Mapping the water erosion risk in the Lakhdar river basin (central High Atlas, Morocco)

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ABSTRACT
The objective of this study is to develop a methodology using the remote sensing and Geographic Information System to map soil degradation by water erosion and highlighting the various levels of soil degradation in the Lakhdar river basin (central High Atlas) during the period between 1987 and 2014. This allows producing a map of soil degradation risk, which can be used as reference document for the decision-makers. The methodology develops a geomatics approach based on the processing of satellite images, using the analysis and the interpretation of spectral indices, such as the Form Index, the Coloration Index, the Brightness Index, and the Normalized Difference Vegetation Index (NDVI). The results show that the surface of soil strongly degraded decreased about 900 ha during the period of study whereas the surface of soil weakly and moderately degraded was subject of a progressive increase for an approximate total of 2800 ha over 27 years. Moreover, the method of spectral indices allowed us to assess and locate soil quantitative loss (organic matter, mineral salts, texture, fertility, etc.) due to the water erosion and climate change. These results are decisive when it comes to establish priority zonation for the interventions of erosion control.

I. Introduction
Water erosion is a genuine menace for natural resources durability, for the quality and morphology of surface water entities, as for the socioeconomic growth of rural areas. In order to deal with this issue, tools were developed allowing the identification and the analysis of the processes of soil degradation, and therefore helping achieving a sustainable development. In particular, areas of high risk in terms of soil degradation must be located in order to resort to the adequate arrangements for the fight against the losses of this nonrenewable resource.

In this context, the present study falls within the framework of the watershed management Program (River Basin management plan) and the water policy (National water plan). It is carried out in partnership with the waters and forests department and aims at first the evaluation of soil degradation caused, among others, by the water erosion and in second, the evaluation of the impact of the arrangements put in place by the River Basin management plan.

This study aims at mapping the high-risk areas of water erosion by remote sensing. Several works have already attested the pertinence of this method in the characterization of the state of grounds surface, especially arid and semi-arid regions. One of the most popular approaches is the spectral indices method, using the Form Index (FI), the Coloration Index (CI), the Brightness Index (BI), and the Normalized Difference Vegetation Index (NDVI) (Chikhaoui et al., 2007; Bannari, El-Harti, Haboudane, Bachaoui, & El-Ghmari, 2008; Escadafal, 1998; Haboudane, Miller, Tremblay, Zarco-Tejada, & Dextraze, 2002; Mathieu, Pouget, Cervelle, & Escadafal, 1998; Mattikalli, 1997).

II. Methodology
The methodology followed in this research consists to map the areas exposed to water erosion risks in Lakhdar river basin in the High Atlas Mountains of Morocco by using the geomatics approach based on the processing of satellite images (Figure 1).

The determination of the indices (BI, CI, FI, NDVI) refers to the shape of grounds spectral reflectance curves. The analysis and the comparison of the various combinations of these indices led to create a neo-canal for mapping the soil degradation by water erosion.

In this study, two satellites image Landsat OLI and TM are exploited for the calculation of the indices...
(Table 1). Firstly, these images were corrected from radiometric and atmospheric effects. Secondly, they were analyzed through a Geographic Information System to estimate the evolution of the soil degradation risk over a period of 28 years (1987–2014).

### III. Geographical and geological context

The study area is located in Moroccan Central Atlas, 30 km southwest of Azilal town. It consists of the upstream part of the Lakhdar river basin, ending in Hassan I dam. Its surface is of 6800 km² (Figure 2). It is situated in the high domain atlasic, where grounds are dominated by carbonate formations.

The upstream part of Lakhdar river basin is constituted by high mountains (between 2000 and 4000 m of height), the central part of low mountain (around 1500 m) and the downstream, near the Hassan I dam, of low mountains (between 900 and 1200 m) (Sabir, Roose, Merzouk, & Nouri, 1999).

The study region is characterized by a semi-arid climate with an average annual rainfall ranging between 273 mm/y (Tabant station) and 575 mm/y (Sgat station). Hence, according to a pluviometric gradient determined by the continental character; the downstream of Lakhdar river basin is more endowed with precipitation than its upstream.

The region contains particular geomorphological structures and varied lithological formation, ranging in age from Trias to mid-Cretaceous (Cenomanian-Turonian). The essential lines of the central High Atlas are shaped by limestones formations. The Lias formations appear in the form of continuous bands decametric, especially on the West, that is the regions of Tabant (Ait Bouguemez) and Mesgounane. In the

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**Table 1.** Spectral index of TM and OLI sensor.

| Index Type                  | Sensor TM   | Sensor OLI   |
|-----------------------------|-------------|--------------|
| Form Index (FI)             | $\frac{TM}{TM}$ | $\frac{OLI}{OLI}$ |
| Brightness Index (BI)       | $\sqrt{TM^2 + TM^2}$ | $\sqrt{OLI^2 + OLI^2}$ |
| Coloration Index (CI)       | $\frac{TM}{TM}$ | $\frac{OLI}{OLI}$ |
| Normalized Difference Vegetation Index (NDVI) | $\frac{TM - TM}{TM + TM}$ | $\frac{OLI - OLI}{OLI + OLI}$ |

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**Figure 1.** The methodology flowchart.

**Figure 2.** Geographical situation of Lakhdar river basin.
center of the anticlines, which are generally broken and asymmetrical, lay the highest summits of the area of Lakhdar river basin such as Jbel Azourki whose crests are monoclinal. Those crests are eroded, and this erosion settle the synclines plateaux of Jurassic limestones (Dogger). Those plateaux sometimes present undulations and fractures such as the plateau of Ait Mhamed. Those structures imply a strongly sloping topography responsible for the dynamics of surface, in particular the erosion forms (stripping of the topsoil, diggings, landslides) (Sabir et al., 1999).

The lithostratigraphy shows two series of limestones alternating with three groups of impermeable layers. Dolomitic basalts, sandstone, marls and saline clays constitute the Trias formations. The Jurassic formations are very susceptible to erosion hence the presence of ravines, like in Bernat and Tabant areas.

The Lias soils, made of limestone-marl, clays and sandstone series, predominate the landscape. Their dark red or greenish layers, resistant to erosion but always thin, are cored in monoclinally dipping. Over the Upper Jurassic and the Lower Cretaceous grounds, lie impermeable and bright-colored formations. Erosion drew monotonous structural reliefs, exploited by mankind, even if grounds are in stiff slope, resulting to recurring disastrous episodes for farms due to water erosion (Ibouh, El Bchari, Bouabdelli, Souhel, & Youbi, 2001).

IV. Results and discussions

Firstly, for a better estimation of the intensity of erosion in Lakhdar river basin, the most appropriate spectral bands of each satellite image were chosen for the calculations of the spectral indices:

- satellite image sensor TM: bands (3–4) for the NDVI, (1–3) for the CI, (3–4) for the BI and (3–2-1) for the FI;
- satellite image sensor OLI: bands (4–5) for the NDVI, (2–4) for the CI, (4–5) for the BI and (4–3-2) for the FI.

The calculation of each spectral index led to the following results (Figure 3):

Secondly, several combinations of colored elements in the system RGB were tested through the image processing system ENVI 5.1, considering the various index (FI, CI, BI, NDVI) (Figure 4).

The comparison and the analysis of the various combinations led to the creation of a neo-canal combining the three indices FI, CI, NDVI. This neo-canal has a high discrimination capacity in terms of soil degradation and more generally of land use (Figures 5 and 6), attested by field knowledge and studies done by the Forest and Desertification Prevention Regional Office.

The grounds highly degraded are associated with low FI values and high CI values, while the grounds lowly degraded show high FI values and low CI values (Chikhaoui et al., 2007; Bannari et al., 2008; Haboudane et al., 2002; Parenteau, Bannari, El-Harti, Bachaoui, & El-Ghmari, 2003). In this semi-arid context, the NDVI demonstrated its potential in the mapping of soil degradation area (Maimouni, Bannari, El-Harti, & El-Ghmari, 2011). The soil degradation distributions resulting from these calculations are shown in the following table (Table 2):

According to the results, a deterioration of the Lakhdar river basin soils is noticeable between 1987 and 2014, the overall surface of degraded soil having increased from 89.78% to 90.93%. On another hand, the class of grounds highly degraded decreased about 900 ha during the period. This could be explained by

![Figure 3. Results of the spectral index (BI, CI, FI, NDVI).](image-url)
the efforts deployed in the course of the Lakhdar river basin development project, a pilot project aiming the improvement of land productivity while ensuring the natural resources good management in mountain areas.

The spatial distribution of soil degradation in 2014 shows that grounds strongly degraded are generally situated in cleared areas. While the grounds averagely degraded cover areas of low to moderately slope and partially covered with vegetation. The lowly degraded soil cover areas of deep soil with arboreal, shrubby, or herbaceous vegetation cover. The realizations of the project were made in the priority zones with highest degradation levels identified beforehand. The record of these physical realizations is as follows:

- Torrential correction, essentially consisting in the preparation of dams, and protection of ravines with gabions and dry stones.
- DRS fruit-bearing forest, an action aiming to improve the productivity of lands and the soil preservation by hindering runoff and increasing the infiltration. It was put into practice over 795 ha;
- Silvo-pastoral scheme consisting in creating favorable to the development of natural forage species and introducing other essences with high forage value in order to reconstitute land cover, improve the productivity of rangeland, and ensure water and soil conservation. The scheme was realized on 120 ha.

Figure 4. Examples of spectral index combinations tested.

Figure 5. Soil degradation map (1987).
Thus, the total balance is 915 ha, that is a surface close to the calculated decrease of highly degraded soils. In spite of these efforts, a progressive evolution of the grounds lowly and moderately degraded surface on approximately 2800 ha occurred over 28 years. Moreover, moderately and highly degraded soils predominate in the study region (respectively 39% and 34% in 2014). This shows the extent of the degradation process and the degree of grounds sensibility to the erosion.

According to the global change map (Figure 7) and its related table (Table 3), the period 1987–2014, knew a surface change equal between area with positive change and area with negative change. While the unchangeable area are insignificant.

The spatialized evolution of grounds degradation shows that positive change is correlated with an improvement of land cover: reforestation activities and implementation of good farming techniques leading to revegetation and bare soils valorization. Also, shade-grown methods (culture under forest cover) knew a clear improvement in the region of study. Such practice optimizes the use of fertile soils while leaving the tree crown cover intact, thereby strengthening soil cohesion and favoring infiltration of water. The zones of negative evolution are located at high altitudes with steep slopes. There, environmental conditions are extremely unfavorable which, combined with the other human and natural factors (topography, soil friability, rainfall erosivity, land cover, etc.), lead to an intense soil degradation.

The present study allowed to characterize the state of grounds degradation by adopting spectral index approach. The obtained results checked against the field data accorded a better precision to this approach. The calculation of spectral index gives more precision and describes rather faithfully the reality of the ground (Chikhaoui et al., 2007). However, certain provisions must be upstream taken, because choice of the adequate bands combination allowing better distinguish of the various levels of grounds degradation is a long and crucial stage which requires an expertise and a good knowledge of the environment being studied.

### IV. Verification of results

The results shown on the following maps are represented in 3D (Figure 8) with three times the exaggeration of the vertical. They highlight four thematic classes namely the vegetation (light green), the soil lowly degraded (light blue), the soil moderately degraded (green), and the soil highly degraded (pink). These computed classes of soil degradation (map of 2014) were confronted with pictures illustrating the field reality.

![Figure 6. Soil degradation map (2014).](image-url)
V. Conclusion

The spectral indices method is suitable to represent the various levels of soil degradation. This method showed that every spectral index has its own behavior relatively to the level of soil degradation. The soils highly degraded are associated with high CI and low FI and NDVI, signature of a reflectance curve due a bedrock outcrop. On the contrary, the soils lowly degraded are associated with low CI and high FI and NDVI. Therefore, this exploitation of satellite data allows mapping the environment state, and more specifically the soil degradation level. The combined use of these variables allows a good discrimination of the various soil states, attested by field data comparison.

Table 3. Change of soil degradation state and corresponding surfaces (1987–2014).

| Area (ha)       | % Area |
|-----------------|--------|
| Zone of positive change | 79,266.67 | 47.15 |
| Unchangeable zone              | 7706.75  | 4.58  |
| Zone of negative change        | 81,137.62 | 48.26 |
| Total                        | 168,111  | 100   |

Figure 7. Map of soil degradation evolution in the Lakhdar river basin (1987–2014).

Figure 8. Aspect of water erosion in the Lakhdar river basin.
The results of ground degradation computed for the Lakhdar river basin show a progressive increase of lowly and moderately degraded soils (approximately 2800 ha over 27 years), while the surface of highly degraded soils decreased about 900 ha during the same period. This is consistent with the Lakhdar river basin development project efforts focused on the areas with the highest deterioration levels.

This methodology can be developed, on a pilot basis, by the competent authorities to estimate the state of grounds degradation in river basins. It can be an adequate tool of planning for monitoring and assessing ground degradation in order to conserve this valuable resource.

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Disclosure statement

No potential conflict of interest was reported by the authors.

References

Bannari, A., El-Harti, A., Haboudane, D., Bachaoui, M., & El-Ghmari, A. (2008). Intégration des variables spectrales et géomorphométriques dans un SIG pour la cartographie des zones exposées à l’érosion. Revue Télédifférence, 7(1–4), 393–404.

Chikhaoui, M., Bonn, F., Merzouk, A., Lacaze, B., & Mejjati, A. M. (2007). Cartographie de la dégradation des sols à l’aide des approches du spectral angle mapper et des indices spectraux en utilisant des données aster. Revue Télédifférence, 7(1–2), 3–4.

Escadafal, R. (1994). Soil spectral properties and their relationships with environmental parameters-examples from arid regions. In Imaging spectrometry—A tool for environmental observations (pp. 71–87). Springer.

Haboudane, D., Miller, J. R., Tremblay, N., Zarco-Tejada, P. J., & Dextraze, L. (2002). Integrated narrow-band vegetation indices for prediction of crop chlorophyll content for application to precision agriculture. Remote Sensing of Environment, 81(2–3), 416–426.

Ibouh, H., El Bchari, F., Bouabdelli, M., Souhel, A., & Youbi, N. (2001). L’accident tizal-azourki haut atlas central du maroc: Déformations synsedimentaires lâisses en extension et conséquences du serrage atlasique. Estudios Geologicos, 57(1–2), 15–30.

Maimouni, S., Bannari, A., El-Harti, A., & El-Ghmari, A. (2011). Potentiels et limites des indices spectraux pour caractériser la dégradation des sols en milieu semi-aride. Canadian Journal of Remote Sensing, 37(3), 285–301.

Mathieu, R., Pouget, M., Cervelle, B., & Escadafal, R. (1998). Relationships between satellite-based radiometric indices simulated using laboratory reflectance data and typic soil color of an arid environment. Remote Sensing of Environment, 66(1), 17–28.

Mattikalli, N. M. (1997). Soil color modeling for the visible and near-infrared bands of Landsat sensors using laboratory spectral measurements. Remote Sensing of Environment, 59(1), 14–28.

Parenteau, M. P., Bannari, A., El-Harti, A., Bachaoui, M., & El-Ghmari, A. (2003). Characterization of the state of soil degradation by erosion using the hue and coloration indices. In Geoscience and remote sensing symposium, 2003. IGARSS’03. Proceedings. 2003 IEEE International (Vol. 4, p. 2284–2286). IEEE.

Sabir, M., Roose, E., Merzouk, A., & Nouri, A. (1999). Techniques traditionnelles de gestion de l’eau et de lutte anti-érosive dans deux terroirs du rif occidental (maroc). Bull. Réseau Érosion, Montpellier, 19, 456–471.