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Evaluating Differences of Erosion Patterns in Natural and Anthropogenic Basins through Scenario Testing: A Case Study of the Claise, France and Nahr Ibrahim, Lebanon

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Abstract

This study assessed soil erosion risks of two basins representing different geographical, topographical, climatological and land occupation/management settings. A comparison and an evaluation of site-specific factors influencing erosion in the French Claise and the Lebanese Nahr Ibrahim basins were performed. The Claise corresponds to a natural park with a flat area and an oceanic climate, and is characterized by the presence of 2179 waterbodies (mostly ponds) considered as hydro-sedimentary alternating structures, while Nahr Ibrahim represents an orographic Mediterranean basin characterized by a random unequal land occupation distribution. The Claise was found to be under 12.48% no erosion (attributed to the dense pond network), 65.66% low, 21.68% moderate and 0.18% high erosion risks; while Nahr Ibrahim was found to be under 4, 39.5 and 56.4%, low, moderate and high erosion risks, along with 66% land degradation determined from the intersection of land capability and land occupation maps. Under the alternative scenario for the Claise where ponds were considered dried, erosion risks became 1.12, 0.52, 76.8 and 21.56%, no erosion, low, moderate and high risks, respectively. For Nahr Ibrahim, and following the Land Degradation Neutrality intervention, high erosion risks decreased by 13.9%, while low and moderate risks increased by 3 and 10.8%.

Keywords: erosion, LDN, land degradation, ponds, Mediterranean climate, oceanic climate

1. Introduction

Soil erosion is considered as the most amplified manifestation of land loss worldwide. It has become one of the most pressuring global problems facing sustainable development at rates exceeding pedogenesis by 10–40 times [1].

According to Lal [2], a worldwide area of 1094 million ha is subject to soil erosion, of which 751 million ha have been severely eroded. As a result of soil erosion, significant declines in land quality due to the loss of the much needed fertile topsoil layers used for agriculture and for providing primary eco-services have been reported [3] particularly in arable lands whose decline accounts for losses in the order of 400 billion US dollars/year globally [4]. From the various erosion forms, water erosion is considered as the most problematic, due to the increase in its extent and intensity, leading to deleterious losses in land capital and environmental sustainability [4, 5]. Europe and the Mediterranean particularly are significantly affected by this process [6, 7] where in Europe, soil erosion is one of the most threatening challenges for soil resources causing losses of 3–40 t/ha/year [8] while in the Mediterranean region, particularly in its Middle Eastern and North African parts [9, 10], soil erosion rates have significantly surpassed Mediterranean pedogenesis rates [11, 12].

In Europe, soil loss can be attributed primarily to water erosion due to climate (abundant rainfall), soil management practices and agrarian intensification coupled to unsustainable practices such as overgrazing [13]. In the Mediterranean region on the other hand, factors are much more complex due to the pronounced rainfall variability and heterogeneity of site-specific characteristics [14] even within the same landscape. As a result of weakly resistant pedology [15], unequal and random land use/land cover distribution [16] occurring due to the absence of governance, management plans and restraints [17], low precipitations, erratic intense rain episodes, prolonged droughts, steep slopes and increasing anthropogenic effects [18], soil erosion has reached an irreversible state in some regions, while in others erosion has ceased because no more soil is left to erode [13]. Consequently, soil erosion has led to the process of land degradation causing significant loss of land capital [19], thereby threatening food security and sustainable development in the region [20]. For that purpose, a simultaneous assessment englobing both soil erosion and land degradation must be carried out. Nevertheless, this task is contested by several factors namely the non-uniqueness of definitions of the process [21], the existence of unmeasurable interdependent driving factors [22] and the absence of clear methodological or application workflows [23].

This deteriorating state of soil erosion in Europe has led to the development of the European common framework for the Thematic Strategy on Soil Protection and the Common Agricultural Policy that highlight the need to protect European soils to reduce soil erosion [4, 24]. In contrast, the Mediterranean basin still lacks concrete and direct policies or legislations targeting soil erosion [25] due to contested definitions of land loss in the region [26]. Under any circumstance and prior to treating soil erosion, assessing its extent and identifying hotspots are required [13, 27]. However, this assessment is not an easy task given the heterogeneity and large spatial/temporal variability of its driving factors [28, 29], particularly in Mediterranean landscapes [30] that are characterized by a complexity of slope, climate and land occupation factors [10].

The process of soil erosion is attributed to various interdependent driving factors, notably climate, pedologic properties, topography and vegetation cover [31]. Despite being a natural process at its origin, soil erosion has significantly increased as a result of anthropogenic activity [32], where land use and land cover changes have become the main drivers of soil erosion [29] combined to soil management and conservation strategies [33]. When considering soil erosion, a multi-scale problem is at hand due to the role and status of soil erosion in several environmental, socioeconomic and developmental processes, often causing a cascade of direct on-site and indirect off-site effects. Under the environmental scope, soil erosion is considered as the main form of soil loss leading to negative impacts on water

quality, biodiversity, organic carbon stocks and eco-services [24]. At the socio-economic scale, soil erosion has become one of the governing factors in land use allocation, notably under the scope of agriculture as function of market economy [34], where increasing needs for increased productivity led to significant removal of natural cover for agricultural expansion rendering large areas vulnerable to soil erosion [33]. At the developmental scale, soil erosion has caused notable declines in the productive capacity of lands, often leading them to become unproductive, ultimately resulting in agrarian abandonment [1]. The latter, in turn, causes an amplification of erosion due to increased exposure of soil to water [35], thus promoting loss of land and soil resources both quantitatively and qualitatively. Collectively, the previously cited factors culminate not only to create short-term losses in agricultural productivity [1], but also to affect long-term food security [36], thus imposing challenges for achieving sustainable development [37, 38].

Further, soil erosion forms the head component of van Rijn's [39] sedimentary cycle, consisting of erosion, transport and deposition, rendering it partly responsible for shaping the hydromorphological aspects of landscapes along with surface runoff, sediment transport, baseflow and stream discharge [40]. Given the status of soil erosion as the head of the sediment transport chain, changes of soil erosion are capable of causing a cascading effect influencing the whole cycle and ultimately modifying both the hydro-sedimentary response and equilibrium of basins, thus creating challenges for watershed managers [41].

Studies regarding soil erosion have received growing interest under different approaches; these have led to the development of several models for estimating erosion [42] of which the USLE [43], MUSLE and RUSLE [44] are some of the most basic yet widely used models. Other models such as EUROSEM [45], WEPP [46], CORINE [47], TOPOG [48] and SedNet [49] have also been employed at different scales and study areas with various degrees of success. Ref. [50] summarized a number of applied approaches for studying erosion that can be grouped under: (a) use of models (e.g., [12, 42, 51]), (b) erosion plot data for direct in-situ measurements (e.g., [52]) and (c) by means of measuring sediment yield (e.g., [53]) since the latter is the net product of soil erosion [54]. Among these various methods, the use of models has been deemed to be the best given its efficiency, not only for displaying current conditions but also for revealing changes resulting from alternative simulations presenting changes of natural conditions [55] in addition to overcoming the problems of field measurements and logistics.

For erosion assessment, the basin scale is considered as most suitable given its capacity to reveal anthropogenic-interference effect [56] and due to the fact that soil erosion is one of the most pronounced problems in basins posing a considerable challenge for hydrologists and basin managers [41]. Given the scope of this study for comparing natural and managed basins having different natural contexts under different land occupation and managed settings, the French Claise and Lebanese Nahr Ibrahim basins are chosen as study areas for establishing a comparative framework between two different geographical and management contexts.

The Claise basin is one of the several basins corresponding to the French Brenne Regional Natural Park. The latter is an international heritage area housing a large number of ponds in its premises, nearly 4500, of which 2179 are in the Claise [57]. It is chosen as a representative of Northern European basins which are often covered by a prevalent number of ponds. In France particularly, three main pond density zones are present; these are the Sologne region, Brenne (Centre France) and Dombes (Eastern France). Ponds are considered to be one of the most important hydro-sedimentary modifying manmade structures [58] that possess an aggregative effect far more important than larger water bodies [59] on altering the regime of basins they take part of. Therefore, in response to the recommendations of the Directive-Cadre

Européenne sur l'eau (DCE) [60], regarding the importance of understanding the impact of hydromorphological factors on watershed processes, the Claise basin which takes part of the Brenne Natural Regional Park is chosen as the natural watershed of this study. In contrast, the Nahr Ibrahim basin represents the managed basin of this study. It is a Lebanese basin known for excessive erosion rates [12] that have led to significant land degradation [61] and landslides [62] coupled to a typical Mediterranean unequal land occupation distribution that has expanded due to the absence of land use planning [20].

The workflow of this chapter consists of using the CORINE erosion model [48] given its relative accuracy with respect to simple data requirements consisting of climate, slope, soil properties and vegetation cover, and its widespread application [63]. Erosion assessment in the Claise basin serves to respond to DCE recommendations for assessment of the effect of hydromorphological altering structures on basins. For Nahr Ibrahim, the CORINE model serves as a tool for mapping land degradation as function of soil erosion. Following the establishment of both actual soil erosion maps, a comparison between the natural and managed settings allows the assessment of the impact of land occupation and management on erosion risks.

Given the flexibility of the CORINE model incorporating both natural (slope, pedology and climate) and vegetation cover (human controlled), alternative vegetation covers for both basins were used to re-assess changes in erosion patterns and risks. This step was performed to pinpoint the impact of ponds on erosion patterns of the Claise basin and to prospect the efficiency of the Land Degradation Neutrality (LDN) concept for erosion reduction through land use planning [64]. LDN is defined by the United Nations Convention to Combat Desertification (UNCCD), [65], to be "a state whereby the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems." LDN aims to halt ongoing losses by land degradation. Unlike past approaches, LDN creates a target for land degradation management by means of a dual phased approach containing measures to avoid or reduce land degradation as a first phase. The second phase presents a combination with the first where specific applications to reverse or to treat past degradation are employed in order to rehabilitate degraded zones. Therefore, the concept of neutrality involves counterbalancing losses and equivalent gains. However, many factors enter in the estimation of losses including the effects of planning decisions (e.g., granting permits for open-cut mining), the effects of past and previous decisions (e.g., continuation of agricultural practices known to deplete soil carbon) and mostly the natural drivers of land degradation (e.g., impacts of drought, wildfire) [67].

Ideally, the most effective strategy would be to take immediate action to prevent land degradation where non-degraded lands are at risk. For effective implementation, it is important to consider the resilience of the counterbalancing intervention over the long term, the potential impacts of climate change and the likely trade-offs between ecosystem services. For these reasons, the proposed land use scenario for the Nahr Ibrahim basin consists of a realistic plan accounting for the trade-off between natural resources and the need to promote sustainable urban development. This task is achieved following the LDN's "soil" indicators of land use/land cover change and soil organic C stocks in analogy to the work done by Al Sayah et al. [66] and in response to the LDN hierarchy involving three actions in descending order of importance: avoid, reduce and reverse.

Through this study, the comparative land occupation framework in addition to the alternative modeling approach aims to provide an understanding

regarding the relationship between land occupation (as land use/land cover and management) and soil erosion, as well as integrating soil erosion as part of land planning.

2. Geographical context and site-specific description of the test-site basins

2.1 The Claise basin: a particular mosaic under a natural setting

The Indre section of the Claise basin (46° 56′ 23.89″ N and 1° 31′ 32.61″ E) is one of the three basins corresponding to the Brenne Regional Natural Park. The 1760 km^2 park is located in the French Centre-Val-de-Loire region and is renowned as the land of thousand ponds due to the presence of 4500 ponds extending in a natural landscape mosaic [57]. A large number of these water bodies are located in the corresponding section of Claise basin (2179 ponds) that describes an area of 707 km^2 [67] (**Figure 1**). These are speculated to be one of the key feeding sources of the 87.6-km-long Claise River (Rougé (1927) in [68]) described by an average flow of 4.50 m^3/s and originating at 146 m of altitude [69] with three main tributaries: the channel of the Five Bonds (or Blizon), the Yoson and Suin Rivers. Despite the proficient presence of water bodies within, the Claise basin is described by a poorly organized and extensively fragmented hydrological network [70]. Since the study area takes part of a national park, the land occupation pattern of the Claise basin has remained relatively unchanged for the last 19 years except for pond proliferation. The land occupation setting of the Claise consists mainly of a homogeneous interlocking mosaic of abundant grasslands, agricultural areas and forests as opposed to a very low urban occupation [69]. The climate of the Claise basin mainly

Figure 1.
Study area description, BNP: Brenne Regional Natural Park.

corresponds to the degraded oceanic continental climate with high oceanic influence having annual average temperatures of 11°C, 8–14 days of temperatures below −5°C and annual cumulative precipitations in the order of 700 mm [71]. However, Nedjai et al. [57] have shown that the pond dense zone possesses the ability to create a local microclimate quite different from its surrounding. In terms of topography, the Claise basin can be described as a flat area with an altitude range of 76–181 m. According to Fischer et al. [72], six soil groups are present in the basin; these are in descending order of spatial coverage: Luvisols, Podzols, Leptosols, Cambisols, Fluvisols and Arenosols. According to Barrier and Gagnaison [73], the geological setting is dominated by Cenomanian, Jurassic and clay deposits and was completed at the end of the Tertiary era.

As a result of its poor hydrographic network, quasi-impermeable pedological setting, litho-stratigraphic composition, flat topography and abundant rainfall, stagnation of incoming water in the basin resulted in the formation of ponds [57, 74]. However, the proliferation of ponds in great numbers is not only due to natural origins, but also a translation of significant anthropogenic interference to overcome economic restraints imposed by the challenging soil productive capacity for use for extensive aquaculture [57, 75]. Despite the proficiency of aquaculture in the region, the Brenne Regional Natural Park displays a population density of 17.9 inhabitants/km^2, which has been considered as one of the lowest in the Région Centre [76] and has been engaging in decreasing trends since the year 2006 [77]. This state leads to a population exodus in the study area, thus constricting further the presence and associated impact of anthropogenic activity.

Overall, the presence of a dominantly natural vegetated land cover and the absence of sloping areas generally imply a low erosive setting. However, given the questions raised regarding the impact of ponds, known to be modifiers of the hydro-sedimentary response of basins, particularly due to their presence in significant numbers and their position as a chain setting, this basin was chosen for investigation of the pond-impact on basin erosion risks.

2.2 The Nahr Ibrahim basin: a representative Mediterranean basin

The Nahr Ibrahim basin is one of the 11 coastal basins of Lebanon. It describes an area of 309 km^2 accounting for 3% of the country's area between 36° 2′ 46″ E, 34° 12′ 46″ N and 35° 38′ 35″ E, 33° 59′ 36″ N [62] and represents one of the most important Lebanese basins. The basin houses the perennial Nahr Ibrahim River, one of the 17 rivers protected by the Lebanese Ministry of Environment [78] given its biological and ecological significance and its role as a vital input for the local economy [79], primarily for agricultural irrigation, freshwater supplies and eco-tourism services [80]. The basin is characterized by a rich hydrological network consisting of several effluents feeding the 27-km-long river that originates from the Afqa and Roueiss springs at an altitude of 1200 m and 1265 m, respectively [62], and flows at 507 million m^3/year [81]. A typical heterogeneous Mediterranean basin land occupation pattern consisting of a heavily urbanized lower part, a semi-natural middle section and a mountainous upper basin accounting for nearly 60% of the basin is observed within. As many other regions of Lebanon, land occupation dynamics have occurred under a lack of governance, regulations, restraints and management plans [17] leading to an unequal repartition in the same landscape, thus giving rise to a heterogeneity of basin processes within. A typical Mediterranean climate showing increasing tendency toward prolonged droughts and more erratic intense rainfall events dominates the study area. Precipitations occur in the form of rainfall ranging from 900 mm to over 1400 mm, while in the upper mountainous part, snowfall is prevalent during the November–March period with a snow cover

Parameters	Claise basin	Nahr Ibrahim basin
Climate	Degraded oceanic	Mediterranean
Hydrological network	Severely fragmented, characterized by the presence of ponds in great numbers	Rich
Topography	Flat	Heterogeneous, characterized by steep slopes
Geology	Dominated by Cenomanian, Jurassic and clay deposits	Dominated by Cenomanian, Jurassic and Quaternary deposits
Pedology	Quasi-impermeable soil groups	Permeable soils with heterogeneous distribution
Land use/Land cover	Dominantly natural with the presence of manmade ponds in large numbers **Homogeneous**	Mountainous upper portion; middle region with a diversity of superficial lands exploited with urban zones, agricultural fields planted with fruit trees, pasture with low vegetation and forestry; heavily urbanized lower region **Heterogeneous**
Anthropogenic pressure	Light showing minor increases	Increasing

Table 1.
Comparison of study area characteristics.

often lasting until late summer [62]. Geomorphologically, the basin corresponds to a mountainous area characterized by a varied topography consisting of hills and valleys with an upward slope gradient of nearly 20–25 m/km, along with a moderately sharp surface relief extending between the coast and 2600 m of altitude [61]. According to Darwish et al. [82], the Nahr Ibrahim basin is comprised of 11 soil groups in descending order of spatial coverage: Soil Associations[1], Leptosols, Andosols, Regosols, Anthrosols, Arenosols, Luvisols, cliffs, Cambisols, Gleysols and Fluvisols. According to Dubertret [83], the geology of the basin is presented by eight rock units dominated by Cenomanian carbonate rocks (70%) followed by the Jurassic (20%), with outcropping stratigraphic sequences revealing rock formations spanning from the Middle Jurassic to the recent epoch. Socioeconomically, and as other regions of Lebanon, the Nahr Ibrahim basin presents a densely populated lower portion corresponding to its coastal area in contrast to a less populated upper mountainous region [10]. In addition to urbanization in its lower part, the Nahr Ibrahim basin suffers from intensive industrial development [84] as opposed to a much less populated mountainous upper part.

As a result of its complex topography, abrupt climatic conditions and pedological composition, the Nahr Ibrahim basin has been reported by Abdallah and Faour [62] to be a region of intensive landslides that cover up to 7.6 km^2 of its area due to the dominance of Leptosols extending over Cenomanian (C4) and Jurassic (J4) formations, generally found over karstic and sloped areas, thus rendering them vulnerable to erosion. Further, as a result of extensive anthropogenic activity, the basin has been reported to be an area of intensive sloping runoff with increasing vulnerability to erosion [12] in addition to increasing trends of land degradation [61], thus making it a suitable target for this study.

Since a comparative framework is targeted in this study, **Figure 1** presents the settings of both study areas, while **Table 1** presents a general comparison.

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1 Calcaric Leptosols, Haplic Leptosols, Skeletic Regosols, Leptic Luvisols and Lithic Luvisols.

3. Methodological workflow and theoretical aspects of the study

3.1 The CORINE erosion risk model framework: basis and concepts

Despite the prevalence of soil erosion assessment models, data availability limits the choice of sought models; therefore, given the data-sparse nature of the Nahr Ibrahim basin and the absence of quantitative soil loss studies in the country [42], the use of a process-based model is not possible. Therefore, a robust reliable model with relatively simple data requirement is sought. Accordingly, the semi-qualitative empirical CORINE erosion model has been chosen given its capability of accurately predicting the spatial distribution of erosion risks with relatively simple data requirement and ease of parameterization [63]. Despite its empirical nature which may provide it with an accuracy less than that of physical or process-based models, the CORINE model was chosen since empirical models are of adequate use for soil conservation studies [85]. Further, several successful applications of the model have been documented in different regions of the world (e.g., [86–88]), therefore giving it adequate reliability, particularly for the Mediterranean and data-sparse regions [89].

For erosion risk assessment using the CORINE model, several factors are required. These, according to Vertessy et al. [48], are:

1. *soil erodibility*, computed from three attributes—soil texture where fine particle fractions are more readily removed than coarser fractions [90], soil depth where deeper soils resist erosion as function of higher water-holding capacities [48] and stoniness given their protective role in the pre-surface runoff stage [87];

2. *soil erosivity*, computed from two climatic indices—the Modified Fournier Index (MFI) to determine rainfall variability [91] and the Bagnouls-Gaussen aridity Index (BGI) [92] to reveal the possibility of abrupt short-storm events during normally dry seasons [48] leading to intensive erosion;

3. *topography*, obtained through slope angle calculation given its pronounced effect on soil erosion, particularly when a certain critical threshold is exceeded [48];

4. *vegetation cover*, obtained from Land Use and Land Cover (LU/LC) maps given their effect on soil fixation via their roots and by reducing rainfall splash effect [5, 93].

The respective input layers were extracted from the databases and inputted into the Raster Calculator tool of ArcGIS for computation and application of the basis, equations and workflow for the CORINE presented in **Figure 2**. Each index was computed after classification into the corresponding CORINE categories, into the erodibility, erosivity and topography components which in turn are part of the potential soil erosion risk formula (**Figure 2**). Having obtained the potential soil erosion risk map, overlaying the vegetation cover layer allowed the computation of the actual soil erosion risk maps. Through scenario testing using a study adapted vegetation cover as an alternative input to the CORINE model, land degradation under the form of soil loss (here erosion) was determined. By quantitatively determining erosion risks using equations presented in **Figure 2**, an accurate representation of soil loss by erosion under current conditions is obtained. This step in turn serves as a reference or a baseline indicator for comparison with alternative scenarios. In the case of Nahr Ibrahim, for elaboration of measures to counterbalance the negative effects of land degradation, and balance land losses by land gains through application of the LDN concept, the CORINE model was used to reveal changes in erosion risks after LDN implementation. The latter is a new concept proposed in 2015 by the UNCCD to protect stable lands, halt ongoing degradation and restore
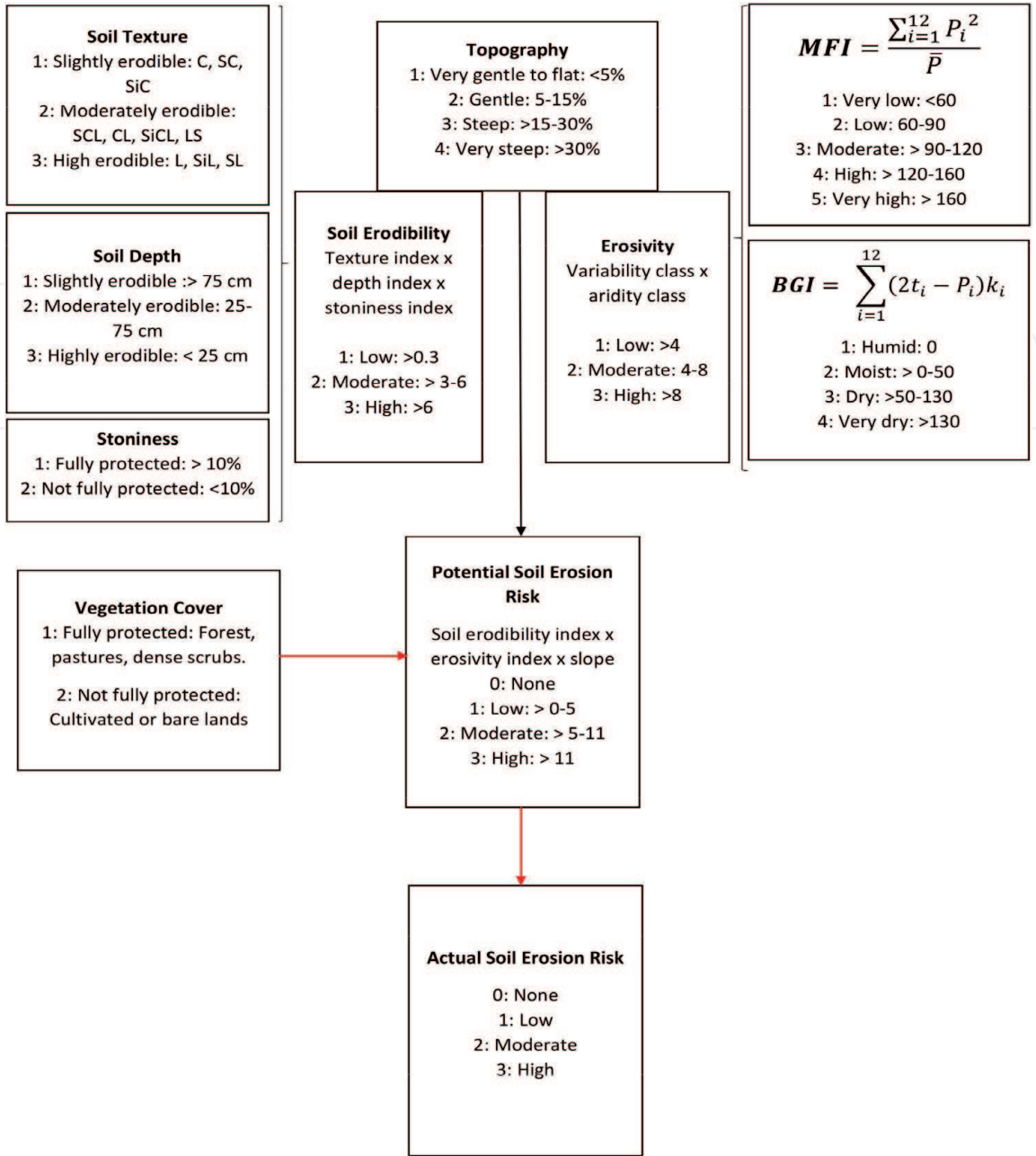
Figure 2.
CORINE model methodology, adapted and modified from CORINE (1992); C: clay, S: sand, Si: silt, L: loam, P_i: total precipitation in month i, Pi: mean annual total precipitation, t_i: mean temperature for the month i, and k_i defined as the proportion of the month in which $2t_i - P_i > 0$.

degraded lands. At the quantitative scale, by computing erosion risks at the current state (reflected by current land occupation) versus LDN state, the quantitative link between the LDN concept and soil erosion by modification of erosion risks after LDN implementation was revealed. For the Claise basin, by means of alternative vegetation cover simulation, the role of ponds on erosion risks was highlighted by revealing changes induced in the shades of their absence or drying.

3.2 Input data and database description

Data availability and quality are one of the main governing factors for any modeling study. The main reason behind the choice of the CORINE model is the data-scarcity state of Nahr Ibrahim where several input data for physical modeling are either lacking or insufficient. Therefore, with respect to the data requirements of the CORINE model, **Table 2** presents the input data for each study area.

3.3 General workflow: a dual approach between current and simulated conditions

The methodological workflow for this study consists of a two-fold approach:

1. Establishment of erosion maps for both study areas under current land occupation settings in order to establish a comparative framework for revealing differences and inferring their sources.

2. Establishment of alternative land use and land cover (LU/LC) scenarios for comparison with current settings: for Nahr Ibrahim based on the LDN concept, and for the Claise basin by means of alternative scenario testing by simulation of pond drying (empty ponds). Alternative simulations are carried out in order to prospect the potential of LDN through land use planning to reduce soil erosion for Nahr Ibrahim, and for determining the pond presence/absence effect in the Claise.

For the LDN approach, the established LU/LC map was intersected under GIS environment with the Lebanese national land capability classification map [95] and the national organic C maps [96] clipped to the Nahr Ibrahim basin in analogy to the LDN indicators. The integration of land capability classification is performed given its importance as an indicator for better use of land, optimization of current LU/LC and for providing insights for future land planning [97, 98]. This step allows a relatively simple yet meaningful tool for land owners and decision-makers for revealing sustainability distribution [66], thus addressing the LDN challenges of land stewardship, and implementing integrated planning approaches for sustainable use of the land and soil resources. After establishing the proposed LDN scenario, based on the concept's response strategy, the LDN-based LU/LC map was used as an alternative input to the CORINE model to compare erosion patterns with those reflecting current conditions in order to reveal LDN's effect on soil erosion in analogy to the work done by Al Sayah et al. [20].

For the Claise basin, study of SAFRAN records for the period 1970–2018, through trend analysis, revealed decreasing precipitations coupled to increases in temperature. Therefore, an alternative scenario assuming that ponds were to be dried was established and inputted again to the CORINE model for comparison with current conditions.

Data	Claise basin	Nahr Ibrahim basin
Land use and land cover maps (classified according to the CORINE classification)	Digitized from ortho-rectified aerial photography 2014, at 0.50 m resolution (R. Nedjai) and verified with ancillary CORINE land use/land cover maps	Digitized from SPOT (2018, 1.5 m) satellite imagery and verified on field—National Council for Scientific Research—Remote Sensing Center
Soil maps	Harmonized World Soil Database [72]	Soil map of Lebanon 1:50000 [82]
DEM	25 m raster; source: Institut Géographique National (IGN) - France	10 m raster, National Council for Scientific Research—Remote Sensing Center
Weather data	Système d'Analyse Fournissant des Renseignements Adaptés à la Nivologie (SAFRAN) model [94]	Lebanese Agricultural Research Institute's Akkoura Weather Station

Table 2.
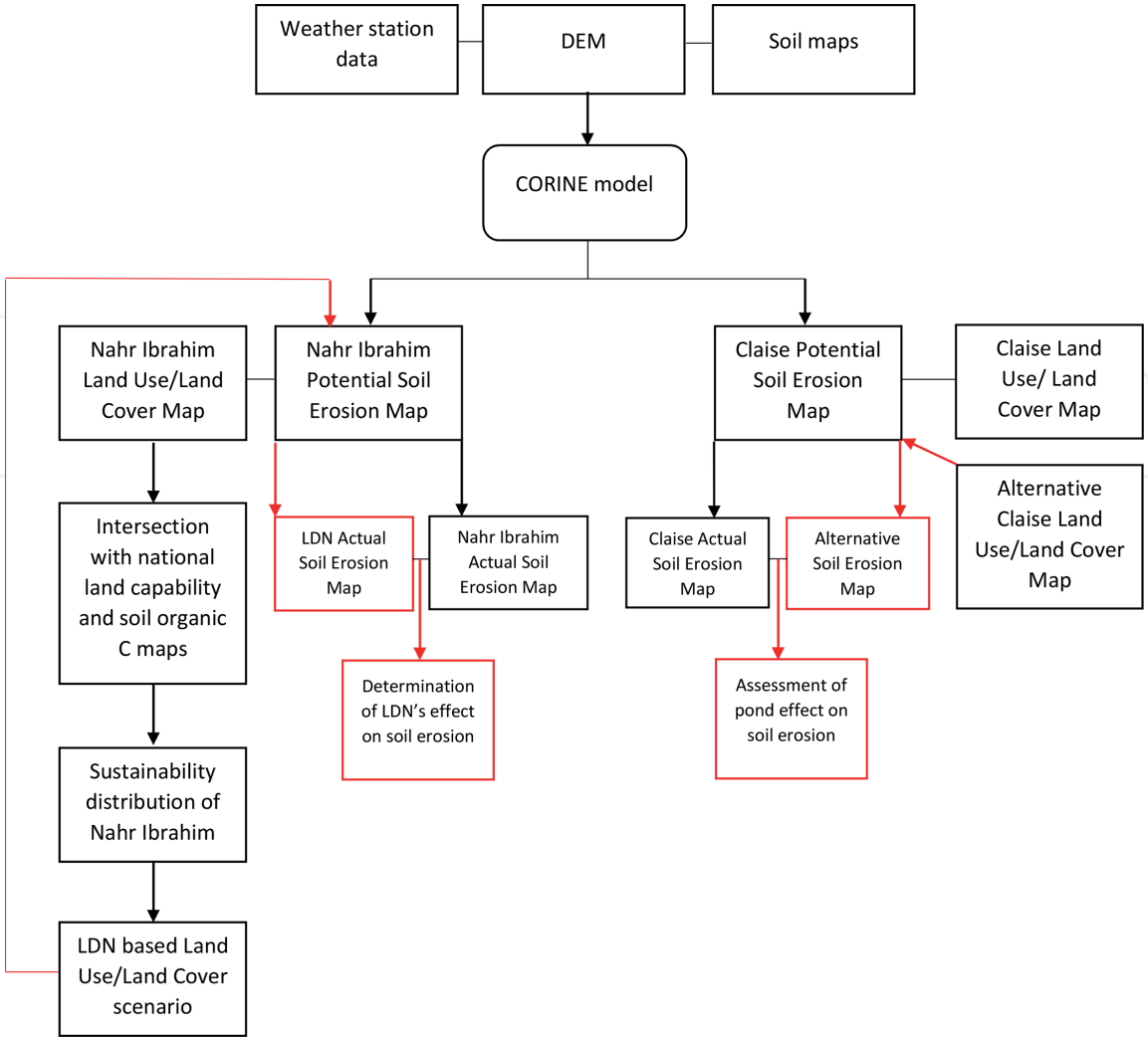*Input data for the CORINE model and source.*

Figure 3.
Methodological workflow.

The produced actual soil erosion map for Nahr Ibrahim was validated on field after a storm event, while for the Claise basin, the actual soil erosion map was validated with ancillary soil erosion maps. **Figure 3** presents the adapted workflow.

4. Results and discussion: comparative analysis of the CORINE's model components for both basins

In this section, a detailed comparison between the two study areas in terms of soil erodibility, erosivity, topography and vegetation cover is first presented. As a second step, the alternative scenarios for both study areas and a comparison with the current conditions for revealing change effects are explained.

4.1 Soil erodibility and pedologic structure of the study areas

With reference to the pedological composition of the study areas, the Claise basin possesses six soil types: Luvisols, Podzols, Leptosols, Cambisols, Fluvisols and Arenosols. On the other hand, the Nahr Ibrahim basin possesses 11 soil types: Leptosols, Andosols, Regosols, Anthrosols, Arenosols, Luvisols, cliffs, Cambisols, Gleysols and Fluvisols. **Tables 3** and **4** present a pedological comparison of the study areas in terms of composition and texture.

With respect to the components of soil erodibility, soil texture in the Claise basin was found to be 68.5% loam, 28.8% loamy sand, 2.5% of clay and the remainder percentage is made of sand. The Nahr Ibrahim basin on the other hand, as function of its more diverse pedological composition, was found to possess more textural classes. These are in descending order of spatial coverage: clay (32.5%), sandy clay loam (26.6%), loamy sand (14.4%), clay loam (10.9%), loam, sandy loam, silty clay loam, silt loam and silty clay. With respect to the CORINE textural classification, the Claise basin mostly corresponds to the highly and moderately erodible texture classes, while Nahr Ibrahim mainly corresponds to the slightly erodible classes. Therefore, in terms of soil texture, the Nahr Ibrahim basin is more erosion resistant than the Claise.

Regarding soil depth, the Claise basin fits to the slightly erodible class with more than 90% of its soils corresponding to the deep (>75 cm) category and the moderately erodible class for its remainder 10%. On the other hand, the Nahr Ibrahim basin presents less than 20% of deep soil classes and more than 40% of shallow depths. Therefore, in terms of soil depth, the Claise basin soils are more resistant to erosion than those of Nahr Ibrahim.

The stone cover of the Claise basin, however, dominantly corresponds to the not fully protected class, while most of the Nahr Ibrahim basin corresponds to the fully protected class, thus giving it a more or less protective stone cover. Globally, the pedological setting of the Nahr Ibrahim basin was found to be more erosion resistant than the Claise.

4.2 Erosivity under different climatic contexts

Since erosivity depends on rainfall, a comparison between the climatic contexts of both study area is presented in **Tables 5** and **6**. As seen, no dry months exist in the Claise and rainfall is much more pronounced than in Nahr Ibrahim. This is observed particularly during summer since rainfall is at its lowest in Nahr Ibrahim as opposed to the Claise where it reaches its maximal values.

At this point, it is important to account for the differences in the climatic settings of both basins, where the Claise corresponds to the degraded oceanic climate, while Nahr Ibrahim is of the Mediterranean type. Therefore, a greater rainfall variability and more prolonged aridity periods are expected for the Nahr Ibrahim, which are characteristic of the Mediterranean climate. This speculation was verified by the Modified Fournier Index (MFI) which was found to be 217 for Nahr Ibrahim (corresponding to the very high erodibility class indexed as 5) and 80 (very low, class 1) for the Claise basin. On the other hand, the Bagnouls-Gaussen aridity index (BGI) further revealed differences between the study areas, where Nahr Ibrahim's BGI is

Claise soil classes	Area (km^2)	Percentage (%)
Calcaric Cambisols	17.38	2.49
Calcaric Fluvisols	4.79	0.69
Cambic Podzols	195.95	28.07
Gleyic Luvisols	439.70	62.99
Luvic Arenosols	2.43	0.35
Rendzic Leptosols	37.83	5.42

Table 3.
Pedological composition of the Claise basin.

Nahr Ibrahim soil classes	Area (km²)	Percentage (%)
Soil Associations	154.05	50.52
Areno-Eutric Leptosols	16.33	5.36
Calcaric Fluvisols	0.92	0.30
Calcaric Leptosols	1.43	0.47
Calcaric Regosols	3.31	1.08
Calcaro-Hortic Anthrosols	8.18	2.68
Calcaro-Mollic Leptosols	25.29	8.29
Endogleyic Anthrosols	0.25	0.08
Endoskeletic Regosols	6.40	2.10
Eutric Arenosols	0.16	0.05
Eutric Cambisols	1.34	0.44
Eutric Fluvisols	0.46	0.15
Eutric Leptosols	51.78	16.98
Gleyic Leptosols	3.05	1.00
Haplic Arenosols	7.36	2.42
Haplic Luvisols	0.18	0.06
Hypoluvic Arenosols	0.72	0.24
Leptic Andosols	13.34	4.37
Leptic Luvisols	4.09	1.34
Luvic Calcisols	0.02	0.01
Mollic Andosols	0.18	0.06
Mollic Gleysols	1.05	0.35
Rendzic Leptosols	4.82	1.58
Skeletic Regosols	0.16	0.05
Vertic Cambisols	0.05	0.02

Table 4.
Pedological composition of the Nahr Ibrahim basin.

49 (corresponding to the moist class 2) and it is 0 for the Claise corresponding to a humid area with respect to the CORINE BGI classification. In analogy to CORINE's erosivity formula, the Claise basin has an erosivity factor of 1, while for Nahr Ibrahim, the erosivity index is 10. Despite the much more pronounced rainfall in the Claise, the even precipitation distribution in the region resulted in a reduction of climate-induced soil erosion [99] as opposed to Nahr Ibrahim, signifying higher climate-induced erosion risks.

4.3 Effect of topography: a contrast between a mountainous and a flat basin

Table 7 presents the slopes of both study areas with respect to the CORINE's model classification.

Topography is one of the most pronounced differences between the study areas, due to differences in the topographic and orographic composition since the Nahr Ibrahim basin presents a Mediterranean mountainous basin. Accordingly, computing the slope from the DEM rasters of each study area using the slope

Claise month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average temp. (°C)	4.7	5.2	7.8	10.4	14.3	17.9	20.1	19.7	16.1	11.8	7.7	4.8
Precipitation (mm)	416	677	1106	1526	1782	2045	2108	1826	1356	818	482	361

Table 5.
Average temperature and precipitation for the Claise basin (1970–2018).

Nahr Ibrahim month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average temp. (°C)	4.5	6.1	8.	11.7	15.	18.3	20.6	21	18.4	15.3	10.5	6.8
Precipitation (mm)	181	125	127	56	33	6	0.16	1	19	55	106	197

Table 6.
Average temperature and precipitation for the Nahr Ibrahim basin (2009–2018).

tool of ArcGIS, the Claise basin corresponds entirely to the flat topography class in contrast to the 85% dominance of steep classes in the Nahr Ibrahim basin. For that reason, a significant difference in erosion patterns is expected given the very pronounced role of slope on erosion risks [100], particularly in the Nahr Ibrahim basin, where its slopes, as reported in Ref. [12, 62], were the main reasons behind its high rates of erosion and landslide occurrences as opposed to the predominantly flat Claise basin.

4.4 Vegetation cover: a pronounced difference between a natural and an anthropogenically managed basin

Given its integral role as the most crucial element for erosion risk assessment in the CORINE erosion model, a particular focus is given to the vegetation cover under a setting of natural versus managed basin. This difference is particularly observed when comparing the land use and land cover settings of both study areas. The 707 km² Claise basin displays a homogeneous distribution of 21 land occupation classes throughout its area (**Table 8**), while the 309 km² Nahr Ibrahim basin occupying an area less than half the area of the Claise presents 43 land use/land cover classes (**Table 9**), which is nearly double the categories of the Claise.

Slope class	Claise (%)	Nahr Ibrahim (%)
Very gentle to flat	99.3	2
Gentle	0.7	13
Steep	—	28
Very steep	—	57

Table 7.
Slope distribution in the study areas.

Claise land occupation	Area (km^2)	Percentage (%)
Agricultural areas	0.15	0.02
Clear broad-leaved forest	2.21	0.31
Clear mixed forest	0.90	0.13
Coniferous forest	26.94	3.70
Dense broad-leaved forest	163.58	23.14
Dense mixed forest	27.00	3.82
Field crops in medium to large terraces	19.14	2.71
Fruit trees	0.20	0.03
Grassland	207.04	29.28
Inland marshes	4.01	0.57
Low-density urban tissue	3.24	0.46
Medium-density urban tissue	1.76	0.25
Mineral extraction site	0.10	0.02
Non-irrigated field crops	151.02	21.36
Pond	79.47	11.24
River	0.55	0.08
Scrubland	2.80	0.40
Scrubland with some bigger dispersed trees	15.36	2.17
Urban expansion site	0.01	0.00
Urban sprawl on clear wooded lands	0.01	0.00
Urban sprawl on field crops	1.01	0.14
Urban sprawl on grassland	1.20	0.17

Table 8.
Distribution of the Claise's land occupation classes.

The land occupation setting of both study areas not only reveals a significant difference between two contexts, but also highlights the effect of management strategies on the studied process. With reference to **Figure 1** and by grouping LU/LC classes into urban/unproductive, agricultural and vegetated (grass, scrublands and forests) areas, a 1.05, 24.07 and 63.01% distribution is observed in the Claise basin, while a 62, 10.27 and 27.73% distribution of the listed class is seen in Nahr Ibrahim. In the Claise, the remainder 11.87% corresponds to water bodies (the Claise River and ponds). Accordingly, with respect to the CORINE erosion model classification, the Claise basin's land occupation pattern corresponds to a 63.58% protected cover and 25.12% not fully protected, while the Nahr Ibrahim basin shows a 29% fully protected cover and a 71% not fully protected. At this point, pronounced differences of topography, climate and vegetation cover are expected to be translated in the erosion maps.

4.5 Actual soil erosion risk maps: a result of contrasting pedological, climatological, topographic and vegetation cover factors

After establishment of the potential soil erosion risk maps in analogy to **Figure 2**, land use and land cover maps of the study areas were intersected to yield the actual soil erosion risk maps of the studied areas (**Figure 4**).

Nahr Ibrahim land occupation	Area (km^2)	Percentage (%)
Medium-density urban tissue	1.7	0.55
Low-density urban tissue	4.16	1.35
Urban expansion sites	0.61	0.2
Industrial or commercial zone	0.31	0.1
Mineral extraction sites	3.18	0.96
Diverse equipment	0.04	0.01
Tourist resorts	0.02	0.01
Field crops in small fields/terraces	4.01	1.02
Urban sprawl on field crops	0.05	0.02
Olives	0.6	0.19
Fruit trees	24.08	7.79
Citrus trees	0.02	0.01
Banana	0.04	0.01
Urban sprawl on permanent crops	2.34	0.76
Greenhouses	0.62	0.2
Dense pine forests	4.42	1.43
Dense oak forests	6.03	1.95
Dense cypress forests	0.08	0.03
Dense juniper forests	0.3	0.1
Dense mixed forests	34.38	11.13
Urban sprawl on dense wooded lands	1.05	0.34
Clear pine forests	1.23	0.4
Clear cypress forests	0.04	0.01
Clear oak forests	9.2	2.98
Clear mixed wooded lands	8.03	2.6
Clear fir forests	0.45	0.15
Clear juniper forests	5.75	1.86
Other type of clear forests	0.05	0.02
Scrublands	2.48	0.8
Scrublands with some bigger dispersed trees	6.34	2.05
Urban sprawl on scrublands	0.0298	0.01
Hill lakes	0.15	0.05
Sand beach	0.03	0.01
Unproductive areas	181.43	58.72
Burnt areas	0.1141	0.04
Abandoned agricultural land	0.74	0.24
Grasslands	5.86	1.9

Table 9.
Distribution of the Nahr Ibrahim's land occupation classes.

The produced maps were in turn verified by field campaigns for the Nahr Ibrahim basin and by cross-validation with ancillary erosion risk maps for the Claise basin. Both maps showed adequate representativity and accuracy in the validation stage. As seen from **Figure 4**, significant differences were observed between the two basins, therefore allowing us to infer several points:

I. Through graphical comparison, the distribution of erosion risks in the two basins is clearly contrasted. The dominance of high erosion risk zones in the Nahr Ibrahim basin is opposed by the prevalence of low erosion risks in the Claise. In the latter, low erosion risks account for 65.6%, moderate risks account for 21.68%, while high erosion risks account for 0.18%. In contrast, the zonal distribution in the Nahr Ibrahim basin is 4% for low risk, 39.5% for moderate risks and 56.42% for high erosion risk zones.

II. The significant difference of erosion patterns between the study areas can be mainly attributed to Nahr Ibrahim's topographic complexity, significant slope steepness, heterogeneous pedological context, dense hydrographic network [31] and its vegetation cover which possesses the most important effect on the CORINE model. Given its status as the only human-controllable input factor, the effect of land management induced by the type of land occupation is also highlighted [101], since a natural setting basin corresponding to a well-managed natural park shows low erosion risks, while a randomly managed basin presents significant erosion levels.

III. In the Claise basin, a no erosion zone is graphically noticed. The latter corresponds to the pond dense zone. At the individual scale, ponds are known for trapping incoming water, increasing its concentration time, decreasing runoff and retaining water, soil and debris by settling, thus trapping eroding soils [102]. At the scale of the Claise, the individual pond effect is much more amplified given the presence of ponds in such large numbers (2179) in a connected matrix, thus increasingly trapping soil/sediment in a collective manner. Their presence as a land occupation class capable of trapping soil and water gives them the role of a protective cover from which soil loss cannot occur, therefore leading to a "no erosion" zone. The collective effect
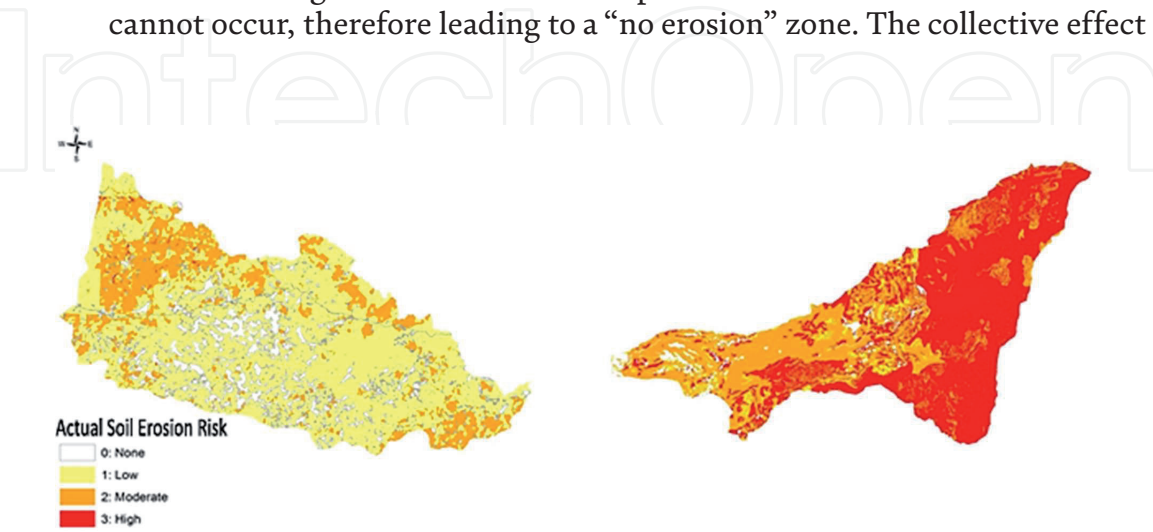

Actual Soil Erosion Risk
0: None
1: Low
2: Moderate
3: High

Figure 4.
Actual soil erosion risk for the study areas under current land occupation conditions.

of aggregated ponds as a result of their setting as a conceptual large surface was discussed by Downing [59]; he reports that, as a result of large numbers in an interlocking setting, individual retention capacities and trapping processes are amplified to rates even greater than those of larger water bodies, such as lakes, making these ponds very effective in the process of soil erosion.

IV. Within the Claise basin, moderate erosion risk zones are observed in the agricultural areas. These observations are concurrent with those of Verheijen et al. [8] who report, despite the similarity of the pedological context along with the topographic factor and climatic conditions, soil erosion is ultimately influenced by the vegetation cover and particularly by the presence of agricultural classes (crops) that have been attributed to the highest erosion rates in Europe [4, 103]. Accordingly, despite the homogeneity of the Claise basin and its natural state, agricultural parcels are seen to have higher erosion risks than their surroundings. This further solidifies the role of human-induced LU/LC management in affecting natural processes even within a natural setting.

V. The alarming erosion risk map of Nahr Ibrahim, not only provides an informative tool for erosion, but also highlights the need for intervention, since the basin is severely subjected to soil loss and consequent land degradation. By pin-pointing zones of different erosion risks, an insight toward a priority-based land use planning, targeting zones of higher threats, is achieved. Therefore, in the case of Nahr Ibrahim, soil erosion mapping revealed the spatial distribution of erosion risks as a first step, and served as a land planning decision-oriented tool by pin-pointing zones at high risks as a second step. Through this dual insight provided from the integration of erosion maps, a holistic approach toward land degradation mapping was achieved. Consequently, a proper understanding regarding the types of foreseen soil conservation measures and optimal land occupation classes [104] is made possible, which reiterates the importance of the integration of soil erosion into soil conservation planning [105] and land degradation mapping.

4.6 Alternative simulations for comparison

Analyzing trends obtained from SAFRAN database and applied to the Claise revealed a decreasing trend of precipitation and increasing trend of temperatures. Given the evaporative regime of ponds, an alternative scenario simulating the absence of ponds was obtained. The latter was input, as the alternative vegetation cover, into the CORINE model for comparison with the current condition erosion map in order to determine the impact of pond presence/absence.

For the Nahr Ibrahim basin, the CORINE erosion map provided a tool for land degradation mapping. In analogy to the LDN concept at the scale of soil loss, the land use/land cover, actual soil erosion, national land capability classification and organic C map were intersected to reveal sustainability distribution. The latter was determined following the methodology for sustainability mapping in Al Sayah et al. (2019a) where the adequacy or inadequacy of the already present LU/LC distribution over the different land capability groups (I–IV representing the arable lands and an additional group V combining the USDA's groups V–VIII) allowed the categorization into sustainable and non-sustainable development zones. **Figure 5** shows sustainability distribution in the Nahr Ibrahim basin.
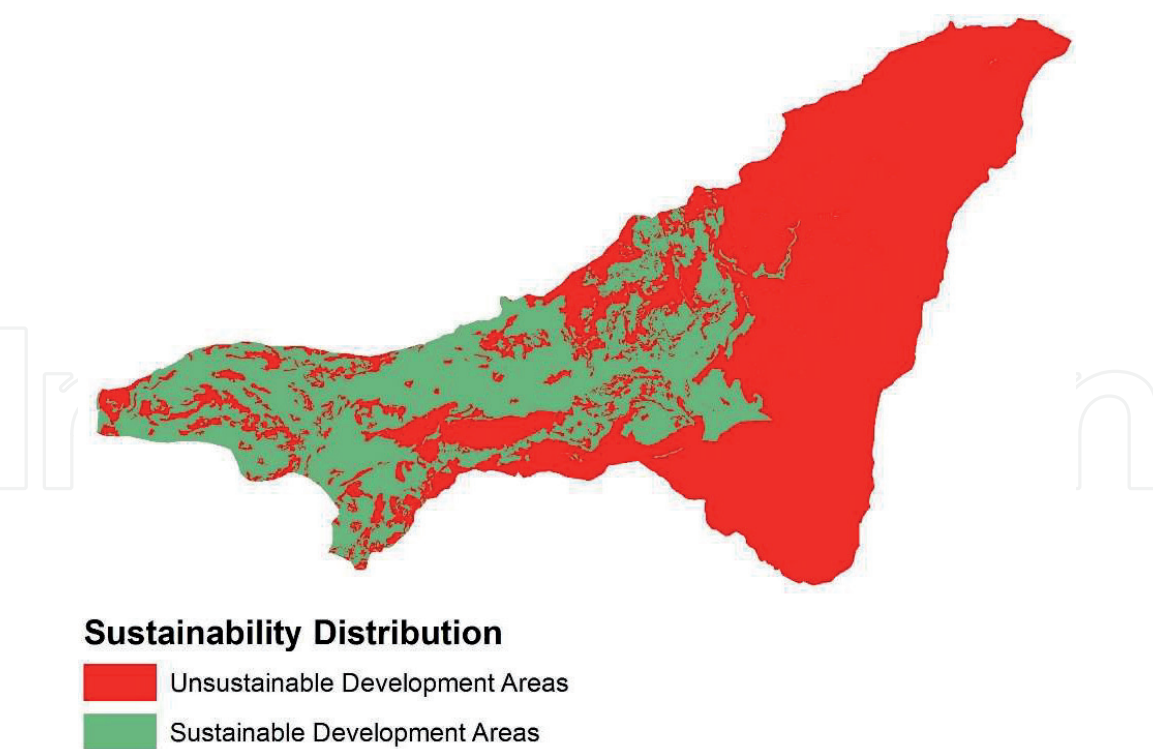
Figure 5.
Sustainability distribution of the Nahr Ibrahim basin obtained from intersecting land use and land cover maps with land capability classification layers.

Noticeably, the prevalence of unsustainable development areas is apparent; these account for 66% of the study area [20]. By optimization of land use and land cover categories covering the soil classes IV and V (19.35% of the basin), an alternative LDN-based scenario was obtained by increasing natural cover (grass, scrublands and forests) over these soils.

By re-using the two alternative vegetation cover scenarios in the CORINE model, **Table 10** was obtained.

Table 10 shows significant shifts of erosion patterns; for Nahr Ibrahim, high erosion risks decreased by 13.9%, low and moderate risks increased by 3 and 10.8%, respectively [20], while for the Claise basin, the opposite was observed with decreases in the no and low erosion risks as compared to increases in the moderate and high erosion risk categories. Thus, the contribution of LDN in reducing erosion highlights the importance of land planning and the effect of management on soil erosion, confining the LDN concept as an effective counter-erosion measure. For the Claise basin, changes in erosion patterns also reveal the importance of ponds as efficient counter-erosion structures that can be used to control areas of significant runoff and excessive erosion.

Erosion risk	Nahr Ibrahim current (%)	Nahr Ibrahim LDN (%)	Claise current (%)	Claise simulation (%)
None	0	0	12.48	1.12
Low	4	7.1	65.66	0.52
Moderate	39.5	50.4	21.68	76.8
High	56.47	42.54	0.18	21.56

Table 10.
Erosion risks of the study areas under current and simulated conditions.

5. Conclusions

As a first step, a simple data demanding CORINE model was used to assess erosion risks of two different geographical settings represented by the Claise and Nahr Ibrahim basins. Several pronounced differences between the two settings were observed as a result of a completely different natural setting and opposing land cover/management practices. A number of conclusions may be drawn from this study; these are listed under fundamental and contextual settings.

1. Fundamentally, despite the abundance of several erosion models, given the data-scarcity of Nahr Ibrahim and for the purpose of comparison between the two study areas, the relatively simple data demanding CORINE model was used. As a first step, the CORINE erosion model proved to be a robust tool for evaluation of the spatial distribution of erosion risks despite its empirical nature where CORINE established maps have shown sufficient accuracy when verified on field and crossed with ancillary maps.

2. In addition to erosion assessment, the CORINE model serves as a proficient tool for land occupation and land management adequacy assessment given its vegetation cover input that reveals the actual erosion risk settings of basins under current conditions. This statement was justified by intersecting land use and land cover maps with the actual soil erosion risk map in Nahr Ibrahim revealing the extent of mismanagement as function of inadequate allocation. In addition, by highlighting zones of high risks, an insight towards prioritized treatment measures is obtained. Moreover, by revealing zones of different risk levels, the CORINE model provides insight for land use planning, thus promoting optimal land occupation allocation. Further, by changing the vegetation cover input as the human-controllable factor and stabilizing all other components, the CORINE model serves also as a tool for alternative scenario assessment by revealing changes of erosion patterns under different scenarios when compared with the current baseline conditions of the studied area, thus revealing the needed steps to follow in terms of land planning or soil and water conservation measures.

3. In Mediterranean settings such as the Nahr Ibrahim basin, the CORINE model can provide a starting point for combatting land degradation, thus filling gaps of LDN application in the Mediterranean basin by contributing to land degradation mapping, integration of site-specific land degradation drivers and promoting sustainable land use planning [64, 106, 107].

Contextually, and by comparing both study areas, several aspects can be pointed out. Despite differences in the geographical setting, the impact of adequate versus random land use planning can be first concluded. This statement is particularly justified in the Claise basin, where despite its challenging pedological settings in terms of weak structure and cover, low and moderate erosion risks are prevalent due to its natural setting that provides the basin a protective cover against erosion. Further, due to the presence of ponds in large numbers, an amplified counter-erosion effect is observed. Their role was solidified by fixing erosivity, erodibility and topographic factors of the model and inputting an alternative scenario with dredged ponds. By comparison with the current actual soil erosion risk map, not only a shift in local erosion risks was observed, but also a complete shift within the basin was shown, thus confining the low erosion state of the Claise to its natural and pond cover and further indicating the efficiency of projecting ponds as an effective counter-erosion measure in basins with high erosion risks such as the Nahr Ibrahim basin.

When comparing the erosive setting of the Claise with Nahr Ibrahim, significant differences were observed namely in high erosion risk zones. This, in turn, is attributed to the climatic, topographic and vegetation cover factors of Nahr Ibrahim where increased climate-induced erosion combined with the very steep slope and anthropogenically induced erosion from alteration of the vegetation cover is prevalent. Under current conditions, the land occupation pattern of Nahr Ibrahim was shown to be unsustainable in terms of distribution above lands of different capabilities and distribution along high erosion risk areas. The most striking difference between the two basins is that the Nahr Ibrahim accounts for nearly double the number of land occupation classes in the Claise basin for an area less than its half. Further, the unequal repartition of land use/land cover classes in the Nahr Ibrahim basin caused a gradient of soil erosion risk patterns, consisting mainly of high erosion risks in its upper section and moderate to low risks in its middle and lower parts.

Despite its (the Nahr Ibrahim basin's) pedological and topographic settings, when vegetation cover was optimized through the application of the LDN concept, erosion risks significantly shifted. This is attributed to its highly erosive state and to its land occupation and management pattern in contrast to the well-controlled Claise basin. Conversely, the use of LDN as a basis for land planning and the use of land planning for implementation of the LDN concept not only allowed sustainability restoration but also proved to be an effective counter-erosion tool given its effect on decreasing high erosion risks and increasing low and moderate ones. The coupling of the CORINE erosion model and LDN concept can play a role in decision-making regarding land use planning, thus highlighting the importance of their implementation at the scale of the Mediterranean landscape. However, a basin like Nahr Ibrahim cannot be converted into a setting similar to the Claise, but a balanced land use plan accounting for the trade-off between natural resources and urban expansion may be the solution for restoring the Nahr Ibrahim landscape.

Finally, through a simple methodological approach, this work can be listed as a response to the European framework for the Thematic Strategy on Soil Protection, recommendations of the DCE for revealing the role of hydromorphological alternating structures on erosion patterns in basins and UNCCD's recommendations for implementation of the LDN concept. Despite the differences between the Thematic Strategy on Soil Protection, DCE and LDN concepts, the common effect of land occupation within these frameworks can be used as a platform to study the extent of anthropogenic influence at the basin scale in an attempt to promote sustainable development and to integrate soil erosion into land planning.

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Conflict of interest

The authors declare no conflict of interest.

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