Mapping Surface Water Contamination Vulnerability by Applying the DKPR Method: The Case of the Kharroub River Watershed (Northern Morocco)

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***Abstract*—Preserving the quality and availability of water resources is undoubtedly one of the major challenges of our century. This imperative requires better management against pollutants, whether of natural or anthropogenic origin. This study is part of this environmental perspective, seeking to develop an innovative approach for efficient and sustainable management of water resources. It aims to elaborate the surface water contamination vulnerability map of the Kharroub River dam by applying the DKPR method. The latter is based on four parameters: the accessibility of the aquatic environment (D), the hydric functioning of the soil and subsoil (K), the watershed physiography (P), and the rainfall erosivity (R). The weighted sum of these parameters provided an index labeled "Vr" that varies between 0 and 4. Using this index, the obtained vulnerability map presents five classes. The zone of moderate vulnerability depicts 56.99% and spreads throughout the watershed. Low and high vulnerability areas occupy 26.91% and 15.23%, respectively, they are scattered all over the study area. Areas of very low vulnerability (0.77%) and very high vulnerability (0.1%) are the least developed and located particularly in the center of the watershed. The analysis of the final vulnerability map of the method mentioned above will be a helpful support for water resource managers and decision-makers to better identify areas of high risk and their protection.**

***Keywords*—contamination, DKPR method, Kharroub River watershed, surface water, vulnerability**

I. Introduction

Water, the fundamental element of life and the cornerstone of ecosystems, has a crucial role in supporting several forms of life on our planet [1, 2]. Even small changes in the water supply will bring about considerable changes in our societies, bodies, and lives [2]. Its availability, accessibility, quality, and equitable distribution are key factors in determining the well-being of humans and the environment [3]. On a global scale, population growth, drought, scarcity of water, water requirements for significant sectors such as agriculture, and the impact of climate change all underscore the critical importance of water management [3, 4]. Water quality and quantity are continually degraded due to climate change and increasing demand for various water uses, particularly in agricultural practices [5].

The problem of surface water pollution constitutes one of the major environmental issues facing developing countries [6]. Generally, surface water is limited in arid and semi-arid regions due to the low rainfall and high evaporation that predominate in these areas [7]. Globally, arid, and semi-arid climate environments are experiencing an increase in surface water deficit [8, 9].

In Morocco, and during the last decades, water is characterized by a temporal irregularity, a spatial rainfall heterogeneity and a strong vulnerability both to climate change and to the misdeeds of human activities (withdrawals, discharges of pollutants, etc.). In this context, Morocco has long been engaged in a dynamic policy to supply the country with a solid hydraulic infrastructure, facilitate access to drinking water, meet the needs of industries and tourism and develop irrigation on a large scale [10]. For this purpose, at the end of the last century, Morocco chose the policy of dam construction to control and store surface water during rainy periods to secure the water supply during dry years [11–14]. Despite the construction of dams, Morocco is experiencing a significant reduction in its water resources, causing structural water stress with major consequences on food security, social stability, and the economy. Therefore, it is imperative to take immediate action to preserve water resources through effective management and monitoring of water quality [15].

Understanding the sources and degree of vulnerability of watershed water resources is the first step in designing strategies to ensure water security for various uses, including human and environmental uses [16]. Assessing vulnerability is essential to understanding the pressures on water resource systems [17] and designing appropriate strategies to address them [18]. Several methods and techniques have been developed in the world literature for the assessment of the vulnerability of water to pollution such as Surface Water (SW) [19], DKPR [20], Technology Enabled Universal Access to Safe Water (TECHNEAU) [21], European Cooperation in Science and Technology (COST) Action 620 [22], the Universal Soil Loss Equation (USLE) [23] and the Revised Universal Soil Loss Equation (RUSLE) [24, 25].

Previous studies carried out in the Kharroub River watershed have used the SW method to identify areas vulnerable to contamination [14] and the RUSLE method to specify those susceptible to water erosion [26], providing essential tools for assessing and managing water quality risks.

Our study contributes to addressing this environmental concern. We used the DKPR method proposed by Douay and Lardieg [20] to create a surface water contamination vulnerability map for the Kharroub River dam. This method has been employed in various Mediterranean watersheds, such as the Martil River watershed [27, 28], the Smir River watershed [29, 30], and the 9 Avril 1947 dam watershed [31, 32]. This method is based on four parameters: The accessibility of the aquatic environment (D), the hydric functioning of the soil and subsoil (K), the watershed physiography (P), and the rainfall erosivity (R). We chose the DKPR method to assess the vulnerability of surface water in the Kharroub River watershed because of its simplicity, the accuracy of its results and the diversity of its parameters.

We aim through this work to provide a solid scientific basis for sustainable and efficient management of the water resources of the dam in question, by minimizing the risks of contamination and preserving the water quality for future generations.

II. Study Area Description

The Kharroub River dam is located 45 km south of Tangier city and 22 km east of Assilah city (Fig. 1). It contributes to the reinforcement of the hydraulic infrastructure in the north of the Kingdom of Morocco. Thus, permitting public access to drinking and industrial water and the exploitation of new resources available [33].

This dam is built at the outlet of the Kharroub River watershed, which is in the Rif belt in the northwest of Morocco and delimited with the following Lambert coordinates: X_{max} = 481.924 km, Y_{max} = 539.307 km, X_{min} = 461.667 km, and Y_{min} = 523.597 km. Its total surface area is approximately 191 km^2, its perimeter is around 72.08 km, and its Gravelius compactness index equates to 1.46, meaning that the watershed has an elongated form. The Kharroub River watershed is identified by a more or less uneven topography and an altitude that fluctuates between 16 m (at the level of the Kharroub River dam) and 1054 m in the ridgeline. The mountains represent 85% while the plains represent 15% [33].

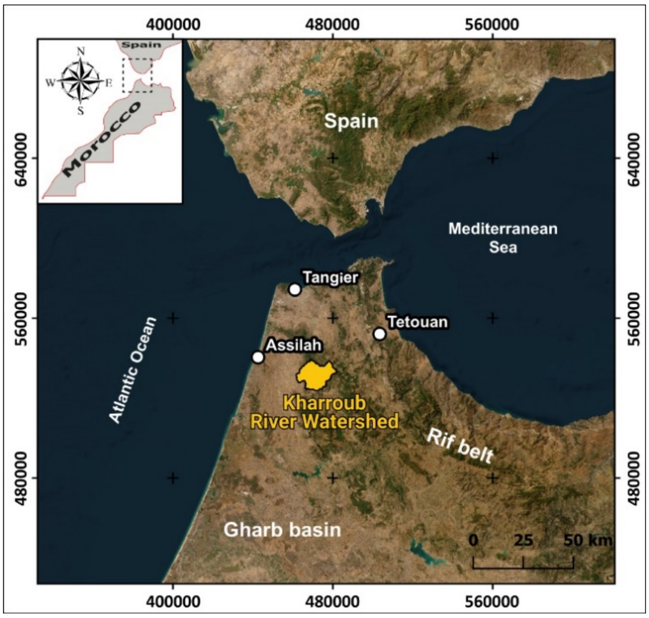

Fig. 1. Location of the Kharroub River watershed.

The Kharroub River watershed is marked by a moderate Mediterranean climate with heavy winter rainfall and dry hot summer. The hydrographic network of the Kharroub River watershed is defined by the El Kerrouk River, which traverses the basin for about 13 km (Fig. 2). A cross-section of it is shown in Fig. 3. Other watercourses also cross the watershed, but they are less active than the main river [33].

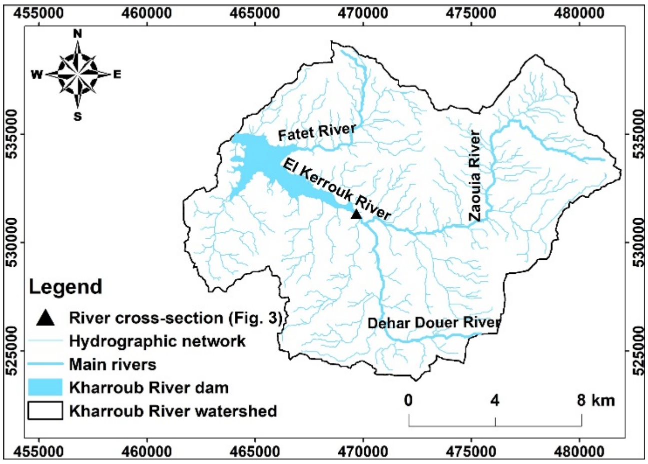

Fig. 2. Hydrographic network map of the Kharroub Rriver watershed.

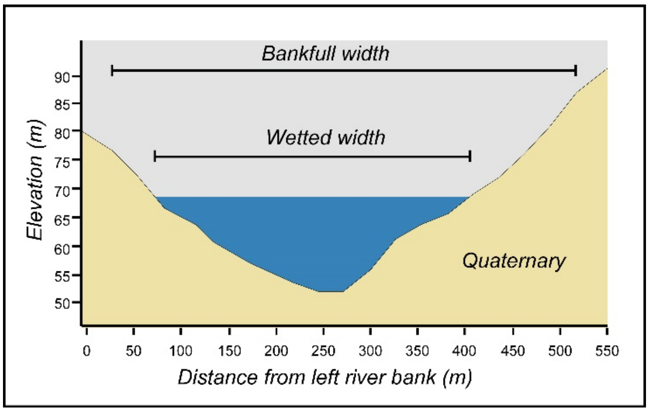

Fig. 3. Cross-section at the level of the El Kerrouk River.

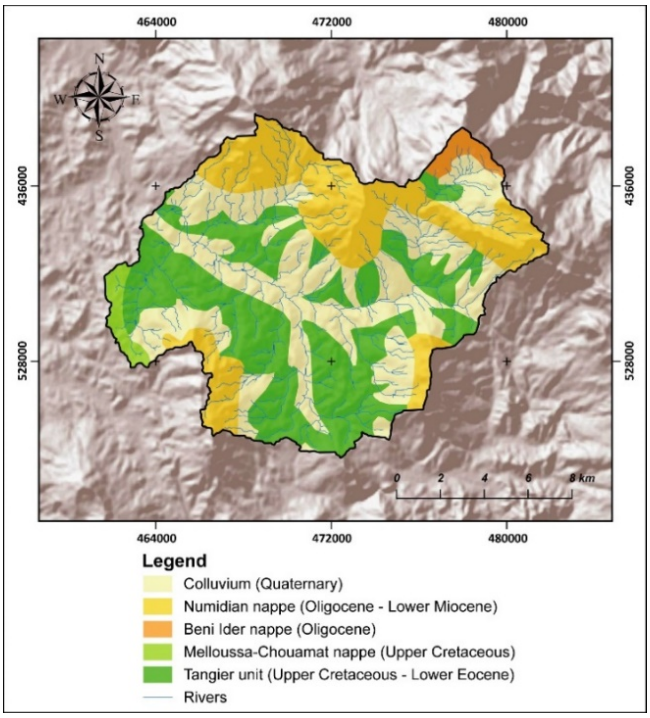

Fig. 4. Geological map of the Kharroub River watershed (extracted from the geological map of the Rif with a scale of 1/500000).

Geologically, the study area is made up of the following units (Fig. 4):

- The Tangier unit: It covers the central and southern parts of the watershed, taking up 35.31% of its total surface.

Essentially, it is materialized by Upper Cretaceous marls and Lower Eocene flinty limestone [34, 35];

- The Melloussa-Chouamat nappe: It makes up approximately 1.98% of the watershed's total surface area. It is composed of alternating Upper Cretaceous sandstones and marly limestones as well as some tertiary materials [36, 37];
- The Beni Ider nappe: It occupies only 1.76% of the watershed's total area and is mainly found in the northeastern part. Micaceous fine sandstones and mudstones of Oligocene age constitute the majority of this nappe's outcrops [38];
- The Numidian nappe: With 25.75% occupancy of the watershed's total area. It is formed by sandstone flysch alternating with Oligocene and Lower Miocene pelites [38, 39];
- Quaternary outcrops generally indicate recent deposits and may include alluvium and colluvium. These materials are the result of recent geological processes, such as erosion, fluvial sedimentation, and landslides [40].

III. Materials and Methods

The data used in this study have been taken from:

- Geological map of the Rif at a scale of 1/500000 [41];
- Tetouan Soil map at a scale of 1/100000 [42];
- Soil map of Tetouan province at a scale of 1/500000 [43];
- Topographic maps at a scale of 1/50000 for the Souk Khemis Des Beni Arouss and Ayacha regions. These maps were provided by the National Agency of Land Conservation, Cadastre, and Cartography (Cartography Service);
- Land cover map at a scale of 1/200000, created by the Directorate of Water and Forests of the Tetouan Province;
- Digital Terrain Model (DTM) obtained from the ASTER GDEM platform with a resolution of 30 m and a WGS 84 projection system;
- Climatological data regarding the recorded precipitation at meteorological stations located near the Kharroub River watershed, for an observation period spanning from 1990 to 2018, supplied by the Hydraulic Basin Agency of Loukkos (HBAL).

The method used in this study is known as DKPR. It aims to study the environmental impacts relating to water pollution linked to natural factors and anthropogenic activities [20]. It allows the mapping of the intrinsic vulnerability of a surface water catchment based on several parameters that are then weighted as shown by Eq. (1) [28–32]:

$$Vr = \sum_{j=1}^{j=n} (Wj \times Rj) \tag{1}$$

where *Vr*: resource vulnerability index, *Wj*: weighting factor for *j* parameter, *Rj*: class of *j* parameter, *n*: number of parameters considered.

The parameters adopted in this method are:

A. Accessibility of the Aquatic Environment (D)

This parameter is related to the distance between the location of pollutants on the watershed surface and the aquatic environment [44]. The closer the sources of pollution are to the aquatic environment, the more the surface water is contaminated [18]. The vulnerability class value assigned to this factor is inversely proportional to the distance "D" [45].

B. Hydric Functioning of the Soil and Subsoil (K)

This parameter characterizes the partition between infiltration and runoff water [27]. The impermeability of the soil and subsoil promotes runoff and leaching with short transit time, which increases the speed of migration of pollutants towards water resources [27]. This parameter is determined by evaluating the classes of three component factors: the network development and persistence index (IDPR), the Battance Index (IB) and the land cover index (Os). The value of K parameter is obtained by applying the Eq. (2) [20]:

$$K = aIDPR + bIB + cOs \tag{2}$$

where *K*: hydric functioning of soil and subsoil criterion index, *IDPR*: network development and persistence index class, *IB*: battance index class, *Os*: land cover index class, *a*, *b*, and *c* are weighting factors ($a = 0.4$, $b = 0.2$, $c = 0.4$, and $a + b + c = 1$).

C. Watershed Physiography (P)

This parameter depends on the slope's intensity and the slope's curvature [31]. A steep slope promotes surface runoff and erosion, whereas a lower slope promotes infiltration and sedimentation [18]. The longitudinal curvature affects the acceleration and deceleration of the flow on the surface [28, 30]. The Planiform curvature refers to the convergence and divergence of the flow on the surface [28, 30]. The P index value is determined by summing the products of the classes of the intensity and curvature of slopes, with corresponding weighting factors according to Eq. (3) [27, 29, 31]:

$$P = dPi + ePc \tag{3}$$

where *P*: watershed physiography criterion index, *Pi*: slope intensity class, *Pc*: slope curvature class, *d* and *e* are weighting factors ($d = 0.8$, $e = 0.2$, and $d + e = 1$).

D. Rainfall Erosivity (R)

This parameter depends on the precipitation intensity and its role in the migration of pollutants [20]. It is based on the average annual rainfall of the stations installed in the watershed [31]. The rainfall erosivity of each station is calculated using the Eq. (4) [46]:

$$R = 0.04830\mathrm{P}^{1.160} \tag{4}$$

where *R*: erosivity parameter index and *P*: average annual rainfall (mm).

The intrinsic vulnerability map of an aquatic environment is developed based on the predefined "D", "K", "P", and "R" parameters by applying weighting factors according to Eq. (5) [20]:

$$Vr = fD + gK + hP + iR \tag{5}$$

where *Vr*: resource vulnerability index, *D*: accessibility to watercourses class, *K*: hydric functioning of the soil and subsoil class, *P*: watershed physiography class, *R*: rainfall erosivity class, *f*, *g*, *h*, and *i* are weighting factors ($f = 0.3$, $g =$

0.4, $h = 0.2$, $i = 0.1$, and $f + g + h + i = 1$).

Each parameter is subdivided into five classes ranging from 0 to 4 according to the degree of vulnerability (Table 1). Consequently, five vulnerability classes are then distinguished from the "Vr" values. The "Vr" final value, therefore, varies from 0 (minimum vulnerability) to 4 (maximum vulnerability) (Table 2).

Table 1. Degrees and classes of vulnerability of the DKPR method parameters [45]

Parameter	Degrees and classes of vulnerability				
	Very high	High	Moderate	Low	Very low
	4	3	2	1	0
D	0–50 m	50–100 m	100–200 m	200–500 m	>500 m
K	3.2–4	2.4–3.19	1.6–2.39	0.8–1.59	0–0.79
P	3.2–4	2.4–3.19	1.6–2.39	0.8–1.59	0–0.79
R	>5000	4000–5000	3000–4000	2000–3000	0–2000

Table 2. Classes of resource vulnerability index "Vr" [20]

Class	"Vr" index values	Vulnerability
0	0–0.79	Very low
1	0.8–1.59	Low
2	1.6–2.39	Moderate
3	2.4–3.19	High
4	3.2–4	Very high

In the results section, several figures are presented, including maps illustrating the spatial distribution of the classes for the four predefined parameters. Fig. 5 shows the distance intervals around the watercourses, Fig. 10 represents the classes' distribution of the K parameter, Fig. 11 is related to slope, and Fig. 12 represents the classes of rainfall erosivity. Finally, Fig. 13 presents the final vulnerability map of the Kharroub River watershed.

IV. Results

A. D Parameter

The spatial distribution of the "D" parameter classes within the Kharroub River watershed is presented in Fig. 5, revealing that approximately 18.75% of the watershed area is situated within 50 m of the watercourses. Almost 45.59% of the study area is between 50 and 200 m from the hydrographic network and 33.58% is from 200 m to 500 m. A very small part of the watershed, representing 2.07% of its total surface area, is beyond 500 m from the watercourses.

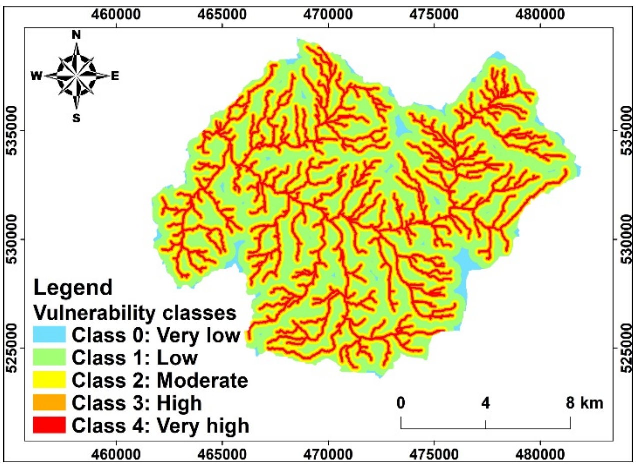

Fig. 5. Vulnerability map of D parameter.

B. K Parameter

1) Network development and persistence index (IDPR)

Fig. 6 shows the "IDPR" index classes. The determined classes in the Kharroub River watershed are three. Class 1 (35.56%) is dominated by permeable facies such as colluvium characterized by a predominant infiltration of water. Class 2 (29.13%) is characterized by mixed circulation, corresponding to the Numidian sandstones, sandstones and pelites of the Beni Ider and Melloussa-Chouamat units. Finally, Class 3 (35.31%) is characterized by impermeable facies (marls of the Tangier unit) that favor water runoff.

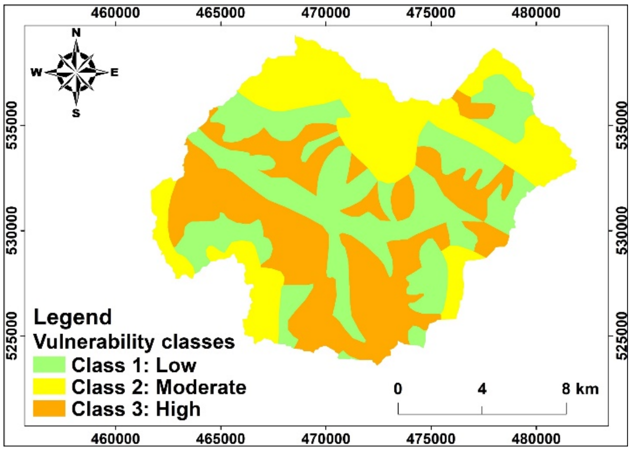

Fig. 6. Network development and persistence index map.

2) Battance Index (IB)

The index of this factor is calculated using the Eq. (6) [20]:

$$IB = \frac{(1.5\times\%LF+0.75\times\%LG)}{(\%A+5\times\%MO)} \tag{6}$$

where *LF*: fine silt, *LG*: coarse silt, *A*: clay, and *MO*: organic matter.

Fig. 7 shows the "IB" index classes: Class 0 (IB<1), Class 1 (1>IB>1.1), and Class 4 (IB>1.3).

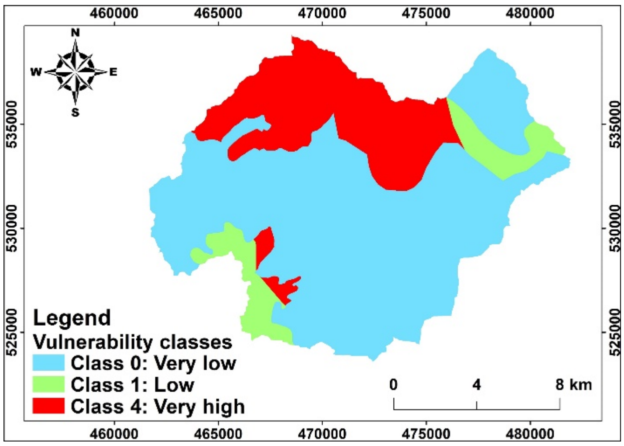

Fig. 7. Battance index map.

3) Land cover index (Os)

The "Os" index classes attributed by the DKPR method to each land cover (Fig. 8) are shown in Table 3 and Fig. 9. The different land covers in the Kharroub River watershed have been classified into five classes according to their degree of vulnerability.

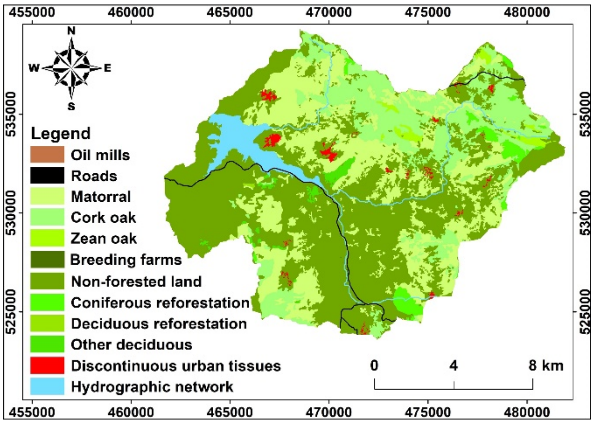

Fig. 8. Land cover map of the Kharroub River watershed.

Table 3. Land covers' degrees and classes in the Kharroub River watershed

Land cover	Vulnerability class	Vulnerability degree
Matorral Cork oak Zean oak Coniferous reforestation Deciduous reforestation Other deciduous Hydrographic network	0	Very low
Non-forested land	1	Low
Breeding farms	2	Moderate
Discontinuous urban tissues	3	High
Roads Oil mills	4	Very high

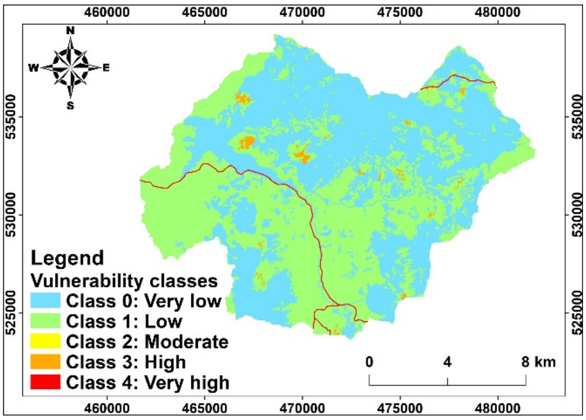

Fig. 9. Land cover index map.

We deduce, after obtaining the "K" parameter map (Fig. 10), that class 3 (1.82%), whose K index is between 2.4 and 3.19, is associated with discontinuous urban tissues, roads, marls of the Tangier unit, and a very high battance index. Class 2 is the most developed (41.28%), and coincides with forests, agricultural lands, and Numidian sandstones. Class 1 represents 24.75% and characterizes bare land, forests, sandstone terrain, and soils with low and very low battance index classes. Class 0 (32.1%) coincides with watercourses, forests, colluvium, and soils with a very low battance index.

C. P Parameter

The development of the map for this parameter depends on two subparameters: slope intensity (Pi) and slope curvature (Pc). The analysis of the P parameter map (Fig. 11) demonstrates that the steep slopes belonging to class 4 (slope > 10°) are located mainly on ridgelines, whereas class 0 (slope < 1.5°) characterizes the reservoir of the dam. The other classes (1, 2, and 3) are generally scattered in the center of the watershed.

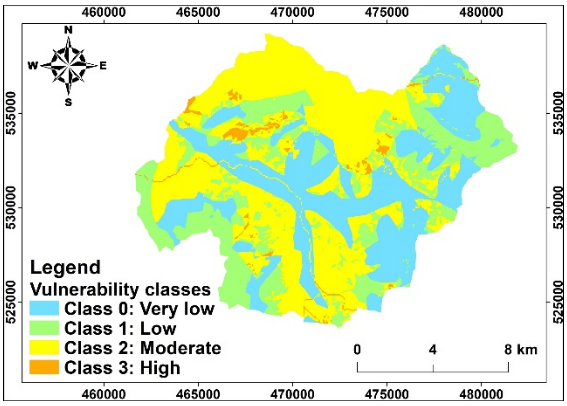

Fig. 10. Vulnerability map of K parameter.

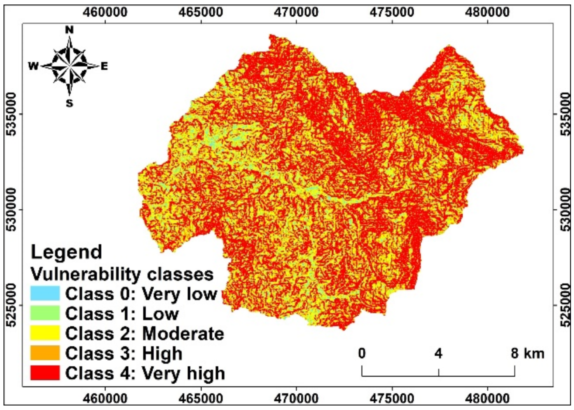

Fig. 11. Vulnerability map of P parameter.

D. R Parameter

The rainfall erosivity index classes for the Kharroub River watershed are shown in Fig. 12. Class 1 of the R index (2000<*R*<3000), located on the Western side, occupies 74.91% of the total watershed surface. Class 2 (3000<R<4000), being on the Eastern part, covers 25.09%.

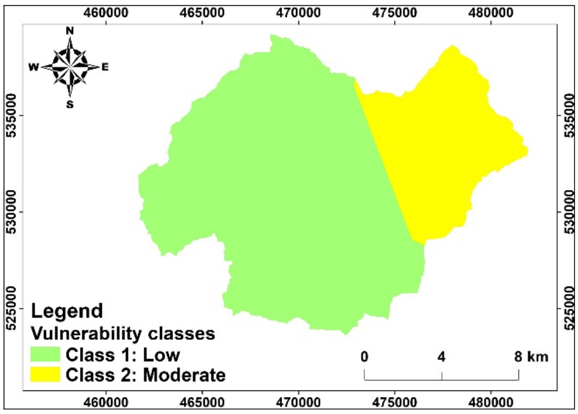

Fig. 12. Vulnerability map of R parameter.

E. Final Vulnerability Map of the Study Area

The final vulnerability classes map of the Kharroub River watershed is shown in Fig. 13. Based on this map, five classes have been identified. The very high vulnerability class is the least developed one (0.1% of the total watershed area). It is mainly associated with slopes greater than 10°, distances of less than 50 m from the hydrographic network, discontinuous urban tissues, and punctual anthropogenic activities. The high vulnerability class represents 15.23% and is attributed to discontinuous urban tissues and unforested terrain. It characterizes the areas closest to the hydrographic network and the steepest areas, which favor the lateral water flow and the erosion processes, and consequently, the exposure rate of water resources to pollution increases. The Moderate vulnerability class accounts for 56.99% of the watershed area. It is mainly related to unforested terrain and scattered forests, which generally develop at distances ranging from 100 m to 200 m from the hydrographic network. The low vulnerability class represents 26.91% of the surface of the study area. It is mainly associated with areas with a low degree of erosion, dense forests, and very low slopes, ranging between 1.5° and 3°. This class coincides with permeable geological formations, mainly colluviums that promote the migration of a large part of surface water to depths, which minimizes the contamination of these resources by pollutants. The class with very low vulnerability represents only 0.77%. It mainly covers colluvial terrain and areas with slopes less than 1.5°, which explains the absence of erosion processes in these areas while reducing the pollution rate of water resources.

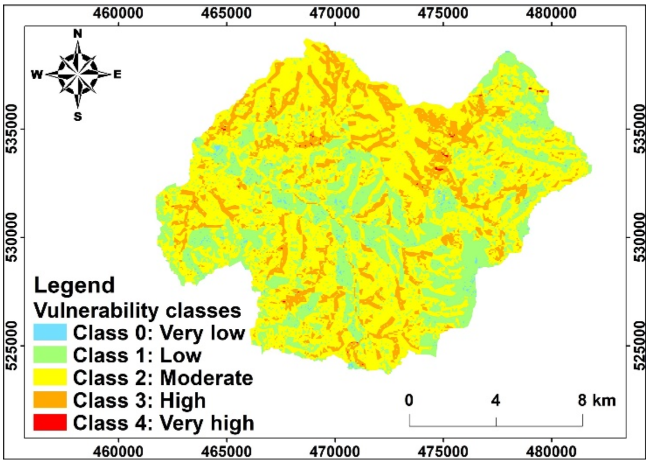

Fig. 13. Vulnerability map to surface water contamination of the Kharroub River watershed.

V. Discussion

The vulnerability degree of the surface water of the Kharroub River watershed is strongly controlled by the parameters K and D, as they have high weighting factors (0.4 and 0.3, respectively). The effect of parameter R on the final vulnerability map is weak because it has only two vulnerability classes throughout the watershed (classes 1 and 2), and its weighting factor is low (0.1). The water vulnerability to contamination in the study area is moderately influenced by the slope parameter, even though its weighting factor is relatively low (0.2), as the slope is a parameter that determines the acceleration or deceleration of pollutant migration. The obtained results match, to a great extent, the results obtained for the 9 Avril 1947 dam watershed [31, 32], which is located next to the Kharoub River watershed. This matching of results is due to the fact that both watershed areas are located in the same region (Tangier province) and are, therefore, subject to the same climatic, geological and hydrological conditions. The areas most vulnerable to contamination represent 15.33% of the total surface area of the study area. They mainly coincide with the steepest areas, with areas close to the hydrographic network, and with impermeable geological formations. These factors increase the vulnerability rate more than anthropogenic activities, which are less frequent in the study area.

In this context, a previous study of the surface water vulnerability mapping was established in the Kharroub River watershed by applying the Surface Water (SW) method [14]. A comparison between the two vulnerability mapping methods, SW and DKPR, reveals significant differences. The SW method is based on three key parameters: the soil functioning hydric, the hydrographic network density, and the importance of agricultural drainage. This generated a final vulnerability map showing four classes. In contrast, the DKPR method uses four main parameters and five subparameters, enabling the identification of five classes with high precision. Both maps indicate the dominance of moderate and low vulnerability classes in the study area, although their percentages vary slightly from one method to another. There is another method that has been used in the Kharroub River watershed, known as the RUSLE method [26]. It is used to quantify soil losses due to water erosion and to spatially identify priority intervention areas in the study area. This approach integrates five factors: rainfall erosivity (R), soil erodibility (K), slope Length and Steepness (LS), cover-management (C), and soil conservation practices (P) [24, 25]. The study revealed that most of the watershed, 66.61%, was affected by very high to excessive soil erosion, which influences the quality of soil and water resources in the watershed. The two approaches, DKPR and RUSLE, have marked similarities in terms of the parameters considered, such as rainfall erosivity, soil erodibility and watershed physiography. However, the difference lies in the qualitative nature of the DKPR method, which assesses vulnerability to anthropogenic and natural contamination. In contrast, the RUSLE method adopts a quantitative approach, focusing on mapping areas at risk of natural water erosion, while analyzing controlling factors and quantifying soil losses on a regional scale. These two methods offer complementary perspectives for understanding the vulnerability of water resources. However, the key advantage of the DKPR method is the detailed approach to the parameters used for a more accurate mapping of surface water vulnerability.

VI. Conclusion

According to the DKPR method, the vulnerability of the Kharroub River watershed is characterized by the dominance of moderate and low classes whereas the very high and very low classes are the least representative. This distinction of vulnerability classes is due to the integration of several parameters, such as the influence of the lithology of geological formations, particularly their permeability, and the proximity or distance from the pollution sources. Slope intervenes in the phenomena of erosion and runoff owing to its shape and inclination. Precipitation carries the pollutants towards the soil, after the atmospheric leaching and accelerates the dissolution of certain pollutants. This study takes an innovative approach by integrating these factors, thus providing a holistic view of environmental vulnerability. It facilitates the process of identifying and classifying areas vulnerable to contamination, ensuring their zoning for optimal protection. In addition, this approach enables the effective implementation of the main qualitative resource management strategies, thereby strengthening watershed control and preserving dam water quality, while avoiding excessive treatment costs. In summary, this research provides valuable tools for sustainable management of the region's water resources.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Y. Touiss conducted the research, collected, and analyzed the data, and wrote the paper. M. Draoui revised and corrected the paper. K. Qarqori, F. Laghrib, and T. Bahaj provided critical revisions and final approval of the article. All authors have approved the final version.

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