EROSION AND SEDIMENT DYNAMICS IN ENXOÉ WATERSHED

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Abstract

The soil covering the surface of the earth has taken millions of years to form and we must learn to respect it. Soil is formed at a rate of only 1 cm every 100 to 400 years and it takes 3 000 to 12 000 years to build enough soil to form productive land. This means that soil is a nonrenewable resource and once destroyed it is gone forever.

First of all I tried to explain the water erosion process, types of erosion, factors affecting soil erosion and the effects and problems caused by all of the above. Soil erosion’s most serious in-site effect is loss of soil quality and the long-term sustainability of agricultural productivity.

Movement of sediment and associated agricultural pollutants into watercourses is the major off-site impact resulting from erosion. This leads to sedimentation in watercourses and dams, disruption of the ecosystems of lakes, and contamination of drinking water.

The purpose of this paper is to analyze the negative effects of surface runoff and soil erosion in watershed, such as eutrophication. Hydrological models are suitable to simulate various combinations of different scenarios of land and water management in a watershed and therefore they are useful for comparative analysis of different options and as a guide to what best model can be adopted to minimize water erosion and its effects.

Models can be used in the understanding of dynamic processes and to predict the rates of these processes.

This paper provides an overview of the problem of soil erosion in Enxoé catchment, based on the data collected from one erosion plot (land use olive trees) and is a part of Eutophos Project.

1. Introduction

"There is nothing in the whole of nature which is more important than or deserves as much attention as the soil. Truly it is the soil that makes the world a friendly environment for man-kind. It is the soil which nourishes and provides for the whole of nature; the whole of creation depends on the soil which is the ultimate foundation of our existence" (Friedrich Albert Fillou, 1862)

Soil erosion is one form of soil degradation along with soil compaction, low organic matter, and loss of soil structure, poor internal drainage, salinization, and soil acidity problems. These other forms of soil degradation, serious in themselves, usually contribute to accelerated soil erosion.

Soil erosion may be a slow process that continues relatively unnoticed, or it may occur at an alarming rate causing serious loss of topsoil. The loss of soil from farmland may be reflected in reduced crop production potential, lower surface water quality and damaged drainage networks.

Water erosion's complex hierarchy of processes mean that erosion by water operates (and is studied) over a wide range of spatial scales. Rainsplash redistribution and the initiation of microrills and rills occur at a scale of millimeters. Rill erosion on agricultural hillslopes operates at a scale of meters to tens of meters, while gully erosion can occur on a scale of hundreds of meters, or even kilometers. The offsite impacts of erosion can affect very large areas, sometimes hundreds or even thousands of square kilometers.

Soil erosion has a range of environmental impacts, including loss of organic matter and nutrients, reduction of crop productivity, and downstream water quality degradation (Newcombe and MacDonald 1991).

Effective control of soil erosion is a critical component of natural resource management when the aim is to achieve sustainable agriculture and acceptable ecosystem integrity (Pimentelet al.1995; Rutherfurd et al.1998).

2. State-of-art

Sedimentation and soil erosion includes the processes of detachment, transportation and deposition of solid particles also known as sediments (Julien, 2002).

Erosion from mountainous areas and agricultural lands are the major source of sediment transported by streams and deposited in reservoirs, flood plains and deltas. Sediment load is also generated by erosion of beds and banks of streams, by the mass movements of sediment such as landslides, rockslides and mud flows, and by construction activity of roads, buildings and dams.

Erosion can be seen as a sequence of three events: detachment, entrainment, and transport. These three processes are often closely related and sometimes not easy distinguished between each other.

- ***Detachment***

Erosion begins with the detachment of a particle from surrounding material. Sometimes detachment requires the breaking of bonds which hold particles together. Many different types of bonds exist each with different levels of particle cohesion. Some of the strongest bonds exist between the particles found within igneous rocks. In these materials, bonds are derived from the growth of mineral crystals during cooling. In sedimentary rocks, bonds are weaker and are mainly caused by the cementing effect of compounds such as iron oxides, silica, or calcium. The particles found in soils are held together by even weaker bonds which result from the cohesion effects of water and the electro-chemical bonds found in clay and particles of organic matter.

Physical, chemical, and biological weathering act to weaken the particle bonds found in rock materials. As a result, weathered materials are normally more susceptible than unaltered rock to the forces of detachment.

- ***Entrainment***

Entrainment is the process of particle lifting by the agent of erosion. In many circumstances, it is hard to distinguish between entrainment and detachment. There are several forces that provide particles with a resistance to this process. The most important force is frictional resistance. Frictional resistance develops from the interaction between the particles to its surroundings. A number of factors increase frictional resistance, including: gravity, particle slope angle relative to the flow direction of eroding medium, particle mass, and surface roughness.

Entrainment also has to overcome the resistance that occurs because of particle cohesive bonds. These bonds are weakened by weathering or forces created by the erosion agent (abrasion, plucking, raindrop impact, and cavitation).

Entrainment Forces

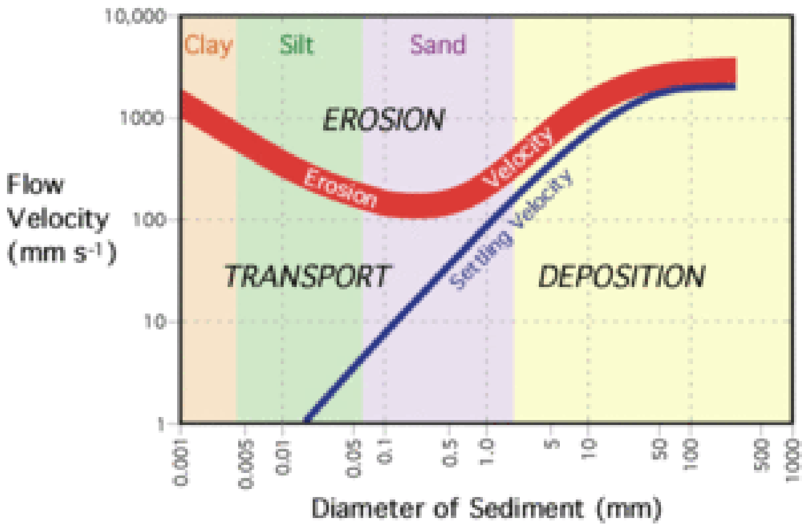

Figure 2.1.: This graph describes the relationship between stream flow velocity and particle erosion, transport, and deposition. (Source: PhysicalGeography.net)

The main force responsible for entrainment is fluid drag. The strength of fluid drag varies with the mass of the eroding medium (water is 9,000 times more dense than air) and its velocity. Fluid drag causes the particle to move because of horizontal force and vertical lift. Within a medium of erosion, both of these forces are controlled by velocity. Horizontal force occurs from the push of the agent against the particle. If this push is sufficient to overcome friction and the resistance of cohesive bonds, the particle moves horizontally. The vertical lift is produced by turbulence or eddies within the flow that pushes the particle upward. Once the particle is lifted the only force resisting its transport is gravity as the forces of friction, slope angle, and cohesion are now non-existent. The particle can also be transported at velocities lower than the entrainment velocities because of the reduction in forces acting on it.

The critical entrainment velocity curve suggests that particles below a certain size are just as resistant to entrainment as particles with larger sizes and masses (Figure 2). Fine silt and clay particles tend to have higher resistance to entrainment because of the strong cohesive bonds between particles. These forces are far stronger than the forces of friction and gravity.

➢ ***Transport***

Once a particle is entrained, it tends to move as long as the velocity of the medium is high enough to transport the particle horizontally. Within the medium, transport can occur in four different ways:

- Suspension is where the particles are carried by the medium without touching the surface of their origin. This can occur in air, water, and ice.
- Saltation is where the particle moves from the surface to the medium in quick continuous repeated cycles. The action of returning to the surface usually has enough force to cause the entrainment of new particles. This process is only active in air and water.
- Traction is the movement of particles by rolling, sliding, and shuffling along the eroded surface. This occurs in all erosional mediums.
- Solution is a transport mechanism that occurs only in aqueous environments. Solution involves the eroded material being dissolved and carried along in water as individual ions.

- ***Deposition***

The erosional transport of material through the landscape is rarely continuous. Instead, we find that particles may undergo repeated cycles of entrainment, transport, and deposition. Transport depends on an appropriate balance of forces within the transporting medium. A reduction in the velocity of the medium, or an increase in the resistance of the particles may upset this balance and cause deposition. Reductions in competence can occur in a variety of ways. In water, lower velocities can be caused by reductions in discharge or a change in the grade of the stream.

The forms of water responsible for soil erosion are raindrop impact, runoff and flowing water (Wischmeier & Smith, 1978).

2.1. *Water erosion*

Water erosion is the detachment and removal of soil material by water. The process may be natural or accelerated by human activity.

Types of Erosion by Water:

- **Raindrop Erosion:** Small soil particles are detached and sent airborne through the impact of raindrops on soil. (figure2.2.)
- **Sheet Erosion:** Raindrops break apart the soil structure and it's moved downslope by water that flows overland as a sheet rather than definitive channels. This occurs frequently during cloud bursts. (figure2.1.a.)
- **Rill Erosion:** This process develops small, short-lived, concentrated flow paths. This path creates a sediment source and delivery system for hillslope erosion. Areas where

precipitation rates exceed soil infiltration rates are more prone to this type of erosion. (figure2.1.b.)

- **Gully Erosion:** Water flows in narrow channels during or directly following heavy rains or melting snow. The gullies can erode to considerable depths. (figure 2.1.c.)

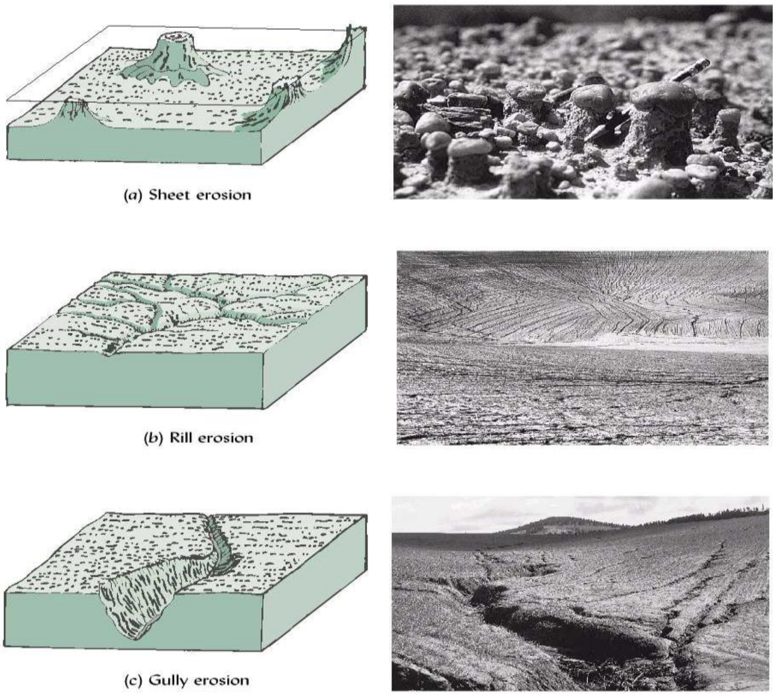

Figure 2.2.Erosion types
(a)-Sheet erosion,
(b)-Rill erosion,
(c)-Gully erosion.

- **Valley or Stream Erosion:** Continual water flow alongside land (along a linear feature) creates this type of erosion. It extends downward, deepening a valley, and head ward, extending the valley into the hillside. This occurs most frequently in times of flooding.
- **Bank Erosion:** Over time, banks of rivers and streams are naturally worn down.

2.1.1. Raindrop erosion

Raindrop erosion is the dislodging of soil particles by large drops of rain. The particles are pushed into the soil spaces, helping to secure the soil surface against infiltration and thereby increasing run-off. Raindrop erosion is most active in tropical, subtropical, and semi-arid environments, particularly where rainfall is intense and the ground is free of vegetation.

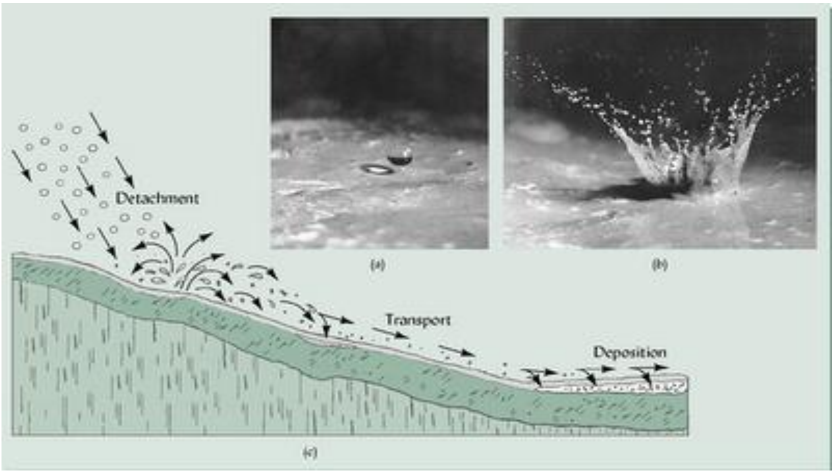

Figure 2.2. Rain erosion progression

When a raindrop hits soil that is not protected by a cover of vegetation and where there are no roots to bind the soil, it has the impact of a bullet. (Oxford Dictionary).

Erosion is caused by the impact of raindrops on bare soil and by the power of running water on the soil surface. Natural erosion rates depend on inherent soil properties, slope, and climate, which together determine the ability of the site to support vegetation. Accelerated erosion occurs when the plant cover is depleted, the space between plants becomes larger, and soil structure is degraded by excessive disturbance or reduced inputs of organic matter.

Compaction increases runoff and the risk of accelerated erosion. Runoff concentrated by poorly designed or maintained roads or trails can cause accelerated erosion on the adjacent slopes and in roadbeds. Many vegetation and soil properties affect the risk of erosion. Each specific soil has its own natural erosion rate. Stable soil aggregates bound together by organic matter resist erosion, enhance infiltration, and result in less runoff. The amount of runoff and the power of water to erode and transport soil are greater on long, steep slopes. Bare soil between plants is most susceptible to erosion.

2.1.2. Sheet erosion

Sheet erosion happens when raindrop impact transports particles and becomes runoff traveling over the surface of the ground (Fortuin, 2006). It results in loss of the finest soil particles that contain most of the available nutrients and organic matter in the soil. Soil loss is so gradual that the erosion usually goes unnoticed, but the cumulative impact accounts for large soil losses.

Soils most vulnerable to sheet erosion are overgrazed and cultivated soils where there is little vegetation to protect and hold the soil.

Early signs of sheet erosion include bare areas, water puddles as soon as rain falls, visible grass roots, exposed tree roots, and exposed subsoil or stony soils. Soil deposits on the high side of obstructions such as fences may indicate active sheet erosion.

2.1.3. Rill and gully erosion

Rill erosion occurs when water from sheet erosion combines to form small concentrated channels (Fortuin, 2006).It results when surface runoff concentrates forming small yet well-defined channels. These channels are called rills when they are small enough to not interfere with field machinery operations.

Erosion rates increase due to higher velocity flows as rill erosion starts. When water in rills concentrates to form larger channels, it results in gully erosion (Fortuin, 2006).

Gully formations can be difficult to control if remedial measures are not designed and properly constructed. Control measures have to consider the cause of the increased flow of water across the landscape, and a multitude of conservation measures come into play.

Operations with farm machinery adjacent to gullies can be quite hazardous when cropping or attempting to reclaim lost land. In many parts of the world, rill and gully erosion is the dominant form of water erosion.

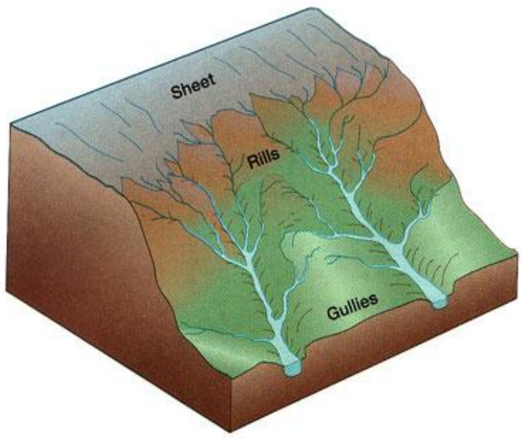

Figure 2.3 . Types of erosion

2.1.4. Stream and Ditch Bank Erosion

Surface runoff, causing gully formation or the enlarging of existing gullies, is usually the result of improper outlet design for local surface and subsurface drainage systems. The soil instability of fully banks, usually associated with seepage of ground water, leads to sloughing and slumping (caving-in) of bank slopes. Such failures usually occur during spring months when the soil water conditions are most conducive to the problem.

Poor construction, or inadequate maintenance, of surface drainage systems, uncontrolled livestock access, and cropping too close to both stream banks has led to bank erosion problems.

The direct damages from bank erosion include:

1. The loss of productive farmland.
2. The undermining of structures such as bridges.
3. The washing out of lanes, roads and fence rows.

Poorly constructed tile outlets may also contribute to stream and ditch bank erosion. Some do not function properly because they have no rigid outlet pipe, or have outlet pipes that have been damaged by erosion, machinery, inadequate or no splash pads, and bank cave-ins.

2.2. *Factors affecting soil erosion*

Climate, topography, soil properties, vegetation characteristics and land management are the main factors effecting soil erosion (Fangmeier et al., 2006; Omuto, 2008). Erosion affects in its turn different factors negatively in and on the soil (Pimentel,2006).

There are also underlying or distant causes, such as population pressure, poverty, high cost and inaccessibility of inputs, insecure land tenure, lack of appropriate production and conservation technologies and many of these are further influenced by various government policies or lack of them.

2.2.1. Rainfall Intensity and Runoff

That fraction of the rainfall which does not infiltrate into the soil will flow downhill under the action of gravity; it is then known as runoff or overland flow. Runoff may occur for two reasons. Firstly, if rain arrives too quickly for it to infiltrate: the runoff which results is then known as infiltration excess runoff, or Hortonian runoff. Secondly, runoff may occur if the soil has already absorbed all the water it can hold. Runoff which results from this situation is known as saturation excess runoff. As runoff moves downhill, it is at first a thin diffuse film of water which has lost virtually all the kinetic energy which it possessed as falling rain. Thus it moves only slowly, has a low flow power, and is generally incapable of detaching or transporting soil particles.

Both rainfall and runoff factors must be considered in assessing a water erosion problem. The impact of raindrops on the soil surface can break down soil aggregates and disperse the aggregate material. Lighter aggregate materials such as very fine sand, silt, clay and organic matter can be easily removed by the raindrop splash and runoff water; greater raindrop energy or runoff amounts might be required to move the larger sand and gravel particles.

Soil movement by rainfall is usually greatest and most noticeable during short-duration, high-intensity thunderstorms. Although the erosion caused by long-lasting and less-intense storms is not as spectacular or noticeable as that produced during thunderstorms, the amount of soil loss can be significant, especially when compounded over time. Runoff can occur whenever there is excess water on a slope that cannot be absorbed into the soil or trapped on the surface. The amount of runoff can be increased if infiltration is reduced due to soil compaction, crusting or freezing. Runoff from the agricultural land may be greatest during spring months when the soils are usually saturated, snow is melting and vegetative cover is minimal.

2.2.2. Topography

Topography, when considered as a soil-forming factor, includes the following: the geologic structural characteristics of elevation above mean sea level, slope configuration, and relative position on a slope. Influences the way the hydrologic cycle affects earth material, principally with respect to runoff processes and evapotranspiration.

The rugged topography and steep slopes affect soil erosion rate through its morphological characteristics. Two of these, namely gradient and slope length, are essential components in quantitative relationships for estimating soil loss (Wischmeier and Smith 1978). On sloping lands, more than one-half of the soil particles that are dislodged by raindrops during rainfall are carried downhill.

Data for assessment of the effect of slope gradient and length on soil erosion is limited. However, it is generally accepted that an increase in slope and slope length will increase erosion because they lead to an increase in overland flow volume and velocity. Runoff on low slopes flows slowly and quickly forms a water layer deep enough to act as surface mulch. Increasing slope length enhances soil loss as more runoff can accumulate on long slopes. Thomas (1991) identified that slope shape together with ground/field attributes exercise a strong influence on the nature and extent of visible erosion damage.

- **Slope Gradient**

Naturally the steeper the slope of a field, the greater the amount of soil loss from erosion by water. Soil erosion by water also increases as the slope length increases due to the greater accumulation of runoff. Consolidation of small fields into larger ones often results in longer slope lengths with increased erosion potential, due to increased velocity of water which permits a greater degree of scouring (carrying capacity for sediment).

- **Slope Length**

The slope length and steepness greatly affect the risk of erosion on cultivated fields. Soil is more easily detached and transported from steep slopes (Fangmeier et al., 2006). The length of the slope is very important, because the greater the size of the sloping area, the greater the concentration of the flooding water

2.2.3. Vegetation cover

Soil erosion potential is increased if the soil has no or very little vegetative cover of plants and/or crop residues. Plant and residue cover protects the soil from raindrop impact and splash, tends to slow down the movement of surface runoff and allows excess surface water to infiltrate.

The erosion-reducing effectiveness of plant and/or residue covers depends on the type, extent and quantity of cover. Vegetation and residue combinations that completely cover the soil, and which intercept all falling raindrops at and close to the surface and the most efficient in controlling soil (e.g. forests, permanent grasses). Partially incorporated residues and residual roots are also important as these provide channels that allow surface water to move into the soil.

The effectiveness of any crop, management system or protective cover also depends on how much protection is available at various periods during the year, relative to the amount of erosive rainfall that falls during these periods. In this respect, crops which provide a food, protective cover for a major portion of the year (for example, alfalfa or winter cover crops) can reduce erosion much more than can crops which leave the soil bare for a longer period of time (e.g. row crops) and particularly during periods of high erosive rainfall (spring and summer).

Soil erosion potential is affected by tillage operations, depending on the depth, direction and timing of plowing, the type of tillage equipment and the number of passes.

Generally, the less the disturbance of vegetation or residue cover at or near the surface, the more effective the tillage practice is in reducing erosion.

The loss of protective vegetation through overgrazing, plowing and fire makes soil vulnerable to being swept away by wind and water. Plants provide protective cover on the land and prevent soil erosion for the following reasons:

- Plants slow down water as it flows over the land and this allows much of the rain to soak into the ground.
- Plant roots hold the soil in position and prevent it from being blown or washed away.
- Plants break the impact of a raindrop before it hits the soil, reducing the soil's ability to erode.
- Plants in wetlands and on the banks of rivers are important as they slow down the flow of the water and their roots bind the soil preventing erosion.

2.2.4. Soil properties

Soils can be degraded because of erosion, but already degraded soils have a higher erosion risk. It is therefore difficult to separate which is the initial cause. Erosion causes reduction in infiltration-and water-storage capacity, nutrient-and organic matter content, soil depth, productivity, vegetation growth and biodiversity. These factors all interact with each other and it is almost impossible to separate the impact one has from another. Erosion increases water runoff which results in reduced water infiltration. Erosion also reduces the water-storage capacity of the soil as there will be less soil to hold the water. This will lead to eroded soils being more susceptible to drought conditions (Pimentel, 2006).

Other soil properties that effect or are affected by erosion are: water retention, bulk density, aggregate stability, soil structure and texture.

- **Water retention**

Poorer water retention leads to less water being retained and the runoff and erosion during rainfall increases.

- **Bulk density**

Higher bulk density leaves less space for channels in the soil where the rain can infiltrate just as a poor soil structure does.

- **Aggregate stability**

A good aggregate stability increases the resistance to mechanical, physical or chemical destructive forces.

Soil texture

Texture refers to the size or combination of sizes of the individual soil particles. Three broad size classifications, ranging from small to large, are clay, silt, and sand. If the texture includes a large percentage of silt the risk of erosion is increased (Fangmeier et al., 2006; Omuto, 2008).

Soil structure

Structure refers to the degree to which soil particles are clumped together, forming larger clumps and pore spaces. Structure influences both the ability of the soil to absorb water and its physical resistance to erosion.

Organic matter in the soil improves soil structure, root penetration, water-holding capacity and infiltration. With increasing organic matter, erodibility decreases (Wischmeier and Smith 1978). Increased water-holding capacity which also leads to increased resistance to seasonal drought is another good result of increased organic matter content.

All this together with improved infiltration through root channels lessens soil erosion (Stocking, 1994).Eroded soil has unfortunately higher organic matter content than the remaining soil because the content of organic matter is higher 6 in the topsoil and topsoil is most eroded. Organic matter content is improved through vegetation growth, which in its turn is diminished when the conditions for plant growth is degraded by the erosion (Pimentel, 2006).

Important plant nutrients like nitrogen, phosphorus, potassium and calcium are carried away with the eroded soil, leaving the soil poorer in nutrients and overall productivity decline.

Soil Erodibility

Soil erodibility is an estimate of the ability of soils to resist erosion, based on the physical characteristics of each soil. Generally, soils with faster infiltration rates, higher levels of organic matter and improved soil structure have a greater resistance to erosion. Sand, sandy loam and loam textured soils tend to be less erodible than silt, very fine sand, and certain clay textured soils.

Tillage and cropping practices which lower soil organic matter levels, cause poor soil structure, and result of compacted contribute to increases in soil erodibility. Decreased infiltration and increased runoff can be a result of compacted subsurface soil layers. A decrease in infiltration can also be caused by a formation of a soil crust, which tends to "seal" the surface. On some sites, a soil crust might decrease the amount of soil loss from sheet or rain splash erosion, however, a corresponding increase in the amount of runoff water can contribute to greater rill erosion problems.

Past erosion has an effect on a soils' erodibility for a number of reasons. Many exposed subsurface soils on eroded sites tend to be more erodible than the original soils were, because of their poorer structure and lower organic matter. The lower nutrient levels often associated with subsoil contribute to lower crop yields and generally poorer crop cover, which in turn provides less crop protection for the soil.

2.3. *Effects and problems*

Water erosion causes two sets of problems:

- An on-site effect: loss of agricultural potential.
- An off-site effect: eutrophication, downstream movement of sediment, causing flooding and the silting up of reservoirs.

2.3.1. On-site effects

The main on-site impact is:

- Reduction in soil quality which results from the loss of the nutrient-rich upper layers of the soil, and the reduced water-holding capacity of many eroded soils. In affluent areas of the world, accelerated water erosion's on-site effects upon agricultural soils can be mitigated by increased use of artificial fertilizers; however this is not an option for much of the earth's population.

Loss of soil quality is a long-term problem; globally, soil erosion's most serious impact may well be its threat to the long-term sustainability of agricultural productivity, which results from the 'on-site' damage which it causes.

The implications of soil erosion extend beyond the removal of valuable topsoil. Crop emergence, growth and yield are directly affected through the loss of natural nutrients and applied fertilizers with the soil. Seeds and plants can be disturbed or completely removed from the eroded site. Organic matter from the soil, residues and any applied manure is relatively light-weight and can be readily transported off the field, particularly during spring thaw conditions.

- Pesticides may also be carried off the site with the eroded soil.
- Soil quality, structure, stability and texture can be affected by the loss of soil. The breakdown of aggregates and the removal of smaller particles or entire layers of soil or

organic matter can weaken the structure and even change the texture. Textural changes can in turn affect the water-holding capacity of the soil, making it more susceptible to extreme condition such a drought.

Therefore the on-site impacts of soil erosion are a present-day problem for many of the developing nations. Such on-site impacts will be a problem only in the long term future for developed areas: as such they are outside the relatively short time horizon within which their policy makers work.

2.3.2. Off-site effects

The main off-site effects are:

- The movement of sediment and agricultural pollutants into watercourses. This can lead to the silting-up of dams, disruption of the ecosystems of lakes, and contamination of drinking water. In some cases, increased downstream flooding may also occur due to the reduced capacity of eroded soil to absorb water.

Movement of sediment and associated agricultural pollutants into watercourses is the major off-site impact resulting from erosion. This leads to sedimentation in watercourses and dams, disruption of the ecosystems of lakes, and contamination of drinking water. Rates of erosion do not have to be high for significant quantities of agricultural pollutants to be transported off-site. This is a shorter-term impact than loss of soil quality; in the more affluent areas of the world it can be the main driver for present-day soil conservation policy initiatives.

- Increased runoff may lead to downstream flooding and local damage to property.

- Another major off-site impact results from the agricultural chemicals that often move with eroded sediment. These chemicals move into, and pollute, downstream watercourses and water bodies. Where inputs of agricultural chemicals are high, costs of removing such pollutants from drinking water can be considerable.

In the short term however, erosion's off-site effects can be a notable problem for developed nations. Off-site impacts may therefore be the major driver for policy changes in such countries.

- Eroded soil, deposited down slope can inhibit or delay the emergence of seeds, bury small seedling and necessitate replanting in the affected areas. Sediment can be deposited on down slope properties and can contribute to road damage.

- Sediment which reaches streams or watercourses can accelerate ban erosion, clog drainage ditches and stream channels, silt in reservoirs, cover fish spawning grounds and reduce downstream water quality. Pesticides and fertilizers, frequently transported along with the eroding soil can contaminate or pollute downstream water sources and recreational areas.
- **Eutrophication**: Much of the phosphorus (P) from erosive soils is transported to water bodies together with eroded soil. Studies clarifying the impact of soil erosion on eutrophication have sought largely to quantify the reserves of P in soil particles that can be desorbed in different types of receiving waters. Aquatic microbiology has revealed that the cycling of P is coupled to the availability of common electron acceptors, Fe oxides and SO_4, through anaerobic mineralization in sediments. Eroded soil is also rich in Fe oxides, and their effect on the coupled cycling of C, Fe, S, and P has been neglected in eutrophication research.

According to the specific ligand exchange theory (Hingston et al., 1967), P bound by Fe and Al oxides is in dynamic 'equilibrium' with P in solution. While in contact with dilute rain or snow melt-water on the surface of a field, during transport in ditches and streams, and finally in P-deficient bodies of water, soil particles gradually lose P by its desorption of some of the oxide-bound reserves (Carritt and Goodgal, 1954; Froelich, 1988; Hartikainen et al., 2010; Yli-Hallaet al., 1995)

2.4. *Models and methodologies for assessing erosion*

Negative effects of surface runoff and soil erosion in watersheds can be controlled and mitigated through hydrological models. Moreover, they are suitable to simulate various combinations of different scenarios of land and water management in a watershed and therefore they are useful for comparative analysis of different options and as a guide to what Best Management Practices (BMPs) can be adopted to minimize pollution from point and nonpoint sources (Shrestha et al., 2006).

The erosion prediction in experimental plots and hillslopes or the erosion modelling of small basins at the same analysis scale have been successful using physical models that require a detailed parameters measurement and a considerable quantity of input data in many cases, with the purpose of being used in the planning and management of watersheds.

2.4.1. USLE – Universal Soil Loss Equation

Several mathematical models were developed to estimate the soil loss by surface erosion, as aresult of the action of raindrops and sheet flow. One of the widely known and used model is

USLE (Universal Soil Loss Equation Universal), developed by Wischmeier & Smith (1978). It estimates soil loss from a hillslope caused by raindrop impact andoverland flow, taking into account factors such as rainfall erosivity, soil type, landscape characteristics, land use (including types of crops) and management practices of agriculture.

The model was developed by applying statistical methods on data obtained through experimental measurements and indicates, with a good precision, the areas with potential gully processes. The equation for calculating the mean annual rate of soil erosion is the following:

$$\mathbf{A=R*K*L*S*C*P} \qquad \mathbf{(1)}$$

where,

A- the average annual soil loss (t $acre^{-1}yr^{-1}$);R- the rainfall erosivity factor, evaluated as a product of the total storm kinetic energy (E) and the maximum 30-min intensity (I_{30});

K- the soil erodibility factor;

L- the slope length factor;

S- the slope gradient factor;

C- the vegetation and crop management factor;

P- the support practices factor.

A new version, RUSLE (Revised Universal Soil Loss Equation), was developed by Renard et al.(1997); it keeps the USLE form, being improved the methods for calculating the terms of the mathematical equation.

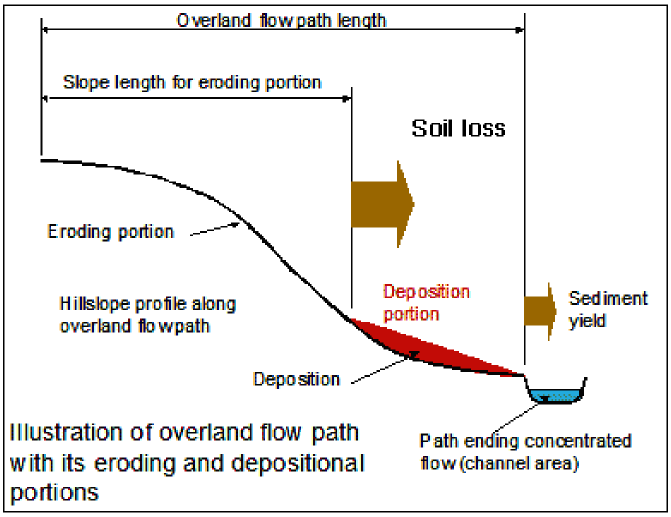

Figure 2.4. Overland flow path

The USLE methodology was adapted to the Romanian soil and climatic conditions by the team of researchers of the Institute of Pedology and Agrochemical Researches in Bucharest. Thus, in1979, Moțoc et al. have developed the ROMSEM model (Romanian Soil Erosion Model), using the experimental data obtained at the several research stations in the country (Perieni-Vaslui county,Aldeni-Buzău county, Bâlceşti-Argeş county, Valea Călugărească-Prahova county and Câmpia Turzii-Cluj county). This model was reconfirmed in 2002(Moțoc & Sevastel, 2002). The estimated annual soil loss is based on the following equation (1):

$$\mathbf{E= K*S*L^{m}*i^{n}*C*C_S} \qquad \textbf{(2)}$$

where ,

-**E**- the average annual rate of the surface erosion (t $ha^{-1}yr^{-1}$);

-**K**- the rainfall erosivity factor, evaluated based on the rainfall aggressiveness, obtained as a result of $H \cdot I_{15}$(H- the amount of precipitation fallen duringthe entire rain event, I_{15}- the intensity of the torrential nucleus lasting 15 minutes);

-**S**- the soil erodibility coefficient;

-$\mathbf{L^{m}}$- the slope length factor; it is determined using a function, where m=0.3 for the straight slopes,m=1.2 for the convex slopes and for the slopes with concave profile m=0,6;

-$\mathbf{i^{n}}$-, where i represents the slope angle (%) and n=1.4;

-**C**- the cover management factor;

-CS- the correction coefficient for the effect of the erosion control measurements.

The factors of the soil erosion processes control are grouping in two categories:

- the factors which trigger erosion: rainfall erosivity (Ap), topography (R) and soil (S);
- the factors that control erosion: vegetation (C)and anti-erosion works (Cs).The combined action of the Ap, R and S factors represents the potential erosion (Ep), while the action of all the factors represents the effective erosion (Eef).

$$Ep= Ap \bullet R \bullet S \qquad \textbf{(3)}$$

$$Eef= Ap \bullet R \bullet S \bullet C \bullet Cs \text{ (Moțoc \& Sevastel, 2002)} \qquad \textbf{(4)}$$

The recent methodology for applying the RUSLE or USLE models requires the use of the GIS techniques (Lu et al., 2004, Saavedra, 2005, Lastoria et al., 2008, Yuksel et al., 2008 etc.).

The importance of the GIS techniques integration to quantify the surface erosion risk is determined by the speed of the performing operations, the accuracy of the results and the possibility of their spatial representation. The database used for estimating the annual rate of surface erosion based on the ROMSEM model was consisting of the Digital Elevation Model(DEM), with 10 m resolution, the soil map (with information about the type, texture, structure and degree of soil erosion), the land use map, based on Corine Land Cover 2000 and corrected according to the 2005 ortophotos with a 0.5 m resolution, the rainfall erosivity index map in Romania (Moțoc &Sevastel, 2002) and information about the distribution of soil erosion.

2.4.2. PESERA- Pan-European Soil Erosion Risk Assessment

The Pan-European Soil Erosion Risk Assessment - PESERA - uses a process-based and spatially distributed model to quantify soil erosion by water and assess its risk across Europe. The conceptual basis of the PESERA model can also be extended to include estimates of tillage and wind erosion. The model is intended as a regional diagnostic tool, replacing comparable existing methods, such as the Universal Soil Loss Equation (USLE), which are less suitable for European conditions and lack compatibility with higher resolution models.

The model results have been validated at catchment level and compared with results of applying other erosion risk assessment methods across Europe at country and pan-European scale. However, further development of the model and a substantial amount of calibration and validation work are essential if PESERA is to become operational.

Preliminary results suggest that, although the model can be applied at regional, national and European levels, low resolution and poor quality input data cause errors and uncertainties. However quantification of the erosion problem enables evaluation of the possible effects of future changes in climate and land use, through scenario analysis and impact assessment taking into account cost-effectiveness, technical feasibility, social acceptability and possibilities for implementation.

Soil erosion indicators developed from a physically based model will not only provide information on the state of soil erosion at any given time, but also assist in understanding the links between different factors causing erosion. Another advantage for policy-making is that scenario analysis for different land use and climate changes are possible using PESERA. This will enable the impacts of agricultural policy, and land use and climate changes to be assessed and monitored across Europe.

Table 2.1. *Input data for the model PESERA (Irvine & Kosmas, 2003)*

Vegetation	Climate	Soil	Topography
- Rooting depth (mm); - Water usable soil surface (mm); - Reduction of the surface roughness of the soil in each month (%); - Soil use; - Coverage in each month (%);	- Average monthly rainfall (mm); - Monthly average temperature (° C); - Monthly temperature range (° C); - Coefficient of variation of rainfall per rain days for each month; - Monthly precipitation / rain day (mm); - Average monthly potential evapotranspiration (mm);	-Availability of water to plants (mm); -Crusting (mm); -Erodibility (mm); Soil depth (mm);	-Standard deviation of altitude (m)

Table2.2. *Classes of soil loss for the basin Enxoé.*

Class (t/ha/year)	%	Area (ha)	Soil loss (t/year)
0-0.5	64.6	3593.77	898.4
0.5-1.0	2.7	151.32	113.5
1.0-2.0	1.8	100.57	150.5
2.0-5.0	7.0	389.69	1363.9
5.0-10.0	3.3	181.95	1364.7
10.0-20.0	1.6	87.97	1319.6
20.0-50.0	0.4	20.23	708.1
>50	18.6	1033.0	51650.1
Total	100	5558.51	57569.1

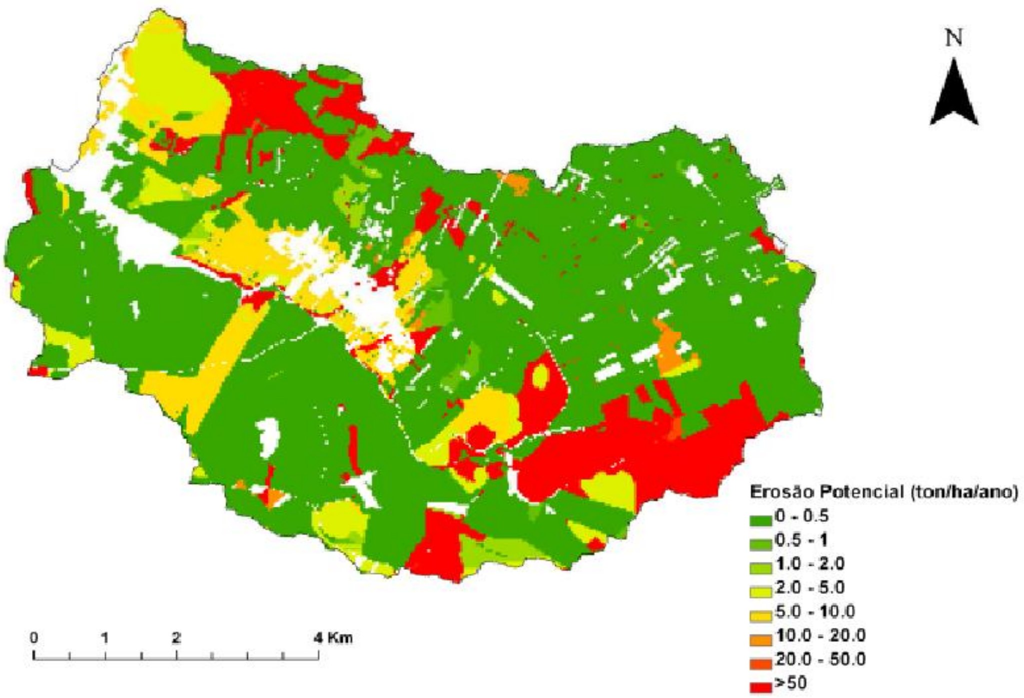

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Fig. 2.5. Evaluation of Potential Soil Erosion Enxoé Basin

2.4.3. WEPP - Water Erosion Prediction Project

The WEPP model is process-based and includes modules for infiltration, runoff, daily water b balance, storm disaggregation, soil erodibility changes, plant growth, and residue accumulation and decomposition (Nearing et al., 1989, Flanagan and Nearing, 1995; Laflen et al., 1997). The WEPP hillslope version simulates the detachment, transport and deposition of sediment on a single hill side.

Rill detachment occurs when two conditions are met:

- hydraulic shear stress of the runoff exceeds the critical shear stress of the soil;
- sediment load in a rill is less than sediment transport capacity of the rill flow.

Interrill erosion depends on interrill soil erodibility, rainfall and runoff intensity, canopy cover, slope steepness and litter or ground cover. Rill erosion and/or deposition depend on the ratio of sediment load to transport capacity, rill erodibility, hydraulic shear stress, surface cover, sub-surface residue, and 2nd Joint Federal soil consolidation.

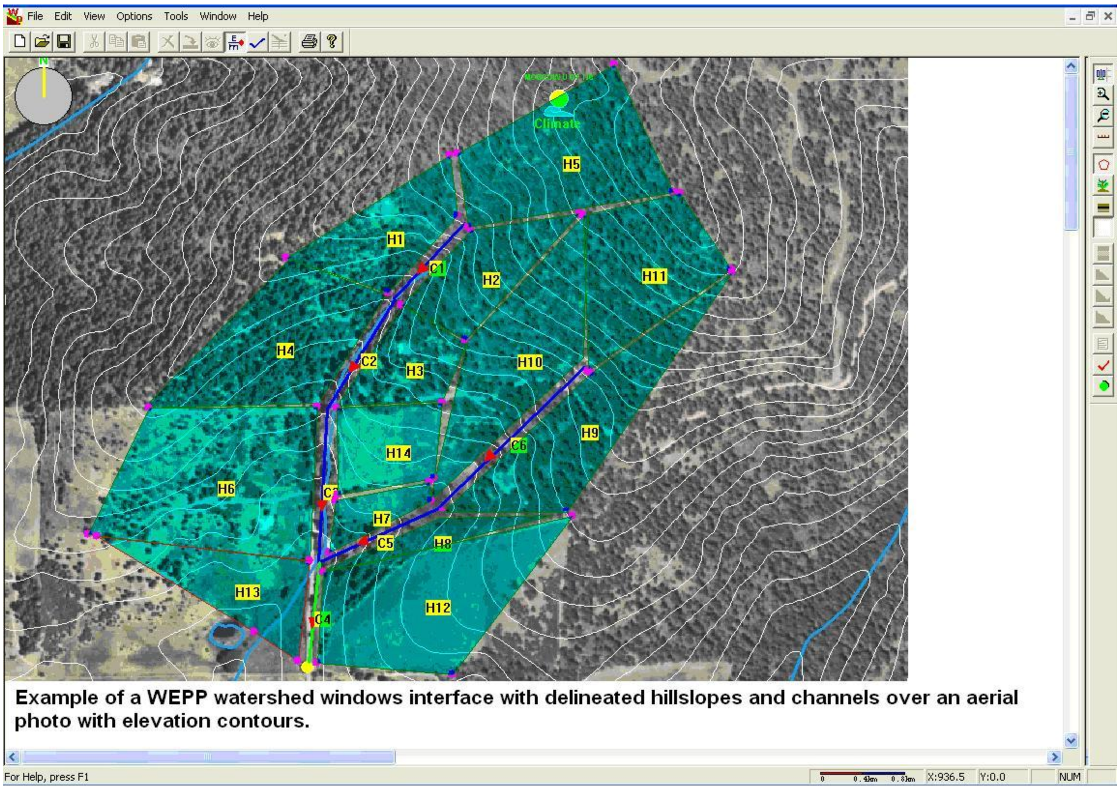


Figure 2.6. Example of WEPP watershed window

The WEPP model has four input files: daily weather, vegetation or management, topography, and soil. The model is a daily simulation model that adjusts the hydrologic status of the land for each day that the simulation is run.

The daily weather inputs include the amount of precipitation and duration, the ratio of peak intensity to average intensity, the time at which peak intensity occurs, solar radiation, maximum and minimum temperature, dew point temperature, and wind velocity and direction. WEPP has been shown to be an effective tool for modeling erosion rates for a wide range of climatic and other conditions, making it well suited to addressing the impacts of a changing climate on soil erosion. WEPP has been subjected to many tests comparing it to observed data and the Universal Soil Loss Equation (USLE); and has in most cases performed satisfactorily. (Laflen et al., 1997; Flanagan and Nearing, 1995; Nearing et al., 1989).

2.4.4. SWAT - Soil and Water Assessment Tool

SWAT is a basin-scale, distributed and continuous-time model, and its land hydrodynamic component solves water balance and relates the meteorological variables with the basin features (topography, soil type and land use). In water quality component, plant growth, nitrogen and phosphorus soil cycles, sediment and pesticides transport, are simulated (Neitsch et al. 2002).

The SWAT model divides the watershed into sub-basins and into HRU (hydrological response units) that are homogeneous in terms of soil, land use and slope (the basic computation units) and soil may be divided into vertical layers.

The nutrient component of the SWAT model includes inputs from agriculture, transport with runoff and groundwater, consumption by plants and generation by mineralization in the soil (Neitsch et al. 2002).

The SWAT model includes the main hydrological and nutrient processes occurring in a watershed in order to describe the singularities of an extensive Mediterranean catchment (flow temporality, crops, agricultural practices, etc.) and was implemented to quantify the balance of the long-term dynamics and to estimate inflows to the Enxoé reservoir.

The land phase of the hydrologic processes, the driving force behind the movement of sediments, nutrients or pesticides, is simulated by the model based on the following water balance equation (4):

- $SW_t = SW_o + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})$ **(5)** where,

  - SW_t is the final soil water content (mm),
  - SW_o is the initial soil water content on day *i* (mm),
  - *t* is the time (days),
  - R_{day} is the amount of precipitation on day *i* (mm),
  - Q_{surf} is the amount of surface runoff in day *i* (mm),
  - E_a is the amount of evapotranspiration on day *i* (mm),
  - W_{seep} is the amount of water entering the vadose zone from the soil profile on day *i* (mm),
  - Q_{gw} is the amount of return flow on day *i* (mm).

Two methods are provided for estimating surface runoff. These are the Soil Conservation Service (SCS) curve number (CN) method (USDA-SCS, 1972) and the Green–Ampt infiltration method (Green and Ampt, 1911). The SCS CN method is given as:

- $Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)}$ **(6)**

where,

- Q_{surf} is the accumulated runoff or rainfall excess (mm),

- R_{day} is the rainfall depth for the day (mm),
- I_a is the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm),
- S is the retention parameter (mm).

Runoff will only occur when $R_{day} > I_a$. The retention parameter varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content.

The retention parameter is defined as:

- $$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad \textbf{(7)}$$

where,

- CN is the curve number for the day.

The peak runoff rate, the maximum runoff rate that occurs with a given rainfall event, is an indicator of the erosive power of a storm. It is used to predict sediment loss. SWAT calculates peak runoff rate with a modified rational method which is given as:

- $$q_{peak} = \frac{C*i*Area}{3.6} \quad \textbf{(8)}$$

where,

- q_{peak} is the peak runoff rate (m^3/s),
- C is the runoff coefficient,
- i is the rainfall intensity (mm/h),
- Area is the sub-basin area (km^2),
- 3.6 is a unit conversion factor from (mm/h) (km^2) to m^3/s.

The SWAT model employs the Modified Universal Soil Loss Equation (MUSLE) developed by Williams and Brendt (1977) to compute sediment yield for each sub-basin. MUSLE is a modified version of the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1965, 1978). The MUSLE is given as:

- $$sed = 11.8(Q_{surf} * q_{peak} * area_{hru})^{0.86} * K_{USLE} * C_{USLE} * \mathrm{PUSLE} * \mathrm{LSUSLE} * \mathrm{CFRG} \quad \textbf{(9)}$$

where,

- sed is the sediment yield on a given day (t),

-Q_{surf} is the surface runoff volume (mm/ha),

- q_{peak} is the peak runoff rate (m^3/s),

- $area_{hru}$ is the area of the HRU (ha),

- K_{USLE} is the USLE soil erodibility factor,-

C_{USLE} is the USLE cover and management factor,

- P_{USLE} is the USLE support practice factor,

- LS_{USLE} is the USLE topographic factor,

- CFRG is the coarse fragment factor.

The SWAT model allows for simultaneous computations on each sub-basin and routes the water, sediment and nutrients from the sub-basin outlets to the basin outlet. The routing model consists of two components—deposition and degradation, which operate simultaneously. The amount of sediment finally reaching the basin's outlet, S_{OUT}, is given as:

- $$S_{OUT} = S_{IN} - S_D + D_T \quad \textbf{(10)}$$

where,

- S_{IN} is the sediment entering the reach,
- S_D is the sediment deposited ,
- D_T is total degradation.

The total degradation is the sum of re-entrainment and bed degradation components, and it is given as:

- $$D_T = (D_r + D_B)(1 - D_R) \quad \textbf{(11)}$$

where,

- D_r is the sediment re-entrained,
- D_B is the bed material degradation component ,
- D_R is the sediment delivery ratio.

2.4.4.1. Model implementation

To implement and validate the model and produce useful information, field data need to be integrated.

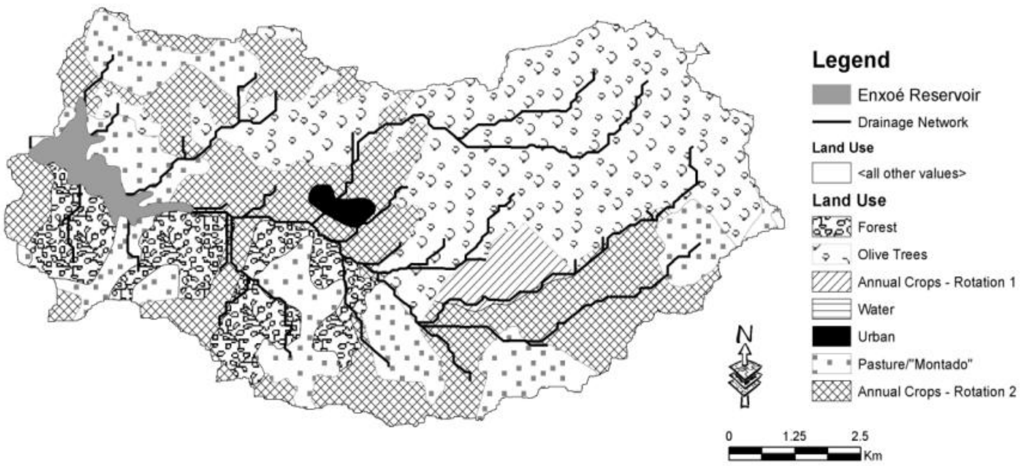


Figure 2.7. The land use map with SWAT classification

2.4.4.2.Model validation

The river data were collected on a weekly basis (with 3 samples collected each time) during the winter and the spring and when water existed during the summer (temporary river). The parameters evaluated in the laboratory were salinity, pH, nutrients, suspended solids, etc.

In terms of flow validation, monthly data from Enxoé reservoir discharges and consumption, precipitation and evaporation were used to estimate the reservoir inflow (2006-2009).

In the area of Alentejo erosion is a major issue for agricultural activities (soil loss) because of the adverse effects on downstream water bodies. Therefore, erosion plots were installed to study erosion patterns and the data from these plots (areas around 60 to 900 m^2) are qualitatively compared with the SWAT results on erosion rates. The runoff volume and concentrations were sampled in the plots in weekly to monthly basis or after strong rain events.

2.4.4.3. Model evaluation

Both qualitative and quantitative measures were used to compare the observed data and the predicted values. Graphical analyses, such as time-series plots, were used to identify the general trends, potential sources of error, and differences between the measured and predicted values.

The SWAT model performance was evaluated using **R^2** (the coefficient of determination that evaluates the correlation between two series), **RMSE** (the root mean squared error, which evaluates the deviation), and the Nash–Sutcliffe Efficiency (**NSE**) (the goodness of-fit criterion for the predicated and observed values) (Nash and Sutcliffe, 1970). NSE values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values <0.0 indicate that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance (Moriasi et al. 2007).

Table 2.4.*Summary of the comparison of the SWAT model results to the collected data in Enxoé reservoir*

Parameter	Period	Data average	Model Average	RMSE	R^2	Nash-Sutcliffe Efficiency
Flow						
Monthly Reservoir Inflow	1996-2009	0.24 $hm^3.month^{-1}$	0.24 $hm^3.month^{-1}$	0.21 $hm^3.month^{-1}$	0.78	0.77
Slope Erosion						
Annual erosion rates	2010-2011	0.1 - 0.2 $ton.ha^{-1}$	0.35 $ton.ha^{-1}$	-	-	-
River Water quality						
Monthly Total Nitrogen Load	2010-2011	0.62 $tonN.month^{-1}$	0.50 $tonN.month^{-1}$	0.46 $tonN.month^{-1}$	0.69	0.65
Monthly Total Suspended Solids Load	2010-2011	1.86 $tonTSS.month^{-1}$	1.80 $tonTSS.month^{-1}$	2.23 $tonTSS.month^{-1}$	0.42	0.19
Monthly Total Phosphorus Load	2010-2011	0.034 $tonP.month^{-1}$	0.030 $tonP.month^{-1}$	0.025 $tonP.month^{-1}$	0.63	0.62

Table 2.5.*Soil loss estimation based on erosion plots and for two hydrological years*

.

Source	***Soil loss (ton/ha) 2009-2010***	***Soil loss (ton/ha) 2010-2011***
Erosion Plot Olive	-	*0.23*

3. Sediment dynamics in Enxoé catchment using Mohid Studio

3.1. Study area description

Enxoé reservoir is located on the left margin of Guadiana River, just to the south of Alqueva reservoir in Alentejo, Portugal – see figure 3.1.

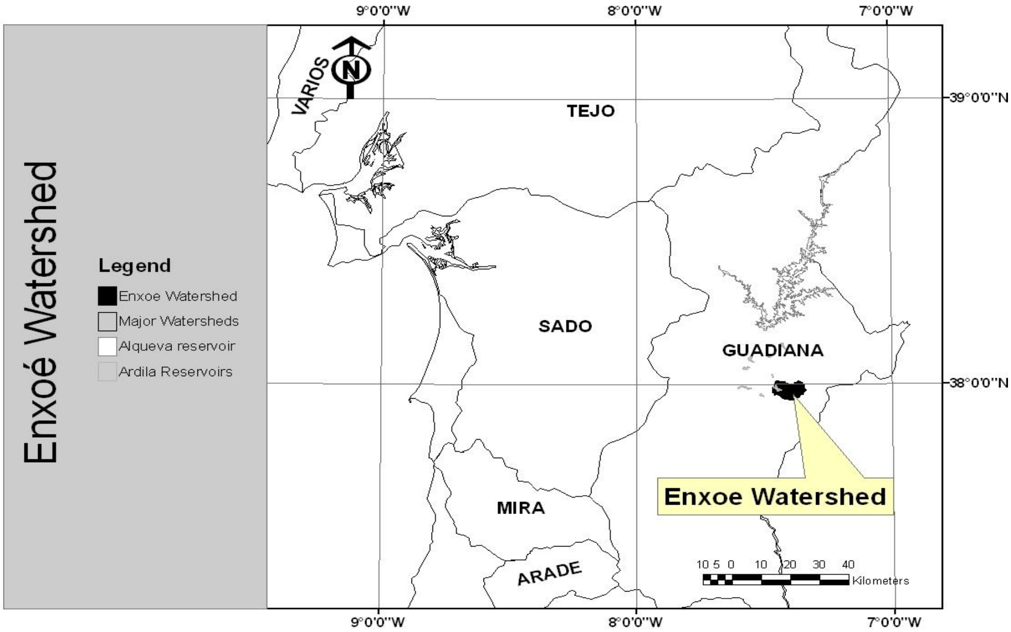


Figure 3.1. Enxoé watershed location in Alentejo, Portugal.

The study site of Enxoé river is located in a country rural area, near the small village of Vale do Vargo, at approximately 40 km from Beja city .

Figure 3.2. The Enxoé river

3.1.1. General characteristics

The study area, corresponding to the Enxoé catchment area of the reservoir, is 6080 ha and has an average altitude of about 200 m.

The reservoir trophic status motivated a number of studies/actions in the catchment not yet fully conclusive. The EU project Aquastress addressed annual loads and built an inverse models suggesting that Phosphorous loads during heavy rain years were the main cause for the reservoir trophic status. The Aguaflash project installed a continuous sampling station to monitor flood events, measuring levels, suspended solids and Nitrate using sensors and an automatic sampler to collect water to analyse in laboratory and verified that flood events are the main responsible for loads hitting the reservoir.

The project Eutrophos is addressing the processes in the catchment to understand the mechanisms responsible for the loads. The project implemented action addressing erosion, addressing the effectiveness of retention basins, addressing properties in the river and addressing the properties in the reservoir.

Table.3.1. *Enxoé river catchment characteristics*

Characteristic	Description
Catchment	Enxoé
Main catchmet	Guadiana
Area (Km^2)	60
Altitude min-max (m)	175-300
Dominant geology	Granites, Calcareous and Schists
Pedology	Luvisols, Cambisols and Calcisols (FAO, WRB2006)
Dominant and secondary soil occupation	Dominant: Olive groves and Oak tree mediterranean woodland “montado” Secondary: winter crops
Rainfall (mm per year)	500
Valley type	Gentle undulating relief
River bed length (Km)	9 (from the source to Enxoé dam)
Hydrological management	
Vegetation	Olive trees, Oak trees, mediterranean woodland
Mean annual discharge ($m^3 s^{-1}$)	Not measured

Characteristic	Description
Mean discharge in low water period ($m^3 s^{-1}$)	Not measured
Bi-annual flood discharge	Not measured
Hydrological regime	Pluvial
Catchment population	1000 inhabitants
Main cities	1 village Vale do Vargo
Waste water treatment station	Yes, but the waste waters are pumped outside Enxoé catchment

3.1.2. Hydro-climatic conditions

This watershed has a Mediterranean climate that is characterized by hot, dry summers and cool, wet winters. According with the Köppen climate classification the south of Portugal is included in the class Csa. The letter *C* stands for Temperate/mesothermal and means that this climate has an average temperature above 10 °C in their warmest months, and a coldest month average between −3 °C and 18 °C. Letter *s* indicates the precipitation pattern which is characterized by dry summers (driest summer month less than 30 mm average precipitation and less than one-third wettest winter month precipitation). Letter *a* indicates degree of summer heat which in this case has the warmest month average temperature above 22 °C with at least 4 months averaging above 10 °C. The annual average temperature is about 16°C and annual reference evapotranspiration varies between 1200 mm and 1300 mm.

In terms of annual precipitation, Enxoé watershed includes isohyets of precipitation from 800mm to 600 mm. The annual average precipitation in the basin is about 500 mm, but the interannual distribution of precipitation is extremely irregular, with more than 80% of the annual total concentrated between October and April. During summer, the Enxoé river frequently runs dry. The nearest climatological station that have data for climatological caracterization is Mértola / Vale Formoso. Based on that data DSRNAH – DS (2003) applied the Thornthwaite method and concluded that the climate in the area was subhumid dry, mesothermic.

The hydrological regime of the catchment is pluvial and is characterized by strong interannual and intrannual variations in discharge.

Precipitation stations used for simulation are from national grid from water national institute (INAG).

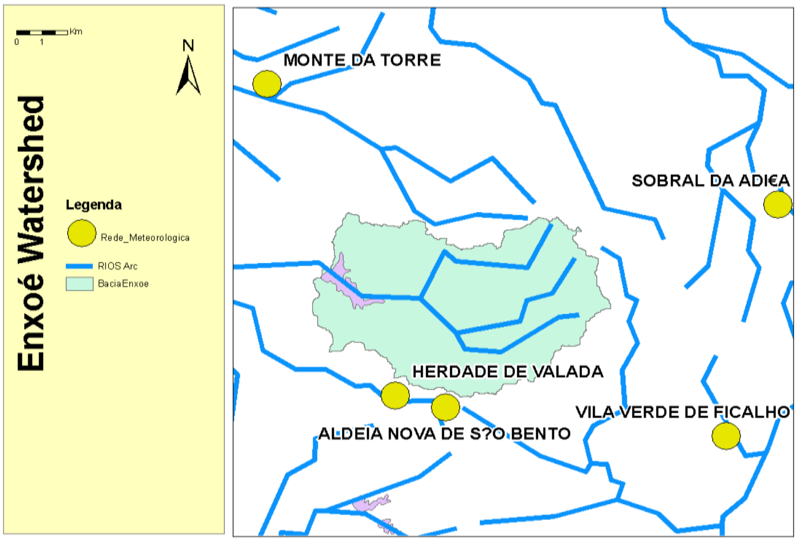


Figure 3.4. Precipitation stations in Enxoé Area

3.1.3. Soil characteristics

In the Enxoé catchment, the dominant soils are Luvisols (FAO, WRB 2006) covering 45% of the area (13% Calcic Luvisols), Cambisols covering about 30% and Calcisols about 15%.

Enxoé has a distribution that range from coarser (less than 18% clay and more than 65% sand) to fine (between 35% and 60% clay) representing both 74% of the area. These correspond to soils that have low and high drainage capacity representing a heterogeneity distribution.

Soil hydraulic parameters for model simulations (conductivity, porosity, hydrologic group, etc.) were obtained from texture using pedotransfer function (Saxton et al., 1986).

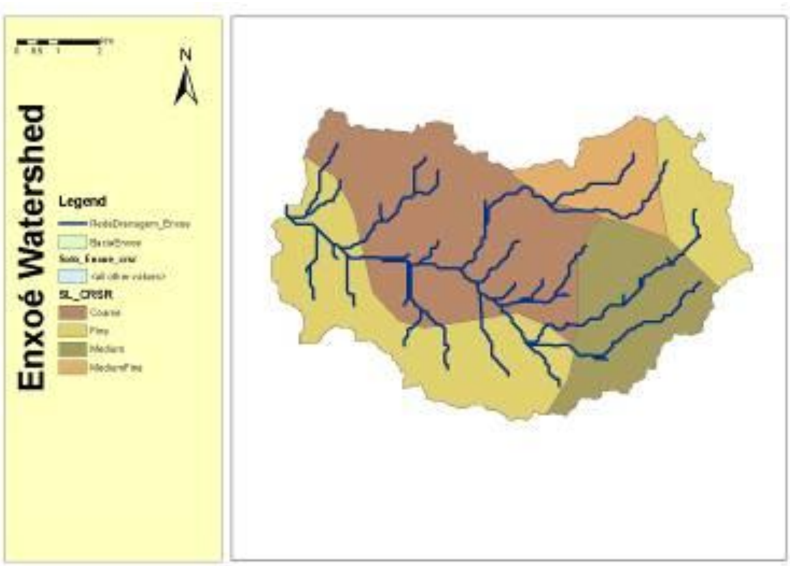


Figure 3.5. – Soil texture in Enxoé from soil bureau.

3.1.4. Land use

The dominant land uses in the Enxoé basin are olive groves (2740 ha), and agro-forestry of holm-oak (2005 ha). Winter crops, maize and pastures (1050 ha), water (205 ha) and urban area (80 ha) are also important land uses to consider.

Land use in the Enxoé catchment is mostly agriculture,forestry (Montado) and extensive cattle growth farms and emergency discharge of the Aldeia do Vargo Waste Water Treatment Plant.

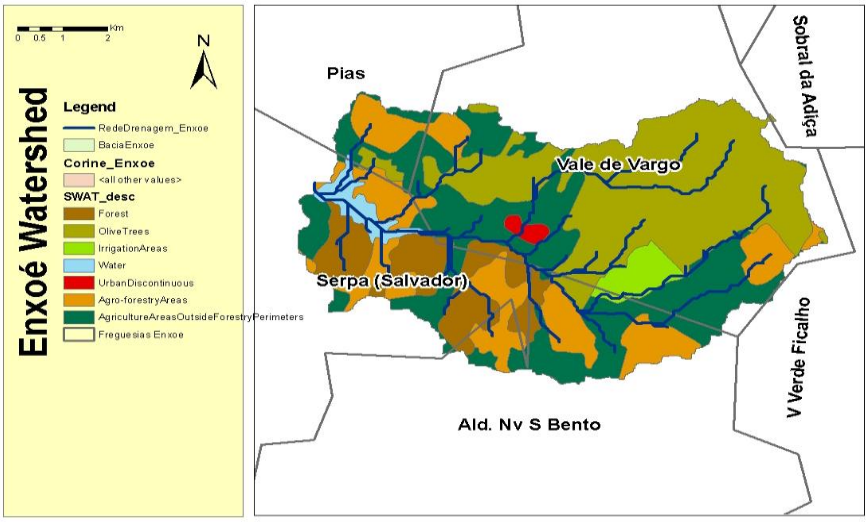


Figure 3.6. Land use in Enxoé from Corine 2000.

3.2. *Mohid Land Description*

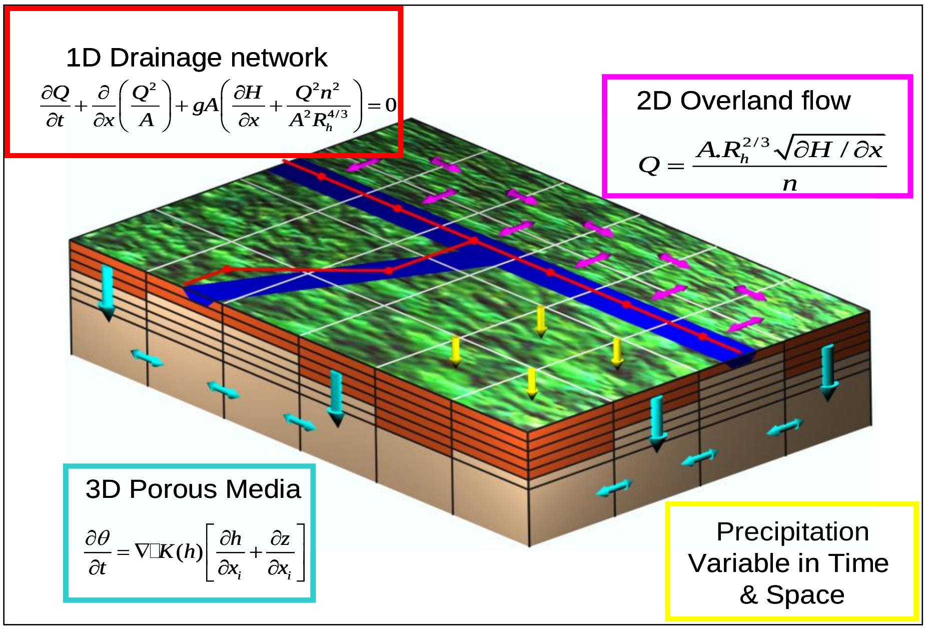
MOHID is the short name for *Modelo Hidrodinâmico* which means Hydrodynamic Model in Portuguese that was the original purpose of the model when it was created back in 1985.

MOHID is a three-dimensional water modeling system, developed by MARETEC (Marine and Environmental Technology Research Center) at Instituto Superior Técnico (IST) which belongs to Technical University of Lisbon.

The MOHID modeling system allows the adoption of an integrated modeling philosophy, not only of processes (physical and biogeochemical), but also of different scales (allowing the use of nested models) and systems (estuaries and watersheds), due to the adoption of an object oriented programming philosophy.

The integration of MOHID different tools, (MOHID Water, MOHID Land and MOHID Soil) can be used to study the water cycle in an integrated approach. Since these tools are based on the same framework, the coupling of them is easily achieved.

MOHID Land is a physically-based, spatially distributed, continuous, variable time step model for the water and property cycles in inland waters and main mediums and equations are presented in next image:



A : surface area [m^2]
h : pressure head [m]
H : total head (m)
K : Darcian hydraulic conductivity [$m*s^{-1}$]
n : Manning coefficient [-]
Q : flow rate [m^3/s^{-1}]
R_h : hydraulic radius [m]
θ : [-]water content

Figure 3.7.: Schematic representation of MOHID Land modules and hydrodynamic equations used.

The main processes solved are:

- 3D Porous Media solving Richard's Equations ;
- 1D Drainage Network solving Kinematic Wave, Diffusion Wave or complete St.Venant equations (dynamic wave) ;
- 2D Overland Flow (solving Diffusion Wave) ;
- Evapotranspiration using Penman Motheith and water availability in soil ;
- Plant growth and agricultural practices (planting, harvest, kill, fertilization, pesticide application, etc.) including dormancy and SWAT crop database ;
- Porous Media interaction with Runoff in Infiltration using continuity (Richard's equation with Head gradient) ;

- Porous Media and Runoff interaction with Drainage Network using continuity (surface gradient between Runoff and Drainage Network. Richard's equation with level gradient between Porous Media and Drainage Network) ;
- Property transport in all mediums and transformation in soil and river (water quality models can be coupled) ;
- Biological and chemical reactions in soil as mineralization, nitrification, denitrification, immobilization, chemical equilibrium, property decay, and processes in river as primary production, nutrient assimilation, property decay, etc.
- Linkage to MOHID Water by Module Discharges ;
- Floods.

3.2.1. MOHID Land Modules

Some modules developed are related with specific processes which occur inside a watershed and on a specific medium, creating thus a modular structure. For user first approach and advanced use, processes solved, equations, input data files examples are presented below for each MOHID Land module:

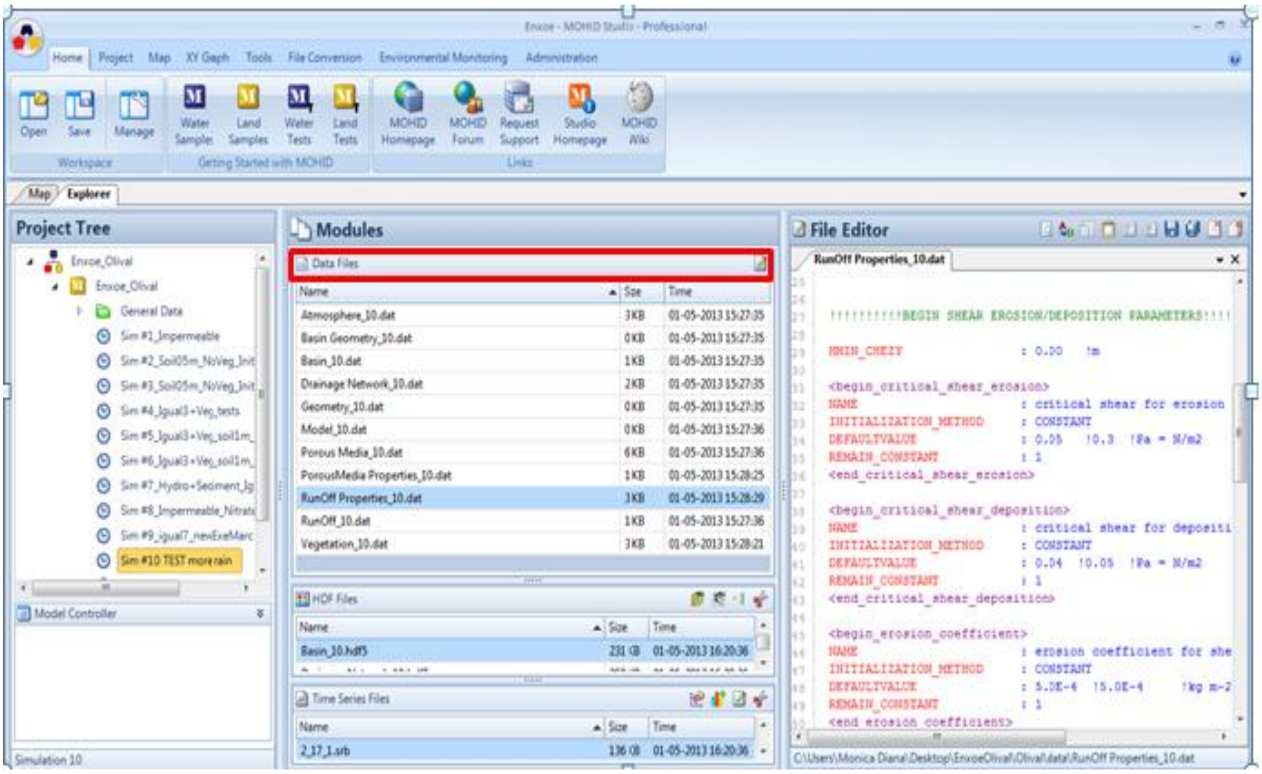


Figure 3.8. Mohid Land Modules

- Module PorousMedia which calculates infiltration, unsaturated and saturated water movement
- Module PorousMediaProperties which calculates property transport and transformation in soil.
- Module SedimentQuality which calculates property transformation in soil driven by microorgansims (mineralization, nitrification, denitrification, etc.).
- Module PREEQC which calculates property transformation in soil through chemical equilibrium.
- Module Runoff which calculates overland runoff;
- Module RunoffProperties which calculates property transport in runoff.
- Module DrainageNetwork which handles water and property routing and property transformation inside rivers.
- Module Vegetation which handles vegetation growth and agricultural practices.
- Module Basin which handles information between modules and computes interface forcing fluxes between atmosphere and soil (e.g. troughfall, potential evapotranspiration, etc.).

3.2.1.1.Module Basin

Overview

Module Basin works as an interface among the different modules of Mohid-Land. Indeed it manages fluxes between modules as precipitation, evapotranspiration, infiltration, etc and updates water column and concentration after each module call. This module is able to compute a water and mass balance for each property transported in all mediums.

Main Processes

The processes made in the Module Basin can be summarized as following:

- Reading entering data and grid construction ;
- Atmospheric processes (precipitation, leaf interception, leaf drainage, evaporation) in order to obtain the potential water column ;
- Call of Module PorousMedia giving potential water column and obtain the infiltration rate ;
- Update of the water column and send it to ModuleRunoff (the holder of water column) ;

- Call of Module PorousMediaProperties and update of water column concentrations send it to the ModuleRunoffProperties ;
- Call of Module Runoff giving the remaining water columns to be transported ;
- Call of Module RunoffProperties (When Module Runoff and RunoffProperties run as they are the holders of water column and water column concentration, no update is needed).
- Call of Module DrainageNetwork to route the water in the river and the new transfered from groundwater and from runoff.
- Output of the different components of the water and property flux .

3.2.1.2. Module Runoff

Overview

Module Runoff allows the calculation of the overland surface runoff over a grid as function of the water column slopes between adjacent cells (dynamic wave). The water column, namely the water located above the terrain, is given by the Module Basin after considering the precipitation input and the losses due to the evaporation and the infiltration. Overland flow is evaluated by the Manning's equation.

Manning Equation

The overland surface runoff flow (m^3/s) is calculated at the cell faces and it is obtained by applying the Manning's equation (Gauckler, P. (1867), Etudes Théoriques et Pratiques sur l'Ecoulement et le Mouvement des Eaux, Comptes Rendues de l'Académie des Sciences, Paris, France, Tome 64, pp. 818–822):

$$Q = \frac{1}{N} * a * R_h^{\frac{2}{3}} * s^{\frac{1}{2}} \tag{1}$$

where:

Q is the overland flow (m3/s)

A is the area of the cross-section (m^2)

n is the Manning coefficient ($s/m^{1/3}$)

Rh is the hydraulic radius (m)

S is the slope of the water surface (m/m)

3.2.1.3. Module Runoff Properties

Overview

This is the module in Mohid Land that handles runoff properties, meaning that controls its transport (dependent on fluxes computed in module Runoff). In this module property transformation is not computed since runoff routing is usually a fast process and there is not time for microbiological activity or chemical equilibrium. This is also the module that handles erosion/deposition to compute sediment and particulate properties sources and sinks (from surface soil to runoff water and vice-versa). Standard units for Module RunoffProperties are mg/L for dissolved and particular properties in the water column and kg/m^2 when deposited in surface soil.

Erosion/Deposition

Erosion and deposition are function of the shear stress at the soil surface, meaning that higher velocities will tend to erode material and lower velocities will tend to deposit. Sediment bed is simulated as a "fluff layer" representing the easy eroded material in soil.

The property erosion equation:

$$\boldsymbol{E_s = E * P_{enr} * \left(\frac{\tau_b}{\tau_{ce}}\right)\ if\ \tau_b > \tau_{ce}} \quad \textbf{(2)}$$

$$\boldsymbol{E_s = 0\ if\ _b < \ _{ce}} \quad \textbf{(3)}$$

where:

Es is the flux of eroded property (kg.m-2.s-1)

E is erosion factor (kg.m-2.s-1)

$\mathbf{P_{enr}}$ is property enrichment ratio to cohesive sediment that exists in sediment bed (kg.m^{-2} Property / kg.m^{-2}sediment)

$_b$ is shear stress at the sediment bed (Pa)

$_{ce}$ is the critical (minimum) shear stress for erosion to occur (Pa)

Erosion of properties occurs dependently on the enrichment ratio of the property in sediment since the erosion rate (E) is dependent on sediment type and cohesion. It is assumed that erosion is a transfer process between sediment in bed to the water column where properties are adsorbed to.

And the property deposition equation:

$$D_S = C * W_S * 1E - 3 * \left(1 - \frac{\tau_b}{\tau_{cd}}\right) \; if \; \tau_b < \tau_{cd} \qquad \textbf{(4)}$$

$$D_s = 0 \; if \; \tau_b \geq \tau_{cd} \qquad \textbf{(5)}$$

where:

Ds is the flux of deposited property (kg.m-2.s-1)

C is property concentration (g/m3)

Ws is property deposition velocity (m/s)

1E-3 is the conversion from grams to kilograms

τ_b is shear stress at the sediment bed (Pa)

τ_{cd} is the critical (maximum) shear stress for deposition to occur (Pa)

τ_{cd} has to be lower than τ_{ce}

Deposition of properties occurs independently on the proportion of the property in sediment. Each property may have a different deposition rate and the process will be proportional to the property concentration since higher concentration will promote flocculation and deposition.

<u>Bottom Shear Stress</u>

Bottom shear stress is the effective shear at the soil surface promoted by water transport in runoff:

$$\tau_b = \frac{\rho * g * n^2 * v^2}{h^{\frac{1}{3}}} \qquad \textbf{(6)}$$

where:

τ_b is bottom shear stress (Pa or kg.m-1.s-2)

ρ is water density (kg.m^{-3})

g is gravity acceleration (m.s^{-2})

n is manning coefficient (s.m$^{(-1/3)}$)

v is velocity at the center of cell (m.s^{-1})

h is water column (m);

<u>Critical shear stress</u>

The critical erosion shear stress depends on a number of factors including sediment composition, bed structure, chemical compositions of eroding fluids, deposition history, and the organic matter and its state of oxidation (Ariathurai and Krone, 1976; Mehta et al., 1989).

3.3. *Modeling approach*

Enxoé watershed is ungauged for flow and water quality so the need to study the watershed dynamics led to the beginning of a monitoring program in Enxoé. It was installed erosion plots in two main land uses of Enxoé: olive and “montado” collecting water and lab analyzes for sediment and nutrients. Also it was performed water sampling in a small ditch downstream of one of the erosion plots to depict deposition/retention time effect on loads from upstream. Also in the river (upstream of Enxoé reservoir) it was performed automatic sampling in floods and manual sampling for water, solids, and nutrients.

In this paper, I will consider the olive tree plot (figure 3.9.)

Figure 3.9. Location of studied erosion plot

In recent years, considerable effort has been made to study the mechanisms of cohesive sediment transport, and many experimental and field studies have been carried out to investigate deposition and erosion rates of cohesive sediments (e.g. Krone, 1962; Mehta, 1973;Thorn and Parsons, 1977; Mehta, 1988; Parchure and Mehta, 1985; Thorn, 1981; Licket al., 1995).

To implement and validate the model in order to get good results, data needs to be integrated. The main objective is to implement MOHID Land model and:

- to collect data in the ungauged watershed (during the period 2010-2011);
- to implement the MOHID model and validate it against field data;
- extrapolate the results to the basin scale and characterize the watershed dynamics (water and nutrient balances)

3.3.1. Data for model implementation

The basic data to implement a model are Digital Terrain Model (Figure 3.9.), land use (figure 3.6.), soil characteristics (figure 3.5.) and precipitation (figure.3.4.).

In Table 3.2 is described the data used to implement MOHID Land model to Enxoé (digital terrain model, land use, soil texture, precipitation stations, weather stations, etc.).

Table 3.2. *Description of data for Mohid Land model implemetation*

Data type	Description	Origin	Resolution	Period	Frequency
DTM	SRTM Digital Elevation	NASA	90 m	-	-
Land Use	Corine Land Cover 2000	EEA	1:100000	1999-2002	-
Soil texture	European Soil database	JRC,EU	1:1000000	1996	-
Precipitation	Station for hourly input	SNIRH,National Water Institute (www.snirh.pt/)	-	1980-2011	hourly
Other Meteorology	Station for hourly input	SNIRH,National Water Institute (www.snirh.pt/)	-	-	hourly

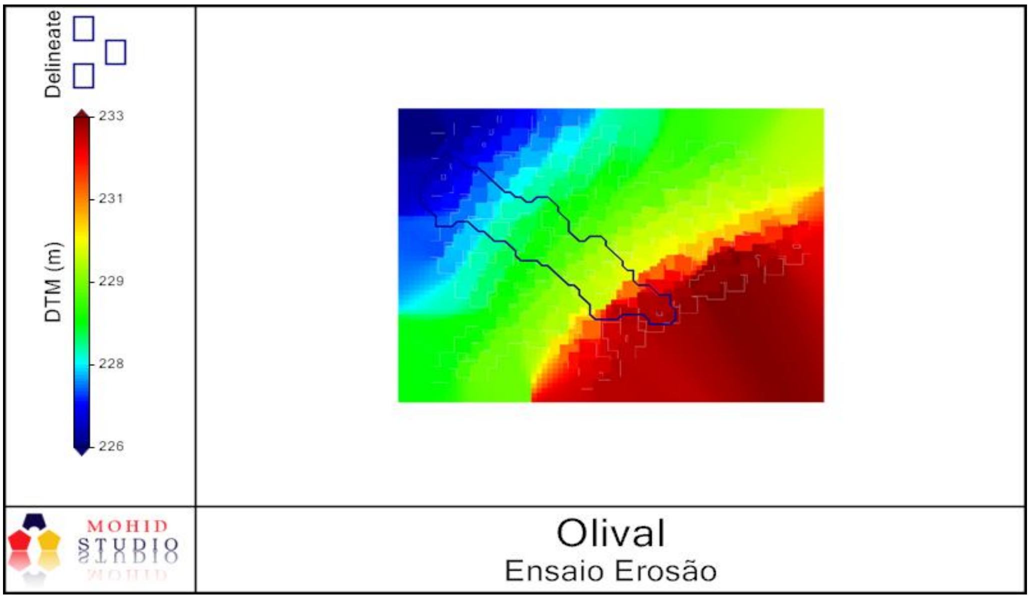


Figure 3.10. Digital Terrain Model Enxoé watershed

Table 3.3. *Enxoé land use distribution areas (Source: Corine 2000)*

Land Use	Area (km^2)	Percentage of total area
Olive trees	21	35 %
Annual crops –Rotation 2	18	30 %
Pasture / "Montado"	11	19 %
Forest	7	11 %
Annual crops- Rotation	2	3 %
Water	1	2 %
Urban area	<1	< 1%
Total	61	100%

3.3.2. Data for model validation

Following the river sampling for floods and as runoff water is an important component of Enxoé dynamic, erosion plots were conducted to depict differences between land uses export of suspended solids and nutrients and the effect of ditches in material retention. Erosion plots runoff water is collected from small basins (200 m^2 in olive plot) in reservoirs and water analyzed for suspended solids and nutrients.

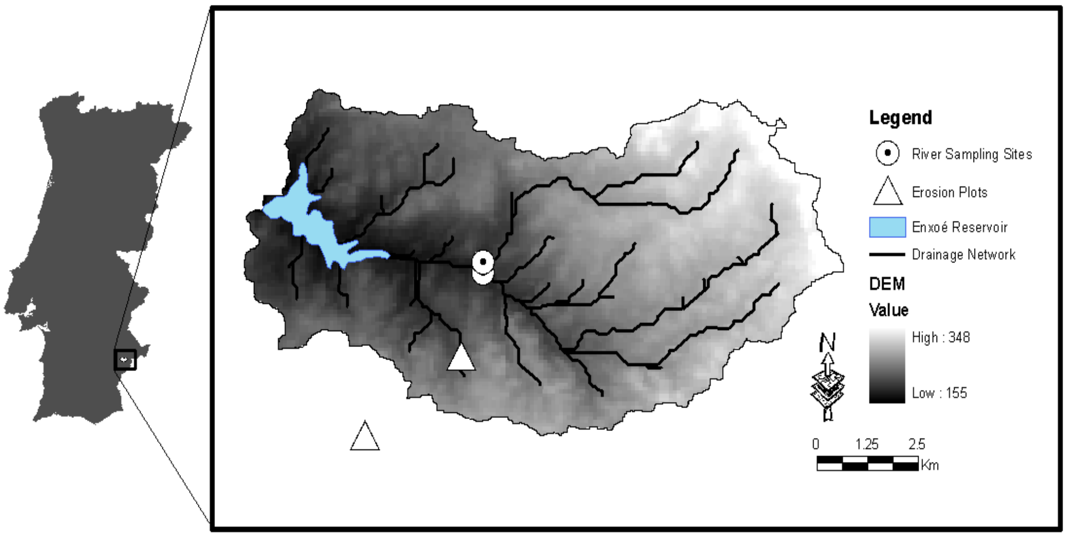


Figure 3.11. River sampling sites

The plot measures started from October 2010 to June 2011 during two hydrological years. In the first year there was a big flood overtopped the water reservoirs and a huge amount of water could not be accounted.

Table 3.4. *Description of data for Mohid Land model validation*

Data type	Station	Origin	Period	Frequency
Reservoir Inflow Reservoir	Enxoé reservoir	SNIRH,National Water Insitute	2005-2009	Monthly
Discharges	Herdade da Valada Sobral Adiça		1980-2011	Daily
Precipitation				
Evaporation	Herdade da Valada Monte da Torre		2001-2011	
Erosion	Two plots in two main land uses. Volume and solid concentration collected	Project	2010-2011	
Erosion rates				Weekly to monthly
Water quality in river	Two station in two main tributaries	Project	2010-2011	Weekly to monthly
Nutrient				

3.3.3. Model implementation and calibration procedure

For Mohid implementation, the data from previous chapters was introduced in Mohid Studio graphical user interface.

To implement and calibrate the model, we need to follow several steps:

- First step is understanding how the program works, is making different tests in order to achieve the wanted results;
- In MohidLand Erosion model, the first reactive term computed is the splash erosion rate using vegetation growth model, precipitations model, soil properties module and porous media module;
- The second erosion reactive term computed is the runoff erosion rate using soil properties and water velocity fields;
- After, deposition rate is computed using sediment water concentration, velocity field, soil properties and fall velocity for an i soil property.

4. Results and discussions

4.1. *Mohid Model Results: Comparison with field data*

The comparison between the Mohid model and the field data was made with respect to two different aspects:

- water inflow to the reservoir
- sediment loads in the river.

Enxoé is a small-sized, gently sloping (usually less than 5%) watershed with a 2% slope in the river. During low flow, the retention time increases drastically and pools tend to form, promoting deposition and making in-pool water quality processes relevant for estimating river concentrations.

4.1.1. Reservoir inflow

Table 4.1.Precipitation field data

Data initial	Data final	Períod	Sum of Precipitation Olival (L)
10/26/2009	12/3/2009	1	2064
12/3/2009	1/5/2010	2	32352
1/5/2010	1/20/2010	3	6012
1/20/2010	2/5/2010	4	1404
2/5/2010	2/24/2010	5	15132
2/24/2010	3/9/2010	6	10944
3/9/2010	3/25/2010	7	960
3/25/2010	4/9/2010	8	2304
4/9/2010	4/28/2010	9	9096
4/28/2010	5/27/2010	10	1632
5/27/2010	6/22/2010	11	2700
6/22/2010	10/15/2010	12	6528
10/15/2010	10/22/2010	13	0
10/22/2010	10/29/2010	14	0
10/29/2010	11/2/2010	15	3972
11/2/2010	11/17/2010	16	2388
11/17/2010	11/24/2010	17	2256
11/24/2010	12/3/2010	18	2064
12/3/2010	12/9/2010	19	4416
12/9/2010	12/15/2010	20	0
12/15/2010	1/11/2011	21	12048
1/11/2011	1/27/2011	22	672

1/27/2011	2/3/2011	23	1212
2/3/2011	2/9/2011	24	0
2/9/2011	2/16/2011	25	3996
2/16/2011	2/23/2011	26	468
2/23/2011	3/2/2011	27	36
3/2/2011	3/16/2011	28	7512
3/16/2011	3/23/2011	29	1308
3/23/2011	4/1/2011	30	1092
4/1/2011	4/8/2011	31	0
4/8/2011	4/14/2011	32	0
4/14/2011	4/20/2011	33	1980
4/20/2011	4/27/2011	34	4512
4/27/2011	5/3/2011	35	4152
5/3/2011	5/11/2011	36	0
5/11/2011	5/19/2011	37	2244
5/19/2011	5/26/2011	38	492
5/26/2011	6/1/2011	39	1476

The Enxoé River represents approximately 75% of the total flow of the two tributaries. In Figure 4.1, the estimated flow during 2010-2011 is presented, and the precipitation is presented on the reverse axis.

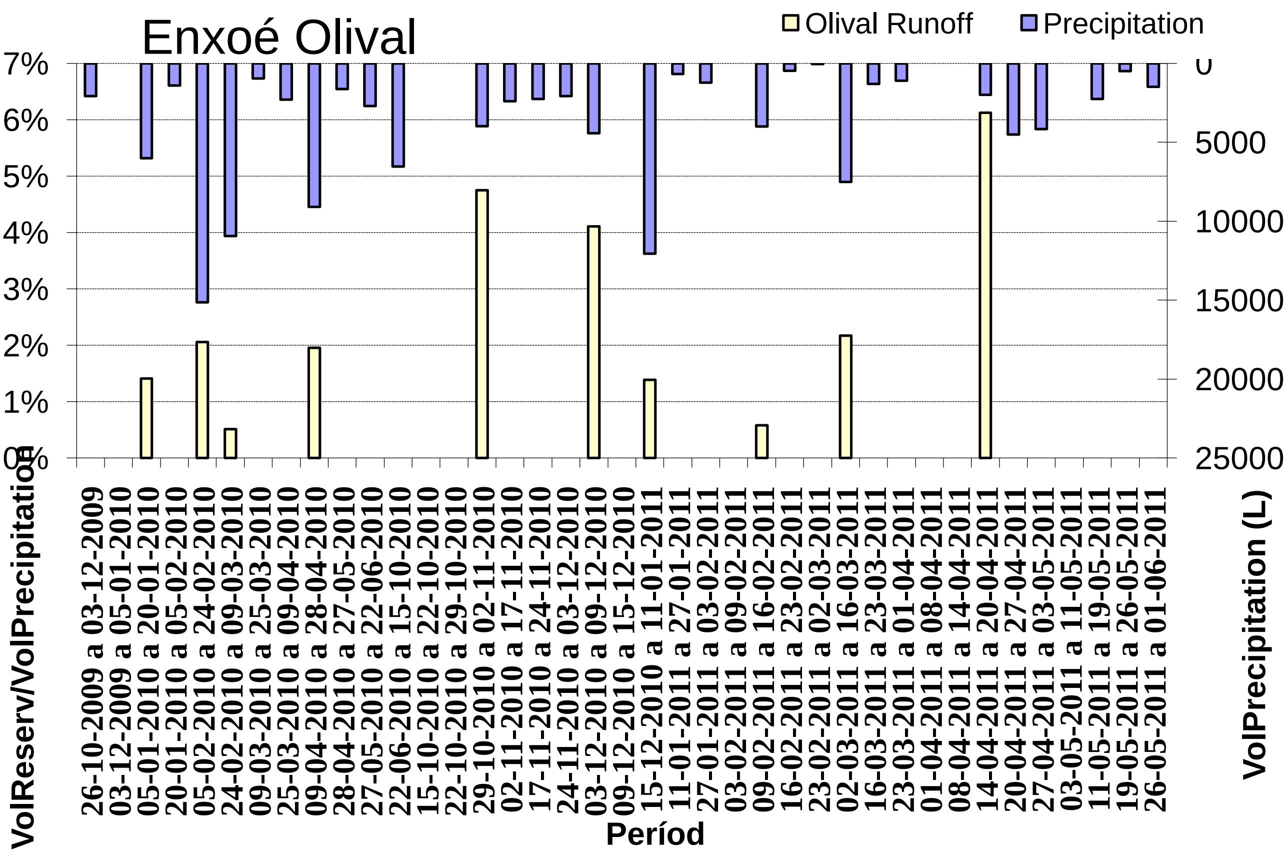


Figure 4.1. Precipitation and runoff in Enxoé reservoir

The river is dry or almost dry from June to October, and the first rain events (October and November) generates flow peaks that are quickly reduced (consistent with observations) because the soil is still not saturated and the groundwater flow is greatly reduced; from December/January to March, the response to the rain events still exists, but because the soil is saturated, base flows are maintained longer but still tend to fall quickly, especially during months in which the total rain was less intense (e.g.,January and February 2011).

The first objective was to model hydrology, accordingly the first six simulations (table 4.2.) were made, and the flow graphics are presented below:

Table 4.2. Centralized simulation data

Sim nr	Name	Description	Modules used	Modifications
1	Imperme able	• No Porous Media=> Impermeable	• Atmosphere • Basin Geometry • Basin • Drainage Network • Geometry • Model • RunOff	
2	Soil 0.5 m , no vegetatio n	• Soil 0.5 m • No vegetation • Initial aquifer 0.5 m • Maximum infiltration • Limited:EVPT(LIMIT_EVAP_WATER_LEVEL=1)	• Equal sim 1 +Porous Media	• Porous Media
3	Soil 0.5 m , no vegetatio n	• Equal sim 2 + • EVPT(LIMIT_EVAP_WATER_LEVEL=0)=> off	• =Sim2	• Evaporation Not Limited
4	Igual3+ Veg_test	• Equal sim 3 + • Vegetation • Root depth 0.5 m	• Equal sim 3 +Vegetation	• Simulation3 +Vegetation • ..\General Data\TimeSeries\TimeSeriesLocation2.dat
5	Igual3+Veg+Soil1m_Imp5%+Cut rain	• Soil 1.0 m • Vegetation • Initial aquifer 0.5 m • Root depth=1.0 m • Impermeable 5% • Cut rain	= Sim4	• POROUS MEDIA-impermeable fraction= 0.05 • ATMOSPHERE: Cut Rain
6	Igual3+Veg+Soil1m_Imp5	• Equal sim 5 + • Real rain	= Sim4	• ATMOSPHERE: Real rain

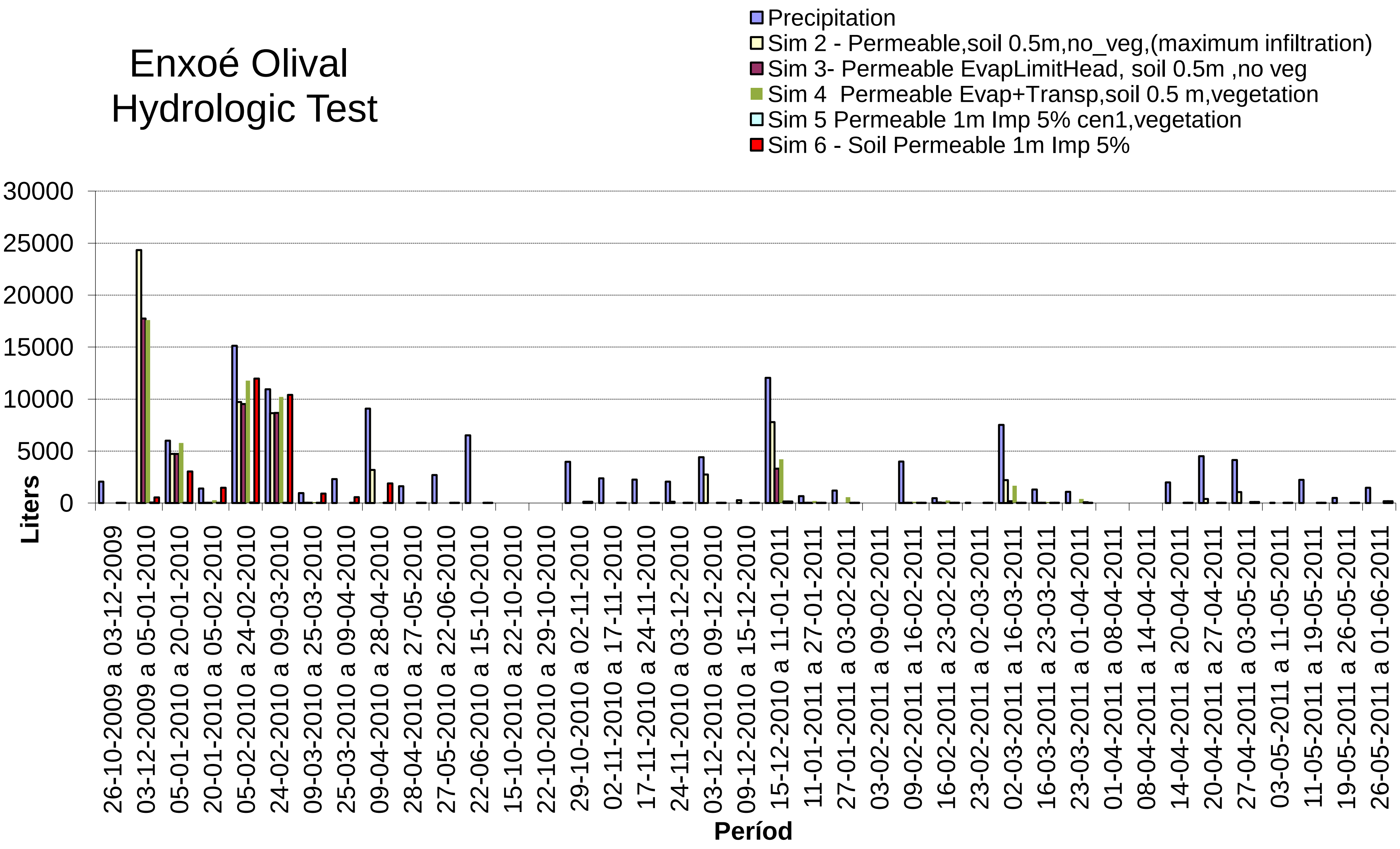


Figure 4.2. A comparison between the estimate from the reservoir balance and the simulation from the Mohid model(L)

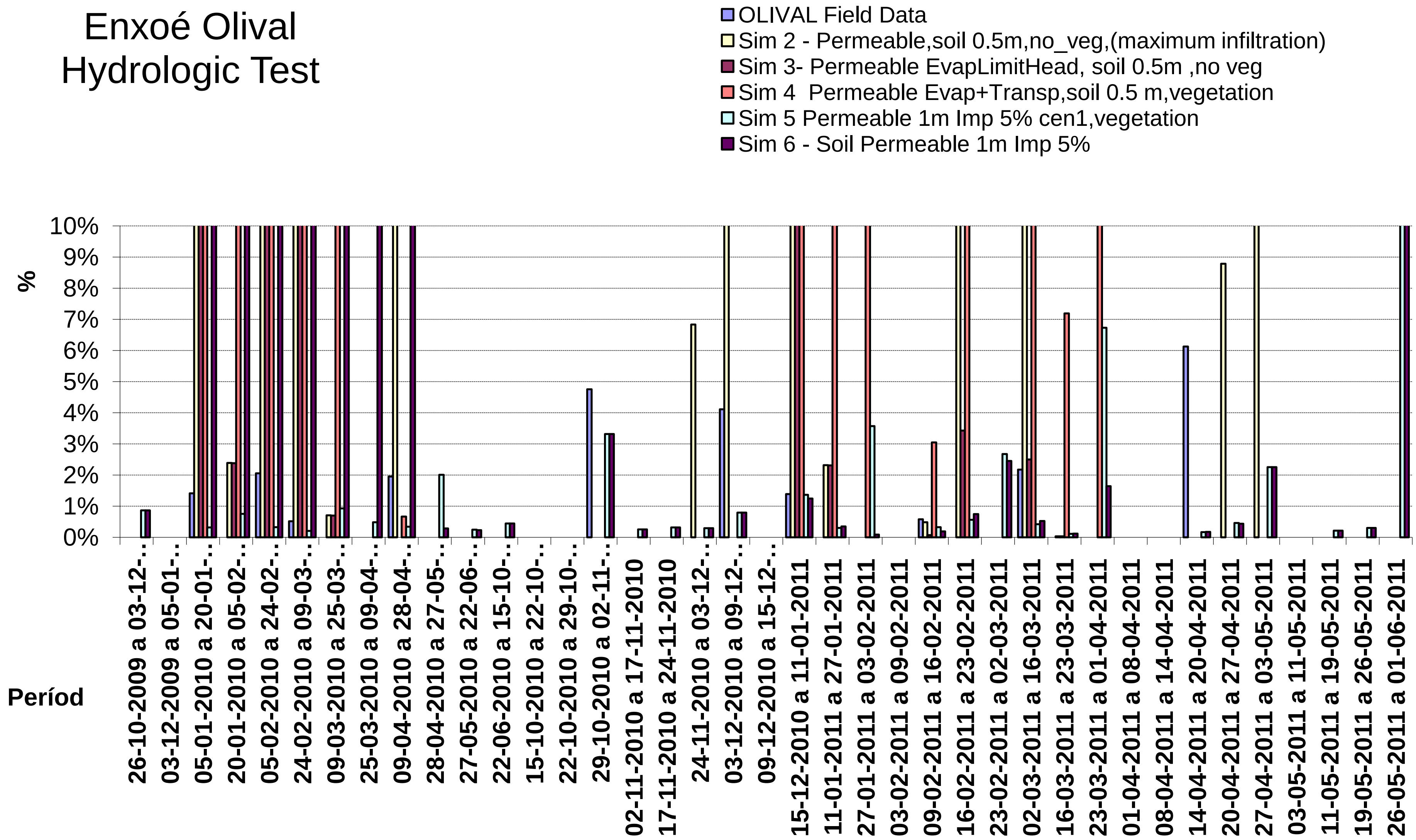


Figure 4.3. A comparison between the estimate from the reservoir balance and the simulation from the Mohid model (%)

4.1.2. Sediment loads

Another important aspect for accurately estimating affluences to the reservoir is the input concentrations and loads.

December 2010 was a month with several rain events, and a significant rain event occurred on 19/12/2010 that delivered 38 mm and generated the higher flow in Figure 4.1. Therefore, it was expected that December 2010 would produce a higher sediment load in the data, as Mohid estimated. The field data were collected three weeks before the event of 19/12/2010, and after the event, the next sample was taken in February. Therefore, the sampled total suspended solids concentrations in December 2010 may not be characteristic of the month and some degree of under prediction linked to the data may be possible. The erosion plot results are only used for indicative comparison because data only exist for one year.

A comparison between the suspended sediments from the data and the Mohid model results (2009-2010) in the Enxoé River is presented below:

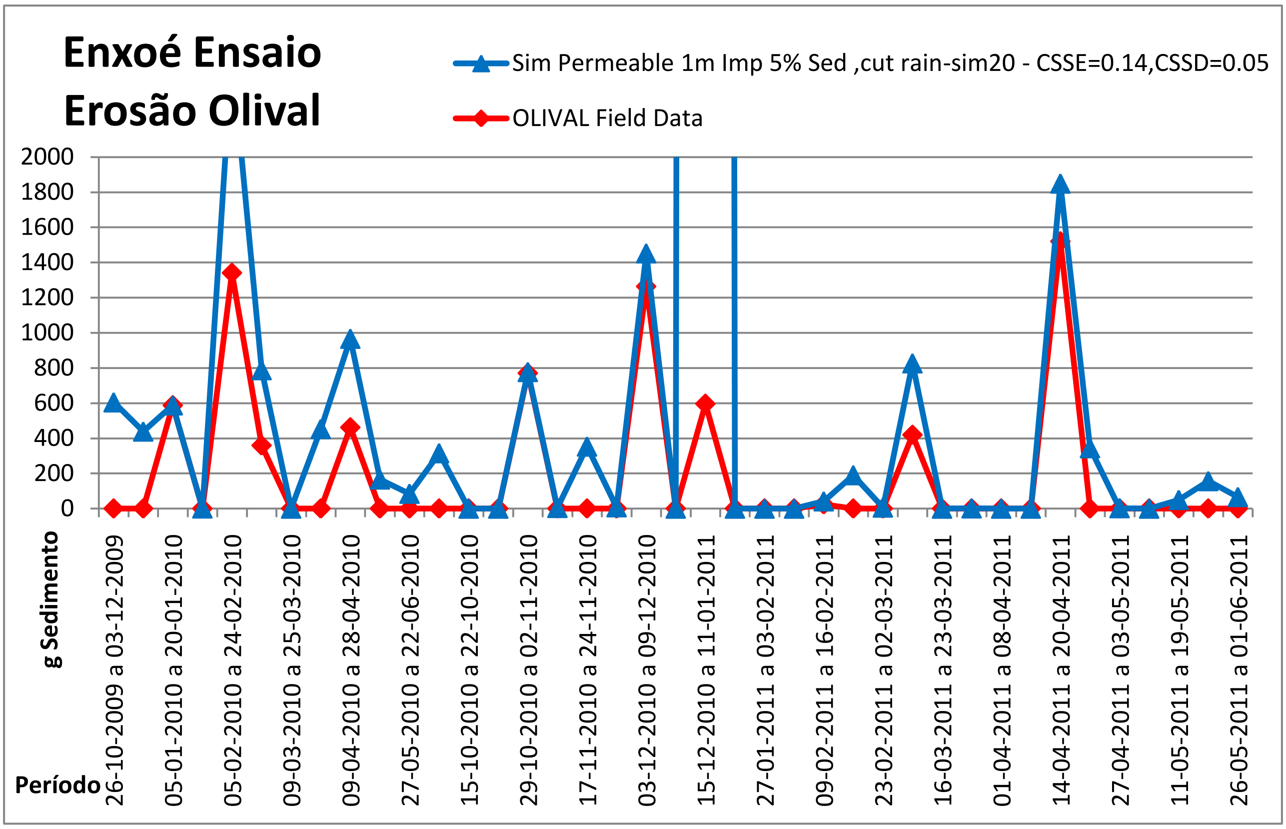
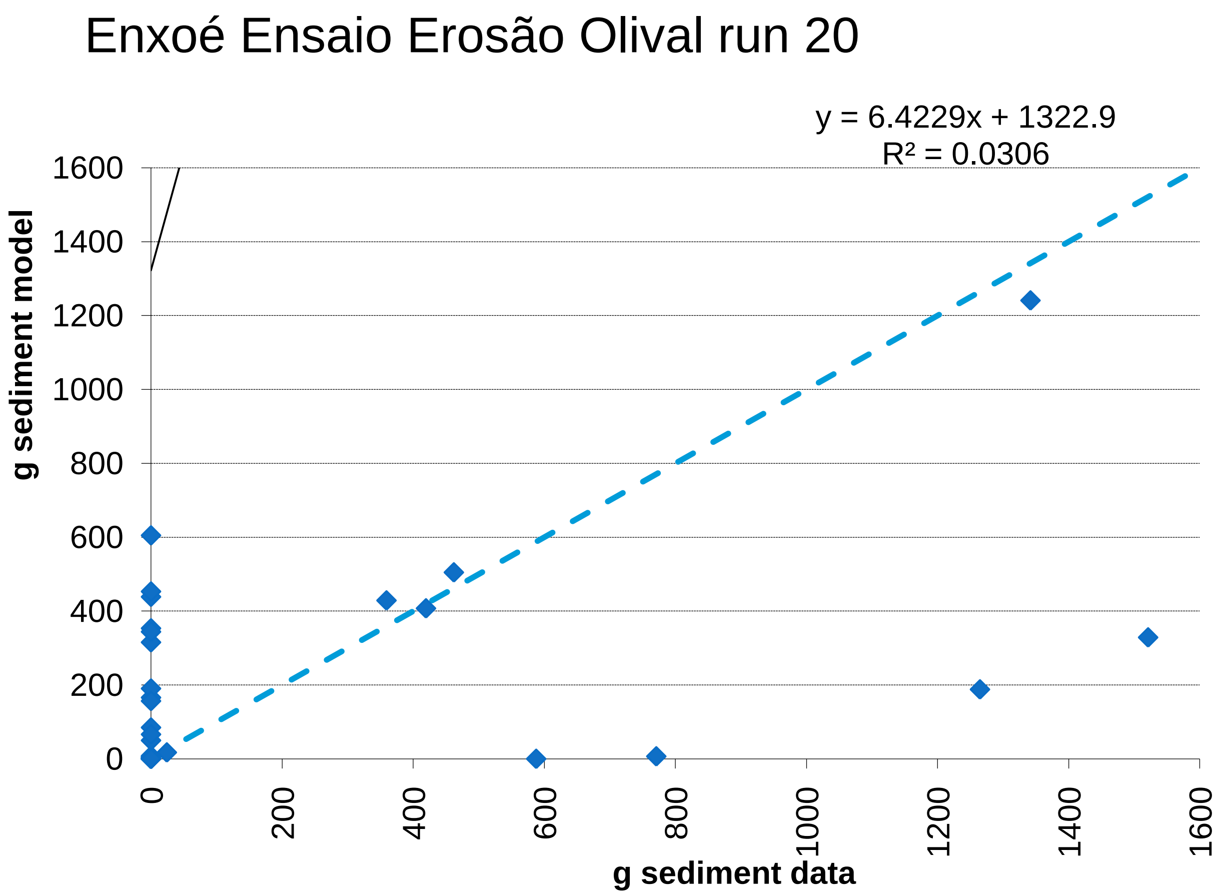
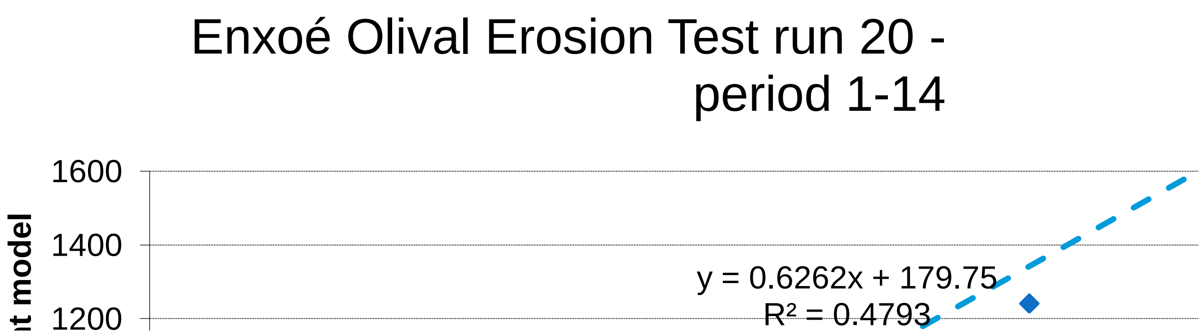
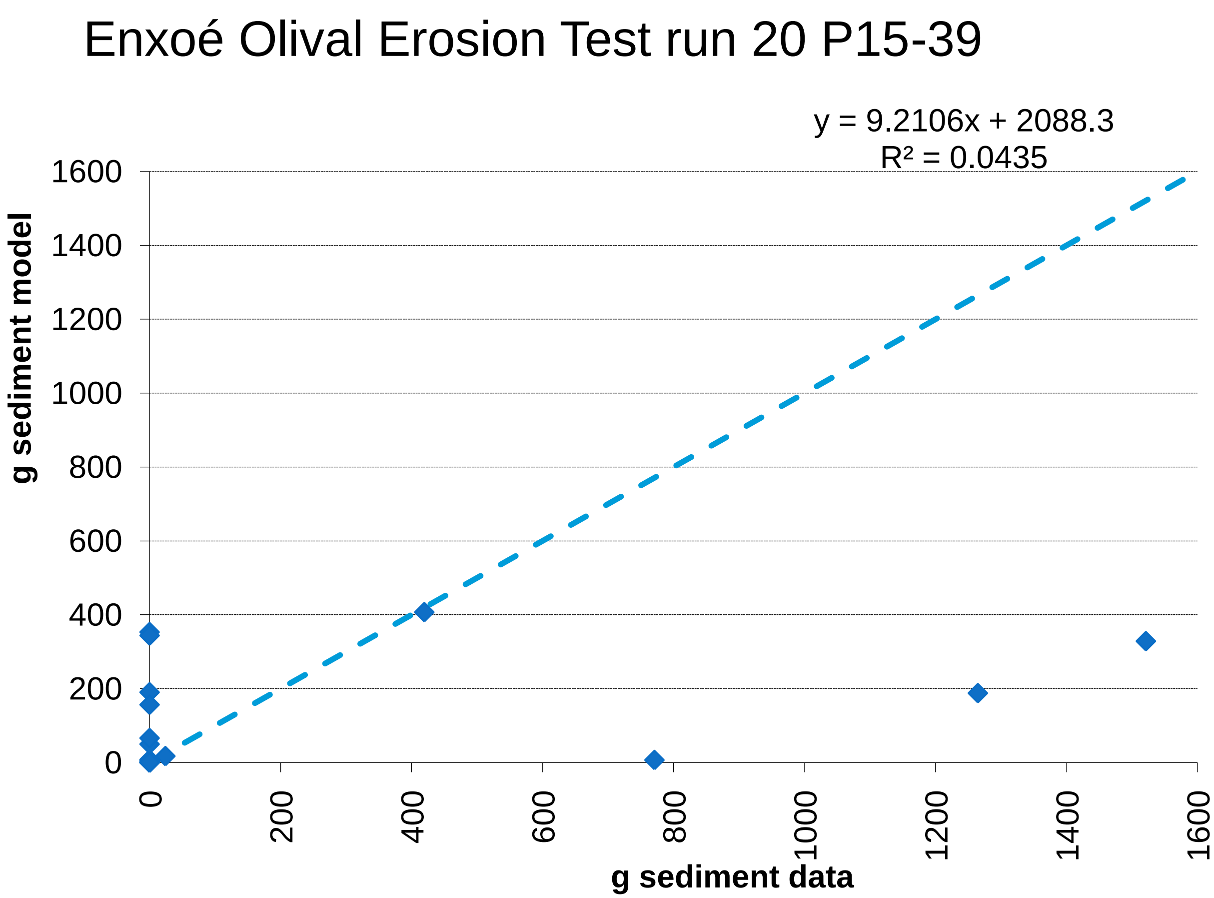


Figure 4.4. Comparison between the suspended sediments from the data and the Mohid model results

Sim nr	Name	Description	Modules used	Modifications
16	Sim Permeable 1m Imp 5% Sed ,cut rain-sim 16 - CSSE=0.14,CSSD= 0.06	• Soil 1.0 m • Vegetation • Initial aquifer 0.5 m • Root depth=1.0 m • Impermeable 5% • Cut rainEqual sim 15 • Changed CSS	-Atmosphere -Basin -Geometry -Basin -Drainage Network(copy sim7) -Geomety -Model -RunOff -RunOff Properties(sim7)	• Period (26.10.2009-01.06.2011) • CSSE 0.14 • CSSD 0.06
17	Sim 17 - SSE=0.15, CSSD=0.03	Equal sim 16 Different CSS	Equal sim 16	• CSSE 0.15 • CSSD 0.03
18	Sim 18 - SSE=0.15, CSSD=0.04	Equal sim 16 Different CSS	Equal sim 16	• CSSE 0.15 • CSSD 0.04
19	Sim 19 - SSE=0.14, CSSD=0.04	Equal sim 16 Different CSS	Equal sim 16	• CSSE 0.14 • CSSD 0.04
20	**Sim 20 - SSE=0.14, CSSD=0.05**	**Equal sim 16 Different CSS**	**Equal sim 16**	• **CSSE 0.14** • **CSSD 0.05**
21	Sim 21 - SSE=0.15, CSSD=0.05	Equal sim 16 Different CSS	Equal sim 16	• CSSE 0.15 • CSSD 0.05
22	Sim 22 - SSE=0.15, CSSD=0.05	Equal sim 16 Different CSS	Equal sim 16	• CSSE 0.13 • CSSD 0.03
23	Sim 23 - SSE=0.15, CSSD=0.05	Equal sim 16 Different CSS	Equal sim 16	• CSSE 0.13 • CSSD 0.04
24	Sim 24 - CSSE=0.15 ,CSSD=0.05	Equal sim 16 Different CSS	Equal sim 16	• CSSE 0.13 • CSSD 0.05


Enxoé Ensaio Erosão Olival run 20
y = 6.4229x + 1322.9
R² = 0.0306
1600
1400
1200
1000
800
600
400
200
0
g sediment model
0
200
400
600
800
1000
1200
1400
1600
g sediment data


Enxoé Olival Erosion Test run 20 - period 1-14
1600
1400
1200
nt model
y = 0.6262x + 179.75
R² = 0.4793


Enxoé Olival Erosion Test run 20 P15-39
y = 9.2106x + 2088.3
R² = 0.0435
g sediment model
1600
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
1600
g sediment data