Erosion risk mapping: A methodological case study in the Colombian Eastern Plains

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ABSTRACT: Soil erosion caused by water is an increasing global problem. Land use and soil conservation planning for large areas requires erosion risk maps, which are typically created using erosion models. These models are often developed for different regions than where they are applied. This paper describes a new qualitative methodology for mapping soil erosion risks over large areas, called Qualitative Erosion Risk Mapping (QUERIM). It is a flexible method that uses decision trees to assign ratings to the erosion-controlling factors. Constructed using expert knowledge, these decision trees reflect the important characteristics influencing erosion risk within a specific region. Ratings for erosion-controlling factors are combined at every location to obtain potential and actual erosion risk maps. QUERIM was applied to the Puerto López municipality in the Colombian Eastern Plains. The obtained erosion risk maps showed agreement with field observations of erosion risk. However, more ground data should be gathered for a better evaluation of the method. It is concluded that a simple qualitative approach such as QUERIM can be more effective in erosion risk mapping than the use of models that were not developed for the region to which they are applied.

Keywords: Colombian Eastern Plains, erosion risk mapping, Geographic Information Systems (GIS), remote sensing, water erosion

Accelerated soil erosion caused by water is an increasing global problem that threatens sustainable agricultural production (Oldeman 1994). Analyzing soil erosion risks is an important task, especially in vulnerable areas. Erosion risk maps of large areas are required to plan land use and soil conservation measures. Many mapping methods exist to fulfill this requirement (e.g. De Jong and Riezebos 1992, Fu and Gulinck 1994, Stocking and Elwell 1973). Each method usually accounts for the following erosion-controlling factors: climatic characteristics, soil properties, topography, and land management (Morgan 1986). These factors are often highly variable in space and time, which makes erosion risk mapping a complicated task.

Most erosion risk mapping methods use empirical or physically-based models. They all address the erosion-controlling factors differently. In general, these models have some important drawbacks. First, they require a large amount of detailed data. Often, these data are not available for large areas, especially in less-developed countries. Second, the models are most often developed for regions other than those to which they are applied, and for scales in which different processes and process-interactions may be important (Favis-Mortlock et al. 1996). Moreover, past studies reveal a low correlation between model outcome and observed soil loss (Favis-Mortlock 1998; Jetten et al. 1999; Nearing 1998; Rudra et al. 1998; Takken et al. 1999).

The most widely applied erosion model for erosion risk studies over large areas is the Universal Soil Loss Equation (USLE) (USDA 1978). It is a statistically calibrated model that combines erosion-controlling factors based on runoff plot data collected in the United States. A point of criticism made by Tricart and KiewietdeJonge (1992) is that the USLE is a simple addition of parameters and thus excludes all interaction and feedback effects in the erosion process, which invalidates its universal use. They advocate a more qualitative approach in mapping erosion risks. While a quantitative approach is necessary for the design of hydraulic infrastructures such as reservoirs, a qualitative approach is usually suitable for land use and conservation planning purposes (Herweg 1996).

Soil erosion risks can be divided into potential and actual risk. Potential erosion risk is defined here as the inherent risk of erosion irrespective of current land use or vegetation cover. Actual erosion risk relates to the risk of erosion under current vegetation and land management conditions.

The aim of this study was to define a methodological framework for qualitative mapping of erosion risks over large areas (several thousand square kilometers), using expert knowledge. It is hypothesized that a relatively simple qualitative approach is sufficient to indicate the spatial distribution of erosion risk. To illustrate the developed methodology, it was applied to the Puerto López municipality in the Eastern Plains of Colombia as part of a study that aimed at exploring simple methods that could be used for land use planning in Colombian municipalities (Beaulieu et al. 2000).

Methodological framework. Erosion studies can benefit from increased attention to the morphogenic-pedogenic balance (Tricart and KiewietdeJonge 1992). Morphogenic processes form the landscape by gravitational or other tangential working forces. Erosion is a typical example of a morphogenic process. Pedogenic processes refer to the development of soil horizons parallel to the soil surface, including rock weathering. Morphogenesis generally proceeds downslope along a topographic gradient, whereas pedogenesis proceeds vertically into the soil profile. As the factors controlling the morphogenic-pedogenic balance vary in space, their study is a good starting point for determining the spatial distribution of erosion risks.

Tricart and KiewietdeJonge (1992) consider geology, soil, relief, vegetation, and climate as being the most important factors influencing the morphogenic-pedogenic balance. The Brazilian National Institute for Space Research (INPE) developed a method to rate these factors (Crepani et al. 1996). If at a certain location a specific factor is favorable to pedogenesis, which implies a low erosion risk for that factor, its value becomes 1.0. For example, if permanent vegetation with a high

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vegetative ground cover (VGC) is present at a specific location, its vegetation factor becomes 1.0. If the factor is favorable to morphogenesis (high erosion risk), its value becomes 3.0. In the case of the vegetation factor, this value would be assigned to bare soil. The values of the five factors are averaged at every location, resulting in an erosion risk map.

INPE's approach intends to analyze erosion risk within the whole of Brazil. Therefore, they use standard values or methods of calculation for each of the five factors across the entire country (Crepani et al. 1999). Although this is a valid approach for analysis on the national scale, it cannot account for regionally distinct processes and process-interactions, nor does it give insight into the characteristics that determine erosion risks within a particular area. A different methodology is needed for erosion risk evaluation on a regional scale, especially considering that erosion control and mitigation strategies are mostly regionally planned.

We propose a new methodology known as Qualitative Erosion Risk Mapping (QUERIM). QUERIM uses the same strategy as INPE in the scaling and averaging of the factors that influence the morphogenic-pedogenic balance. The factors are essentially the same, although the vegetation factor is renamed the management factor to account for human impact such as tillage and conservation measures. The main difference between INPE's approach and QUERIM is the way the factor values are derived. QUERIM divides the five factors into sub-factors, which reflect the physical parameters that affect the erosion processes in the region. These parameters can be derived from the available spatial data and are assigned a qualitative rating, which may be the same as the rating from the data classes. To extract a final numerical index for each factor, the occurring value combinations of the sub-factors are evaluated using decision trees that are a qualitative representation of the relationships between each of the sub-factors. The average of the geology, soil, relief, and climate factors at each location results in the potential erosion risk map, whereas the average of all five factors (including management) gives the actual risk map.

Two other aspects of the QUERIM method should be noted. First, sub-factors and decision trees can vary according to region. Second, the success of the method depends on the use of appropriate expert knowledge. Experts that have worked on soil erosion in the region under study form a valuable source of information. They often understand the regionally occurring erosion processes and they usually know the locally significant parameters controlling those processes. QUERIM uses the knowledge of these experts in the definition and selection of the sub-factors, which are subsequently extracted from the available data. The experts also help create the decision trees by assigning an appropriate numerical index to each factor according to the occurring combinations of sub-factor values. QUERIM translates expert knowledge into a formal structure that uses available spatial data to create erosion risk maps.

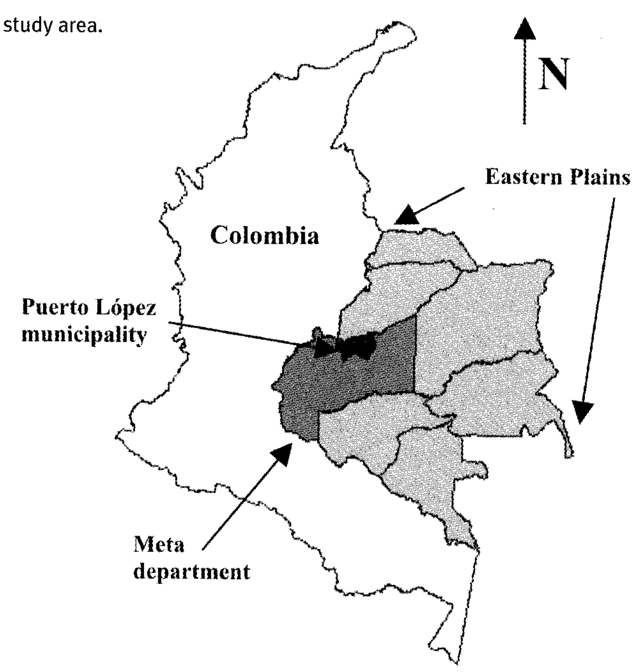
In principle, QUERIM can be applied to a zoned area, when the zones have the same characteristics and a high degree of internal uniformity. In this case, erosion-controlling factors have to be evaluated for each zone. But it can also be used in a raster environment to account for the high spatial variability of erosion risks. Then factors are analyzed per pixel. The choice also depends on the data availability. Either way, a geographic information system (GIS) is an indispensable tool for analysis of the spatial data.

Study area. QUERIM was applied to the Puerto López municipality, located in the department of Meta, Colombia (Figure 1). It covers an area of 6907 km^2 (2667 mi^2) and belongs to the Colombian Eastern Plains. The region has an average temperature of 27°C (81°F) and an annual rainfall, most of which occurs in high intensity storms between April and November, of 2800 mm (110 in). On an annual basis, rainfall amount and characteristics are distributed evenly over the municipality. Terrain elevations vary from 180 to 300 m (590 to 980 ft)above mean sea level.

The area consists of low-lying alluvial plains where floods occur and a higher elevation that is called the *altillanura* (high plains). These high plains can be divided into non-dissected and dissected regions. They are underlain by coarse to medium sands with argillic horizons at varying depths and layers of gravel and petroferric rock that appear on the surface of hills. The alluvial plains are composed of younger material with finer sands, clay, and cemented gravel. Introduced and natural pastures form the main ground cover in the high plains, whereas forest vegetation can be found along the drainage network. Analysis of Landsat Thematic Mapper (TM) data shows that pastures constitute 50%, forest 20%, and transitional vegetation 25% of the area. The remainder consists mainly of agricultural crops, of which lowland rice is the most important.

Soils in the municipality generally have a low infiltration capacity, which results from

Figure 1
Location of study area.



low organic matter content, poor soil structure, and surface crusting. Rainfall with intensities of more than 20 mm h^{-1} (0.79 in h^{-1}) causes Hortonian runoff and erosion (Amézquita and Londoño 1997). Given the present rainfall regime, the area is at high risk for soil erosion, and a good vegetation cover is essential to prevent the soil from being eroded.

Methods and Materials

We used three available spatial data sources for the Puerto López municipality. The first is a soil survey done by the Colombian Geographical Institute (IGAC) (1978), which resulted in a soil map on a scale of 1:100,000. The study is well documented; for each cartographic unit the constituting soil profiles are described in terms of their physical and chemical properties. The second data source is a Digital Elevation Model (DEM) that was interpolated from contour lines and point elevation data. The third data source is a Landsat TM image from August 10, 1998. The soil survey data were converted into a 25-m (82-ft) grid format and the Landsat TM image was resampled to obtain the same 25-m (82-ft) grid as the DEM. This allowed a pixel-based evaluation of erosion risk within a GIS. In this study PCI Geomatics software was used, but any raster-based GIS package could be applied for this purpose.

In addition, ground data of land use and VGC were gathered using a Global Positioning System (GPS). Border coordinates of parcels or homogeneous vegetation areas were measured, resulting in a collection of polygons. For every polygon, land use and average VGC were determined. The average VGC was estimated visually.

Apart from vegetation data, the GPS was used to indicate areas with clear signs of erosion and that suffer from a very high erosion risk. Erosion risk verification data were taken at seven locations distributed over the study area. After construction of the risk maps, we observed signs of erosion and estimated topsoil, geology, topography, and vegetation characteristics.

We interviewed four soil experts who have worked in the region. Three of them have performed soil erosion studies within the Puerto López municipality or in its vicinity. The experts identified the sub-factors to select and extract from the available spatial data, as well as the relationships needed for the construction of decision trees.

Results and Discussion

The selected sub-factors are shown in Table 1. Every sub-factor was given a qualitative rating that was subsequently used in the decision trees. Note that this value is not necessarily between 1.0 and 3.0. In this study, the climate factor was not used, as annual rainfall can be assumed homogeneous in the study area and therefore climate would not contribute to the spatial distribution of the erosion risk. The sub-factors for geology and soil were selected from the attributes contained in the soil survey by IGAC (Colombian Geographical Institute, 1978). The geology sub-factor, alteration degree, was defined as the degree of physical and chemical change that occurs in rocks at the ground surface or close to it through atmospheric agents (SSSA 1987). The relief attributes followed from the DEM. Slope gradient was calculated and dissection grade was visually interpreted. For the management factor, a

Table 1. Factors and sub-factors for Qualitative Erosion Risk Mapping (QUERIM) in Puerto López, Colombia.

Factor	Sub-factor	Rating	Description	Criteria
GEOLOGY	Alteration degree	1	Strongly weathered	
		2	Moderately weathered	
		3	Slightly weathered	
SOILS	Effective depth	1	Moderately deep	> 50 cm
		2	Superficial	25 - 50 cm
		3	Very superficial	10 - 25 cm
		4	Excessively superficial	0 - 10 cm
	Topsoil texture	1	Fine	
		2	Medium	
		3	Coarse	
	Organic matter content (topsoil)	1	Very high	> 6.0%
		2	High	2.5 - 6.0%
		3	Medium	1.5 - 2.5%
		4	Low	1.0 - 1.5%
		5	Very low	< 1.0%
	Structure	1	Strong	
		2	Moderate	
		3	Weak	
		4	Structureless - massive	
RELIEF	Dissection grade	1	Not dissected	
		2	Slightly dissected	
		3	Moderately dissected	
		4	Very dissected	
	Slope gradient	1	Flat	0 - 3%
		2	Slightly inclining	3 - 7%
		3	Moderately inclining	7 - 12%
		4	Strongly inclining	12 - 25%
		5	Steep	25 - 50%
		6	Very steep	>50%
MANAGEMENT	Land use	1	Water	
		2	Tree and shrub vegetation	
		3	Natural pastures	
		4	Introduced pastures	
		5	Lowland rice	
		6	Bare and burned land	
	Vegetative ground cover	1	High	80 - 100%
		2	Moderately high	60 - 80%
		3	Moderate	40 - 60%
		4	Low	20 - 40%
		5	Very low	0 - 20%
		6	None	0%

maximum likelihood classification was performed, using the Landsat TM image and ground data on land use, to obtain a land use map. The overall accuracy of this map was 84%. The VGC was determined for the total area by relating the ground estimates to the normalized difference vegetation index (NDVI) extracted from the image. Neither erosion prevention measures nor practices of conservation tillage are present in the area, and therefore these factors were not included in this study.

A numerical index between 1.0 and 3.0 was assigned to each factor by the local experts through qualitative evaluation of the occurring combinations of sub-factor values, as shown in the decision trees (Tables 2, 3, and 4). The geology factor obtained the same rating as in Table 1. Table 2 shows the decision tree for the soil factor. The experts gave the four sub-factors nearly equal weight in determining erosion risk, although structureless massive soils (structure rating = 4) considerably increased the risk. Table 3 shows the decision tree for the relief factor. Experts indicated that the slope gradient should receive the highest weight, but stressed the increased erosion risk in highly dissected terrain. Table 4 shows the decision tree for the management factor. Erosion risk is highest on the pastures (land use ratings = 3 and 4) that form a great part of the area, as well as on bare soils (mainly burned pastures; land use rating = 6. The VGC is the most determining sub-factor according to the experts.

A map was constructed for each factor, resulting in a numerical index for every pixel. The averages of the geology, soil, and relief factors per pixel produced the potential erosion risk map (Figure 2), whereas the averages of the geology, soil, relief, and management factors resulted in the actual erosion risk map (Figure 3). Table 5 reclassifies the values to obtain a more comprehensible legend.

The potential erosion risk map (Figure 2) shows a high risk for the dissected high plains (center and south) and the low-lying areas (western and northern boundary), which consist of young unstable alluvial sediments. A low risk is found on the non-dissected high plains (north). A similar attenuated pattern can be seen on the actual erosion risk map (Figure 3). This attenuation does not hold for patches with bare soil or pastures with a very low VGC. As the geology, soil, and relief factors are much more stable over time than the management factor, recurrent satellite remote sensing imagery should be used for better monitoring of the actual erosion risk. This allows timely identification of management changes, such as pastures that have been burnt, resulting in a low VGC and therefore a high actual risk.

The erosion risk verification data showed a correspondence between areas in the field with advanced signs of erosion or high erosion risk, and areas on the map indicating a high erosion risk at all of the seven locations visited. At four locations advanced signs of sheet erosion and gully formation could be observed, whereas at the remaining three locations favorable conditions for erosion (steep slopes, bare soil, etc.) were present. In spite of this correspondence between high erosion risk areas on the map and in the field, the study could benefit from a more thorough ground check. We suggest selecting several sites, not larger than 0.2 km^2 (50 ac), with clear differences in erosion risk on the maps. Within these sites the interrelations between the erosion-controlling factors can be identified through detailed field estimations of topsoil characteristics, geology, topography, and vegetation cover. Combined, these estimations can help predict site-specific erosion processes, which will result in a qualitative rating of the erosion risk.

It could be argued that QUERIM is a simple averaging of parameters, but the region-specific decision trees representing the

Table 2. Decision tree for soil factor.*

Effective depth	Topsoil texture	Organic matter content	Structure	Soil factor
1	1	4	3	1.4
1	2	2	3	1.3
1	2	3	1	1.3
1	2	3	2	1.4
1	2	4	2	1.5
1	2	4	4	2.3
2	2	1	2	1.7
2	2	2	2	1.9
2	2	4	1	2.2
2	2	5	3	2.4
2	3	3	2	2.3
2	3	5	4	2.8
3	1	1	3	2.0
3	2	3	2	2.5
3	2	3	3	2.6
3	2	4	3	2.7
4	3	5	4	3.0

***The decision tree shows the occurring value combinations of the specific sub-factors. These values correspond with Table 1. The last column shows the final factor rating as assigned by the local experts for each sub-factor combination.**

Table 3. Decision tree for relief factor.*

Dissection grade	Slope gradient	Relief factor
1	1	1.0
1	2	1.3
1	3	1.8
1	4	2.1
1	5	2.3
1	6	2.5
2	1	1.4
2	2	1.7
2	3	2.0
2	4	2.3
2	5	2.5
2	6	2.7
3	1	1.9
3	2	2.2
3	3	2.4
3	4	2.6
3	5	2.8
3	6	2.9
4	1	2.2
4	2	2.6
4	3	2.8
4	4	2.9
4	5	3.0
4	6	3.0

***The decision tree shows the occurring value combinations of the specific sub-factors. These values correspond with Table 1. The last column shows the final factor rating as assigned by the local experts for each sub-factor combination.**

Table 4. Decision tree for management factor.*

Land use	Vegetative ground cover	Factor management
1	6	1.0
2	1	1.0
2	2	1.2
3	1	1.3
3	2	1.5
3	3	1.9
3	4	2.3
3	5	2.7
4	1	1.4
4	2	1.6
4	3	2.0
4	4	2.4
4	5	2.8
5	3	1.8
6	6	3.0

***The decision tree shows the occurring value combinations of the specific sub-factors. These values correspond with Table 1. The last column shows the final factor rating as assigned by the local experts for each sub-factor combination.**

Table 5. Reclassification of erosion risk classes.

Rating	Erosion risk
1.0 - 1.3	very low
1.4 - 1.6	low
1.7 - 1.9	medium
2.0 - 2.2	high
2.3 - 3.0	very high

Figure 2
Qualitative Erosion Risk Mapping (QUERIM) potential erosion risk map of Puerto López municipality.

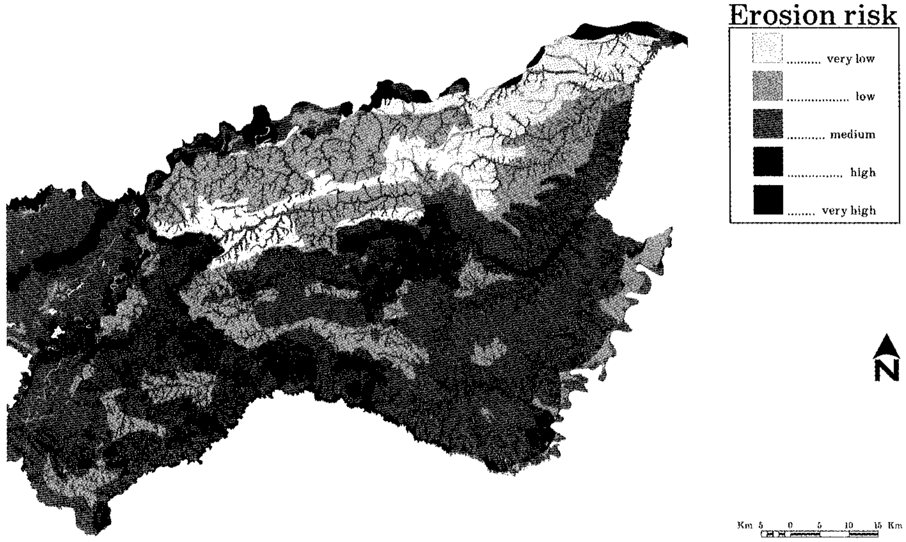


Figure 3
Qualitative Erosion Risk Mapping (QUERIM) actual erosion risk map of Puerto López municipality.

interactions between sub-factors lend flexibility to the method. In the Puerto López study, the important controlling role of vegetation (management) becomes clear through the overall attenuated pattern of actual erosion risk as compared to potential erosion risk. If vegetation were removed, soil characteristics influencing the infiltration rate would become a key factor, as well as the stability of the underlying material (geology factor). Obviously, low infiltration rates would create more runoff and erosion in steep and highly dissected terrain.

The merit of applying QUERIM to the Puerto López municipality is that it has produced a map of areas under potential or actual erosion risk. This will encourage proper land use and conservation planning, mostly by identifying areas threatened by erosion if, for example, vegetation were removed or burnt, or fields taken under cultivation. Land use planning using QUERIM results will direct these activities to "safer" areas. Moreover, areas having high actual erosion risk will qualify for being re-planted. Implications for conservation planning principally relate to recommendations of tillage practices, on either present or future agricultural fields.

As a qualitative method, QUERIM cannot give quantitative estimates of erosion, other than through the upscaling of erosion measurements that could be executed in the previously mentioned sites of 0.2 km^2 (50 ac). This may be a shortcoming for high-relief regions, if radical measures, such as terraces or dams, are to be constructed. QUERIM can indicate areas of interest within a larger region, but other quantitative methods such as the Water Erosion Prediction Project (WEPP) (USDA-ARS 1995), may have to be used in these areas for final conservation planning.

Summary and Conclusion

A simple qualitative approach that takes expert knowledge into account is a valuable tool for erosion risk mapping, especially when this mapping is conducted to focus soil conservation actions or to establish land use restrictions. Such an approach can be more effective than the use of quantitative models that were not developed for the region to which they are applied. QUERIM provides a methodological framework for mapping erosion risks over large areas. A ground check indicated that it is an appropriate method for mapping erosion risks in the Puerto López municipality. More detailed ground data is desirable for a better verification.

The flexibility of QUERIM has several advantages. First, although the erosion-controlling factors have to be accounted for, QUERIM has no fixed data requirement, such as necessary parameters. This makes the method applicable to a wide variety of regions for which studies are available that do not necessarily contain model parameters. Second, the choice of sub-factors and their combinations can be adapted by region, so locally-important processes and factors can be accounted for. Furthermore, QUERIM uses the knowledge of experts that have worked for a long time in the region under study. The absence of local expert input is a main shortcoming of present geographical data integration. Current models that integrate geographical data seldom serve the purpose for which they are used.

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