Dynamic Model of Soil Erosion and Sediment Deposit in Watersheds

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Abstract: Soil erosion is one of the most pressing environmental problems facing the reservoir watersheds of any place in the world. Many studies in the last decades have addressed soil erosion and its prediction and have devised many different methods to do it. Revised Universal Soil Loss Equation (RUSLE) is the most widely used method to calculate possible erosion. A dynamic model is constructed in Stella environment based on RUSLE factor interconnections. The study model is developed from empirical data of an on-going case study in Alqueva dam watershed area in south Portugal. The modelling results show that erosion can have a significant impact on the ability to hold water. In the best case scenario, soil erosion process over a course of 100 years decreases the reservoir capacity by less than 1%, while in the worst case 25% of initial capacity is lost. These extreme scenarios reflect the problems associated with maintaining the reservoir capacity. This model is useful for highlighting the factors that have the most impact on soil erosion in different situations. It will be used to model different scenarios by changing in some geographically restricted areas only those factors that can be changed to mitigate the risk of erosion.

Key-Words: Environmental modelling, object-based modelling, simulation, soil erosion, reservoir, water conservation

1. Introduction
Despite the advances in environmental management, soil erosion is still an important environmental threat in Portugal, because of deforestation and improper soil use [15]. The typical ecosystems of Iberian Peninsula are called "montados". These 'man-made' ecosystems are characterized by savannah-type low density woodlands dominated by Mediterranean evergreen oak species [21]. These ecosystems belong to the Mediterranean basin, where regeneration is difficult and soil is often deeply scarred [11]. usually there will be long dry periods, followed by erosive rains, another characteristic of the Mediterranean basin [23].

Soil in south Portugal is often mismanaged and short term gains are often considered more important that the long-term effects. Following intensive soil management techniques, soil is harrowed annually or before cork harvesting, in order to establish fodder species, increase aeration and destroy shrubs and other weeds, leaving bare soil exposed to erosion [22].

A place of special interest is the Alqueva dam in Alentejo region of south Portugal. The Alqueva reservoir is the largest artificial lake in Western Europe. It has a surface area of 250 km², extends for 83 km long and has a maximum storage capacity of 4150 hm³ (add reference attached). Increased erosion at this large watershed means more sediments being deposited in the reservoir. This in turn decreases the capacity of the reservoir to store water and shortens the expected useful period of the dam which has a big economic impact not only on the loss of the 260MW of power generation but also because Alqueva dam and lake are part of a multipurpose hydraulic project built to provide water for agriculture irrigation, drinking, and leisure activities.

Shortened period of use of the dam means a big decrease in the return on investment and is likely to need new investments much sooner. Therefore soil erosion in the area has to be carefully evaluated in order to take sustainable soil management measures, especially because the area is planned to be further developed.

The objective of this study is to create a dynamic model to predict soil erosion and sediment deposition using RUSLE factors. The model will then be expanded to include factor components interconnections. This study model is constructed as a part of an ongoing case study in Alqueva dam, Portugal and will use experimental data collected from sampling points close the reservoir.

2. Theoretical background
2.1. Erosion prediction
There has been extensive research about soil erosion in the past few years in order to find the most appropriate
and versatile way to predict the effects of erosion – soil loss and sediment amount. Available methods in the literature for sediment yield estimation can be grouped in three categories: physically-oriented models, empirical models and conceptual models [30, 9, 16]. These models differ in terms of complexity, processes considered and the data required [23]. None of the models is considered to be the most appropriate for every situation, because it depends on the intended use and characteristics of the catchment considered. [30]

Physically-based models are used to describe the essential mechanisms controlling the erosion process in a high level of detail. Conceptual models focus on some physics processes and represent catchments as series of internal storages, including a general and aggregated description of catchment processes without including specific details of process interactions [30]. Empirical models are based primarily on the analysis of observations and seek to characterise response from these data. These models require less parameters than the other models and can often be supported by rough measurements which is why they are often used instead of more complex models [30, 16]. They are particularly useful as a first step to identify the sources of sediment generation.

One of the most widely used empirical equations is the Revised Universal Soil Loss Equation (RUSLE) which can be used for estimating annual soil loss from agricultural watersheds [27]. RUSLE has been defined as:

$$A = R \times K \times LS \times C \times P$$

where A is the potential erosion and the factors involved are:

- R – rainfall-runoff factor,
- K – soil erodibility factor,
- LS – slope, length and gradient factor,
- C – vegetation cover factor,
- P – vegetation control practices factor.

Each of these factors is calculated separately with further equations. R factor is known as one of the most important indicators of the erosive potential of rain intensity impact [10]. K factor represents soil loss rate per erosion index unit for a specified soil as measured on a standard plot. To estimate K factor, researches has to obtain data about soil properties, such as soil texture, amount of organic matter, soil structure and permeability [27]. LS factor accounts for the topography and hydrology effects on soil erosion. It is based on slope length (L) and slope steepness (S). Slope length is the horizontal distance from the origin of overland flow to the point where the slope gradient decreases enough that deposition begins or runoff becomes concentrated in a defined channel. Slope steepness shows the influence of the slope gradient [8]. C factor shows the effect of cropping and management practices on soil erosion [27]. P factor reflects the effect of mechanical practiced on rangeland erosion. These practices can affect surface cover, runoff amount, runoff rate, flow direction of runoff and hydraulic forces exerted by runoff on the soil.

2.2. Simulation based dynamic modelling

Despite the fact that RUSLE is a popular erosion prediction tool, the soil erosion estimation process can be very time and capital-consuming [22]. Simulation modelling is useful, because time does not have to be spent on complex mathematical equations and the model can be easily modified and applied for many various situations [20].

There are two types of models – static and dynamic. Static models cover assumptions about systems at rest while dynamic models include assumptions about the time-evolution [14, 12]. Simulations aim to solve equations of dynamic models to imitate the evolution of a real system over time. Simulation based dynamic modelling has more advantages than static modelling. Some of the advantages include modelling complex rule-based interaction between flowing entities, visualization of process steps, development of accurate models through comparison with measurement data and enhanced confidence in predictions regarding performance [18].

Simulations are used in many natural and social science researches. Computer simulations are considered to be the most effective, however they have to be well confirmed and understood otherwise they might produce false results, especially due to the discreet nature of calculations. However, simulation models represent computer experiments which can often replace real experiments due to minimized risk. Furthermore, they can suggest new theories, hypothesis and models [12].

Object-based modelling environments see the world as a set of objects that can implement data, behaviour and interact with each other [13]. It offers certain advantages, the most predominant one being reusability. Objects are extendable and it is possible to craft new objects out of existing ones. Furthermore, object-oriented simulations are modular where objects are the modules. This means all the information about an object is stored in one place and is easy to find. It enables modellers to easily change the meaning of an object or modify its behaviour [6].

There are many modelling environments available and there is no ‘best’ software for every occasion.. For
example, QPR ProcessGuide is mostly used as a business consulting tool and is designed to specifically reflect business processes [26]. Extend is generally used for discrete-event systems simulations and effectively reflects queuing systems through library-based iconic blocks [28]. SimEnvir++ is an object-based environment that is quite flexible yet is mostly useful for assembly line simulations [6]. NetLogo is a multi-agent based software that reflects how agents interact among each other as well as with the surrounding environment [29].

Stella has been previously used in various environmental and ecological studies [20, 1]. It is often used when conducting real-life experiments and observations is either unproductive (time-consuming, resource-intensive, situation-changing) or impossible. Many ecosystems are full of interdependencies and it is often difficult to understand how one thing affects another [2]. As a result, modelling has been often used to depict a particular process. Stella is often the choice of software, because it is easy to use, object-oriented and successfully works with various functions and calculations [5].

3. Methodology

Data used in this study has been collected from an area of 25000 ha around the lake which is within the direct watershed influence zone. The case-study takes place in a 739 ha area which represents roughly 2.9% of the total dam enveloping land. Empirical data is currently available for 95 samples.

To use empirical case-study data as credible input data, it is important that data from sampling sites reflect reality of the site accurately. If the data has a normal statistical distribution pattern, then area situation is represented correctly. Kolmogorov-Smirnov test was performed for each parameter in SPSS statistical analysis program. It was found that with 95% reliability data has a normal distribution pattern. The case study modelling area is a small part of the total watershed land. There is currently little empirical information about the other areas, however it is presumed that the soil has analogical properties and erosion can be assumed to be similar.

3.1. Model structure

The model constructed for this study is based on equations and factors provided by RUSLE. RUSLE is simple and easy to use, however it lacks insights on the soil erosion process and mechanism. The various factors are linked only through the equation; influences between factor components are not considered. Previous studies indicate that there are connection between other factors, such as vegetation cover and rainfall, organic matter, hydraulic permeability and soil structure [14, 15, 16, 17]. The model was therefore expanded to represent these factor component interconnections.

3.1.1. Model interface

Models are generally constructed in the model interface. It shows the essential features that are defined in terms of stocks, flows and auxiliary parameters (converters). Icons for each of these features are placed and connected in the modelling area [4]. Stocks accumulate whatever comes in or goes out therefore they can be increased or decreased by ingoing or outgoing flows.

The study model produces two results. One shows how many tons of sediments are deposited in the Alqueva dam watershed while the other shows how it affects the capacity (water volume) of the watershed. To do this, there are two different stocks and two different flows in the model – one represents the erosion process while the other represents the situation in the watershed (Fig.2). The results from the sediments stock are fed to the outgoing watershed capacity flow, thus decreasing the total usable volume of the dam.

Factor components that are shown as converters can be modified through the user interface. Other factor components are calculated by the model, based on the input data provided by the user.

3.1.2. User interface

The user interface allows the modeller to change characteristics that are important for the situation. This can also be done during the course of the simulation, allowing for greater flexibility. According to Wang et al. [31], not paying enough attention to detailed area-specific information can lead to improper conclusions, therefore the devised user interface allows for many modifications. Range of the entry data for this model is based on empirical values from the case study. These can be easily modified through the user interface before running the model to adjust for different site values.

P factor is not present in the user interface at this stage of the model.
4. Results

Three scenarios were modelled based on the average, most and least erosion-prone sampling site data. The results of the model show that the heaviest erosion is in the site with a steep slope, relatively low vegetation cover, low organic matter amount, low hydraulic conductivity and high percentage of sand in the soil. The highest erosion is 249.38 t/ha which result in more than 184 thousands of tons of sediments to be deposited in the watershed annually. Such high erosion values are rare for the study area, however they result in a large sediment increase.

The study area covers 2.9 % of the watershed. If all the other areas have similar erosion then the absolute worst total watershed area erosion would be almost 5.5 million tons of sediments. This means that within 100 years, almost 25% of the water volume holding capacity would be lost due to simple erosion process. Furthermore, such a decline would cause important changes in the area before and after the dam, because the water not being held by the reservoir would have to be distributed elsewhere.

In comparison, the least erosion-prone area amounts to 2.53 t/ha of sediments which result in 1870 tons to be deposited in the water reservoir annually. This means that the watershed capacity from the total enveloping area is less than 1% (0.0007%) which is an insignificant amount. In 100 years, less than 1% of water capacity would be lost, which means that there is almost no productivity loss for the dam.

The average soil loss from erosion for the study area is 22.9 t/ha [8], which results in 16923 tons of sediments from the study area or 572498 tons of sediments from the total area annually. Within 100 years, a little over 2% of total dam capacity would be lost. For a water volume of 4150 hm³, such a loss is not yet critical, however the situation has to be evaluated carefully to sustain the productivity of the dam and the enveloping area. If the water volume in the reservoir cannot be maintained, the decreased productivity of the dam can have a strong impact on the economy and agriculture of Portugal.

5. Conclusions and discussion

The study shows that an erosion model can quickly simulate different possible erosion scenarios based on data available. Using a model that is based on RUSLE is easier to use and requires less time to be spent to predict erosion amount. A model that is expanded to include factor interconnections is more precise and shows more insight in erosion processes which has been a disadvantage of RUSLE.

Research model can be used to model soil erosion near watersheds. The results of the modelled on-going case-study of Alqueva dam, Portugal, show that erosion...
can have a significant impact on a watershed’s ability to store water (its productivity). In the best case scenario, soil erosion process over a course of 100 years decreases the watershed capacity by less than 1%, while in the worst case 25% of initial capacity is lost. Although these extreme scenarios are not likely to happen, they reflect the problems associated with maintaining the watershed capacity.

The research model has to be further developed as more data is collected for the case-study. Data about vegetation control practices has not yet been gathered and defined, therefore this model does not represent the impact of vegetation and control practices on the area. These practices, however, will have further impact on such factor components as soil structure, slope, hydraulic properties, vegetation cover and others. This model should be further developed in the future to indicate how anthropogenic activities and land management influences the state of the soil and territory. This can be used in connection with a decision support system.

Data about electrical conductivity and cation exchange capacity reflects the state of aggregation of particles in the soil which can be used to indirectly determine the soil structure which is currently not reflected in the model because these factors require a thorough soil sample analysis with specific equipment.

This model is useful for highlighting the important factors that have the most impact on soil erosion in the area. It will be used to model different scenarios by changing in some geographically restricted areas only those factors that can be changed to mitigate the risk of erosion. Small changes might be required to be made in the model or user interface however the model is generally applicable in any area near watersheds.

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