Predicting soil erosion at the Alqueva dam watershed: seasonal variations

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Abstract: - Soil erosion has been considered as one of the most complex environmental and economic issues in Mediterranean regions, sensitive mainly to land-use changes and due to global warming. Alqueva dam surrounding region now has new challenges and some land-use changes are possible. This paper emphasizes the aspect of seasonality in soil erosion on this region. A comprehensive methodology that integrates Revised Universal Soil Loss Equation (RUSLE) model and Geographic Information Systems (GIS) was adopted. RUSLE was updating using seasonal rainfall erosivity data and vegetation cover series data from remote-sensing. Maps for predicted soil erosion were produced on smaller sub-watersheds of Alqueva. The overlay results show an annual soil loss with a mean of 28.9 t/ha and the highest values are associated mainly to high slopes and low vegetation. The study confirmed the seasonal variations in soil erosion rates. The highest erosion is more likely to occur during the autumn, contributing this season with about 56% toward annual erosion. This is explained by the lag between rainfall and vegetation growth. In the autumn, after a long dry summer soil is exposed to intense rain. Meanwhile, in winter vegetation cover is thicker and protects the soil. Understanding seasonal variations and identifying the critical months when most erosion occurs is essential to outlining soil conservation plans with specific land uses.

Key-words: - soil erosion; seasonality; rainfall erosivity; vegetation cover; land-use; soil management.

1 Introduction

Soil erosion has been considered as one of the most complex environmental and economic issues. The negative effects are related with the decline of soil fertility and the increase of runoff, which have become a treat to sustainability [1, 2]. Furthermore, it often causes negative downstream impacts, such as the sedimentation in rivers and reservoirs reducing their storage capacity as well as life span [3]. Soil erosion is sensitive mainly to land-use changes and to global warming, which is expected to cause more frequent high intensity rainfall events falling in fragile soils, particularly in Mediterranean regions [4, 5, 6].

During the last decades, several initiatives have been made to assess soil erosion. Over the years the RUSLE [7] became the standard tool for predicting annual soil erosion by from agricultural watersheds, because it is simple, economic to use and can be employed with limited data [8]. RUSLE is defined as:

\[ A = R \times K \times L \times S \times C \times P \]

where \( A \) = potential erosion (computed annual average soil loss in t ha\(^{-1}\) year\(^{-1}\)), \( R \) = rainfall and runoff erosivity factor (MJ ha\(^{-1}\) mm h\(^{-1}\)), \( K \) = soil erodibility factor (t h MJ\(^{-1}\) mm\(^{-1}\)), \( L \) = slope length and gradient factor (dimensionless), \( C \) = vegetation cover factor (dimensionless) and \( P \) = vegetation control practice factor (dimensionless).

Geographic Information Systems (GIS) techniques and remote sensing have been successfully used in combination with these models because they make soil erosion estimation and its spatial distribution feasible, with reasonable costs and accuracy [9, 10].

The RUSLE-family models are normally used to assess the annual soil loss and pay little attention to seasonal changes, despite the evidence in the literature which suggests that soil erosion may change rapidly according to intra-annual rainfall rates and vegetation cover [11, 12].

Modeling effectively soil erosion and its seasonal variances provide information about current trends and identify the critical periods during the year. It is of great importance to create a Decision Support System, allowing the delineation of seasonal strategies for different land-use scenarios, in order to reduce soil erosion rates.
2 Problem Formulation

2.1. Objectives
The Alqueva reservoir constitutes the largest artificial lake in Europe, though the capacity cannot be maintained due to a yearly deposition of sediment resulting in a silting up. Alqueva surrounding region now has new challenges. Land-uses are expected to change through the intensification of agriculture and irrigated area, biomass production and tourism development land in the surrounding region. Mapping soil erosion in that area is increasing needed to promote for sustainability of the ecosystems, helping spend less money and increasing the dam’s life span.

Annual soil erosion risk has been estimated before on smaller sub-watershed according RUSLE model in combination with Geographic Information System (GIS) and geostatistical techniques, however without considering intra-annual changes [13]. This study was undertaken also to model soil erosion but taking into account the effect of seasonality in rainfall and vegetation data. In other words, the study aims to improve our understanding of intra-annual variations concerning to erosion resistance and local conditions, identifying hotspots.

2.2. Study area
The Alqueva reservoir is located on the river Guadiana in Alentejo, a semi-arid region in the south of Portugal (8º30’ W, 38º30’ N) (Figure 1). It covers an area of 250 km² (from which 35 km² are in Spain) and the total capacity of the reservoir is 4150 hm³. The lake total shoreline is approximately 1100 km, it extends for 83 km and is considered one of the biggest in Europe [13]. The Alqueva dam is located at the southmost part of the lake.

The first smaller sub-watershed that was chosen to study the susceptibility to soil erosion is shown in Figure 1. It is in Herdade do Roncão, beside the dam, near the Reguengos de Monsaraz city. A tourism project will be implemented in this site (included in “Parque do Alqueva” project). This study area has about 739 ha and the future land-uses are: a marina, a hotel and several golf areas. Currently, the typical local landscape is called “montado”, an agro-silvo pastoral system. The main vegetative species are Quercus ilex L., Quercus suber L., Olea europaea L., cereals and fodder plants. The climate of the area is continental Mediterranean, with very hot and dry summers and mild winters.

2.3. Methods
In this study RUSLE was used to predict soil loss. Looking at the RUSLE factors (Equation 1) there are some that can be considered time-invariant. These parameters are topography and most of the protection measures (e.g. terracing). Soil erodibility displays an intermediate state, however it is hard to evaluate in large geographic scales, thus it is assumed to be constant. On the other hand rainfall and vegetation figures are highly time-variant and have been assessed for each season [11, 12,14].

The rainfall-runoff erosivity (R) is usually known as one of the most important indicators for erosive potential of raindrops impact. It also reflects the potential of runoff generated by erosive storms. R
factor is the sum of erosive storm values EI30, which result for the product of total storm kinetic energy (E) times the maximum 30 minute intensity (I30), where E is in MJ/ha and I30 is in mm/h [7]. In this study we use monthly EI30 values from Vale Formoso station (near Alqueva dam) published by Tomás (1997) [15]. These values are from 1963/64 to 1992/93 to accommodate apparent cyclical rainfall patterns. We interpreted this data according different seasons, considering autumn (October to December), winter (January to March), spring (April to Jun) and summer (July to September).

Soil erodibility factor (K) represents the susceptibility of a soil to erode and the amount of runoff, as measured under the standard unit plot condition (a continuously cultivated fallow plot, 22.1 m long with a slope of 9%). K factor was estimated experimentally using the nomograph [7]:

$$K = \frac{2.1 \times 10^4 (120 \cdot OM)^{1.14} + 3.25 \cdot s^2 + 2.5 \cdot p^3}{100}$$  \hspace{1cm} (2)

where OM is organic matter, s is soil structure, and p is permeability class. M is the product of the primary particle size fractions (% Silt) × (%Silt + %Sand), where % Silt is percent modified silt (0.002-0.1 mm), and % Sand is percent modified sand (0.1-2 mm). A total of eighty-two (82) soil samples (0–20 cm depth) were collected and later analyzed in laboratory. Computed K factor for each soil sample unit were added into GIS environment and a continuous surface representing the spatial distribution using geostatistics.

Factor LS indicates the impact of topography on soil erosion. Slope length (L) is the horizontal distance from the origin of overland flow to the point where the slope decreases and deposition begins or runoff becomes concentrated in a demarcated channel. The slope steepness (S) shows the influence of slope gradient [7]. The combined LS factor was computed in ArcGIS software using a Digital Elevation Model (DEM). We followed the Equation 3, as proposed by Moore and Burch (1986) [16].

$$LS = (\text{flow accum.} \times \text{cell size}/22.13)^{0.4} \times (\sin \alpha/0.0896)^{1.3}$$  \hspace{1cm} (3)

Where flow accumulation signifies the accumulated upslope contributing area for a given cell, cell size is the size of DEM grid cell and \( \alpha \) is the slope degree value.

The C factor reflects the effect of cropping and management practices on erosion rate [7], considering that vegetation reduces the erosive impact of precipitation and slow down overland flow. This factor ranges between 0 and 1, and is 1 for bare soil. The C factor has a close linkage to land use types. Vegetation cover can be estimated using vegetation indices derived from satellite images. The most widely used remote-sensing derived indicator of vegetation growth is the Normalized Difference Vegetation Index (NDVI), that ranges from -1 to 1 [14, 17]. In this study Landsat TM data was used and the NDVI was therefore computed utilizing band 3 (red) and band 4 (near-infrared) as follows:

$$\text{NDVI} = \frac{(\text{Band4} - \text{Band3})/(\text{Band4} - \text{Band3})}{1}$$  \hspace{1cm} (4)

In this research satellite images from different seasons with a spatial resolution of 30 m were used. To estimate C factor, the most common procedure using NDVI involves the use of regression equation model derived from the correlation analysis between the C factor values measured in the field and a satellite-derived NDVI [14, 18]. Landsat TM images were processed and the following formula was used to generate a C factor surface from NDVI values [14]:

$$C = e^{[-2 \cdot \text{NDVI} / (1 - \text{NDVI})]}$$  \hspace{1cm} (5)

C factor maps were produced for different season with ArcGIS software.

The support practices factor (P) reflects the effects of specific practices that can be used to reduce the amount and rate of erosion, since the practices modify the flow pattern, grade, or direction of surface runoff [7]. In this case P factor was assigned the value of 1 (no support practice factor), because the support practices in this area are mainly nonexistent (before the implementation of the tourism project).

3 Problem Solution

To compare seasonal soil erosion, the erodibility (K) and topographic (LS) factor were aggregate as “static”, and rainfall erosivity (R) and vegetation cover (C) factors were analysed per month looking each season.

In this small sub-watershed, soils are mostly sandy loam soils that are formed mainly with sand (62.7%), followed by silt (22.0%) and clay (15.3%) with relativity low average of organic matter and moderate to fast hydraulic conductivity (1.5-15.1 cm/h). The associated K factor values were predicted to vary from 0.0026 to 0.047 t ha h ha \(^{-1} \) MJ \(^{-1} \) mm \(^{-1} \), with a mean value of 0.023 t ha h ha \(^{-1} \) MJ \(^{-1} \) mm \(^{-1} \). The highest soil erodibility values are mainly located in the south and
north sections, where soils have the highest amounts of susceptible particles (silt and very fine sand).

The elevation in this area ranges between 145-215 meters and the slope values vary from 0 to 36% with a mean of 5.4%, whereas only 2.5% of the study area exceeds a slope of 15%. The LS factor in the study area, which depends on slopes and flow accumulation, varies from 0 to 28.96, with a mean of 1.62. The LS factor shows high correlation with slope, because areas with the highest slope gradients have the highest LS factor values.

Rainfall erosivity values were estimated according to rainfall data from 1963/64 to 1992/93. Table 1 shows the average values of monthly erosivity. As expected, observed monthly values exhibited considerably more variation than annual values when compared to long-term means. As shown in Table 1, the high rainfall erosivity values occur in autumn and the low values in the summer, especially in July. The annual erosivity was found to be 1040 MJ mm ha\(^{-1}\) h\(^{-1}\) month\(^{-1}\). These values and trends are according to the results obtained in other studies in Mediterranean regions [14, 19] especially Iberian peninsula [20].

### Table 1 – Monthly rainfall erosivity values for each season.

<table>
<thead>
<tr>
<th>Season</th>
<th>Month</th>
<th>Erosivity Values (MJ mm ha(^{-1}) h(^{-1}) month(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>January</td>
<td>99.6</td>
</tr>
<tr>
<td></td>
<td>February</td>
<td>75.8</td>
</tr>
<tr>
<td></td>
<td>March</td>
<td>94.5</td>
</tr>
<tr>
<td>Spring</td>
<td>April</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>May</td>
<td>35.3</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>74.7</td>
</tr>
<tr>
<td>Summer</td>
<td>July</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>August</td>
<td>11.4</td>
</tr>
<tr>
<td></td>
<td>September</td>
<td>87.2</td>
</tr>
<tr>
<td>Autumn</td>
<td>October</td>
<td>182.7</td>
</tr>
<tr>
<td></td>
<td>November</td>
<td>188.9</td>
</tr>
<tr>
<td></td>
<td>December</td>
<td>123.5</td>
</tr>
</tbody>
</table>

Annual erosivity (MJ mm ha\(^{-1}\) h\(^{-1}\) yr\(^{-1}\)) \(\times 1040\)

Using satellite images we obtained NDVI values. NDVI values are higher in the winter (with a mean of 0.43) and lower in the summer (mean of 0.098). In the spring and autumn these values are similar and also low, with a mean of 0.133 and 0.116, respectively. It shows that the vegetation in the wet period is denser than in dry period, typical in Mediterranean regions [14]. The vegetation cover is clearly related to seasonal changes. Comparing values it can be concluded that C Factor has a negative correlation with NDVI values. The highest values of NDVI caused the lowest values of C factor, resulting in low contribution to soil erosion. The results revealed that C factor values in winter (with a mean of 0.24) are lower than in summer (with a mean of 0.80).

The RUSLE factors were integrated within the raster calculator option of the ArcGIS spatial analyst to obtain and quantify soil erosion rates for each season. The spatial distribution of soil erosion for each season is shown in Figure 2. The maps show the average values per month (in t/ha/month).

**Fig. 2** – Prediction maps for seasonal soil erosion.

Throughout the maps it can be seen several variations. The highest values of soil loss are more likely to occur in autumn (14.5% of the area with soil loss higher than 10 t ha\(^{-1}\) month\(^{-1}\)), when the soil
erosivity reaches the peak due to heavy rainstorms. In this period the soil is susceptible to erosion since vegetation cover is still low-moderate after the summer. On the other hand, winter shows the lowest erosion (only 0.8% of the area with soil loss higher than 10 t ha\(^{-1}\) month\(^{-1}\)) especially due to high vegetation cover. In the spring and summer the rainfall erosivity values are the lowest but soil erosion is higher than in the winter, since the vegetation cover is little.

It was estimated monthly erosion maps (in t/ha), from which an annual map was generated with aggregation (Figure 3). The mean of annual erosion in this area was found to be 28.9 t ha\(^{-1}\) year\(^{-1}\) with 15.8% of the area upper than 50 t ha\(^{-1}\) year\(^{-1}\). The highest values are associated mainly to high slopes and low vegetation.

The contribution of each season in the annual soil erosion is shown more evidently in Figure 4. Throughout the chart it can be seen easily that autumn is the season that contributes more to annual erosion (with 56%), followed by spring, and summer and winter have the same impact. The maximum variation in soil erosion between seasons is 44%. This can be explained with the lag between rainfall events and vegetation growth. In autumn, the surface is exposed to the first intensive rainfall episodes after a long dry period (summer).

These results show that it is important to maintain the soil cover all through the year, especially in the higher precipitation period, to avoid high soil erosion rates. Ongoing human interventions, ever-changing cultivation and forest degradation in the watersheds could increase sediment yield in the future. It should be emphasized that the areas with high susceptible soils condition would need special priority for implementation of soil conservation practices. For effective watershed planning there must be a close coordination between vegetative and structural control measures. This can be done by using annual cultures.

![Fig. 3 – Potential annual soil erosion.](image)

![Fig. 4 – Contribution of each season to annual soil erosion.](image)

### 4 Conclusion

The study confirmed the seasonality of soil erosion. This phenomenon is intensely affected by changes in rainfall erosivity and vegetation cover during the year. Some studies have already evaluated these differences [12]. However these are especially notable in the Mediterranean regions that have especial climate conditions [11, 14]. Climate change could possibly intensify the differences between seasons and increase the frequency of heavy rainstorms throughout the year.

The intra-annual rates of soil erosion can be monitored by updating the RUSLE model with the corresponding vegetation and rainfall erosivity data for each period. Seasonal soil degradation maps can be used to determine the relation between climate, vegetation and soil erosion in the region. This new approach would allow erosion figures to be linked to specific land uses.

Knowledge about seasonal variations and critical periods for soil erosion has shown to be essential to delineating appropriate strategies in possible different land-uses. An optimal balance between rainfall and vegetation cover is essential to reduce soil erosion during the year. This is possible also with restricting soil-conservation management techniques.
References:


