitation in winter and dry hot summer (HBAL, 2014).

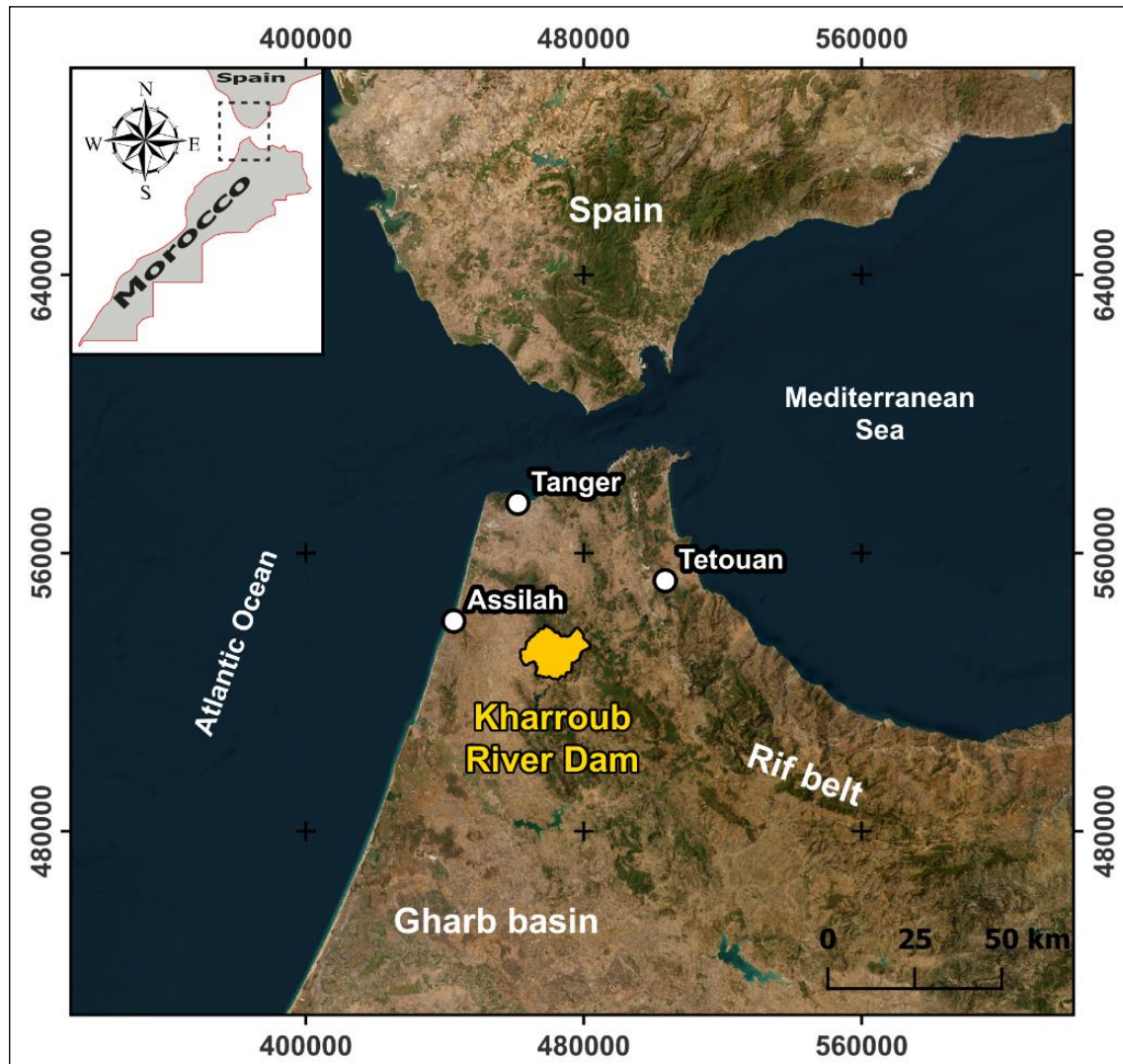


Fig.1. Location of the Kharroub River watershed.

Geologically, the study area is part of the northern Rifian domain of Morocco, containing the flysch nappes and the Tanger unit which constitutes the substratum of these nappes. The latter are composed of several series engaged in a tectonic of allochthonous formations. These units are as follows (Fig.3):

- The Tanger unit: it is the most representative; it occupies 35.31% of the surface of the study area, spreading over the central and southern parts of the study area. It is essentially formed of Upper Cretaceous marl and Lower Eocene flinty limestone (Vázquez et al., 2013; Maaté et al., 2017).
- The Melloussa-Chouamat nappe: with a surface area of around 1.98% of the total surface area of the watershed; it is made up of alternating sandstones and marly limestones from the Upper Cretaceous as well as some Tertiary elements (Durand-Delga et al., 1962; Romagny, 2016).
- The Beni Ider nappe: is mainly located in the north-eastern part of the watershed and covers only 1.76% of the total surface area of this basin. It results from the stacking of layers a few hundred meters thick. The main material of this nappe contains micaceous fine sandstones and mudstones of the Oligocene age (Michard et al., 2006).
- The Numidian nappe: it covers 25.75% of the surface of the watershed in the northern, south-eastern, and south-western parts of the study area and is formed by sandstone flysch alternating with pelites of Oligocene and Lower Miocene age (Michard et al., 2006; El Abdellaoui, 2019).

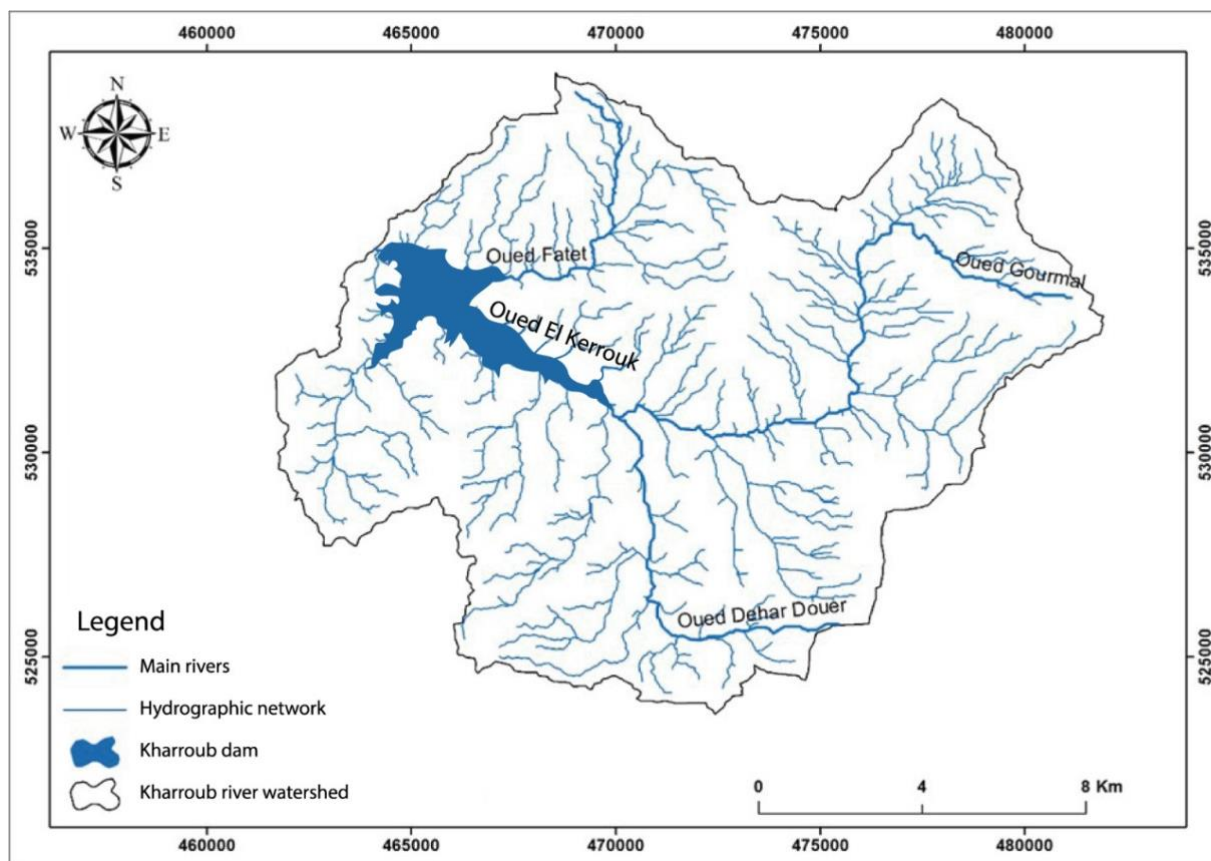


Fig.2. Map of the hydrographic network of the Kharroub river watershed

- Quaternary Colluvium: it reflects the lithology of the upper slope and is generally found in the central part of the watershed. In the pedological context and according to the pedological maps of Tetouan 1/100000 and 1/500000, the study area contains the following soil types (PDA, 1987; Lanoue, 2007) (Fig.4).
- Vertisols: they represent 8.14% of the total surface of the study area. These are dark-coloured soils, without a very high organic matter content, rich in swelling clay. In the dry season, they show large shrinkage cracks to a depth of 50 to 80 cm. They are developed on fine-textured materials.
- Weakly developed soils: they occupy 1.87% of the area of the basin. The soils in this class have a clear humus horizon, sometimes quite large. The alteration of the bedrock is extensive, but it is often difficult, from the simple observation of the profile, to determine the direction of evolution due to the youth of the soil or the climate, which do not allow for clear-cut evolutionary processes. They are developed on sandstone-quartzite, marl-limestone, and clay materials.
- Calcimagnesian soils: they represent 4.22%, developed on clayey-sandstone flysch in mountainous areas. These soils are dependent on calcium and magnesium carbonates and sulphates. They are AC or A(B)C profile soils, generally not very thick. Low-humic hydromorphic pseudogley soils: these are found on 1.82 km² (0.95%). These soils are generally found mainly on the slopes. They have a sandy or sandy-clay texture on the surface, which becomes more and more clay at depth. The increasing clay content in the deeper horizons.

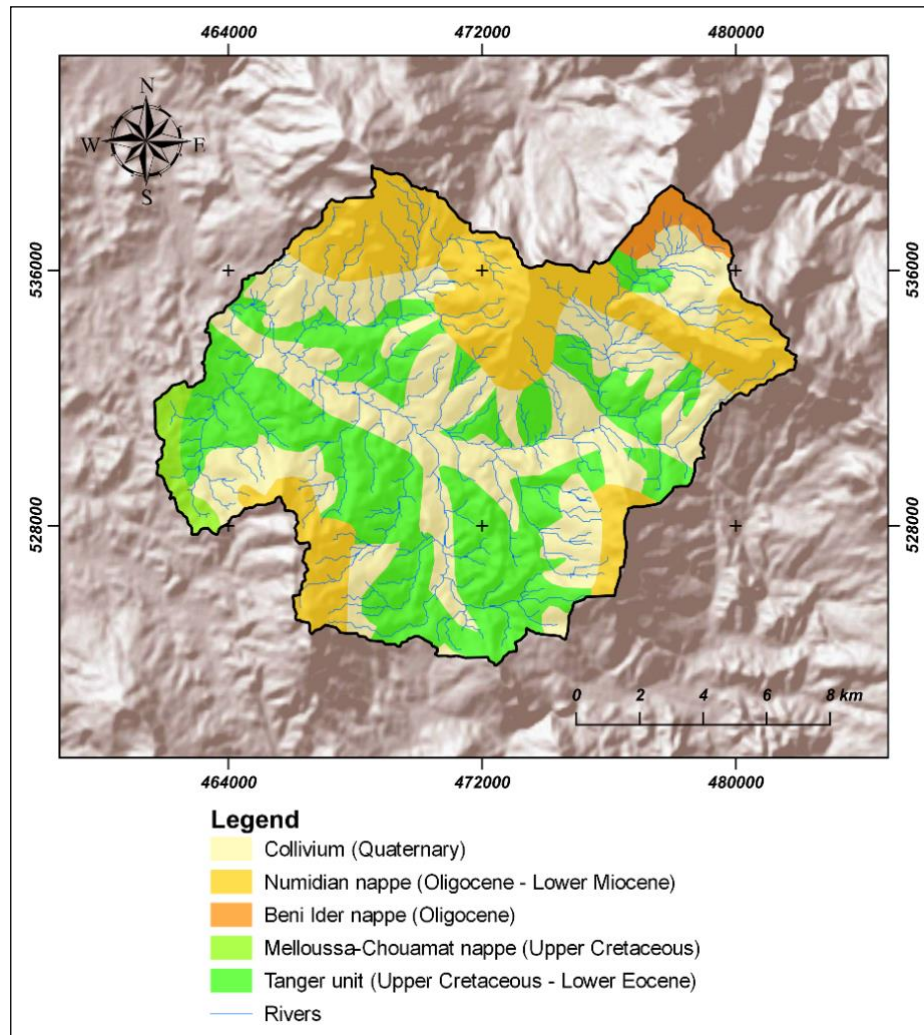


Fig.3. Geological map of the Kharroub river watershed (extracted from the geological map of the Rif with a scale of 1/500000)

- makes them increasingly impermeable. This creates a temporary hydromorphy in the deeper horizons with the appearance of pseudogley.
- Hydromorphic brown soils: these represent only 0.59%. In this class clay and humus form fewer stable aggregates. Migration of clay is possible. A clay-iron-humus complex gives the soil a brownish colour. The release of iron is hardly visible.
- Complex soils: these are made up of a mixture of two or more soil classes and occupy a large area of the basin, reaching 160.82 km² (84.23%).

3. Materials and Methods

The data used in this study have been obtained from:

Geological map of the Rif at a scale of 1/500000, provided by the Ministry of Energy and Mines (Geology Directorate), published by Suter (1980).

Soil map of Tetouan at a scale of 1/100000, drawn up by the Provincial Directorate of Agriculture (PDA) of Tetouan in 1987.

Soil map of the province of Tetouan at a scale of 1/500000 (Lanoue, 2009).

- Digital Terrain Model (DTM) extracted from the ASTER GDEM platform with a resolution of 30 m and a projection (WGS 84).

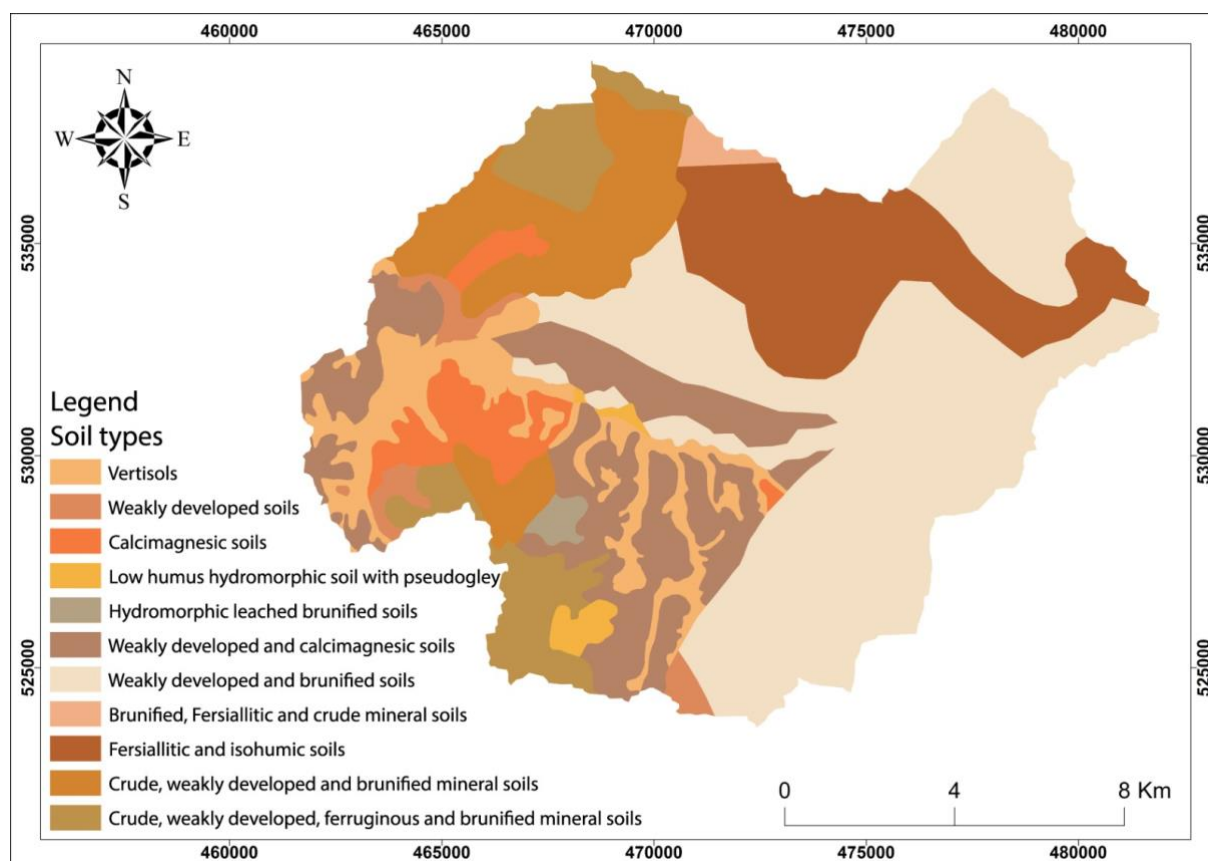


Fig.4. Soil map of the Kharroub river watershed

In this study, SW is the method adopted for mapping the vulnerability to contamination of the surface water of the Kharroub river dam, it consists of the classification of areas that have the same degree of vulnerability to pollution following synthesis of data of various natures: pedological, geological and hydrological, resulting mainly from the quantification of three parameters (Grappe, 2006), which are:

The type of hydric functioning of the soils: this parameter characterizes the partition between infiltration water and runoff water. Based on pedological expertise, the soil units described in the study area will be classified according to their characteristics (hydromorphone, texture, ...) into hydric functioning units according to their degree of permeability. The method gives each type of hydric functioning a hydrological typology that varies between 1 and 9.

The density of the hydrographic network: this parameter allows us to assess the proximity of surface water resources to the emission of pollutants. Transfers occur via spray drift and surface and subsurface runoff from the source of pollution to the aquatic resource. It is evaluated by the ratio of the sum of the lengths of the watercourses in a given territory divided by its surface area.

$$\text{Hydrographic network density} = \frac{\sum \text{Lengths of the watercourses}}{\text{Surface area}}$$

There are three classes of the density of the hydrographic network:

Low density between 0 and 0.5 km⁻¹.

Medium density between 0.5 and 2 km⁻¹.

High density of more than 2 km⁻¹.

The importance of agricultural drainage: it is considered that agricultural drainage accentuates the phenomena of migration of pollutants to surface waters by increasing the surface areas contributing to the supply of watercourses and by intercepting part of the water that should migrate to the depths.

Each of these three parameters is quantified by a typology, according to its natural rank which expresses its importance in determining the degree of vulnerability to contamination. The surface water contamination vulnerability map of the SW method is obtained by combining the relative typologies of the three parameters (Herhar et al., 2014).

4. Results and Discussion

To obtain the final vulnerability map, the vulnerability maps of the three predefined parameters are developed and superposed.

4.1. Soil Hydric Functioning Map

The elaboration of this map begins with the determination of the hydric functioning units, which aim to determine the dominant modes of circulation of water, which is the vector for the circulation of polluting substances towards aquatic resources. The typologies are attributed to the soils according to their permeability, the lower the permeability the higher the hydric functioning typology (Hilal et al, 2015). The typologies of hydric functioning are provided from the studies of Herhar (2015) and Afilal (2019). Table 1. presents the different types of soil in the Kharroub river watershed, their typologies, their circulation modes, and the vulnerability classes

Table 1. Soil types in the Kharroub river watershed

Soil classes	Typology of hydric functioning	Water circulation	Vulnerability class
Weakly developed soils	4	Dominant vertical circulation	Low
Calcimagnesian soils	4	Dominant vertical circulation	Low
Weakly developed and calcimagnesian soils	4	Dominant vertical circulation	Low
Weakly developed and brunified soils	4	Dominant vertical circulation	Low
Brunified, Fersiallitic and lithosolic soils	4	Dominant vertical circulation	Low
Weakly developed, brunified and lithosolic soils	4	Dominant vertical circulation	Low
Weakly developed, ferruginous, brunified and lithosolic soils	4	Dominant vertical circulation	Low
Low-humic hydromorphic pseudogley soils	5	Mixed water circulation	Medium
Hydromorphic brown soils	5	Mixed water circulation	Medium
Fersiallitic isohumic soils	5	Mixed water circulation	Medium
Vertisols	8	Dominant horizontal circulation	High

Fig.5 represents the spatial distribution of the types of hydric functioning associated with the Kharroub river watershed, we deduce that:

Typology zone 4 is spread over 76.11% of the study area and contains soils with high permeability and vertical water circulation.

Typology zone 5 is developed over about 15.75% of the study area. It coincides with hydromorphic soils characterized by mixed water circulation. It mainly occupies the north-eastern part of the watershed in question.

Typology zone 8 occupies 8.14% of the total area of our basin to the west. It is associated with Vertisols, which are characterized by their high impermeability and, subsequently, a dominant horizontal circulation.

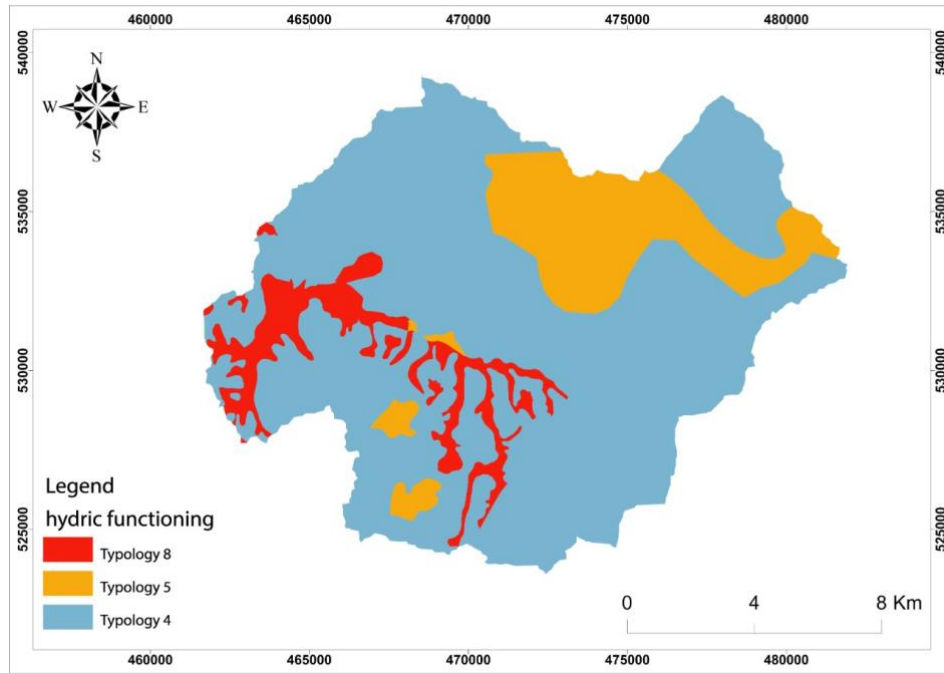


Fig.5. Hydric functioning map of the Kharroub river watershed

Table 2. The values of the hydrographic density at the watershed level of the Kharroub river

Type of soil	hydrographic density (km^{-1})	Vulnerability class
Vertisols	1,88	Medium
Weakly developed soils	2,06	High
Calcimagnesian soils	1,90	Medium
Hydromorphic brown soils	1,40	Medium
Low-humic hydromorphic pseudogley soils	2,43	High
Weakly developed and brunified soils	1,96	Medium
Weakly developed and calcimagnesian soils	2,08	High
Fersiallitic isohumic soils	1,73	Medium
Brunified, Fersiallitic and lithosolic soils	2,26	High
Weakly developed, brunified and lithosolic soils	2,43	High
Weakly developed, ferruginous, brunified and lithosolic soils	1,51	Medium

4.2. Hydrographic Density Map

Given the importance of the nature of the soil in the hydrographic network development, we have opted to calculate the hydrographic density for each type of soil. The denser the hydrographic network, the closer the rivers are to sources of pollution. Thus, the water vulnerability to pollution increases. The results obtained are presented in Table 2 and Fig.6.

At the watershed level, we can distinguish the dominance of two hydrographic density classes (Fig.6):

- The medium class of hydrographic density (between 0.5 and 2 km^{-1}) represents approximately 71.26%; it is mainly distributed over the eastern and western parts of the watershed.

- The high class of hydrographic density (higher than 2 km^{-1}) covers almost 28.74% of the total surface of the study area; it appears in the western half of the watershed.

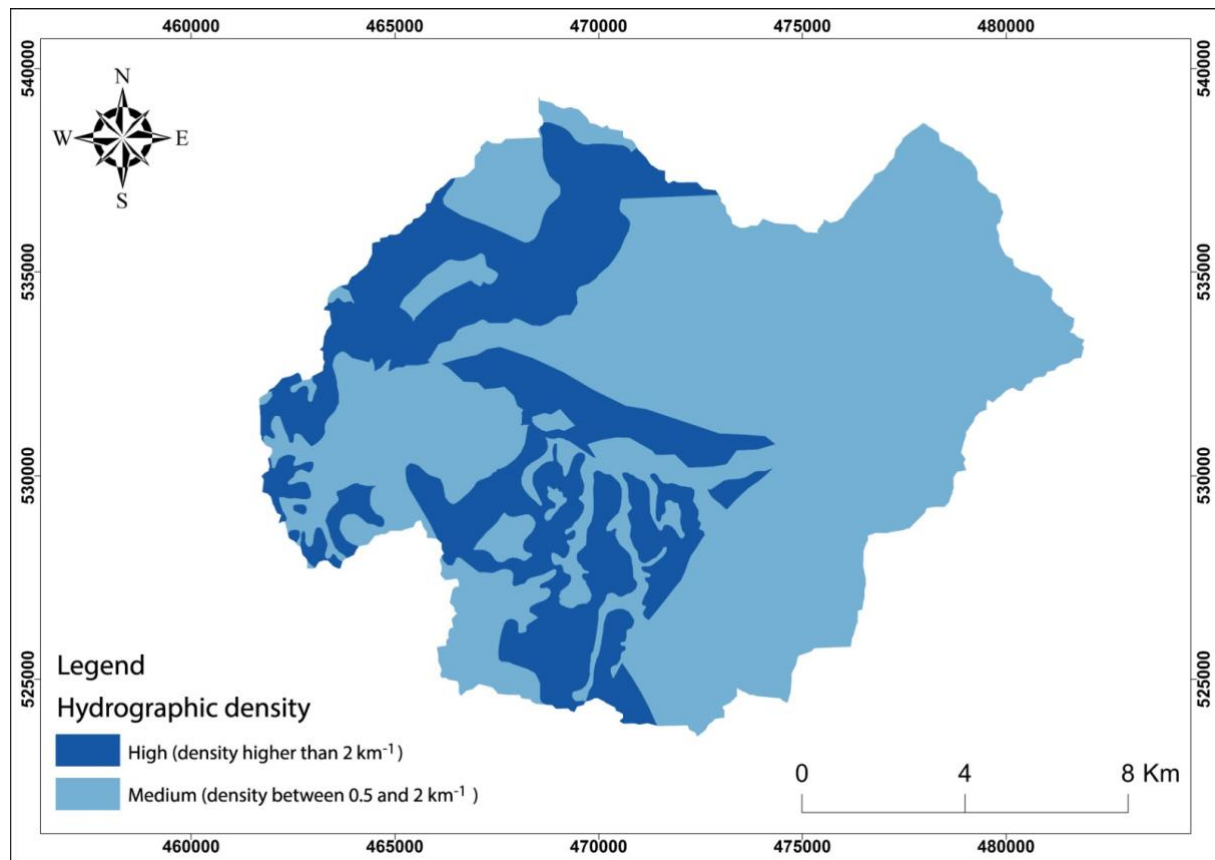


Fig.6. Hydrographic density map of the Kharooub river watershed

4.3. Agricultural Drainage Map

In our case, and due to the lack of data on this factor, the agricultural drainage map is obtained based on the permeability of the different soil and subsoil units using a combination table between soil and subsoil hydric functioning (Afilal, 2019) (Table 3).

Table 3. Combinations of hydric functioning of soils and subsoils, and the associated agricultural drainage classes

Soil	Subsoil	Vulnerability class
Impermeable	Impermeable	Low
Impermeable	Semi-permeable	Low
Impermeable	Permeable	Low
Semi-permeable	Impermeable	High
Semi-permeable	Semi-permeable	High
Semi-permeable	Permeable	Medium
Permeable	Impermeable	High
Permeable	Semi-permeable	Medium
Permeable	Permeable	Low

According to the map of agricultural drainage (Fig.7), we can distinguish three typologies which are distributed as follows:

- The northeast, northwest, southeast and southwest end parts of the watershed are characterized by medium agricultural drainage covering approximately 20% of the total surface of the study area. This drainage class coincides both with semi-permeable soils (such as Low-humic hydromorphic pseudogley soils and fersiallitic isohumic soils) which overlie a permeable subsoil made up of colluviums and with permeable soils (weakly developed soils, calcimagnesian soils, weakly developed and brunified soils, weakly developed, brunified and lithosolic soils, brunified, fersiallitic and lithosolic soils, weakly developed, ferruginous, brunified and lithosolic soils) associated with sandstones.
- 38.46% of the watershed is characterized by low agricultural drainage. This is attributed to impermeable soils (vertisols), as well as to permeable soils which overlie permeable colluvial subsoils.
- The central and southern parts of the watershed are dominated by high agricultural drainage which covers 41.54% of the total area. This typology coincides, on the one hand, with the semi-permeable soils (Hydromorphic brown soils, Low-humic hydromorphic pseudogley soils and fersiallitic isohumic soils) overlying either the marls of the Tanger unit, or the sandstones, and on the other hand, with permeable soils (weakly developed and calcimagnesian soils, weakly developed and brunified soils, weakly developed, brunified and lithosolic soils, weakly developed, ferruginous, brunified and lithosolic soils) which overlie the impermeable subsoils (marls).

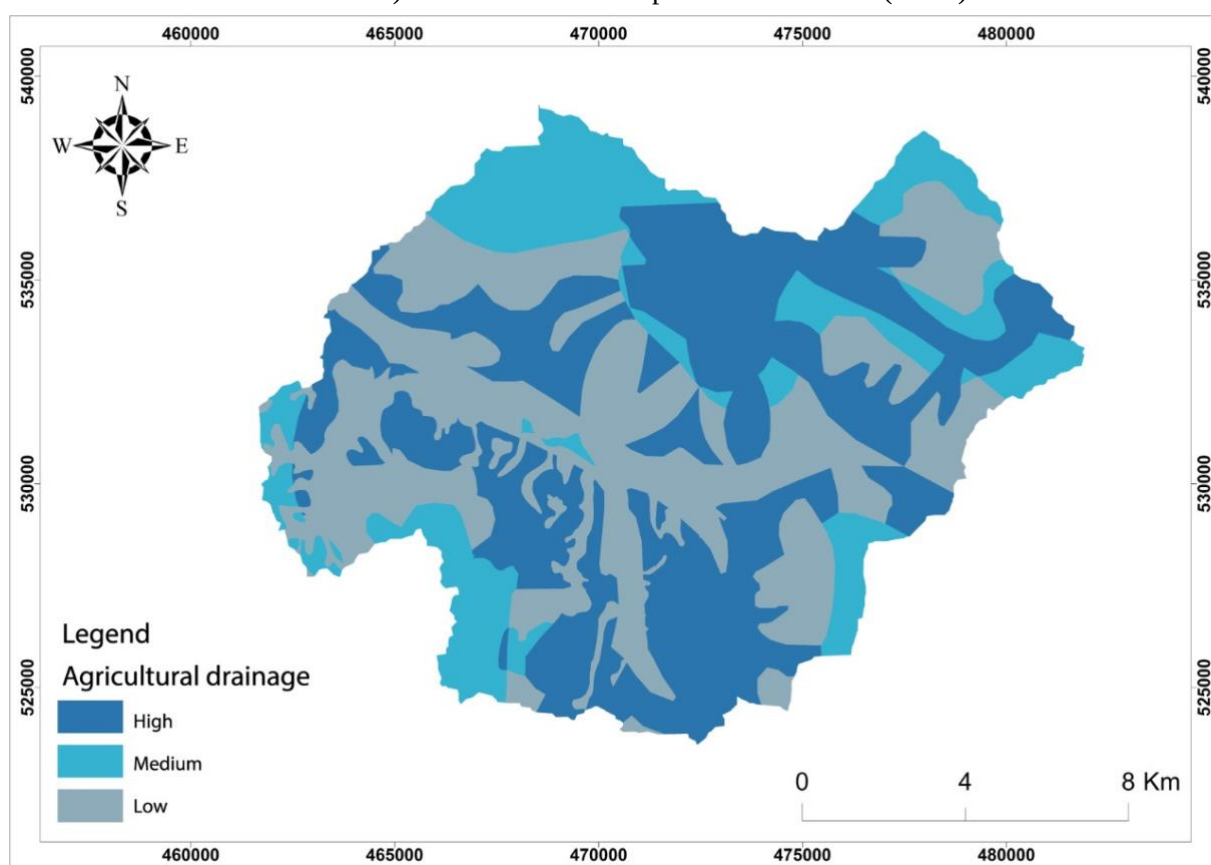


Fig.7. Agricultural drainage map in the Kharroub river watershed

4.4. Elaboration of the Vulnerability Map to Surface Water Contamination of the Kharroub River Watershed

From an operational point of view, the determination of vulnerability classes according to the SW method is done through combinations of typologies related to the three parameters used (Herhar, 2015). The combinations obtained in the Kharroub river watershed and the associated vulnerability classes are presented in Table 4.

The class of very high vulnerability occupies 0.95% (1.82 km²) of the total surface of the study area, generally towards the center and the south of the watershed. It corresponds to Low-humic hydromorphic pseudogley soils (temporary waterlogging soils) characterized by a mixed circulation. The areas of this class are characterized by a high density of the hydrographic network (2.43 km⁻¹) which makes the water more vulnerable to pollution, and a medium to high agricultural drainage because of the existence of sandstone and marls, which prevent the infiltration of water towards the depths.

The high vulnerability class is distributed over about 24.65% (47.05 km²) of the watershed surface. This class is associated with permeable soils (weakly developed soils, weakly developed and calcimagnesian soils, weakly developed, brunified and lithosolic soils) and semi-permeable soils (hydromorphic brown soils, fersiallitic isohumic soils). These soils develop on the marls of the Tanger unit and the Numidian sandstones, which increases the rate of agricultural drainage and, consequently, the water will be vulnerable to pollution. Hydrographic density is well developed by contributing more to water contamination.

Table 4. Combinations of typologies of parameters and the attributed vulnerability classes in the Kharroub river watershed

Hydric functioning	Density of hydrographic network	Agricultural drainage	Combinations	Vulnerability class	Percentage of vulnerability class (in %)
Dominant vertical circulation	Medium	Low	Combination 4		20,22
Dominant vertical circulation	Medium	Medium	Combination 5	Low Low Low	11,60
Dominant vertical circulation	High	Low	Combination 6		10,09
Dominant vertical circulation	Medium	High	Combination 8		16,50
Dominant vertical circulation	High	Medium	Combination 9	Medium Medium Medium Medium	5,76
Dominant mixed circulation	Medium	Medium	Combination 10		2,09
Dominant lateral circulation	Medium	Low	Combination 11		8,14
Dominant mixed circulation	Medium	High	Combination 12		12,70
Dominant vertical circulation	High	High	Combination 13	High High	11,94
Dominant mixed circulation	High	Medium to high	Combination 14	Very high	0.95

The medium vulnerability class is developed over approximately 32.49% (62.03 km²) of the entire study area. It coincides with the vertisols to which predominant lateral circulation; a medium hydrographic density and low agricultural drainage are attributed. And with certain types of soils whose water circulation is vertical (weakly developed soils, calcimagnesian soils, weakly developed, brunified and lithosolic soils, Brunified, Fersiallitic and lithosolic soils, weakly developed and brunified soils, weakly developed, ferruginous, brunified and lithosolic soils). These soils are generally developed on sandstone and marl, from which comes the importance of agricultural drainage contributing to water pollution. The hydrographic network is developed in a moderate way, which makes the water moderately vulnerable to contamination.

The low vulnerability class is developed over approximately 80.02 km² (41.91%). It is associated with permeable soils to which a predominant vertical circulation is attributed and, therefore, the water of these areas is less likely to be contaminated. It is noted that the agricultural drainage of these areas is less developed, which reduces the possibility of contamination of surface water resources. The hydrographic network, in general, is moderately developed.

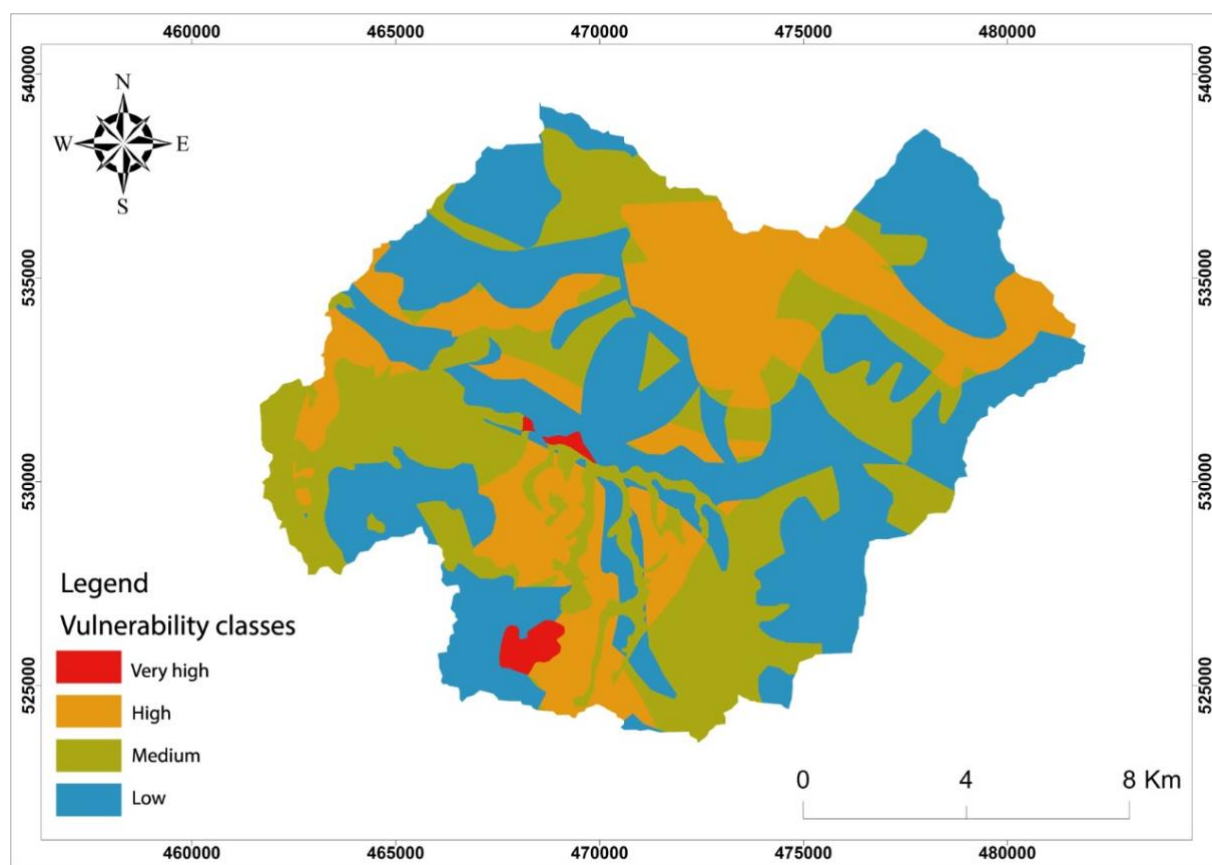


Fig.8. Vulnerability map to surface water contamination of the Kharroub river watershed

According to the analysis of the obtained results, we note that the degree of surface water vulnerability is strongly influenced by the lithological characteristics and the soil nature. The presence of an impermeable or semi-permeable soil or substratum favors the runoff of water all along the slopes of the watershed from which the migration of pollutants comes to the water resources, and the development of the hydrographic network, which minimizes the distance between the watercourses and the pollution sources. On the contrary, the high permeability reduces water drainage on the surface and the hydrographic density in favor of the groundwater network, and this decreases the rate of pollution of surface water resources.

Studies conducted in the Martil river watershed (Herhar et al., 2014), April the 9th, 1947 watershed (Hilal et al. 2015; Hilal, 2015), and Smir river watershed (Afilal, 2019), show different results from ours. This is due to the difference in lithological, pedological and hydrological characteristics from one watershed to another. In some cases, and due to the lack of official data concerning the parameter of agricultural drainage, some authors replace it by other parameters leading to different findings. The study of April the 9th, 1947 watershed (close to our watershed) shows a high degree of vulnerability (72% of the total area of the watershed) even though the two watersheds have similar lithological and pedological characteristics. This is mainly due to the replacement of the agricultural drainage parameter by the slope parameter, which has an effective relationship with the geomorphology of the watershed.

5. Conclusions

According to the SW method, the low and medium vulnerability classes are the most representative (41.91% and 32.49% respectively), and they spread throughout the basin. This is mainly due to the nature of the soils to which a predominant vertical circulation is attributed, which leads to the infiltration of water towards the depths. Most of these areas are characterized by weak agricultural drainage and a less developed hydrographic network, which minimizes the likelihood of contamination of surface water resources.

For areas with a high to a very high degree of vulnerability, which represent 24.65% and 0.95% respectively, water contamination is mainly due to the existence of soils whose water circulation is mixed. This makes a large part of this water susceptible to pollution. Thus, the importance of agricultural drainage and the hydrographic network contribute to making water more vulnerable to pollution. Several measures are recommended to maintain the quality of surface water in these areas:

- Review the location of any installed activity in such a way as to either relocate it or require procedures to reduce its contaminating effect.
- Properly manage the spatial distribution of future activities to avoid as much as possible that it coincides with vulnerable areas.
- Identify sources of pollution (diffuse and punctual) and, for the most important pollutants, assess concentrations, total quantities, and the timing of discharges.
- Set up an autonomous sewerage network to prohibit any clandestine discharge of wastewater into the rivers and their tributaries.

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