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Chapter

Spatial Analysis of the Erosive Hazard of Soils and Natural Risks of Reservoir Siltation

Rabii El Gaatib and Abdelkader Larabi

Abstract

The initial state of several watersheds, in West Africa, is characterized by a socio-ecological vulnerability linked to the water erosion risks. Thus, the Oued Beht watershed (430,728 ha), which is located in Morocco, reveals the extent of impact of soil erosion and water quality degradations. Especially, the consequences of soil loss alter its hydrological behavior in terms of efficiency to produce good water quality and include damages to the functional activities (agricultural and forestry) and structural challenges (lands and dams). This study suggests a methodology, reproducible and generalizable, to assess the water erosion risks. The results show that the erosion process is characterized by the combination of several types of erosion including sheet, rill, and gully. Therefore, the soil erosion is active and visible on more than 3/4 of the Oued Beht watershed, and the spatial analysis evaluates the soil loss which generates a decrease in the storage capacity of El Kansra dam (-3.03 million m^3/year). The erosion risk management is evaluated by combining susceptibility maps with an analysis of potential consequences. Moreover, the interactive mode obtained from this work is based on a statistical autocorrelation approach concerning risk factors in order to delimit the areas requiring priority planning (hot spots).

Keywords: soil erosion, watershed, hot spots, spatial autocorrelation, risk management

1. Introduction

The soil erosion characterizes the majority of Morocco reliefs, and a spectacular expansion of erosion processes reveals more disturbing aspects. Thus, the soils degradation upstream is the origin of siltation phenomenon and decreasing storage capacities of dams with 50 million m^3/year [1]. Particularly, the erosion hazard imposes significant costs on the Moroccan economy by reducing soil productivity and the consequences are manifested by dam siltation downstream.

In this sense, the results obtained in the first phase of this study have shown the importance of erosion in Oued Beht watershed revealing that combined forms are meaningful (sheet, rill, and gully) and many factors, both physical and human, promote erosion risk. Moreover, the human context is generally characterized by high density of rural population [2, 3].

In this perspective, this study provides a roadmap relating to biophysical, hydrological, and socio-economic backgrounds to develop a dynamic methodology that will identify and visualize development scenarios. The specific objectives that are identified include the following:

- Analyzing the biophysical context and highlighting the environmental potentialities and constraints.

- Developing the spatial modeling of soil and water degradation processes with integration of empirical models in a GIS environment to determine the potential soil loss.

- Prescribing the strategic orientations of Master Plan Management to allow the sustainability of the main actions linked to erosion control.

- Defining the action plan to be used in priority areas and identify the biological measures and appropriate soil conservation practices to be implemented in order to mitigate negative effects of erosion hazard.

2. Study area

The Oued Beht watershed is located upstream of El Kansra dam (85 km east from Rabat), which crosses the Central Highlands and the Middle Atlas of Morocco (**Figure 1**). The main stream is Oued Beht, affluent of Sebou river, one of the most important watersheds in the kingdom. Thus, the watershed overlaps the administrative territory erected into 5 provinces and 26 rural communes (**Figure 2**).

The delimitation of the watershed in the geographic information system (GIS) provides a total area of 430,728 ha with an elongated form (**Figure 2**). It owns a developed urban system, occupying a central place in socio-economic
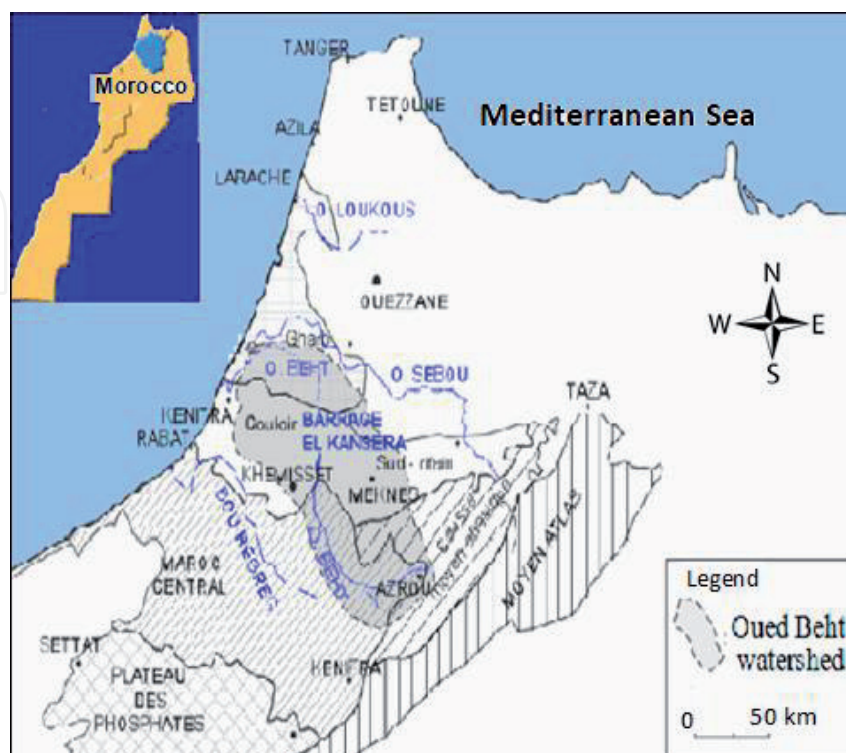
Figure 1.
Localization of the study area inside Morocco country.
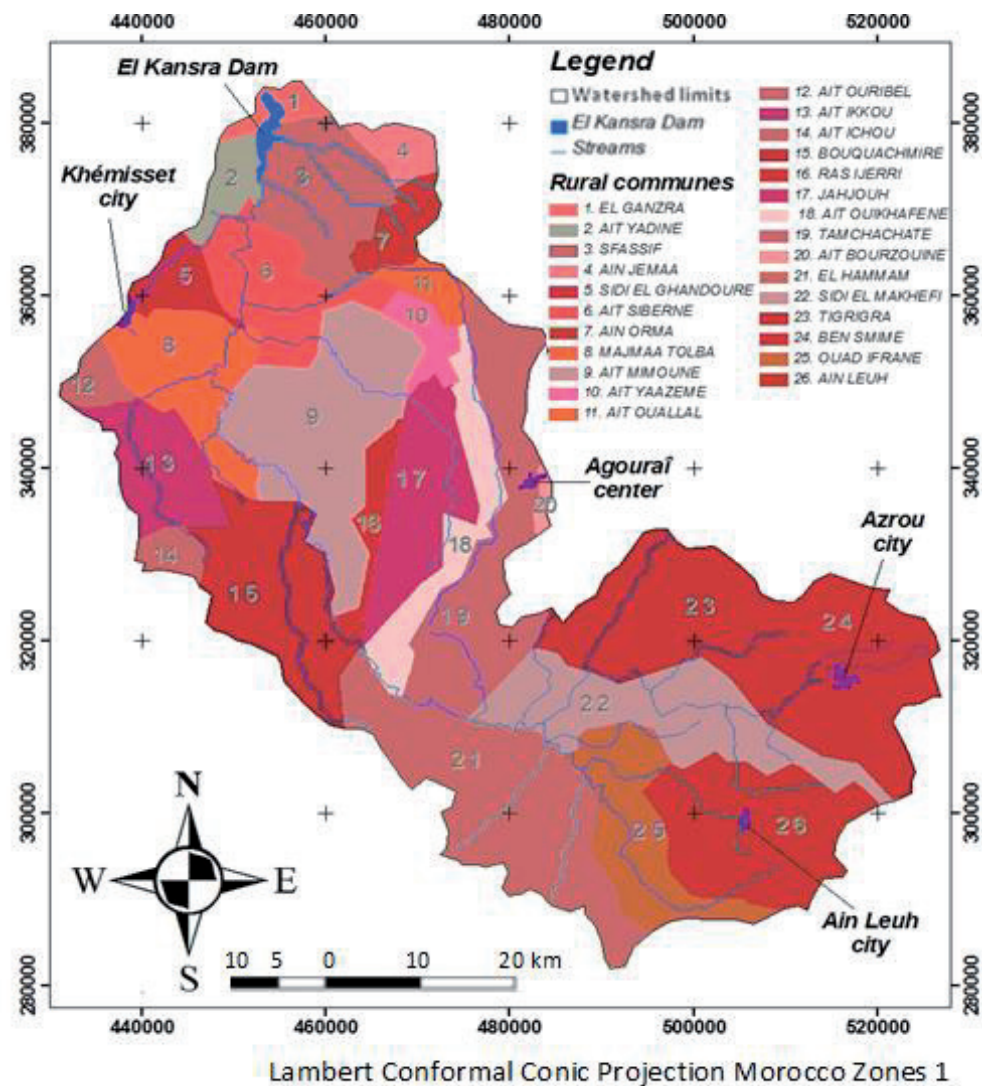
Figure 2.
Distribution map of rural communes in the Oued Beht watershed.

activities; it is Khemisset city (542,000 inhabitants), Azrou (47,540 inhabitants), and urban centers of Agourai and Ain Leuh [4]. Concerning climate context, the watershed presents characteristics of Mediterranean climate with a rainy winter and a dry summer [5].

The coordinates of the map (longitude is x and latitude is y) are described in a map projection. Thus, the cartographic representation of the whole watershed surface on a two-dimensional map (X, Y) is based on the use of the Lambert conformal conic projection. Consequently, the Oued Beht watershed is located between the rectangle designated by the following Lambert coordinates: (X1 = 430,347, Y1 = 282,142) and (X2 = 527,857, Y2 = 383,572).

3. Materials and methods

The adopted methodological framework allows meeting the specific objectives of this study. Indeed, the guidelines of this strategic watershed management are based on critical analysis of the current situation and the definition of predictive interventions to revitalize natural ecosystems and to develop pastoral resources in order to support the local population needs of forage and fuelwood.

In this perspective, the spatial aggregate functions are used to identify priority areas by statistics combination of significant values in the GIS database obtained in

previous work on this study linked to biophysical and hydrological environments. The hot spot analysis is used to calculate the Getis-Ord Gi* statistics for each feature related to erosion hazard zoning from neighboring entities in spatial data set [6].

3.1 Mapping of erosion susceptibility

The input data preparation and spatial analysis of projected actions to control soil loss hazard are performed in the GIS environment (ArcGIS 9.3). Thus, the biophysical and hydrometeorological data assessment is based on empirical models to produce decisional maps of the priority areas to be developed.

3.1.1 Biophysical and hydrometeorological data

The data used for the soils susceptibility analysis are divided into five groups of explanatory variables (R, K, LS, C, and P). These are climatic, geomorphology, topography (gradient and length slopes), geological and geomorphological data, hydrographic parameters (river density, distance to streams), and soil occupation. Thus, thematic maps are produced by geoprocessing of information obtained.

The map of climatic aggressiveness is extrapolated from climatic data available in the stations characterized by long observation periods more than 20 years. Therefore, the topographic parameters (LS) are derived from the Digital Terrain Model DTM Aster, and planimetric and altimetric accuracies are, respectively, 30 and 20 m. The interpretation of the soil characteristics is used also to classify soils in the Wischmeier Abacus and to approach erodibility factor [7, 8]. Furthermore, the land cover map is extracted from SPOT satellite images (resolution is 20 m) combined with recent Landsat ETM+ imagery through the supervised classification method and field observations.

3.1.2 Decisional maps

Soils susceptibility assessment corresponds to the spatial occurrence of soil loss (number of representative pixels) that has taken place under the impact of local environmental conditions. Thus, the analytical approach adopted is based on simulation models integrated with GIS tools in order to evaluate the behavior of the dependent variable (land loss location) from a spatial combination of predictive variables in homogeneous geomorphic units (pixels). The soils susceptibility is simulated by the Universal Soil Loss model [9, 10], considered the most robust approach for spatial assessment of the soil erosion hazard (A). Moreover, the basic hypothesis is that the potential soil loss will be triggered under the same conditions as in the past.

$$A = R \times K \times LS \times C \times P \tag{1}$$

where A is the mean annual soil loss (t ha^{-1} year^{-1}), R is the rainfall erosivity factor (MJ.mm.ha^{-1}.h^{-1}.year^{-1}), K is soil erodibility factor (t.h.MJ^{-1}.mm^{-1}), L and S are the slope-length and the slope-steepness factors (dimensionless), C is the cover and management factor (dimensionless), and P is the support practice factor (dimensionless).

Second, hydrometeorological study is used for flood sites. The flood hazard is one of the most destructive natural hazards of the environment that can cause severe social as well as economic losses. In majority situations, the modern methods

of passive and active flood protection provide rational protection for people and property within watersheds. Consequently, the refinement of probabilistic and technical methods is totally justified.

The flood analysis is based on the dependence applied in the Francou-Rodier model [11] and on the distribution function characteristic of the extreme values. This approach is the most widely used in Morocco, as a regional empirical formula that has the advantage of making the flow value, with the defined exceedance probability, dependent on the basin area function.

The possibility to estimate the biggest possible flood that could appear during the extreme conditions is the significant element of the estimation of the potential hazard. Therefore, the Gradex model determines the flood flow characteristics and the regional parameter (k_t) in a gauged station located in the Oued Beht watershed [12]. Subsequently, the data obtained are extrapolated to the other sub-catchments by Francou-Rodier method, based on the regional coefficient (k_t) calculated in the gauged station called Ouljet Soltane [11].

Below, the two significant formulas, which enable the estimation of the form of the maximum flows envelopes, are described:

$$\frac{Q(t)}{Q_0} = \left(\frac{S}{S_0}\right)^{1-\frac{k_t}{10}} \tag{2}$$

where Q(t) is the maximum flow value in the ungauged sub-catchment (m^3/s), S is the area of ungauged sub-catchment (km^2), Q_0: 10^6 m^3/s, S_0: 10^8 km^2, and k_t is the parameter of Francou-Rodier, which is a regional parameter in the right of the gauged station (called Ouljet Soltane station).

Therefore, the first step consists in calculating the Francou-Rodier parameter (k_t), by using the flow Q_A for a determined return period, in the Ouljet Soltane gauged basin, whose area is S_A. Considering the data available on the gauged basin, the flow Q_A is calculated by the Gradex method.

$$k_t = 10 \times \left[1 - \frac{\ln\frac{Q_A}{10^6}}{\ln\frac{S_A}{10^8}}\right] \tag{3}$$

where Q_A is the flood flow in the gauged sub-catchment (m^3/s) and S_A is the area of the gauged sub-catchment of Ouljet Soltane (km^2).

The final map is the result of geoprocessing by spatial crossing of information linked to soils degradation by natural erosion and flood power to contribute to El Kansra dam siltation. As a result, the production of this qualitative map is used to provide a systematic vision to identify priority areas with homogeneous environmental characteristics and to study the alternatives of development upstream/downstream.

3.2 Socio-economic analysis

The methodological protocol used to characterize the socio-economic aspect is based on survey data [2, 3]. Thus, the analysis of mechanisms essentially linked to lifestyle needs and household income is used to better understand the socio-economic vulnerability in the watershed. The aim is to prepare a reference situation for the future socio-economic or environmental project.

The surveys are conducted in homogeneous areas using some direct conversations with groups surveyed (focus-group), with a freedom to structure the interview to better understand the population profile, their real needs, and to identify constraints that limit wealth production (natural, financial and commercial

constraints, land structures, and incomes). Moreover, spatial distribution of the farms (units to investigate) is selected using a stratified sampling plan with 5% error and 95% confidence level. The randomness of the villages (sampling units) is made from the list available in the general agricultural census [13]. Based on the number of households in the watershed studied (19,987 farmers), the number of farmers to be interviewed is 378 in 50 villages.

Consequently, in order to reduce the heterogeneity linked to utilized agricultural land (UAL), which represents a discriminatory factor for management techniques and income sources, the stratification is performed according to farm size, and three classes are selected (UAL < 5 ha, 5 ha < UAL < 15 ha, and UAL > 15 ha).

3.3 Potential consequences

The potential consequences are evaluated by an analytical approach based on the identification of the exposed elements and the assessment of their vulnerabilities. In this approach, the potential damages are not expressed in numerical values but in hierarchical classes (qualitative assessment). The consequence typology differs: (1) direct structural damages (CS) affecting the land goods and the El Kansra dam and (2) direct functional damages (CF) related to disruption of agricultural activities with local and immediate consequences.

The consequence assessment is a fundamental part of erosion risk analysis. Thus, the various components of the vulnerability are structured according to a decreasing exponential function. Moreover, the vulnerability analysis is based on the observation protocol of damage, original and reproducible, applicable to the soil loss analysis due to past erosion events. The erosion cost is defined by the difference between the initial net revenue per hectare and the net revenue with the effect of erosion:

$$R_t = R_0 \, e^{-xp(t)} \tag{4}$$

where R_t is the yield in the year t (t/ha), R_0 is the initial yield (t/ha), x is the damage coefficient (yield loss parameter), and p(t) is the cumulative land loss in the year t (t/ha).

The vulnerability input is based on the results of socio-economic surveys describing the current yields (or revenue) and the latest census data available in the Office of the High Commissioner for Planning (HCP), the government agency in charge of producing statistics [3, 14–16]. Thus, the damage process typology helps to prioritize the consequences classes: low (C1), moderate (C2), high (C3), and very high (C4).

3.4 Erosion risk assessment

On the technical side, the terms "risk" and "hazard" are linked to each other but should be clearly distinguished. The risk mainly signifies a probability of the occurrence of (negative) impacts and expected losses resulting from a given hazard to a given element at danger or peril, over a specified time period.

Therefore, the purpose is to hierarchy the erosion menace that compromises land goods, human activities, and property of people. Thus, the analysis of the soil degradation levels obtained allows to prioritize the susceptibility classes: low (S1), moderate (S2), high (S3), and very high (S4).

In addition, the spatial combination of susceptibility (S1 < S2 < S3 < S4) and potential consequence (C1 < C2 < C3 < C4) are translated into risk classes using a correlation matrix of double entries [17]. Consequently, the erosion risk classes are prioritized in order to guide planning decisions (**Figure 3**): low (R1), moderate (R2), and strong (R3).
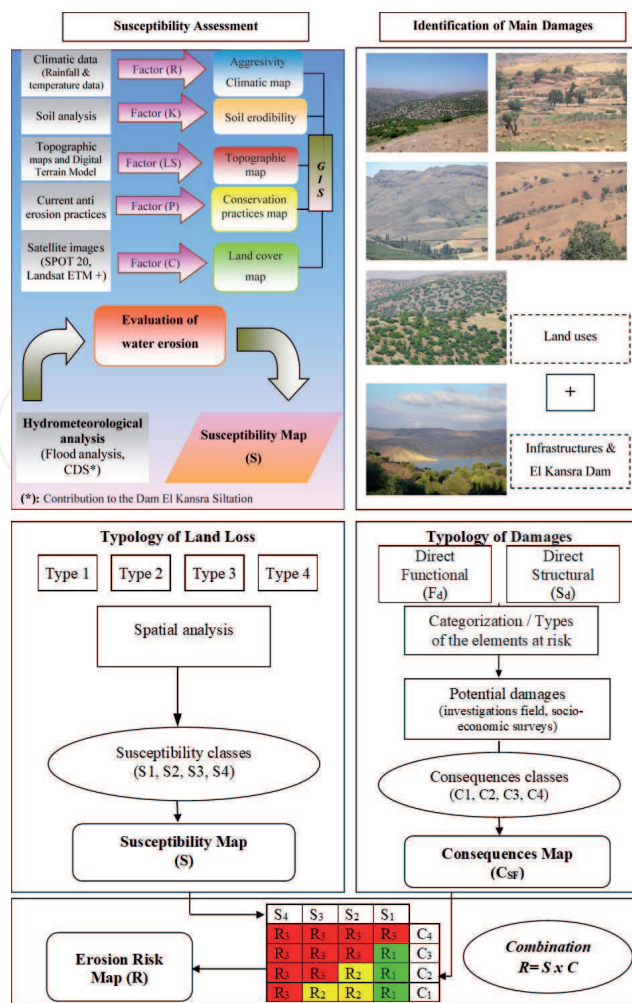
Figure 3.
The methodological flowchart to identify priority areas and evaluate soil erosion risk.

3.5 Watershed management plan

Using the analysis of the existing opportunities in Oued Beht watershed, the present master plan is based on an action program focused on erosion control. Indeed, the identification of the package of management actions is based on the diagnosis results of biophysical and socio-economic backgrounds. Thus, the management approach of priority areas is based on operational actions (biological and technical treatments) that are compatible with the intrinsic characteristics of the watershed studied. In this sense, the objectives that promote the action plan are as follows:

- Bioengineering techniques for soil erosion protection and slope stabilization to conserve natural resources upstream and to protect El Kansra dam against siltation.

- Reconstruction of degraded ecosystems to promote biodiversity conservation.

3.5.1 Strategic planning

The long-term planning is used to establish the framework and key elements of Oued Beht watershed and to reflect a clear vision created in an open process. Guidelines for the many departments which will draw up specific plans will be

established. Thus, the key elements are reviewed for potential effects with uniform land uses (agricultural, rangelands, and forest).

The interventions program includes the conservation actions and environmental rehabilitation. The measures selected are grouped into the following categories: agricultural land use, rangelands management, forest management, river system protection, and ravines treatment.

3.5.2 Priority planning

The Hot Spot Analysis tool calculates the Getis-Ord Gi* statistic for each feature in a spatial data. The resultant "z-score" (standard deviation) tells us where features with either high or low values cluster spatially. This tool works by looking at each feature within the context of neighboring features. A feature with a high value is interesting, but may not be a statistically significant hot spot. Thus, to be a statistically significant hot spot, a feature will have a high value and be surrounded by other features with high values as well. The local sum for a feature and its neighbors is compared proportionally to the sum of all features; when the local sum is much different than the expected local sum, and that difference is too large to be the result of random chance, a statistically significant "z-score" results.

The Gi* statistic returned for each feature in the dataset is a "z-score." For statistically significant positive "z-score," the larger the "z-score" is, the more intense the clustering of high values (hot spot); and for statistically significant negative "z-score," the smaller the "z-score" is, the more intense the clustering of low values (cold spot).

In this study, the use of the statistical method "Getis-Ord Gi*" allows the analysis of each entity (pixel) in relation with neighborhood in the spatial dataset [6]. The nearest neighbor analysis is based on comparing the distribution of the distances from each data point to its nearest neighbor in a given dataset with a randomly distributed dataset.

Indeed, this statistical approach tells us if we may reject or not the null hypothesis CSR (complete spatial randomness) that expresses the absence of spatial correlation between the following events: 1) significant soil loss and degraded vegetation cover and (2) soil erosion and steep slopes. Thus, the results, expressed in "z-score" (standard deviation) and "p-value" (independence probability), are used to measure the statistical significance of spatial autocorrelation (**Figure 4**).
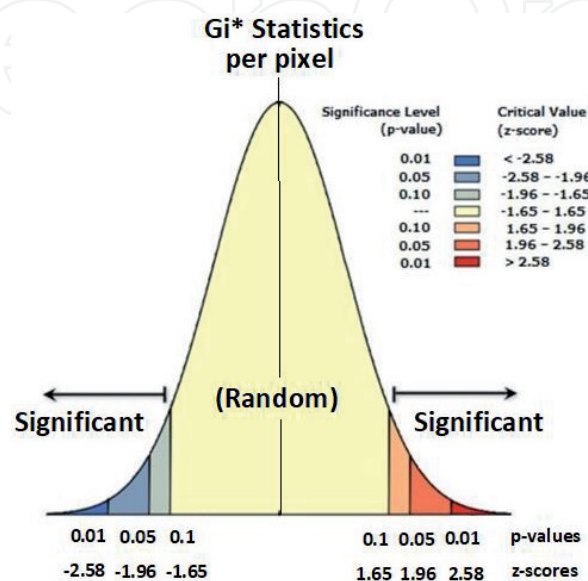
Figure 4.
Distribution of spatial autocorrelation indicators (adapted from [18]).

Furthermore, for confidence level 90%, if the z-score obtained is between −1.65 and +1.65, the probability of independence (p-value) will be automatically higher than 0.10 and the null hypothesis of independence is not rejected [18]. Thus, the biological actions are programmed in areas with strong spatial autocorrelation (hot spot) between erosion hazard and vegetation cover; and technical measures correspond specially to areas with high spatial autocorrelation between the natural hazard and topographic factors that will be modified by the action plan.

4. Results and discussion

4.1 Biophysical factors analysis

4.1.1 Topographic context

The topography of the Oued Beht watershed is the result of factors with a combination involving topographic effect of altitudinal amplitudes, exposure, slope gradient, and slope length.

4.1.1.1 Hypsometric analysis

The spatial analysis of the digital terrain model (DTM) shows that the watershed has a regularly altitudinal distribution along its elongated form. Thus, altitudes classes obtained follow a decreasing gradient, from upstream to downstream, in perpendicular bands to the axis, which coincides with the flow direction of Oued Beht (**Figure 5**).
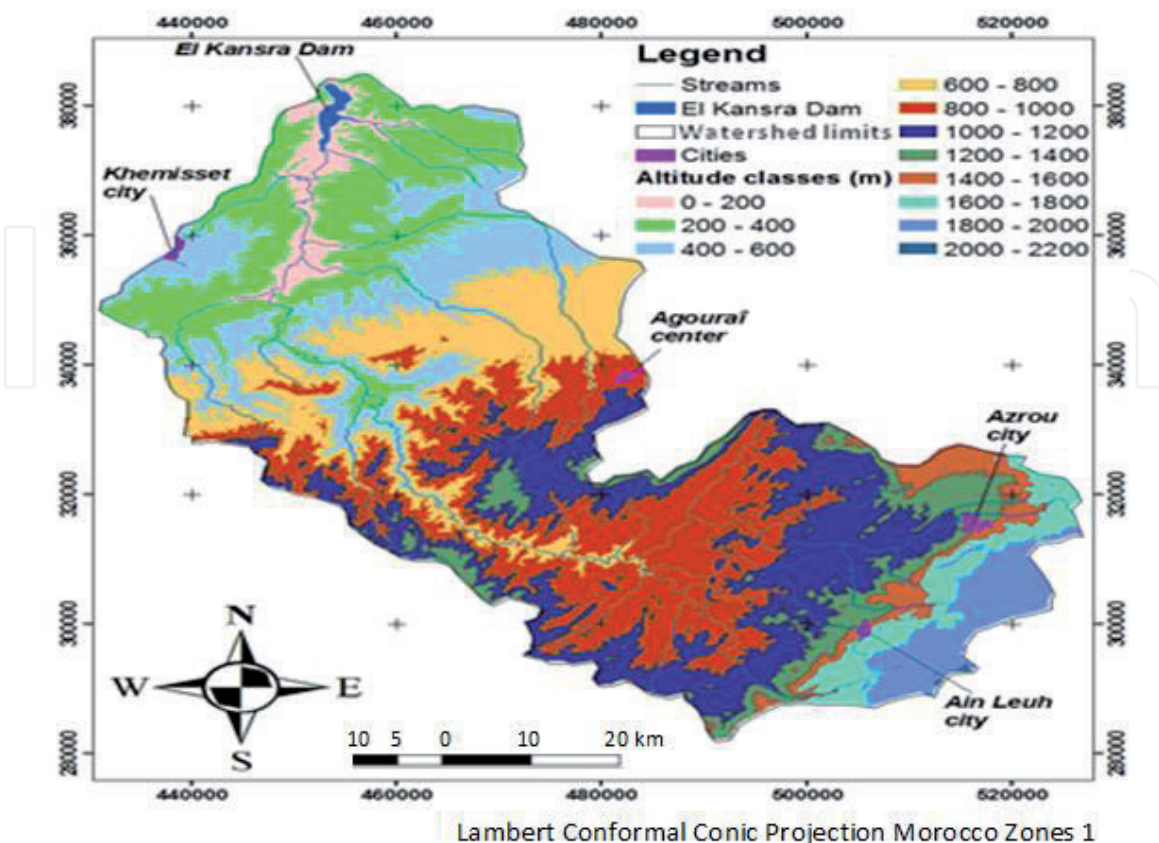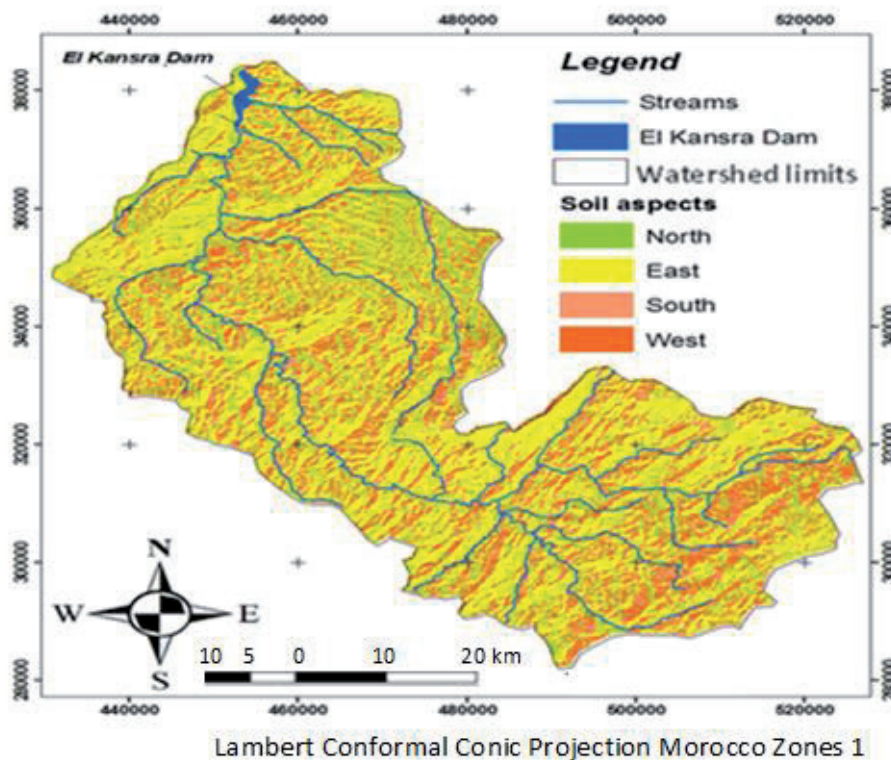

Figure 5.
Hypsometric map.

Figure 6.
Aspect map.

The watershed presents a high altitudinal range, between the highest point 2121 m and the lowest point 108 m, which coincides with the level of the El Kansra dam. Thus, the total length midline crossing the watershed is 177 km, and the altitude difference of 2013 m represents a real hydrologic indicator that promotes erosive process.

4.1.1.2 Soil aspects

The aspect map is used to establish the slope exposure of the watershed and to give an idea about the relief forms and the cover land. The distribution of soil aspects shows that east facing slopes dominate, particularly at upstream part of Oued Beht watershed (38%). However, the other exposures are equal, almost 20%, while specifying that the investigations show that the north and west slopes present a humid character. Furthermore, the areas representing a flat field (with 0% of slope) are limited and localized mainly in the small depressions or hilltops (**Figure 6**).

4.1.1.3 Slope gradient analysis

The DTM spatial analysis shows that the low slopes (less than 15%) are dispersed and occupy more than half of the watershed (57%). Thus, steep slopes are concentrated in central and upstream areas. The map of the slope length classes gives an indication of the transport distance traveled by soil particles detached. The slope lengths distribution shows that almost half of the watershed (55%) is less than 1000 m with a majority (30%) lower than 500 m (**Figure 7**).

In this sense, the digital terrain model (DTM) is the main source of data for the extraction of many parameters used such as slope lengths, direction of flow of
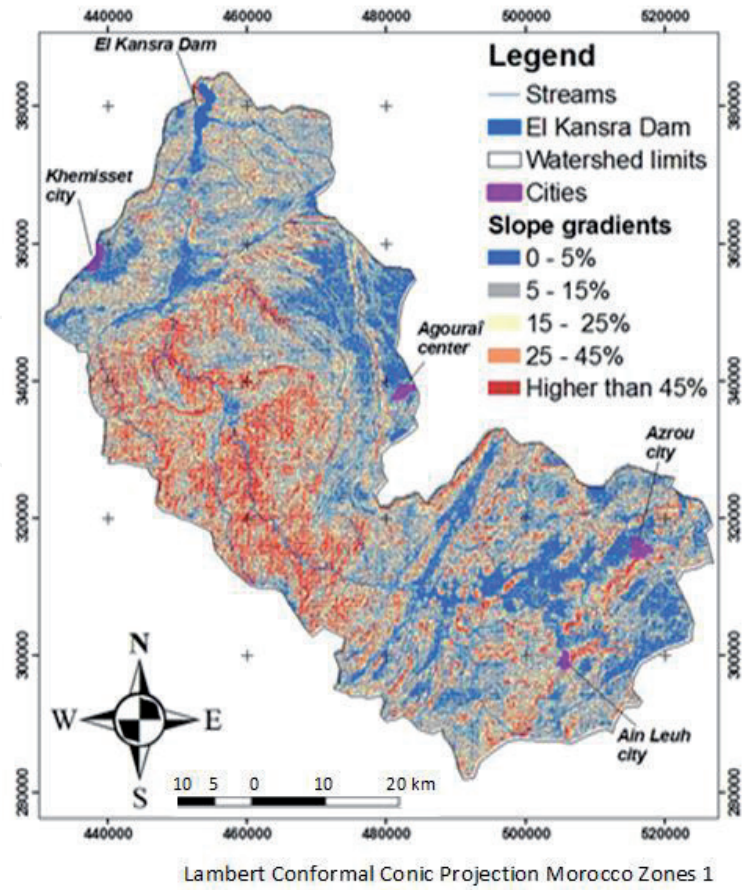
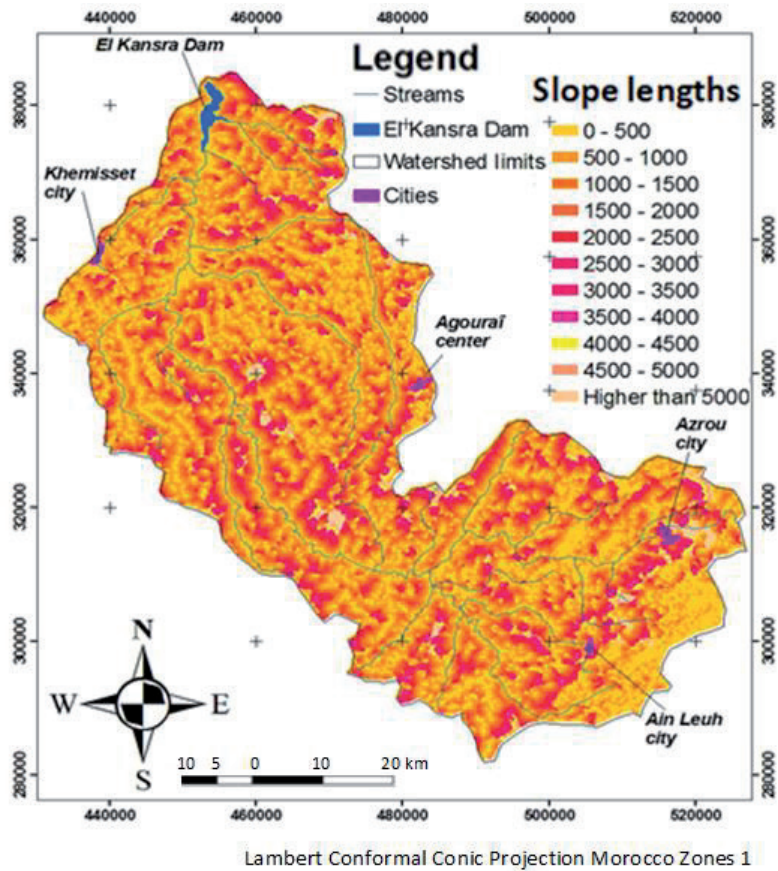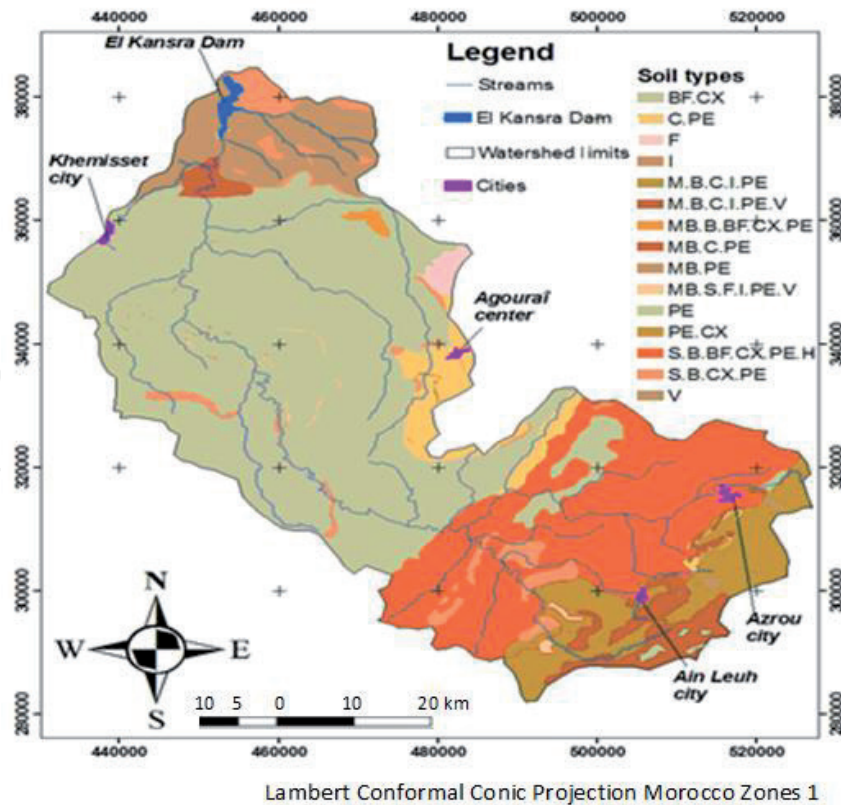**Figure 7.**
Slope gradient map of the study area.

Figure 8.
Slope length map.

Figure 9.
Soils map.

water, topographic index, etc. The spatial distribution of the slope length classes is heterogeneous, and no zone is characterized by a single slope length class (**Figure 8**). Also, their importance decreases to a minimum corresponding to the class exceeding 5000 m with only 1%.

In conclusion, the topographic factor analysis reveals the combination of slope length effects with slope gradient characterizing Oued Beht watershed.

4.1.2 Soil resources

The soil analysis in Oued Beht watershed shows a strong dominance (45%) of slightly developed soils (PE). This soil type is dispersed and used not only for agriculture and forestry but also in rangelands. Moreover, Brown soils (B) and Forest Brown (BF) soils are concentrated at the upstream where the forests are developed (6%). Thus, this kind of soil is enriched by the litter decomposition (**Figure 9**). Specially, the poor soils, characterized by the bedrock outcrop, are located near El Kansra dam and at the extreme south of watershed (upstream).

In conclusion, the watershed soils analysis shows the diversity and heterogeneity of pedogenesis factors. Thus, this diversification of soils is mainly due to bedrock types and their degree of friability, morphology, topography, climate aggression, and land use (**Figure 10**).

4.1.3 Hydrometeorological analysis

The geographical distribution of climate stations selected presents good spatial coverage and long periods of observation that allow an eminent climate analysis in Oued Beht watershed. The weather stations used to characterize the thermal regime and deduct bioclimatic classes are the stations of El Kansra, Khemisset, and Ifrane (**Figure 11**). In this way, the continentality is quite significant with a neat decrease
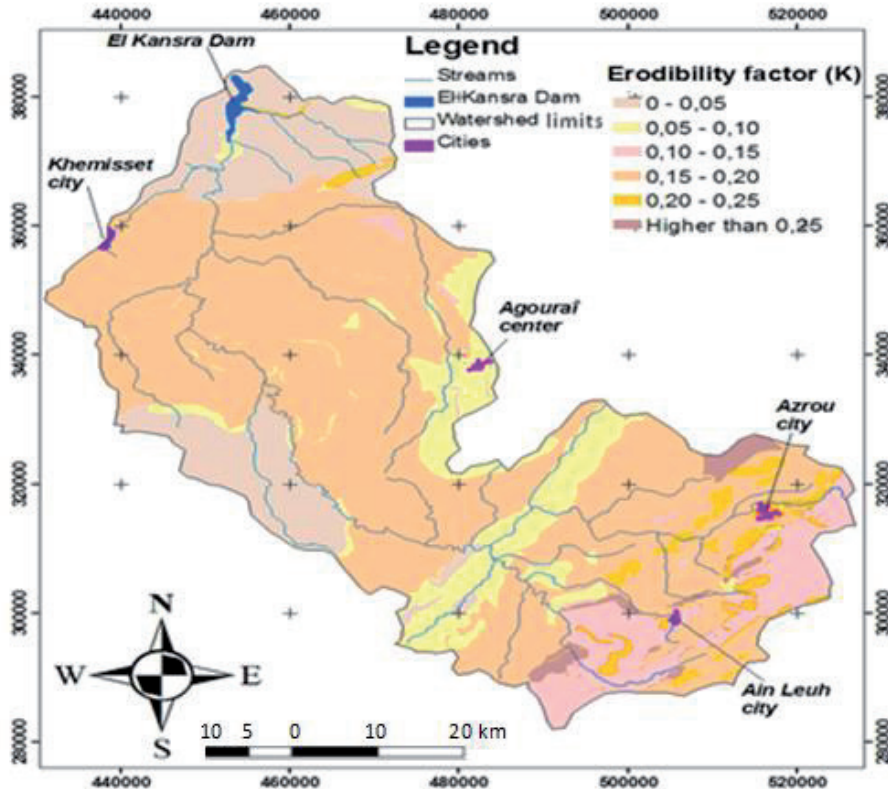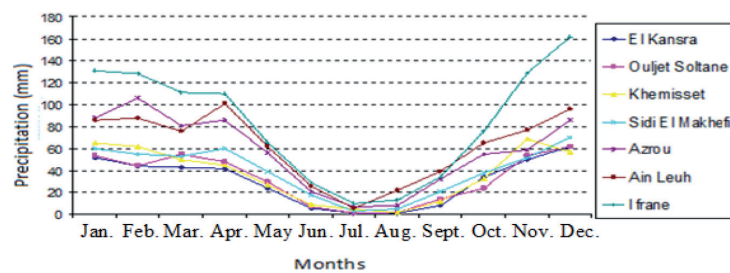
Figure 10.
Soil erodibility distribution.
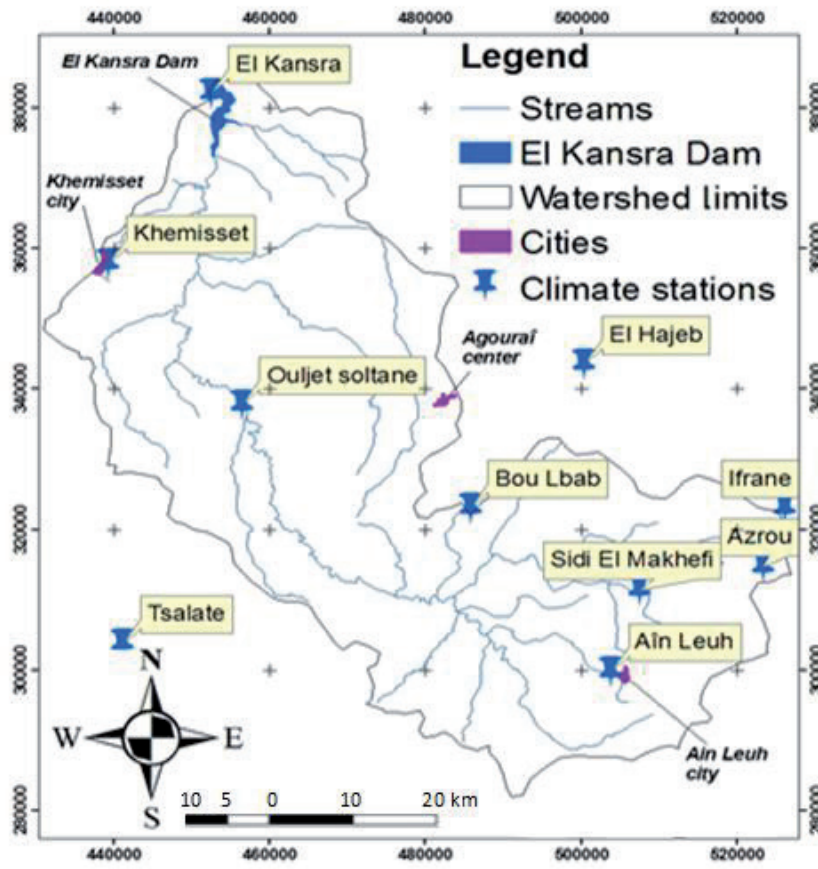
Figure 11.
Distribution of climate stations.

Figure 12.
Distribution of average monthly rainfall data by station.

in temperature associated with increasing altitude. Moreover, the thermal regime is characterized by average temperatures that vary between 10°C in the east and 26°C in the north and north-west. Thus, the studied watershed is influenced by altitude and latitude factors.

On the other hand, the rainfall regime is irregular and the rainy period is concentrated between October and May (**Figure 12**). As a result, the precipitation distribution analysis shows that the watershed has a rainy winter and a dry summer period. Therefore, the upland areas (mountains) are wetter than the areas that are close to the sea. Thus, the altitude effect on rainfall (R-factor) is more dominant than the approximation of the sea.

4.1.3.1 Bioclimatic synthesis

Bioclimatic data analysis is based on quotient Emberger index (Q2). This quotient, especially adapted to the Mediterranean regions, is based on the annual rainfall, the average maximum temperatures of the warmest month (M °C), and the average minimum temperatures of the coldest month (m °C) [19]. Thus, Oued Beht watershed is characterized by several bioclimatic architectures:

- In the north and northwest, the climate is semi-arid with temperate winter.

- In the center, the climate is sub-humid with temperate winter.

- The east of the watershed presents a humid climate with cold winter.

In addition to the data mentioned above, linked to altitudinal impact (2013 m), the watershed hydrological behavior is conditioned also by the bioclimatic changes affecting inevitably the nature of the developed vegetation, the resilience of different ecosystems, and intensity of erosion hazard.

4.1.3.2 Rainfall aggressiveness (R)

The rainfall erosive power, or the rainfall erosivity factor (MJ mm $ha^{-1} h^{-1} year^{-1}$), is calculated by the application of the formula using data of average monthly and annual rainfall in the selected meteorological stations [17, 20]. Thus, the rainfall aggressiveness values (R) are between 64 and 130, respectively, recorded at El Kansra and Ifrane stations. Moreover, in the east, the rains are more aggressive than in the north and west. Also, the upstream area shows the higher rainfall aggressiveness indexes (**Figure 13**).

In conclusion, the rainfall aggressiveness, associated with the heterogeneity of the rainfall distribution, is spatially variable and adheres to erosion processes [21, 22].
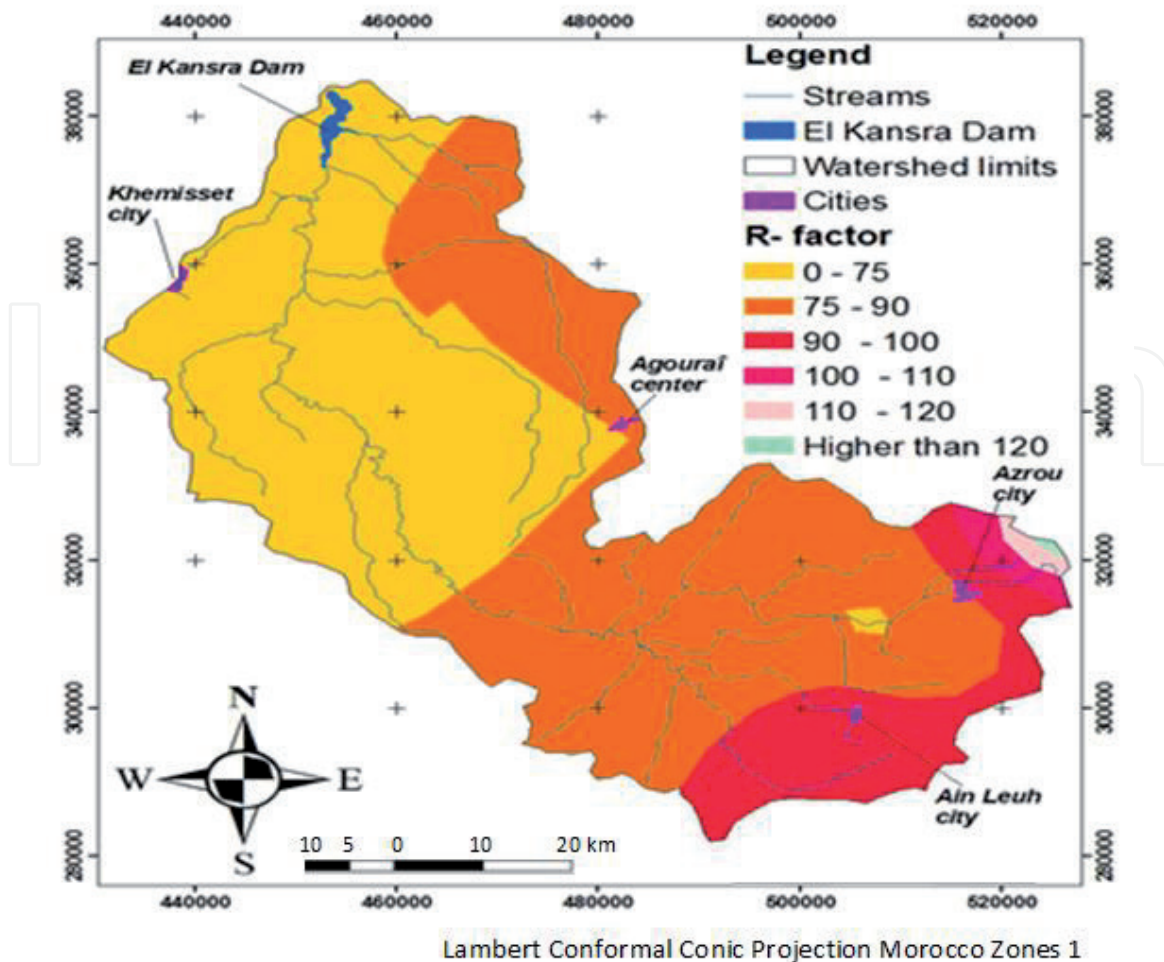
Figure 13.
R-factor distribution.

4.1.4 Land uses

The watershed has a variety of land uses related to the bioclimatic variation and topo-edaphical diversity. Thus, the rangelands area is the most common type of land cover (44%). Forests represent second place with 29%, reflecting the pastoral charac-ter of the watershed (**Figure 14**). Moreover, the forestry formations are concentrated mainly in the central and upstream. Furthermore, we note the presence of unplanted lands, covered by rocks, which are generally concentrated near the dam El Kansra.

4.1.5 Vegetation index

Normalized difference vegetation index (NDVI) is the most common measurement used for measuring vegetation cover. NDVI calculation allows to quantify vegetation by measuring the difference between near-infrared "NIR" (which vegetation strongly reflects) and red light (which vegetation absorbs), according to the following formula:

$$\text{NDVI} = \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red})} \tag{5}$$

The NDVI will be computed temporally to understand the change of land cover during the study period. It ranges from values −1 to +1. Thus, very low values of NDVI (−0.1 and below) correspond to barren areas of rock, sand, or urban/built-up. Zero indicates the water cover. Moderate values represent low density of vegetation (0.1–0.3), while high values indicate vegetation (0.6–0.8).

Lambert Conformal Conic Projection Morocco Zones 1
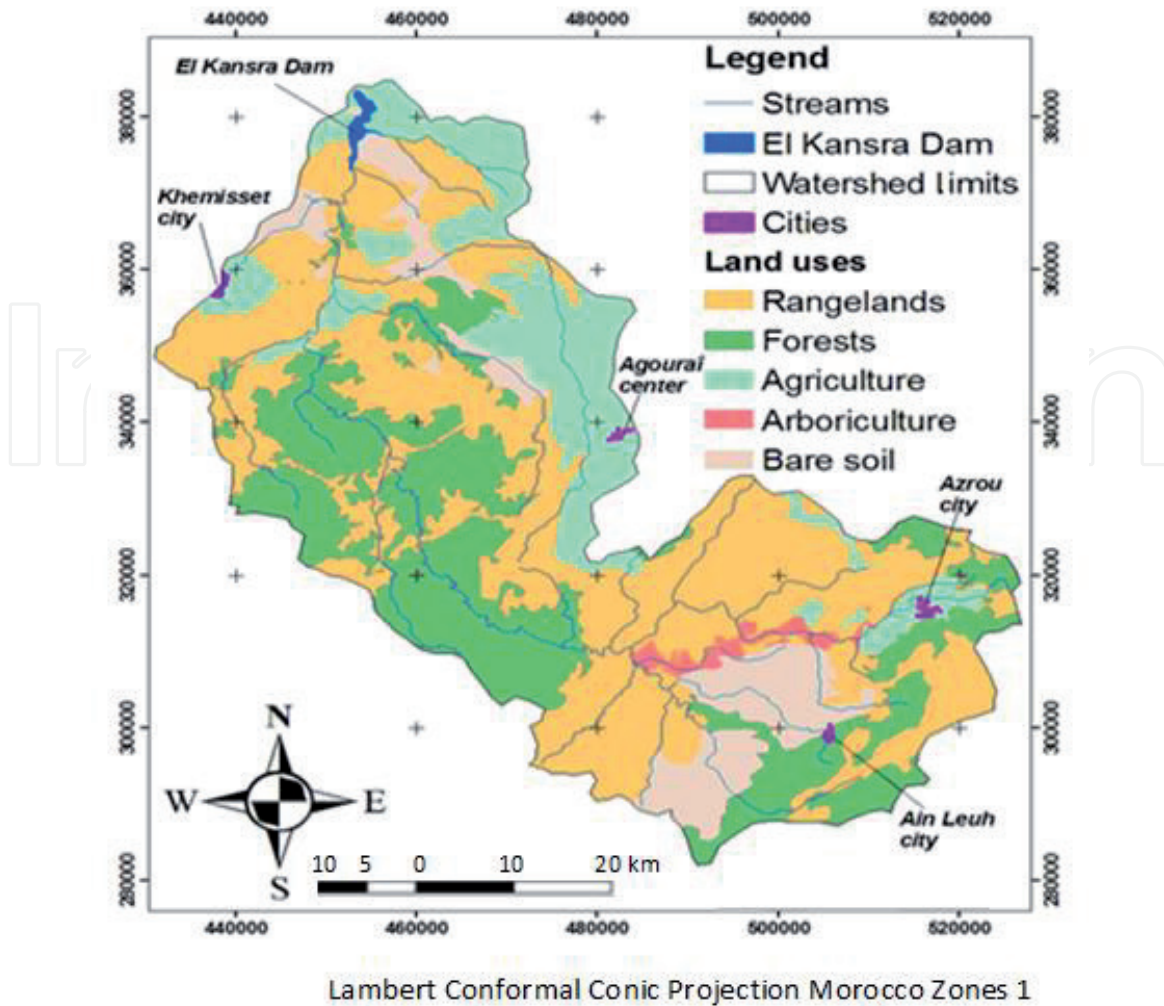
Figure 14.
Land use map.

The results obtained from the NDVI analysis show that the recovery rate is characterized by dominance of the low class, grouping generally rangelands and crop fields. Thus, both classes "low" and "very low" represent 72% of the total area. Consequently, this indicator reflects the low coverage capacity even if the land cover is almost complete and denuded soils rate is only 9.5% (**Figure 15**).

Moreover, agricultural lands are specially based on cereals and annual crops with short growing cycles. Thus, the rangelands consist of perennial grass vegetation with short development cycle. In conclusion, the land use duration is short, especially during periods of heavy rain.

The analysis of vegetation cover (C-factor) also confirms the low recovery rate. Thus, more than half of the watershed (55%) has a C-factor exceeding 0.5 and 72% has values greater than 0.2 (**Figure 16**). Therefore, these results are consistent with the biophysical analysis describing the low recovery rate.

In conclusion, this factor has a detrimental effect on the erosion process by promoting the sediments production in low soil coverage, and especially if it is combined with other determinant factors.

4.1.6 Hydrological behavior

The establishment of the hydrological system map, based on DTM spatial analysis, allows to determine the rivers' directions and the accumulation of their flow (flow accumulation). Indeed, the river system obtained is ramified along the entire watershed. Thus, it consists of the main stream named Oued Beht, which
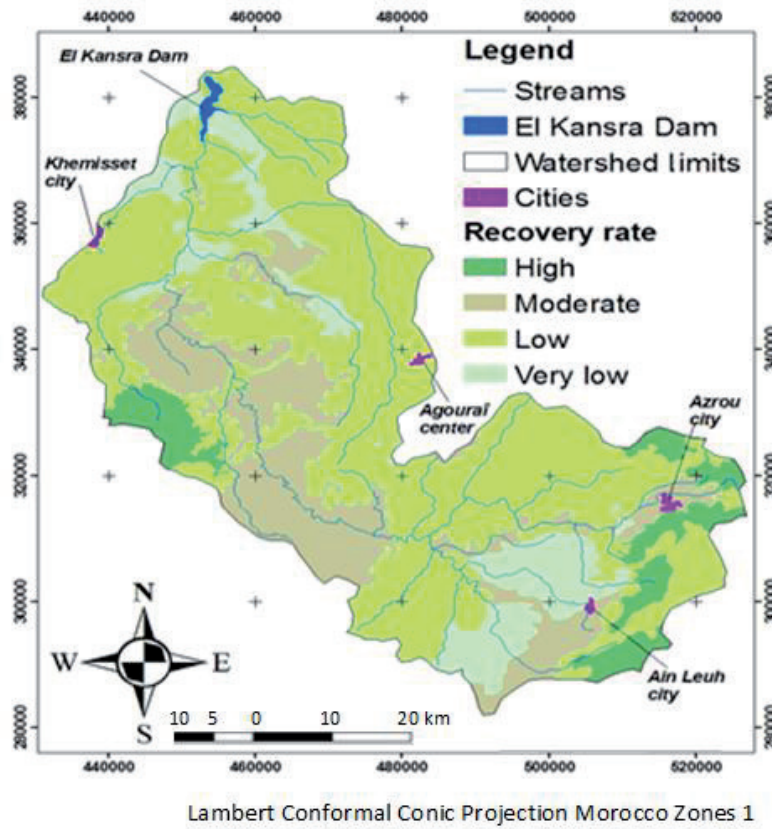
Figure 15.
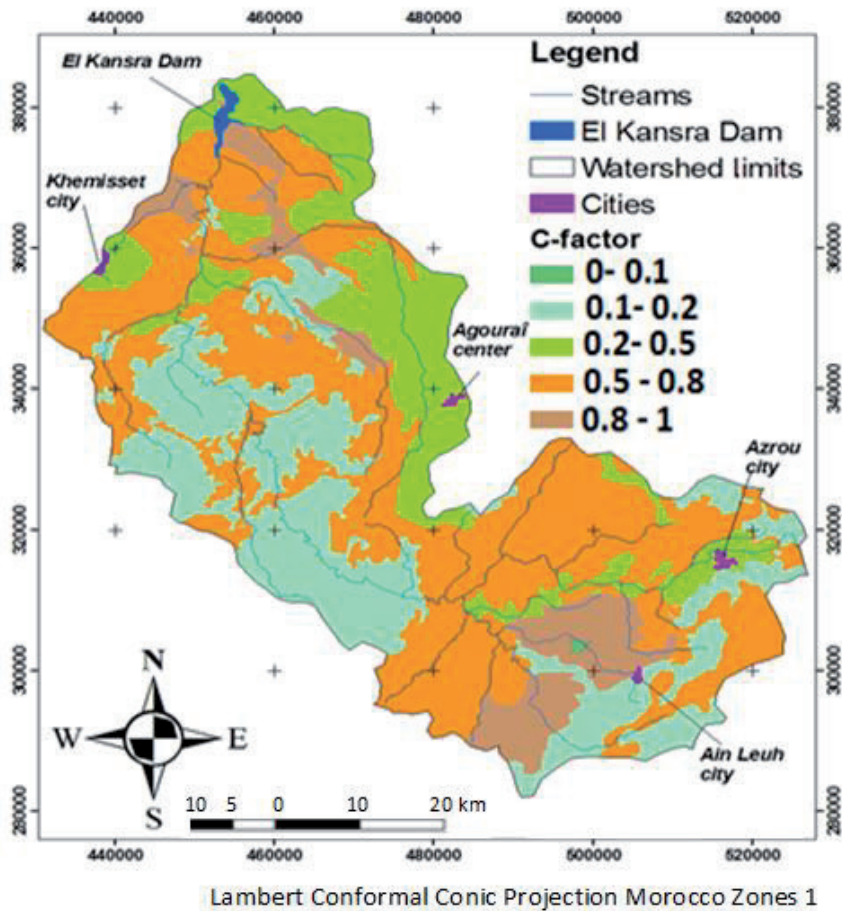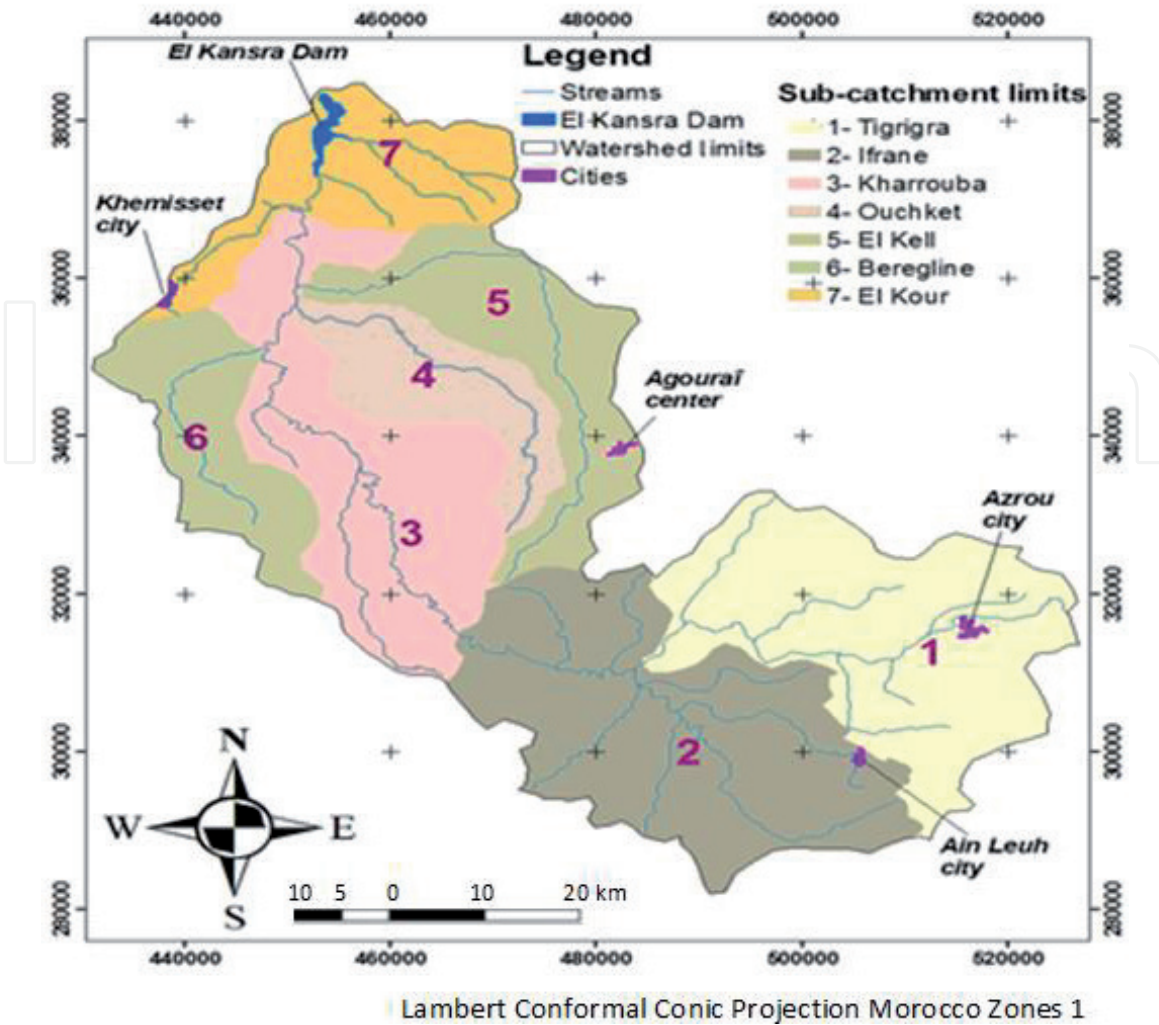*Normalized difference vegetation index map.*

Figure 16.
C-factor distribution.

17

Figure 17.
Sub-catchment delimitation.

is powered by the waters of several tributaries: Beht, Tigrigra, Ifrane, El Kell, Ouchket, Kharrouba, Beregline, and El Kour (**Figure 17**).

4.1.6.1 Drainage density

The surface drainage in the Oued Beht watershed is assured by a hierarchical arsenal of rivers. Thus, the density is influenced by its topo-geological structure and relief. Indeed, the river system is characterized by the importance of its elements, since their original ramifications upstream, domiciled in the Middle Atlas chain, to the main collector which is the El Kansra dam. Therefore, the river system is characterized by a total length about 667.77 km and an average density 0.16 km/km^2.

4.1.6.2 Concentration time

The time (t_c) that is necessary for the farthest water particle to arrive at watershed outlet, is estimated by the formula of Passini [23], which is presented as follows:

$$t_c = 0.108 \times \frac{(S \times L)^{\frac{1}{3}}}{I^{\frac{1}{2}}} \qquad (6)$$

where t_c is the concentration time (h), S is the surface of the sub-catchment (km^2), I is the average slope of the sub-catchment (%), and L is the length of the longest path flow (km).

Therefore, the concentration time (t_c) is relatively low at the majority of sub-catchments (SBC) and varies from 2:30 hours (in SBC/Kharrouba) to almost 5 hours (in SBC/Tigrigra).

In conclusion, the elongated form of the Oued Beht watershed and the low concentration time for the majority of sub-basins are favorable conditions for the development of flood and river flows that cause sediment deposits in the stream beds and El Kansra dam.

4.1.6.3 El Kansra dam siltation

The bathymetric data analysis implemented since the construction of the El Kansra dam is used to assess the quantity of soil loss which compromises the storage capacity and quality of water flow. Thus, for a period of 23 years (1981–2004), the average El Kansra dam siltation is 3 million m^3/year.

4.1.6.4 Floods study

The central objective is the prioritization of sub-catchments presenting high flood risk and soil erosion. The data linked to maximum flood flows are obtained by calculating the extreme gradient values (Gradex method) from the decennial flow in the reference station of Ouljet Soltane (**Table 1**). Thus, the hydrological analysis involved determination of design floods for a large number of sub-catchments by the Gradex method:

- First, samples of annual maximum daily rainfall were used to calculate parameters P0 and G of Gumbel distribution for the various raingauge stations (P0 = ordinate of origin and G = slope or gradex).

- The Gradex method was next used, with a daily time-step, applied to all stream gauging stations available. Thus, the pivot point was taken as $T^* = 10$ years. Conversion from daily discharge $Q_j(T)$ into peak discharge $Q_p(T)$ was done by considering the mean Q_p/Q_j ratio from a small sample of hydrographs.

- Lastly, the results obtained (**Table 2**) are synthesized using the following equation for calculating the maximum instantaneous flow $Q_p(T)$, for the return period T:

$$Q_p(T) = Q(T^* = 10 \text{ years}) + C_p * G_d * (u(T) - u(T^*)) \qquad (7)$$

where G_d is Gradex flow, defined by the following formula:

$$G_d = G_p * S/(3.6 * t_c) \qquad (8)$$

Return period T (years)	10	20	50	100	1000
Q (m3/s)	488	586	712	807	1121

Table 1.
Statistical adjustment of annual maximum flows, in the gauging station of Ouljet Soltane.

Streams	Area (km2)	Q p	Q p	Q p	Q p	Q p
		T = 10 years	T = 20 years	T = 50 years	T = 100 years	T = 1000 years
Tigrigra	909.37	241	294	364	417	597
Ifrane	1019.6	261	318	394	451	643
El Kell	487.2	154	190	238	275	401
Ouchket	326.53	115	143	181	210	310
El Kour	413.2	137	169	213	246	361
Kharrouba	798.12	219	268	333	382	549
Beregline	353.26	122	152	191	221	326

Table 2.
Flood flows Q_p of the principal rivers (m^3/s).

where G_p is the Gradex rainfall, S is the area of the watershed (km^2), t_c is the concentration time (h) (Eq. (5)), C_p is the pivot point, and u(T) is the variable of Gumbel.

For the other neighboring ungauged sub-watersheds, the application of Francou-Rodier formula gives the following results (Eq. (2)):

4.1.7 Potential erosion

Compared to Eq. (1), the potential erosion allows to evaluate the power of soils to produce sediments under the effect of rainfall and topological factors, without considering land cover (C-factor) and erosion control practices (P-factor). The crossing of thematic layers of rainfall aggressiveness (R), soil erodibility (K), and the topographic data (LS) is used to synthesize potential impacts according to the formula defined as follows [9, 10]:

$$E_p = R \times K \times LS \qquad (9)$$

where E_p is the potential average annual soil loss (t/ha/year), R is the rainfall aggressiveness index ($MJ.mm.ha^{-1}.h^{-1}.year^{-1}$), K is the soil erodibility ($t.h.MJ^{-1}.mm^{-1}$), and LS is the topographical factor (dimensionless).

The results analysis shows that the potential average annual soil loss is 54 t/ha, and the average annual quantity is 23.25 million t/year. Moreover, the importance of soil loss differences between extreme values obtained (pixels) shows the power of eminent soil units to produce sediments under the rainfall aggressiveness [24].

Two-thirds of the Oued Beht watershed are characterized by soil loss quantity, which is less than 50 t/ha/year, and almost 30% corresponds to the potential erosion class between 50 and 300 t/ha/year. Thus, on the broken reliefs located in the upstream part (in Tigrigra and Ifrane sub-catchments), with steep slopes, generally exceeding 25%, the potential erosion is high with values that may exceed 200 t/ha/year (**Figure 18**). Moreover, these erodible areas are characterized particularly by high and medium soil friability.

Second, some areas near El Kansra dam present high values of the potential erosion exceeding 200 t/ha/year. These vulnerable sectors correspond mainly to northern sub-catchments with low altitudes (less than 400 m) with high soil friability. Therefore, the great erosive power of adjacent areas to El Kansra dam is a real danger involving the dam siltation and compromising its service life.
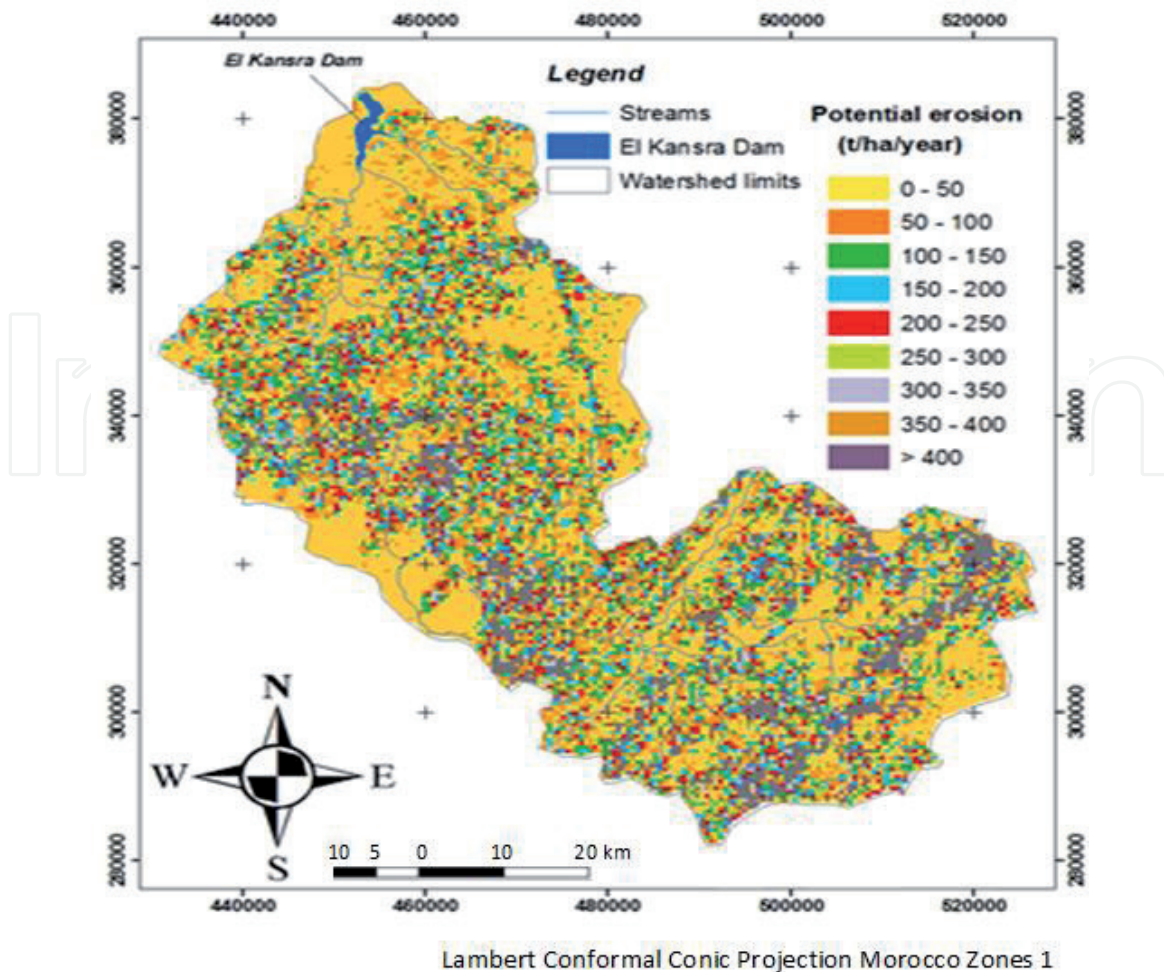
Figure 18.
Potential erosion map.

Furthermore, the investigative visits show that the upstream part is very sensitive to the potential erosion, but it should be noted, by location, the presence of medium and high levels of vegetation cover that can reduce the erosive potential.

The priority areas delimitation is performed through the spatial crossing of the specific degradation map, the map of sub-catchment contribution to dam siltation, and flood generation. This analysis is further developed by the socio-economic vulnerability map (**Figure 18**). Thus, we note that the results obtained reveal that the majority of areas identified and delineated as priority areas are occupied generally by soils with strong erosion risks. Consequently, the vulnerability linked to soil degradation characterizes 32% of Oued Beht watershed (**Figure 19**).

In conclusion, 24 rural communes know high contribution to dam siltation and include areas with high erosion risks and high poverty level. Therefore, urgent biological and technical actions are needed in this region to control erosion impact [25]. Therefore, these rural communes are concerned by action plans linked to land uses (agriculture, livestock, and forests).

4.2 Mapping erosion susceptibility

The hazard zoning obtained and the analysis of cumulative curves (number of pixels) define four susceptibility classes in the Oued Beht watershed:

- Low susceptibility (S1): The start of the erosion is negligible in almost half of the watershed (44.5%). In fact, local conditions contribute to the stability of
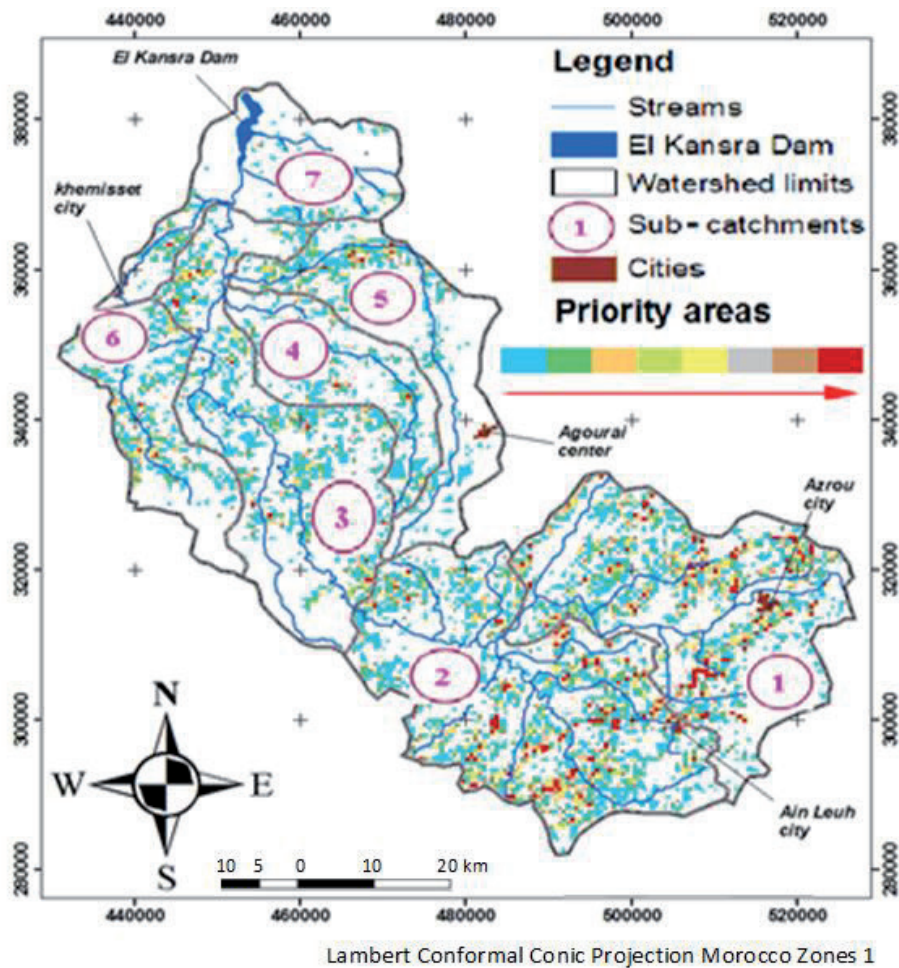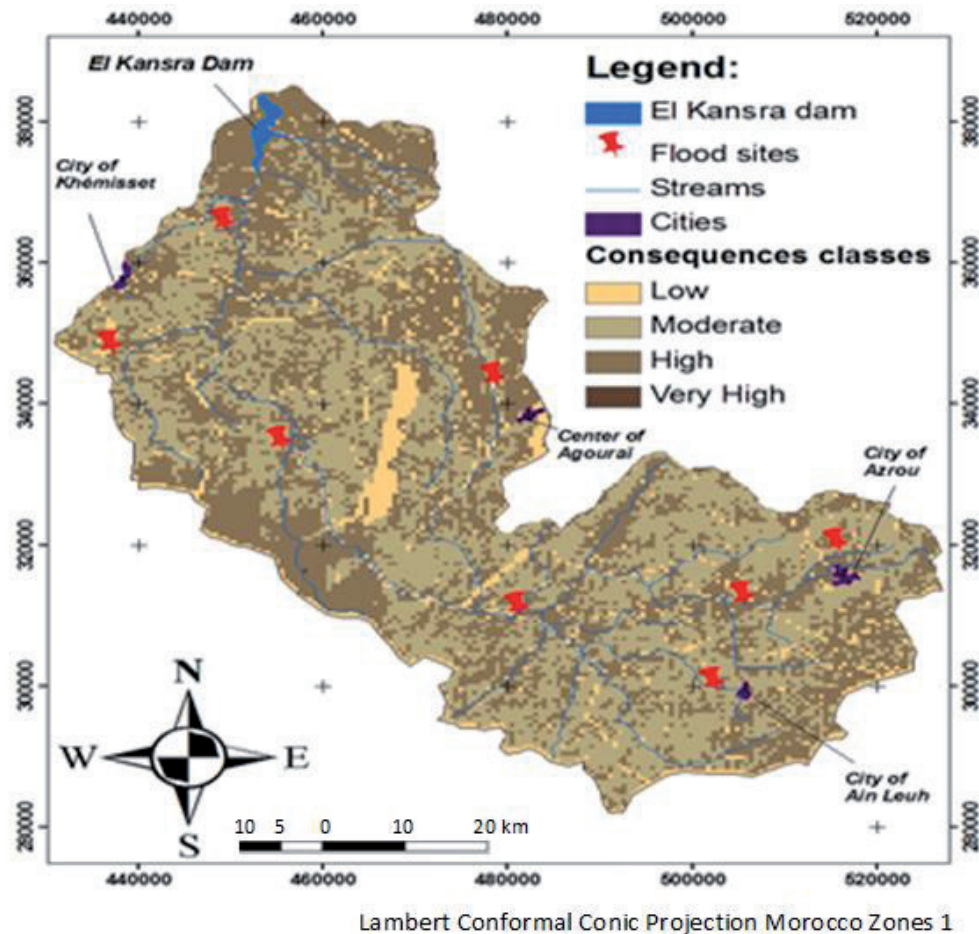
Figure 19.
Distribution of vulnerable areas.

the land. Gradients of the slopes are very low (lower than 5%) on agricultural land which is well maintained and well drained.

- Moderate susceptibility (S2): Local environmental conditions are also favorable to the onset of low land loss in almost a quarter of the watershed (24.4%). It is protected by forest areas and the slope gradients are low to moderate (5–25%). However, the abandonment of the reservation land or the local presence of slope failure could lead to destabilization.

- High susceptibility (S3): Local environmental conditions are favorable for triggering erosion (11.4%). It is rangeland and unprotected forest formations located on moderately degraded soils and characterized by poor soil drainage techniques. The degrees of slopes are moderate to strong (25–45%).

- Very high susceptibility (S4): The possibilities of the start of erosion are strong and the local environmental conditions are very favorable for that in 19.7% of the watershed. Soils are severely degraded, poorly maintained, and managed. The general appearance is marked by the absence of vegetation or forests. Thus, the erosion is very active with a significant soil loss with strong slope gradient (more than 45%).

In conclusion, this exploratory procedure shows amply the system capacity to generate automatically the hazard zoning. Almost a third (31%) of the Oued Beht watershed presents high to very strong susceptibility. The four hazard levels can

Figure 20.
Potential consequences map.

be combined with vulnerability with four levels. This integrated analysis would produce risk maps, or rather the existing deficit protection.

4.3 Potential consequences analysis

The analysis of the socio-economic vulnerability of the watershed is based on the assessment of damage related to the effect of past erosive events on the profit-ability of soil resources and the income of the farmers surveyed in this study. Thus, the preparation of input data is based on the results of socio-economic surveys describing the decline in land yield year after year (income loss).

As a result, the yield loss parameters that tell us the annual cost of erosion are defined by the differences between the net initial income per hectare and the net income with the effect of erosion (Eq. (4)).

In addition, the results of the socio-economic surveys show that the local economy is mainly represented by the primary sector (farming and poly-culture). The structural and functional damage map (CSF) describes the combination of damages due to land loss and El Kansra dam siltation that affect human activities. Therefore, the potential damage map (**Figure 20**) is obtained from the qualitative assessment of the state of land degradation (the importance of sheet, rill, and gully erosion) and this, to structure the cost of erosion and to highlight the homogeneous areas of vulnerability. Indeed, the analysis of cumulative curves (number of pixels) has identified four consequences classes for the Oued Beht watershed.

- Low consequences (C1): Minor damages to these lands are obsolete (1%) and hazard causes as much damage to human activities.

- Moderate consequences (C2): Mild to serious damage to soils and to infrastructures, which are characterized by half of the watershed (49%), mainly in the south watershed (upstream side) and partly downstream. Moreover, disruption of socio-economic activities is also moderate.

- High consequences (C3): Moderate to severe disturbances of human activities. Thus, strong and direct consequences are confined in space, but can be felt over the agricultural seasons; also, they represent almost half of Oued Beht watershed (50%). These consequences are partly located in the north watershed (downstream) and mainly around the El Kansra dam but locally extending toward the center and south.

- Very high consequences (C4): The very strong damage is minimal and negligible (0.02%); this kind of erosion events would exceed the human capacity and prevention authorities concerned.

4.4 Erosion risk management

The risk map (**Figure 21**), derived from a spatial combination of susceptibility and potential consequences classes, shows that high-risk areas (R3) are developed on 6% of the territory. These sites identify the major risks and disruptions of human activities. The warning areas correspond to areas with high consequences (C3), located immediately in the upstream side and locally to the center, presenting a very high to moderate
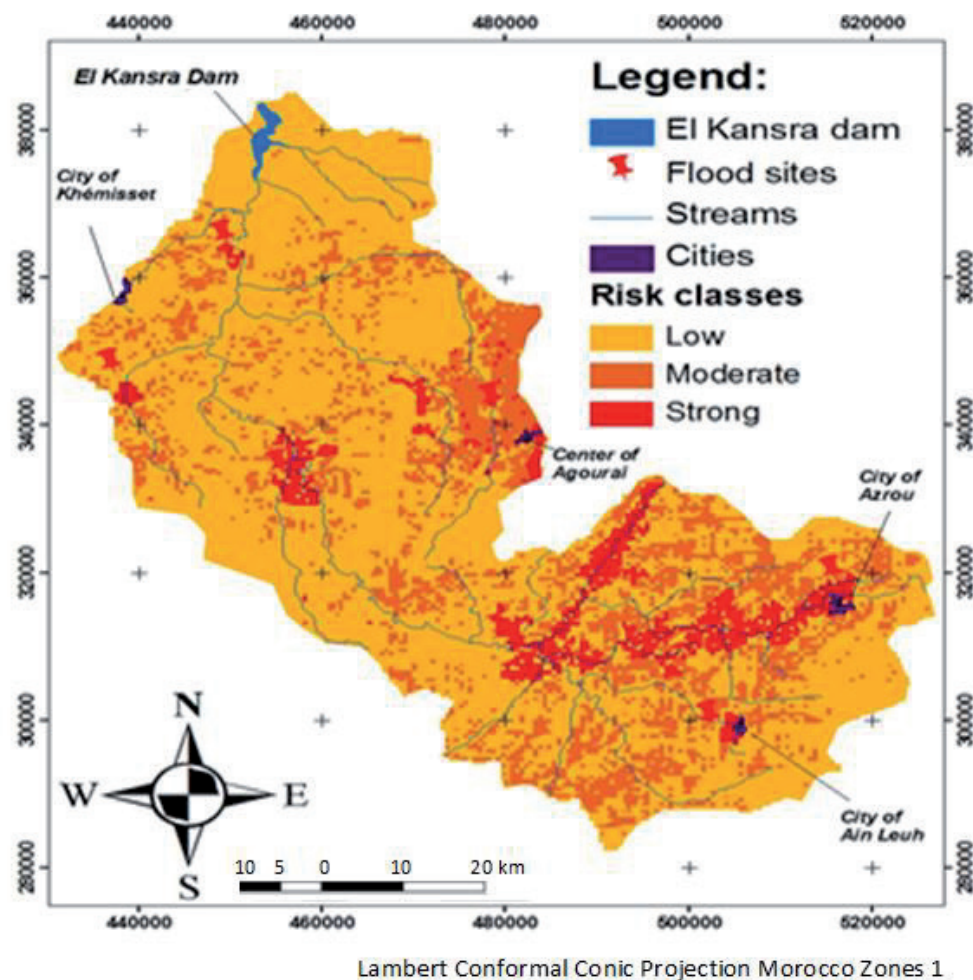
Figure 21.
Natural erosion risks.
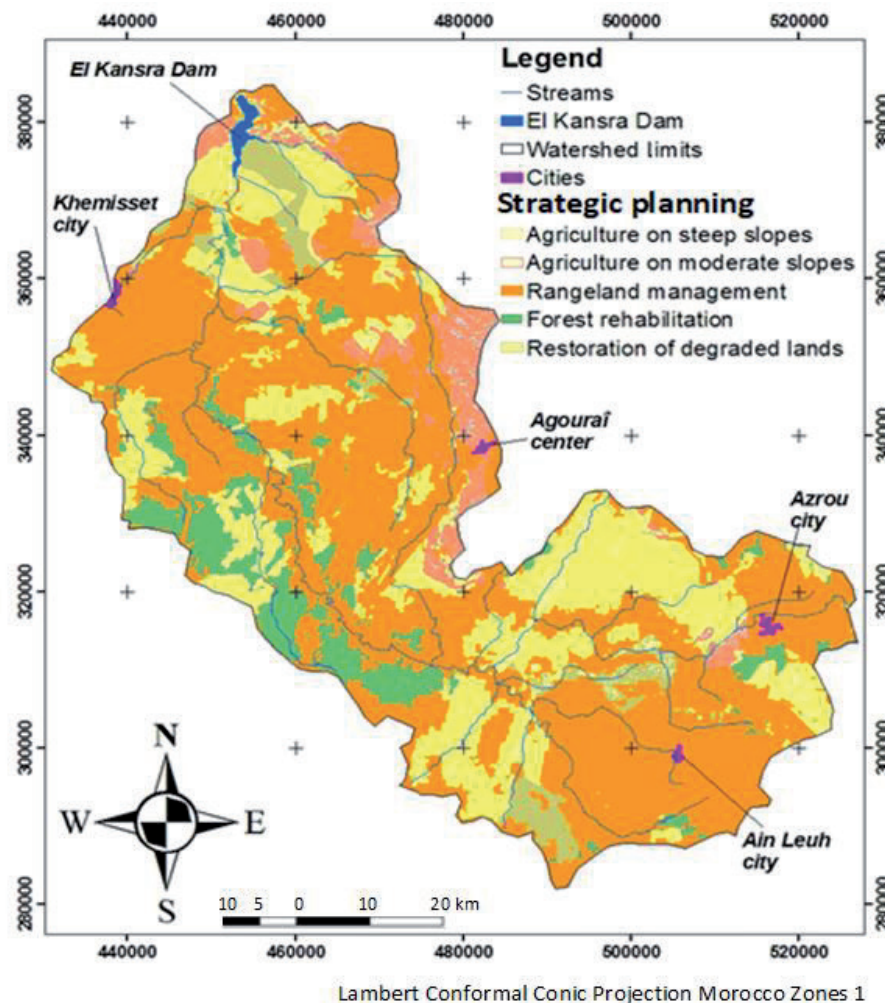
Figure 22.
Master plan of the Oued Beht watershed management.

susceptibility (S2, S3, and S4). Thus, appropriate precaution measures must be established (protected areas) and a risk prevention plan (RPP) must be implemented.

Elsewhere, outside large spaces present a low risk (R1) on 72% of watershed, representing the concept of acceptable risk. The risk level is moderate (R2) in 22% of the watershed (e.g., steep slopes but with low to moderate consequences). This menace presents a moderate disruption to human activities and serious damage to infrastructure including El Kansra dam. In conclusion, if improper resource management is implemented, this part of the watershed affected by moderate risk (22%) can be aggravated. Therefore, the potential risk can meet 28% of the watershed. Certainly, the development of management scenarios can complete this mapping study to improve the prevention of erosion risk.

4.5 Master plan for strategic planning

The formulation of Strategic Action Program (SAP) is based on the results of erosion risk mapping (**Figure 21**) to identify priority areas, where measures against soil erosion or reservoir siltation should be taken. The approach used is translated into operational actions (biological and technical), which are compatible with the intrinsic possibilities of the studied watershed (**Figure 22**). Thus, the Strategic Action Plan aims to achieve the priority objectives as follows:

- Measuring and monitoring soil erosion in order to preserve the natural resources and control El Kansra dam siltation.

- Flood analysis in order to reduce the flood risks with implementation of technical actions and Hydro-Agricultural Infrastructure Protection Plan (HIPP) including the El Kansra dam and the land goods.

- Implementation of biological actions, which consist of plantation and reforestation in degraded areas.

4.5.1 Agricultural land management

The agricultural development board assists rural households in the Oued Beht watershed to develop their agricultural business according to the lithological formations, and topographical and climatic constraints. Indeed, the agricultural lands, including arboriculture, cover an area of 74,577 ha, nearly 17% of the watershed area. Moreover, the operating systems are basically extensive with the cultivation of a maximum surface whatever the slope (even in the steep slopes).

On the other hand, the production systems adopted are characterized generally by inappropriate farming practices that promote soil erosion. Thus, the socio-economic study shows that 96% of rural population is conscious of the water and soils degradation.

In this sense, the selected actions aim to achieve a progressive evolution of production systems and land uses in accordance with soils vocation, with limitation of annual crops on steep slopes, the development of arboriculture, and improvement of forage production for livestock. Therefore, the implementation of actions mentioned below will lead to the increase of agricultural incomes and the establishment of a space management model to ensure local sustainability according to the following practices:

- Low to medium slopes (0–15%): The biophysical data analysis shows that the lands with low to medium slopes (0–15%) are subject to an erosive process generally manifested by sheet, rill, and rarely gully erosion. Thus, the aggressive rainfall and inappropriate farming practices (soil tillage in the direction of the slope, overgrazing) are the main factors that increase soil erosion.

The correctional measures include improving productivity through appropriate use of culture techniques. Thus, on low to medium slopes, the soil tillage must follow the contours and be combined with cultures in alternate bands.

In conclusion, to maintain this type of soil vegetation cover as long as possible during the year, it is necessary to promote culture associations. The rotations of "cereal-legume-forage" or "cereal-legume-cereal" are retained. For rangeland improvement, the vetch-oats, alfalfa, and clover present important opportunities for pastoral production and contribute significantly to soil protection.

- Steep slopes (higher than 15%): The results analysis shows that higher slopes are commonly used by cereal cultures that give low yields. Especially, in this case, the soil tillage in the direction of slopes causes ridges that eventually become water runoff channels (gullies) that quickly develop the gullies and ravines. Moreover, the tillage soils according to the slope direction increase erosion.

In conclusion, a sustainable soil management on steep slopes is necessary through the restoration of vegetation cover by the planting of multiple use species following the contours. This plantation technique must be combined with isohypse structures (benches, ditches, and cords) to conserve water and soil.

In the case of the Oued Beht watershed, fruit trees cultivation presents a promoter axis of the erosion control in the difficult terrain. The tree species proposed depend on agro-ecological areas. This operation needs also the consultation with the farmers concerned to choose trees species. Moreover, the olive, fig, and almond trees seem the most desired fruit trees by the population and the best adapted to the ecological conditions in the watershed. Second, the interline space will be used for the practice of the usual cultures respecting the principles of tillage soils following contour lines.

4.5.2 Rangeland management

The socio-economic study shows that the actual animal demand is high compared to production potential. Thus, the confrontation of the rangeland offers and livestock demand reveals an important deficit −31%.

The results analysis shows that the three livestock types (sheep, cattle, and goats) use rangelands intensively and continuously. Generally, the state of rangelands presents advanced degradation of vegetation resources. In addition, this usage mode is accentuated first by the severity of soil and climatic conditions which are often unfavorable and second by the nature land status that promotes non-rational exploitation of forage justified by its gratuity.

In this situation, the pastoral improvement is fully justified by the need to implement an intervention program to save the pastoral resources in the Oued Beht watershed. Thus, short-term actions are based particularly on the development and rational management of pastoral space, and then, in the medium term, the program can implement actions linked to improving driving livestock. Normally, the proposed actions tend to change the pastoralist habits and to support the incentive mechanisms related to fattening to reduce the pressure on the pastoral spaces.

- Rangeland users organization: The users organization into pastoral associations (or cooperatives) is a central action to be taken in parallel with the technical actions (plantation, closing and deferred grazing, and water point for livestock) in order to ensure sustainable use of rangelands. This organizational approach is the population interface with all partners to monitor actions and to defend the pastoral potential of the watershed.

- Deferred rotation grazing: In this case, the deferred rotation grazing is the technique used to enhance and restore the herbaceous and shrubs potential. It consists of prohibiting grazing in degraded areas in order to allow the natural regeneration with the development of herbaceous species richness and of forage quantity.

The duration of the deferred grazing depends on pastoral species. A short duration grazing is a rotation on 2–4 years, which is sufficient for the regeneration of herbaceous species and for the improvement of pastoral potential. However, the limitation of rights to use rangelands will be able to generate a forage imbalance that will directly increase the pressure on the surrounding lands and cause the accentuation of their degradation. Thus, to anticipate this problem, it is imperative to choose pastoral species with high nutrient supplies and to provide accompanying measures for population like compensation system linked to unexploited forage units and development of forage crops irrigated.

- Planting shrubs: In the case of the studied watershed, the survey analysis shows clearly that fodder shrubs are highly attractive to farmers. Thus, the

shrubs present the advantage to provide their production in a late period of the year when other forage crops (including herbaceous vegetation) are low or zero. The introduction of tree plantations consists of soil tillage in the autumn before the first rains with the digging holes along the contour lines for planting shrubs and installing bleachers for planting cactus.

In conclusion, this technique aims to improve water balance and fight against erosion. The shrubs species that are recommended are Atriplex nummularia, *Medicago arborea*, Chamaecytisus albidus, and *Opuntia ficus-indica*. Moreover, the use of cactus plantations presents his pastoral role with the advantage of producing highly appreciated fruit that can provide substantial revenue for the users.

- Livestock watering points: The analysis of the surveys data shows that water shortage presents a major constraint, especially as the dry spells became frequent. In the summer, water resources become scarce and fail to cover the livestock needs. Several techniques for collecting and mobilization of water when they are available (in winters and flood periods) are proposed based on the watershed characteristics.

The proposed actions present great social utility and do not require large investments; they are adapted either to an individual or collective use. Thus, the actions include the preparation of water reservoirs, the capture from surface water sources, the development of existing wells, and the digging of new wells.

4.5.3 Forest management

Implementation of action plan linked to watershed forestry resource consists to restore degraded natural ecosystems (evergreen oak and thuya), which represent an economic and ecological importance. Thus, these actions aim to improve the vegetation cover, to protect the soil against erosion, and finally to halt the forest degradation.

- Forest rehabilitation: The biophysical analysis shows that watershed forests are located generally in difficult areas upstream. These ligneous formations have good adaptability and resistance to the negative impacts of climate and anthropogenic pressure. Thus, most of these forests suffer from a lack of natural regeneration.

Therefore, this difficult situation requires efforts in terms of natural regeneration with native species to ensure sustainability of these natural areas. Thus, the intervention program gives priority to the parties that have the potential for regeneration.

These actions are accompanied by water and soil conservation measures to reduce erosion and increase water storage capacity (step elements, benches, and terracing).

- Reforestation protection: The introduction of artificial plantations aims at the protection of degraded forests. Thus, the reforestation of denuded lands and badlands, with forest vocation, allows the soil protection, the runoff quality and quantity improvement, and production of wood products.

Considering the watershed bioclimatic conditions, the spectrum obtained from tree species proposed for reforestation is maritime pine, Aleppo pine, brutia pine, cypress, and eucalyptus trees.

• River system and badlands development: The hydrographic network is characterized by high density ratio of river and lakes; the soil losses are accentuated by this river system, and the erosion is generally active on soft to moderately vulnerable areas. This phenomenon is strongly observed in the central part of the watershed where the river system becomes increasingly ramified and individualized (**Figure 11**). This regressive evolution leads to a densification of ravines that can achieve the generalized gully erosion. This situation is clearly illustrated in the downstream part at the El Kansra dam. The sediment quantities resulting from this erosion are mainly transported downstream and contribute significantly to the dam siltation.

Finally, the proposed management strategy for vulnerable areas is based on a combination of two main actions: biological fixation and mechanical ravine correction. Thus, the two integrated actions stimulate vegetation installation and slope correction. The chosen technique combines the advantages, not only to limit sediment yield but also to promote the defense of infrastructure, good land, and public and private properties.

This socio-ecological development program gives special attention to aspects of social vulnerability, a major dimension of vulnerability to multiple factors including: low incomes, social exclusion, and natural hazards. Referring to this approach,
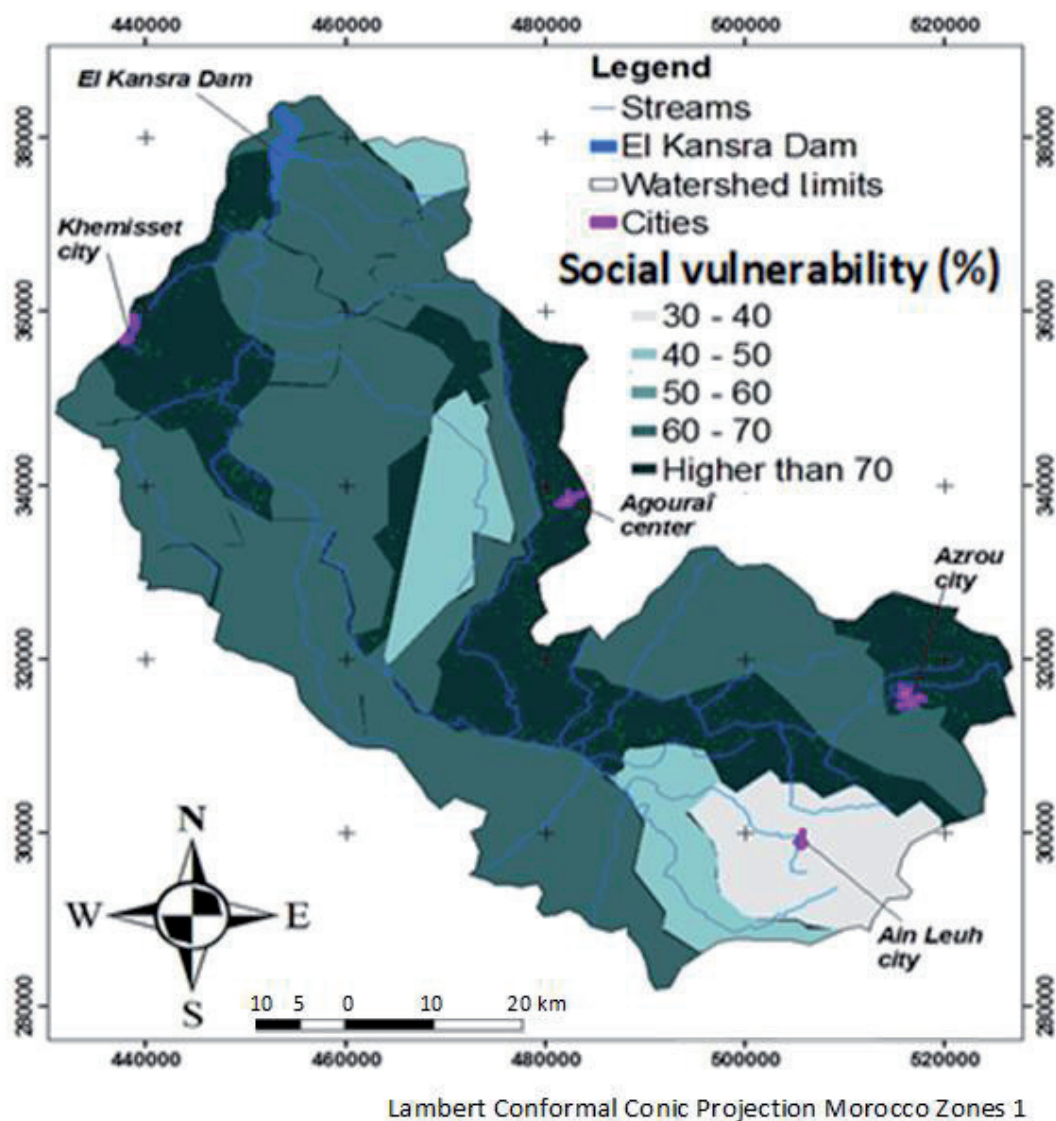
Figure 23.
Social vulnerability.

all people whose consumption expenditure is below the poverty line, which represents the minimum income considered adequate for each person, are considered vulnerable. In Morocco, on average, the poverty line is US $ 2.4 per person per day in rural areas [14, 15].

In fact, the survey design conducted in this study allowed us to exploit the income data of sampled individuals and to develop a simplified map representing, by homogeneous area, the percentage of individuals with an income below the minimum income deemed appropriate for each person (**Figure 23**).

4.6 Operational management program

The autocorrelation maps obtained (z-score) are used to delineate the priority interventions which correspond to the z-scores, statistically significant with values higher than 1.65 or less than −1.65 (**Figure 13**). Furthermore, the biological actions in degraded areas (by fruit plantation, regeneration, and reforestation) are materialized in spaces that express high spatial aggregation between soil loss and degraded vegetation cover. Consequently, the total area covered by this type of intervention
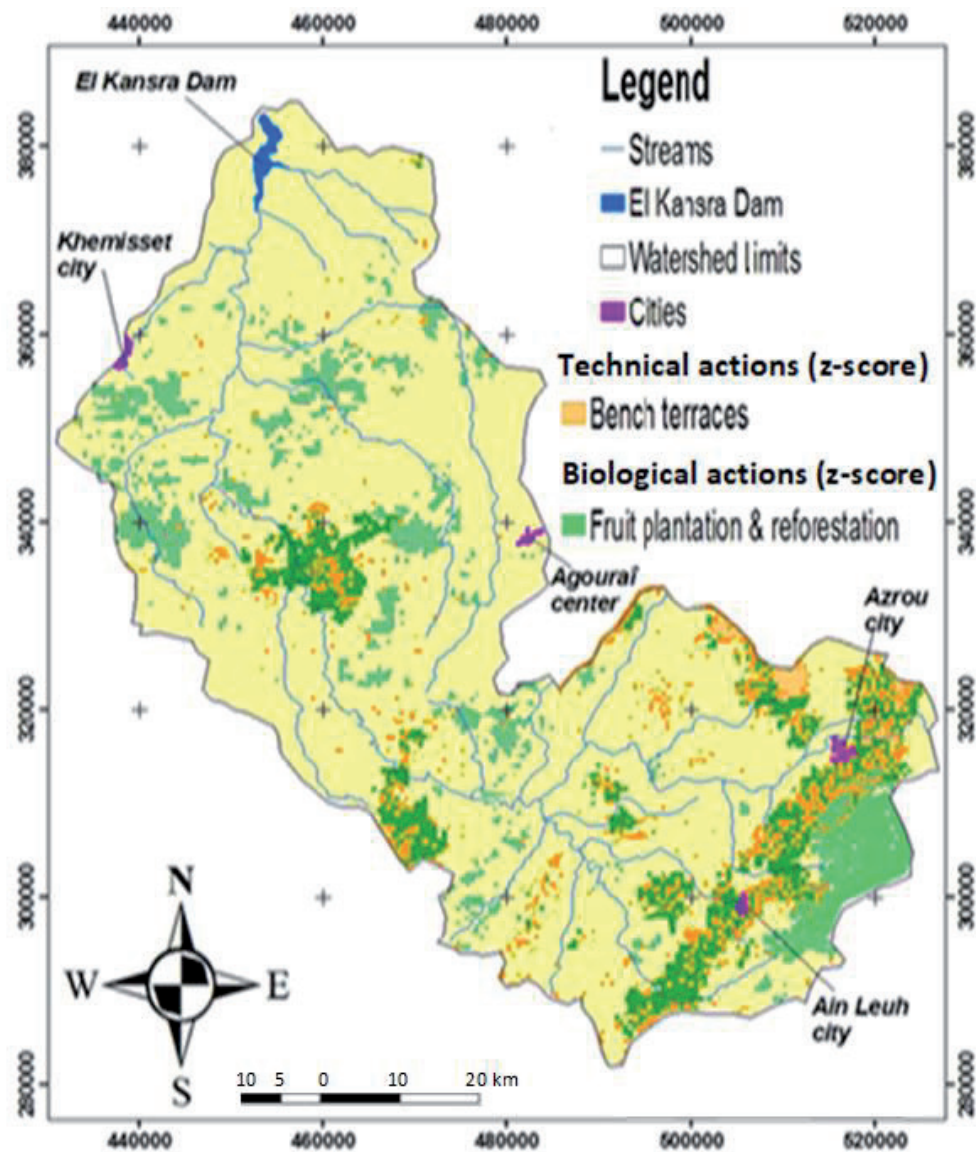

Lambert Conformal Conic Projection Morocco Zones 1

Figure 24.
Biological interventions.

is 87,351 ha, which represents 20% of the Oued Beht watershed. These biological interventions are concentrated mainly in the priority sub-catchments of Tigrigra, Ifrane, and Kharrouba (**Figure 24**).

On the other hand, the technical actions designed to reduce the slope effect consist in the establishment of benches, ditches, and terracing. These structures are programmed in high spatial aggregation between soil erosion and steep slopes. The total area covered by technical intervention is 22,753 ha, and a quarter of biological interventions is combined with technical measures, especially in the upstream part of the watershed (**Figure 24**).

In conclusion, the package of techniques of soil conservation and erosion control is developed in agricultural and sylvopastoral areas, starting from various types of soil tillage and vegetation cover, to different types of terraces, check dams, and stone bunds. Thus, the terracing is the selected agricultural technique for collecting surface runoff water, thus increasing infiltration and controlling water erosion used to transform landscape to steeped agrosystems in the mountainous regions (upstream).

5. Conclusion

This research paper proposes the development of a methodology analysis for soil erosion hazard and risk administration, especially a very few studies are dedicated to the mapping of soil loss risks. The use of analytical models based on space technology information processing has developed a GIS database on biophysical and topoclimatic parameters in Oued Beht watershed. Thus, the procedure described evaluates the soil loss risk and siltation of El Kansra dam, located in the upstream side.

The present study has implemented a cartographic approach based on the integration of spatial remote sensing tools (GIS) and spatial analysis functionalities linked to the initial state of the studied watershed. Thus, the central objective is to define the guidelines of the strategic spatial planning dedicated to erosion risk management. Moreover, although some studies have combined biophysical data and the constraints identified in the socio-economic analysis in order to understand the conditions of water erosion, they generally do not consider the statistical autocorrelation to develop strategy for priority management of watersheds. In this perspective, the cartographic restitution of spatial clusters obtained identifies priority areas and establishes the first interventions across the watershed.

The results obtained from the spatial autocorrelation analysis concerning socio-ecological components show that the priority actions are needed for almost 20% of the Oued Beht watershed. Thus, all priority areas identified are affected by the biological techniques (fruit plantation, regeneration, and reforestation in adequate slopes) that mitigate the factor, which expresses the lack of vegetation cover.

In addition to that, the spatial aggregation map shows also that the appropriate soil conservation practices (terracing) correspond to a quarter (15%) of the priority areas. Thus, this category of intervention aims to reduce the negative effects of the topographic factor with the establishment of terracing structures (**Figure 13**). The main purpose of the terracing application is to improve the usefulness of steep slopes and to increase their agricultural potential. This function is realized by creating the level surfaces according to contour lines of transformed slopes. The level, bench platform allows spreading the surface runoff water, decreases its speed, and thus allows more time for water infiltration into soil profile.

In conclusion, this approach has allowed developing a planning program with successful techniques for soil erosion control in degraded areas linked to steep slopes, climatic conditions, and erodible soils.

It is obvious that this approach, based on ground measurements combined with geographic information systems, must be accompanied by a regular monitoring system by updating continuously the part of the spatial model derived from remote sensing. Furthermore, the stable part of the geospatial database consists of intrinsic factors (lithology, soil, drainage density, etc.) and the dynamic part to control includes biotic factors related to the soil occupation and needs evolution of the local population.

Although this analysis was conducted to the master plan of watershed development and has identified environmental constraints (soil and water degradation) characterizing priority areas, it is necessary to refine this analysis through a participatory action plan. Thus, this zonal analysis will specify for each year the interventions to be implemented and the financial package, by considering the needs and perspectives of the rural population. Moreover, the effectiveness of the proposed techniques can be limited especially if the local population is opposed or, in some cases, found to be expensive to build and maintain.

Finally, this research work demonstrates the potential and merits of spatial analysis techniques to evaluate the erosion risks. An indicative mapping designed for the management and risk prevention is obtained, to control the source and quality of input and to characterize the conditions of validity of the models. However, the difficulties encountered in the collection of quantitative damage data, usually, due to the lack of historical information, refer to the idea that it would be necessary to create an observatory and full database related to water erosion damage. Thus, research is needed to introduce also the temporal component (probability of erosion and return period) in a decision support perspective to implement a regional sustainable planning.

Acknowledgements

Dedication

I dedicate this paper to my parents Ahmed and Jamila, my sisters and my nephew Mouad, my dear family, and to the soul of my uncle Hassan Touissate. I also dedicate this modest work to my dear wife Ihsane, friends, and colleagues, and without their encouragement, I could not have written this.

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