Post Forest-Fire Runoff & Soil Erosion Modeling with LISEM: A Case Study of Vale Torto – Portugal

Eduardo A.C. dos Reis

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Post Forest-Fire Runoff & Soil Erosion Modeling with LISEM: A Case Study of Vale Torto – Portugal

by

Eduardo A.C. dos Reis

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Thesis Assessment Board

Prof. Dr. V.G. Jetten (Chair)

Dr. Ir. C.M.M. (Chris) Mannaerts

Dr. R. van Beek (External Examiner)

Dr. David Rossiter (RTL Delegate)

ITC

INTERNATIONAL INSTITUTE FOR GEO-INFORMATION SCIENCE AND EARTH OBSERVATION

ENSCHEDE, THE NETHERLANDS

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This document describes work undertaken as part of a programme of study at the International Institute for Geo-information Science and Earth Observation. All views and opinions expressed therein remain the sole responsibility of the author, and do not necessarily represent those of the institute.

I dedicate this work to my beloved daughter

Belinda Inês Rodrigues dos Reis

for all the patience, understanding, and support given, throughout this phase

I love you

Abstract

This research is intended to strengthen our knowledge and provide further information about the changes that might occur, after induced fire, on some soil physical properties and whether or not they can be quantified or measured. Furthermore, how we can represent (parameterize) such occurrence through use of a physically based model – LISEM, as well as simulate the effects of surface runoff and sediment erosion on the catchment. Several studies have been undertaken, and are available on literatures, on the effects of temperature on soil properties changes, it is known that the severity of the fire and the duration have important roles. Meanwhile, it is also known that their roles are dependant of other factors such as the existence and the quantity of dead and live biomass (combustion), air temperature, humidity, wind and topography of the site.

This research, concerning the effects of induced fire on runoff and consequent soil erosion, is inserted within one of the objectives of project DESIRE, which is the establishment of promising alternatives of land use and management. The selected study area, Valtorto catchment, is a 10 ha experimental patch, selected within DESIRE project scope to carry out the fire-induced effects study on soil properties. It is located at around 55 Km west of Coimbra (Portugal), at the Latitude 40° 06' 21" 0N, Longitude 8° 07' 05" 60W, and at the Altitude ranging from approximately 600 to 750 meters. The study used LISEM model, and except for DEM derived maps, the remaining required data were directly measured on the field, and in some special cases, literature data were also used. The experimental fire occurred on February 20th 2009, after some failed attempts, due to weather conditions. The fire took approximately 3 hours to consume the entire catchment, and the temperature registered at different soil depth (0 cm, 1 cm and 3 cm). However, the temperature registered on the soil was not significant enough to lead to any changes on soils physical properties. At the depth of 3 cm the registered temperatures ranged from 6.5°C to 22.5°C, which is still within range of low to mild severity fire. The results of statistical analysis carried out (Annexes 2, 3, 4, and 5) of the variance analysis for parameters used in LISEM model for pre and post fire, and they clearly illustrate the significance of the occurred changes. The simulations for Valtorto, the designed storm rainfall, the infiltration decreased from pre fire 95% to 44% post fire, and the total discharge increased from 75m^3 to 1,785m^3 post fire. Furthermore, due to the changes occurred on the soil surface, the flow detachment increased from 2.8 ton in pre fire conditions to 600 ton post fire. These changes also triggered the total soil loss to jump from the 1.6 ton on pre fire condition to 385 ton post fire, over the entire catchment. Regarding the simulations carried out with the two field storms (moderate and high intensities) showed basically the same trend as the design rainfall.

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1. Introduction

1.1. Background

Since the early years of its existence, up until the present day, mankind has lived and coexisted with a variety of natural hazards and disasters, such as volcanic eruptions, cyclones, earthquakes, flooding, and drought, amongst other, which, not only makes him cohabit with them, but also lead him to find ways of attenuating their effects to its minimum. However, the efforts made towards a sustainable outcome to, at least, predict and avoid some of its damages, are far from being the desirable, and as it has been stated before, every year natural and manmade disasters are accruing in various parts of the earth (Jat, 2008), showing the human vulnerability to their effects.

Meanwhile, forest fire figures as one of the most devastating kind of natural hazards, and mankind has yet to find a sustainable technique to prevent it, for each year millions of hectares are destroyed across the world. According to Chandra (Chandra, 2005) climatic, phenology variations and topography, apart from local factors are some of the main causes of frequent occurrence of wild forest fires. Moreover, forest fire does not only destroy the trees, or other types of vegetation. It destroys, a lot more than just the vegetation. In fact it affects the soil physical, and hydrological properties, which may contribute to affect productivity (Rab, 1996) through increase of soil erosion.

Because shrubland soils are often shallow with low water holding capacities, and are on slopes prone to erosion, disturbances such as fire can adversely affect their physical properties and hydrologic response. The nature of post-fire hydrologic response and subsequent erosion is, in part, dependent on changes in soil physical properties and the depth and spatial variability of the soil water repellency (Hubbert et al., 2006). Fires create hydrophobic layers when through condensation of vaporized organic matter on the soil surface or at a certain depth in the soil. Surface runoff and sediment transport changes according to the depth of the hydrophobic or water repellent layer. The shallower the depth of water repellent layer the higher the surface runoff and sediment transport downhill (Gabet, 2003). Then, runoff and the soil erosion emerge as consequence of the damages caused by forest fires, due to the organic matter consumption, the reduction of soil moistures and infiltration, combined with local climatic variants (temperature, relative humidity, etc.) and other local factors such as the topography (gradient, length, and exposition), texture and water holding capacity of the soil.

Either forest or induced fire, in this case can be appointed as the initial factor to trigger and accelerate the runoff and soil erosion processes. However, the scientific community has always been in search of detailed understandings of such process, and has used every tool and technique within its reach, to cope with this subject.

With the mind set on achieving its goal, many different models have been developed to better understand the process. Amongst the models built, LISEM (**Li**mburg **S**oil **E**rosion **M**odeling) is a physically-based hydrological and soil erosion model for basin-scale water and sediment management (De Roo and Offermans, 1995). Therefore, and it will be used to predict the effects of the forest fire on the study area.

1.2. Significance of study

On average, forest fires, consume yearly more than 100,000 hectares of Portuguese forests causing an important impact on both environment and economy (Freire et al., 2002). The Mediterranean climatic characteristics are the self incentive to the occurrence of forest fires – the summers present, normally, high temperatures, the precipitation is low, the evaporation is high and the vegetation due to the summer drought are easily inflammable. Thus, besides being a worldwide concern, forest fire, for its effects on the environment and the economy of the countries, has constituted one of the prime threaten in this region of the world (Begni and Moreno, 2002).

Runoff and consequent soil erosion have been a constraint for many years, and have deserved special attention to the scientific community around the world, once there are innumerous studies on the subject. Furthermore, many concrete results have been found, but there is still an array of questions waiting to be answered.

As stated by Inbar et al. (1998), runoff and related erosion after fire have been little studied in these [Mediterranean] landscape–ecosystem types, and the increase of surface erosion, caused by changes in geomorphic processes, can cause the loss of a high percentage of the soil and affect, in an irreversible way, the complex interaction between soil, hydrology, climate, vegetation and landform development. Meanwhile, during the Barcelona meeting about "Fire Effects on Soil Properties" in 2007 one of the results obtained was that the scientific community *"should contribute with better information on the intrinsic characteristics of fire, vegetation behavior, alterations of soil properties and hydrological modifications, fire propagation patterns, relation to climatic conditions and relation to geomorphologic processes"*, so that it should be able *"to model and predict fire behavior and, consequently, will improve our capacity to successfully manage the impacts of forest fires"*. Furthermore, Stoof (2008) reaffirmed that *"fire-induced changes in soil water retention characteristics have received little attention so far, despite their large influence on soil water movement in unsaturated soils and their importance in process-based hydrologic and erosion models"*.

Through the logic of the development of this subject throughout the years, we can only presume that, of all the studies carried out so far, there are still details about this same subject that should be understood, so that we could obtain adequate scientific answers for the definitive resolution of the problem. Thus, when elaborating a study, on runoff and soil erosion modeling after forest fire, we are contributing decisively for the progress towards the resolution of the problem.

The praised objective of fire induced effects on runoff and soil erosion modeling using LISEM, certainly provides results that enlighten the scientific community for future researches, as well as assist the local, regional, or national decision makers decide the measures to be taken in order to avoid forthcoming damages.

The questions formulated for this thesis, shall fill some gaps left by previous studies. LISEM, is a very versatile software, which has not been widely used for modeling runoff and soil erosion after forest fire, and its capacity on providing a better outcome. Through the simulation of the model, using the various parameters of the burned and unburned catchment, LISEM shall provide an in depth information about water yield trend and sediment detachment, transportation and sedimentation, using different scenarios.

1.3. Research objectives, questions, hypothesis

1.3.1. Research Questions

The questions formulated, for the research are the following:

- After a forest fire, are there significant changes in the soil water infiltration rate, soil water retention, soil hydraulic conductivity and soil erodibility, and can these soil property changes be quantified or measured?
- Can fire incidence on soils be represented (parameterized) in the LISEM model and can the model be used to simulate the effect of induced forest fire on catchment runoff and soil erosion?

1.3.2. Research Objectives

The ultimate goal of the research, is to build up LISEM based models for runoff and soil erosion on the study site to evaluate the changes that occur after a fire:

- To make an assessment of changes in soil properties after the vegetation is removed by fire;
- To estimate the effects of fire on runoff and soil erosion in a small catchment using the physical-based model LISEM;

1.3.3. Research Hypothesis

The formulated questions to be answered on the proposed research paper suggests the following hypothesis

- Soil water infiltration rate, and soil water retention, are influenced by fire incidence on the soil surface;
- Forest/induced fire have therefore a significant impact on soil hydrology like runoff generation and soil erosion (rainfall soil detachment & transport);

- the quantification and estimation of these effects can be done by simulation using a physical catchment runoff and erosion model LISEM;

1.4. Scope of study

This research is intended to strengthen our knowledge and provide further information about the changes that might occur, after induced fire, on some soil physical properties and whether or not they can be quantified or measured. Furthermore, how can we represent (parameterize) such occurrence through use of a physically based model – LISEM, as well as simulate the effects of surface runoff and sediment erosion on the catchment.

Several studies have been undertaken, and are available on literatures, on the effects of temperature on soil properties changes, it is known that the severity of the fire and the duration have important roles (DeBano, 2000). Meanwhile, it is also known that their roles are dependant of other factors such as the existence and the quantity of dead and live biomass (combustion), air temperature, humidity, wind and topography of the site (Certini, 2005).

Great portion of this document is based upon field studies undertaken in a Portuguese shrubland located in the Center Region of the country, where in the last few years, forest (wild) fires have been a common phenomena (Ferreira et al., 2008). Thus, an evaluation of the pre-fire soil physical properties was made, in order to allow us to make a comparison with the evaluation of post fire. Such comparison should enlighten us to find changes occurred, and through proper analysis verify which parameter has more impact.

1.5. Framework of study (DESIRE Project)

This research, concerning the effects of induced fire on runoff and consequent soil erosion, is inserted within one of the objectives of project DESIRE, which is the establishment of promising alternatives of land use and management. The project expects to achieve this objective, based upon a strict collaboration between researchers and the local communities, to ensure viable techniques of soil and water conservation, as well as a solid scientific basis for its effectiveness at the large scale (Elsen, 2007).

This project funded by European Union (EU), counts with the participation of 28 scientific institutions/partners from across the world (Africa, Asia, Australia, Europe, North, and South America), and 18 (eighteen) study sites (or hotspots). Moreover, most of the institutions/partners are located in countries within boundaries of tropics parallel (Cancer and Capricorn), and they are all affected by one or more desertification related problems (Joost, 2007). We may recall that desertification phenomenon, affects a population of more than 250 million people worldwide. Due to the diversity of ecosystems and land use type and management, along with their background and socio-economic differences DESIRE project will be provided with a broad perspective to apply conservation and rehabilitation techniques, as well as finding new and innovative techniques (Joost, 2007).

Portugal is one of the countries represented by two strategic partners in the project - Escola Superior Agrária de Coimbra (ESAC)[1], and Universidade de Aveiro[2] - whose main subject of the study is the effect of the forest fires on desertification. However, given the importance of this study, ESAC in partnership with three other partners of the project – Alterra (Netherlands), Swansea University (Wales, UK), and Cornell University (the USA) – joined forces to pursue research on the effect of fire at multiple scales using field, lab and modeling techniques.

It is within such framework that the site at Valtorto was selected as an experimental area. The works at this site started in the year of 2007, with data collection and monitoring, and it scheduled to end in the year of 2011.

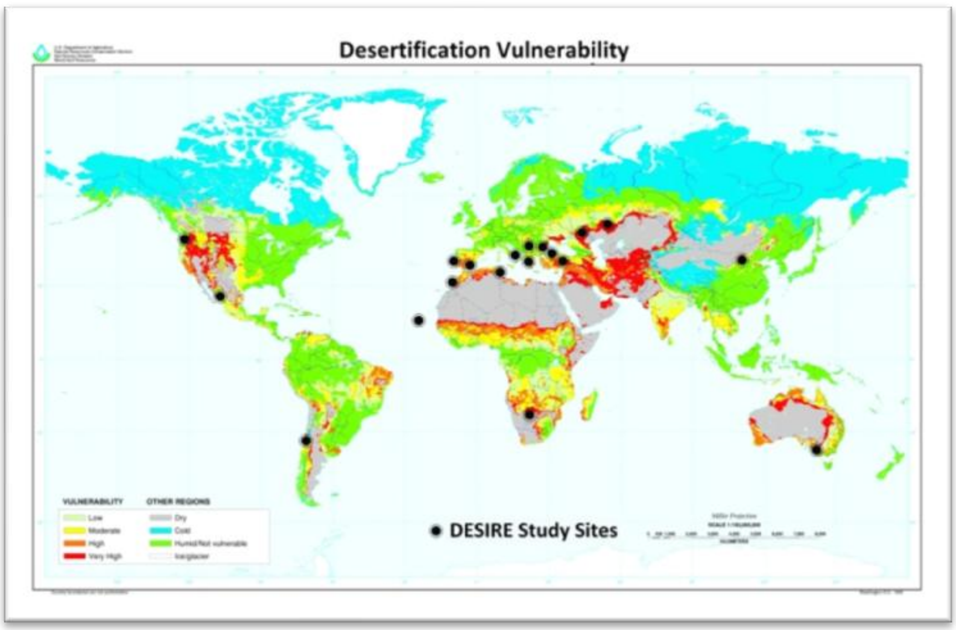


Figure 1.1 – Areas vulnerable to desertification, and location of DESIRE study sites

1.6. Thesis outline

The whole thesis consists of 6 chapters portraying the following subjects:

Chapter One provides a background o the problem, how important the subject is to science and to mankind. Also it explains the framework of this research, the objectives, research questions, and the hypothesis.

Chapter Two gives an overview of the literatures reviewed to undertake the study. This chapter is of extreme importance, for it provides a background of the studies previously done, provide us with some theories, methodologies, and the progresses done over the years.

[1] Agrarian Superior School of Coimbra (ESAC)

[2] University of Aveiro

Chapter Three presents the study site, the research strategies used during the work, the methodologies used, and the materials/equipment used during the research.

Chapter Four reports the comparative statistical analysis of pre & post fire soil and vegetation data

Chapter Five portraits the LISEM modeling of induced fire effects

Chapter Six presents some recommendation and conclusion of the study

2. Literature review

2.1. Forest fire effects on soils

Since the early years, the subject of the effect of the forest fires, either induced or wild, has been studied with certain concern, in order to allow us a deeper scientific knowledge of the behavior of the factors involved, and assist us on taking preventive measures in the sense of lessening the damages they cause on the environment. In spite of the effects that fire has on the entire ecosystem (fauna, flora, atmosphere, and soil properties), most of the early researches have not focused on the effects that occur on soil physical properties such as aggregate stability, pore size distribution, and water repellency, for instance (Doerr and Cerdà 2005), and the consequences of the changes on the runoff and soil erosion. The knowledge about the behavior of these individual parameters, and how they are linked to each other, is of key importance for a solid comprehension of the fire effects on the runoff and soil erosion..

Forest fires, or wildfires, are caused by natural factors such as lightning strike in a dry season, and seldom in a very dry and hot climate when some source of fuel (i.e. litter) is available. Furthermore, many wildfires are caused by unknown reasons, however, the involuntary causes (negligence or accidents) are the most frequent in most countries (Alexandrian, 1999). Prescribed fire, contrarily to the wildfire, is applied in a controlled fashion *"to forest fuels on a specific land area under selected weather conditions to accomplish predetermined, well-defined management objectives"* according to Wade (1990).

The changes caused by fire has direct effects on the hydrologic regime of the sites, which consequently changes the movement of soils and sediments on the catchment (Swanson, 1978). In the early years, researchers had to rely almost entirely in personal communications and popular accounts (Swanson, 1978), and they soon realized that two factors perform key role; the intensity and duration of the fire are perform a key role on the changes on the soil properties reflecting directly on the runoff and erosion. In a research carried out by Beadle (1940), he was able to compare the soil heat under a 2 hour and an 8 hour fire at various soil depth, and clearly the soil temperature difference between them at various depths, was obvious to dissipate any doubts concerning this issue.

Table 2.1 – Maximal Soil Temperature (Beadle, 1940)

	Temperature [°C]	
Depth [in]	**Fire burning for 2 hr.**	**Fire burning for 8 hr.**
1	175 – 180	> 250
3	95 – 105	213 – 233
6	59 – 67	81 – 90
9	40 T	57 – 59

Temperature [°C]		
Depth [in]	**Fire burning for 2 hr.**	**Fire burning for 8 hr.**
12	22 T	43 – 50
15	13 T	–

Having into consideration the values of the table above the first step towards a great progress concerning the fire effects on soils physical properties was accomplished, once known that the intensity of the heat determines the level of severity of the damages caused. Severity of fire is highly dependent on the interactions between duration and intensity, as well as the characteristics of the biomass, soil, terrain and local climate (Doerr et al., 2006; Shakesby and Doerr, 2006).

Notwithstanding the source, forest fires in general, either wildfire or caused by the man, modify the cycle of nutrients, and the physical characteristics, the moisture content, the vegetation cover, and the temperature of the soil. Naturally, also causing many other related impacts to the ecosystem (Thornes, 1995). These impacts can be classified as insignificant, when the effects are not very serious, presenting little or no repercussion at the ecosystem level; or on the other hand, they can have effects that range from moderate the very severe, with serious damages to the ecosystem. Regarding the latter effects, as a reminder, the intensity and the duration of the fire, are the two factors that play a very important role. In addition to these two factors considered important, the frequency of the fire, soil type and moisture, vegetation cover and amount, topography, season of burning, and pre- and post-fire weather conditions (Clark, 2001), can also be crucial.

Forest fires are normally classified into three main types, namely ground (affecting the organic layer of decaying leaves), surface (affecting mainly grass and shrub vegetation cover), and canopy (affecting higher leaves and branches of trees) (Shakesby and Doerr, 2006), however, severity is generally rated vertically from low to extreme in accordance to spatial energy and height of fire, and the level of damages (see Table 2.2). Therefore, such rating does not provide full reliability to some changes that occur to soil regarding their impacts (Inbar et al., 1998; Swanson, 1978).

Table 2.2 – Fire severity and estimated intensity rating for eucalypt-dominated sclerophyll vegetation communities in south–eastern Australia (modified from Chafer et al., 2004) (Doerr et al., 2006)

Severity rating	Fire Intensity[3] [kW m^{-1}]	Max. Flame height [m]	Typical severity characteristics
Low	<500	1.5	Only ground fuel and shrubs < 2 m burnt
Moderate	501-3000	5.0	All ground fuel and shrub vegetation < 4 m consumed by fire
High	3001-7000	10.0	All ground and shrub vegetation consumed by

[3] The fire intensity index, as defined by Byram (1959)

Severity rating	Fire Intensity[3] [kW m^{-1}]	Max. Flame height [m]	Typical severity characteristics
			fire and lower tree canopy <10 m scorched
Very High	7000-70000	10-30	All green vegetation including tree canopy to 30 m, and woody vegetation < 5 mm diameter consumed by fire
Extreme	70001-100000+	20-40	All green and woody vegetation < 10 mm diameter consumed by fire

Besides the vegetation and the litter, fire can induce significant changes of soil surfaces, leading sometimes, to a direct impact on the geomorphology, or may be the cause for the intensification of hydrological and geomorphological processes during the post fire period, until the rehabilitation of the initial environmental conditions (Shakesby and Doerr, 2006).

Since the end of the XIX century, the effects of fire on the parent materials have been reported, with a cracking/decaying effect on the rocks (Blackwelder, 1927), due to the heat changes that occur, provoking the phenomena of expansion and contraction. Fire, as a key agent of rock degradation due to the abrupt and sudden heat changes was, at the time, presented in a descriptive form, rather than being quantified (Allison and Bristow, 1999; Goudie et al., 1992), and only much later, through laboratory experiments, it was possible to reveal the behavior of different lithologic formation when exposed to fire. The weathering effects of fire on the rocks, autonomously of styles or rates, greatly depends on its physical properties, dimension, and water content (Shakesby and Doerr, 2006), and the most common types are spalling (detachment of rock flakes), vertical fracturing (affecting the entire rock of usually smaller than 30 cm of diameter), and irregular linear and curvilinear fractures (Goudie et al., 1992; Shakesby and Doerr, 2006).

As described above, we may observe that fire is an important factor on the pedogenic process, in which each soil type with deriving from different sources of parent material, and hence with its own characteristics. However, many researchers have carried out studies, and enhanced the physical properties of soils that intensely change the rate of soil erosion after the fire (see Table 2.3 below).

Table 2.3 – Example of scientific literature evidence on soil properties affected by fire

AUTHORS	DATE	SOIL PROPERTIES										
		Organic Matter	Soil Structure / Texture	pH	Water Repellency	Infiltration	Soil Moisture	Water Retention Capacity	Bulk Density	Hydraulic Conductivity	Wetting front	Aggregate Stability
(Swanson)	1978	•	•		•			•			•	•
(DeBano et al.)	1979	•	•	•	•	•	•		•			•

AUTHORS	DATE	SOIL PROPERTIES										
		Organic Matter	Soil Structure / Texture	pH	Water Repellency	Infiltration	Soil Moisture	Water Retention Capacity	Bulk Density	Hydraulic Conductivity	Wetting front	Aggregate Stability
(Neary et al.)	1999	•	•		•	•	•	•	•	•		
(Cammeraat and Imeson)	1999	•	•		•	•	•					
(DeBano)	2000	•	•		•	•	•					
(Shakesby et al.)	2000	•	•		•	•	•					•
(Ferreira et al.)	2005	•	•		•		•	•		•	•	
(MacDonald and Huffman)	2004		•		•	•	•					
(Certini)	2005	•	•	•	•				•			
(González-Pelayo et al.)	2006	•	•	•	•		•	•				
(Ekjnci)	2006	•	•	•			•	•	•	•		
(Shakesby and Doerr)	2006	•	•		•	•	•	•			•	
(Tessler et al.).	2008	•	•		•	•	•					

Through the table 2.3, it is noticeable that recently many studies have been conducted concerning soils physical parameters that undergo through post fire change. However, they are never researched in a desultory way, since the change of each physical parameter is normally linked to the other. The majority of the soils (clay, sand, and silt) are aggregated in structural units according to the presence of organic matter and clay particles, although there are types of soils that do not possess such structure and maintain loose. The organic matter primarily accounts for the topsoil (A horizon) soil aggregation, while the clay particles operates at a deeper soil layer (Neary et al., 1999), notwithstanding the fact that the soil properties changes depends on the soil density (type) and the temperature of the fire on the soil (Kim et al., 1999), and according to Certini (2005) and Tessler (2008) soil properties can experience short-term, long-term, or permanent fire-induced changes. If conceivably the temperature of the soil reaches 400° C, the aggregate stability and the soil the structures are reduced due to loss of hydroxides (OH) from clay (DeBano, 1998; Neary, 1999), with direct influence on soil water infiltration and posterior increase in surface runoff and soil erosion.

2.2. Runoff Models

The water balance process, and all processes connected to water movement, such as the soils water erosion, requires detailed studies of watersheds, as hydrological unit, and its characteristics being one of the important factors for the quantity and quality of water it produces (Whitehead, 1993). The area of catchment is closely linked to the quantity of water that can be generated, the slope or topography of the land is linked to the rate this water is generated, and also determine the form and the quantity the soil is eroded. Concomitantly, yet a set of physical processes, and the behavior of other factors still need to be understood in details, so that we are able to make an insightful research and obtain answers to many questions of scientific nature in order to solve problems.

Due to the complexity of this process, the hydrological models are efficient tools that allow the researchers to simulate the behavior of the catchment through the equationalization of these processes, despite the impossibility of making a mathematical translation of all the involving factors (Rennó, 2000).

A model is a simplified demonstration of the reality, based upon the understanding of the natural processes. In recent years, models have been frequently used in the environmental sciences field, as a support to help us understand the impact of the environmental changes, and provide us clues to forecast future changes.

The runoff models can be viewed as stochastic or deterministic, in which the first deal very much with the probability of hydrological distribution of the parameters, whereas that the other makes the simulation of the physical processes in catchment, culminating in the excess water runoff (Ward and Robinson, 1990)

Presently many models, with different characteristics, are available. Among the available physically-based models we selected LISEM (De Roo and Offermans, 1995) to carry out our research.

3. Data and methods

3.1. Desire research project: Valtorto experimental catchment

3.1.1. Description of the Study Area

The study site at Valtorto (or Vale Torto), is a 10 ha experimental patch, selected within DESIRE project scope to carry out the fire-induced effects study on soil properties, and consequent hydrological and soil erosion. It is located in the Northern portion of Serra de Lousã Watershed at approximately 55 Km west of Coimbra, at the Latitude 40° 06' 21" 0N, Longitude 8° 07' 05" 60W, and at the Altitude ranging from approximately 600 to 750 meters, within boundaries of the Municipality of Góis, District of Coimbra. Among others activities that characterize the District of Coimbra, the industry of wine and agriculture have a strong expression, due to the presence of Rio Mondego (the only river with the total extension inside the country) and of one of its main tributaries, the Rio Ceira. Valtorto catchment, has previously staged 2 (two) fire events; in 1990 it was struck by a wildfire, and in 1996 a prescribed fire

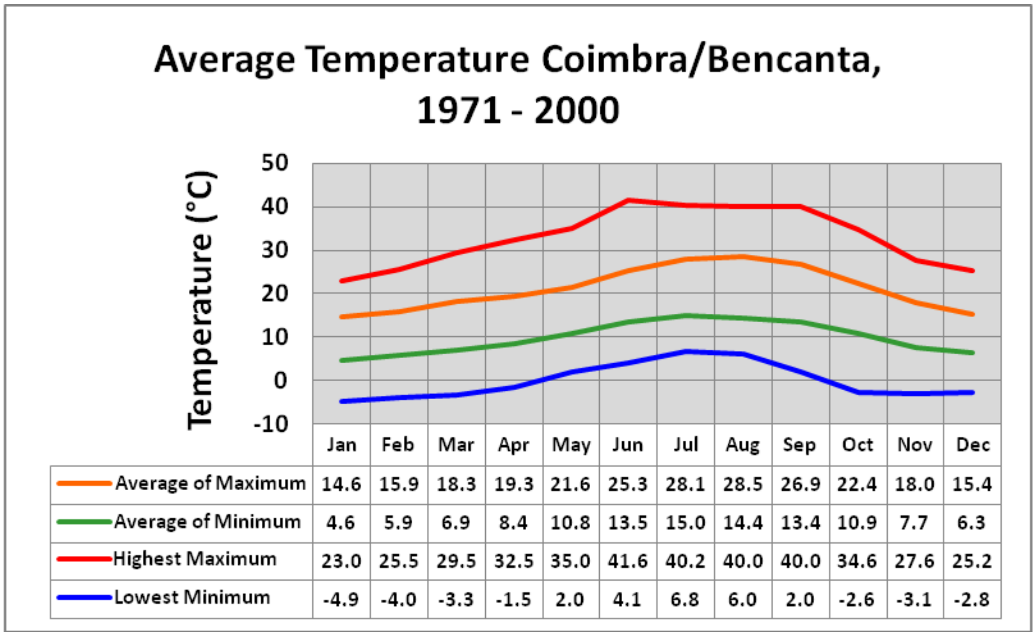
Figure 3.1 – Localization of Valtorto (Vale Torto) study site catchment[4]

3.1.2. Climate

3.1.2.1. ***Temperature***

Coimbra has a transition climate between Mediterranean and Maritime, the yearly temperature of the research study site ranges from the minimum registered low of -5° C to a maximum registered high of 42° C, respectively during the months of January and July. The annual mean temperature in Coimbra is approximately 22° C, which is still above the country's mean annual temperature which about 15° C.

[4] Source of images: *Sources: (www.google.earth.com; http://images.google.com/imgres?imgurl=http://www.portugalweb.net/mp/MapaDistrito/coimbra.gif&imgrefurl=http://www.portugalweb.net/mp/distritocoimbra.asp&usg=__N8UVGKejkQUJsr2YSY3KIVUM2pU=&h=310&w=412&sz=8&hl=en&start=7&sig2=uK68PYsKYT5WgI0RZKr)*



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average of Maximum	14.6	15.9	18.3	19.3	21.6	25.3	28.1	28.5	26.9	22.4	18.0	15.4
Average of Minimum	4.6	5.9	6.9	8.4	10.8	13.5	15.0	14.4	13.4	10.9	7.7	6.3
Highest Maximum	23.0	25.5	29.5	32.5	35.0	41.6	40.2	40.0	40.0	34.6	27.6	25.2
Lowest Minimum	-4.9	-4.0	-3.3	-1.5	2.0	4.1	6.8	6.0	2.0	-2.6	-3.1	-2.8

Figure 3.2 – Average Annual Temperature at Coimbra/Bencanta, 1971 - 2000[5]

3.1.2.2. *Precipitation/Humidity*

The wettest months go from January through February, in which the rainfall may reach the 200mm, and the driest months go from July through August in which the rainfall does not exceed 20mm, but the annual mean rainfall is approximately 1000mm.

The humidity throughout the have a slight oscillation between 60 to 80%, and the mean annual is approximately 75%.

[5] Source: http://www.meteo.pt/pt/oclima/normais/index.html?page=normais_cbr.xml

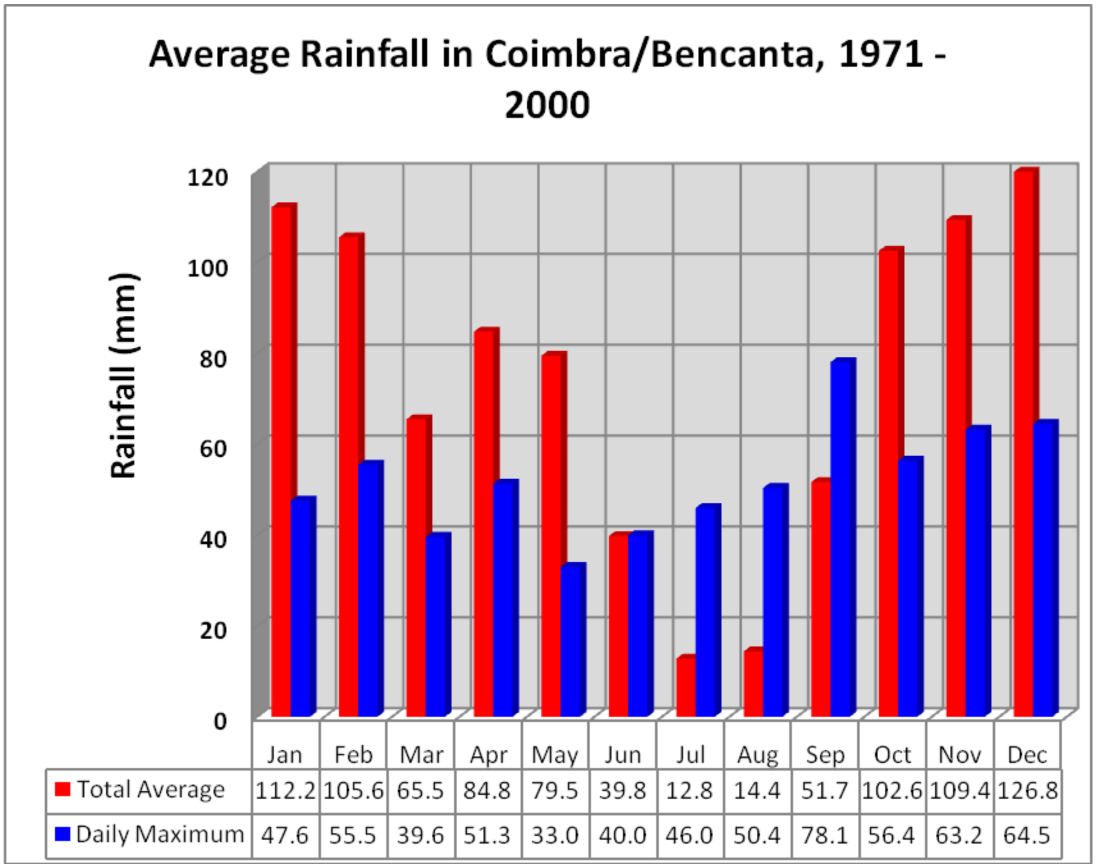


Figure 3.3 – Average Rainfall at Coimbra/Bencanta, 1971 - 2000[6]

3.1.3. Hydrology

The Center North region of the Portugal is the dry part of the country the dry season goes from May to September, and the wet season goes from October to April.

3.1.4. Geology/Soil

The geological substract is constituted by Schist Complex, and the soils are generally characterized as shallow, for the depth hardly exceeds 30cm, rocky, and with partial outcrops, classified as Litossols. Most of the catchment is covered with small schist stone layer at the surface. The depth of the soil on the upper part of the catchment is very shallow (depth hardly exceeding 10cm), which contrasts with the lower part of the catchment where it is much deeper (reaching beyond 50cm), justifying the existence of much denser and much more developed vegetation community.

[6] Source: http://www.meteo.pt/pt/oclima/normais/index.html?page=normais_cbr.xml

3.1.5. Land Use/Vegetation

The study area was then a shrubland/grassland without any proper management. Before the experimental, the catchment presented an homogeneous shrub land, predominantly *Calluna vulgaris, Erica cinerea, Erica umbellata* and *Pterospartum tridentatum,* with some grass and moss (Drooger, 2009). However, after the prescribed fire burn the soil was totally bare, but after 6 months from the experimental burning, it presented some sprouted vegetation.

3.2. Research Procedure

The achievement of the objectives of this research, was made possible through a schematic working structure put in place. This chapter was divided into three distinct phases: pre-fieldwork, fieldwork, and post-fieldwork, carefully illustrated on Figure 3.4.

3.2.1. Pre field work

Throughout this phase, the efforts were primarily directed to the literature reviews, about the proposed research theme, and become acquainted with the different new technologies that we could learn to apply. Moreover, during this phase of the research the thesis objectives and questions, were meticulously formulated, concomitantly with the fieldwork plan and methodologies to be followed. We ought to enhance that the methodologies of field data collections and measurements, was prepared accordingly to the previously established plan, whereas the experimental site has been monitored since the beginning of the project, in 2007. All the existing field data, regarding the period prior to the experimental fire, was as well obtained, so that previous assessment could be undertaken.

The scientific literatures on the effects of fire on soil physical properties, and modeling was also thoroughly reviewed, which partly permitted us to answer the first research question.

3.2.2. Fieldwork

The approach for this stage of the research started with the preparation of the necessary equipment and materials that would allow us to collect and measure all data required, for further analysis and consequent accomplishment of expected results. It took place in October 2009, during 10 days in Valtorto, which was almost totally dedicated to data collection and measurements. During this time frame, all possible data and information to make this study successful was thoroughly collected. Bellow, there is a list of the information and data collected:

- Soil moisture data collection (download registered data from data loggers to a laptop)
- Rainfall data collection (download registered data from data loggers to a laptop)
- Discharge data collection (download registered data from data loggers to a laptop)[7];

[7] Data also collected at the Espinho Catchment (testimony)

- Vegetation Height
- Soil Cover Percentage
- Stone fraction Percentage
- Soil Cohesion measurements
- Soil Sampling (aggregate stability)
- Random Roughness measurement

3.2.3. Post Fieldwork

As a follow-up of the previous stages, according to the program, complimentary works were carried out with the laboratory analysis[8] of the collected soil samples, to determine the values of the required parameters to run LISEM model. Concomitantly, some time was also be allocated on organizing and processing the attribute data of the study site, as well as selecting additional supporting literatures.

Regarding the physical modeling, a variety of different scenarios were experimented using different values for the parameters that affects runoff and soil erosion to produce different results, and allow us to build up different scenarios, which will later be used to draw some conclusions, and make the respective recommendations.

[8] Laboratory analysis was carried out at Wageningen University

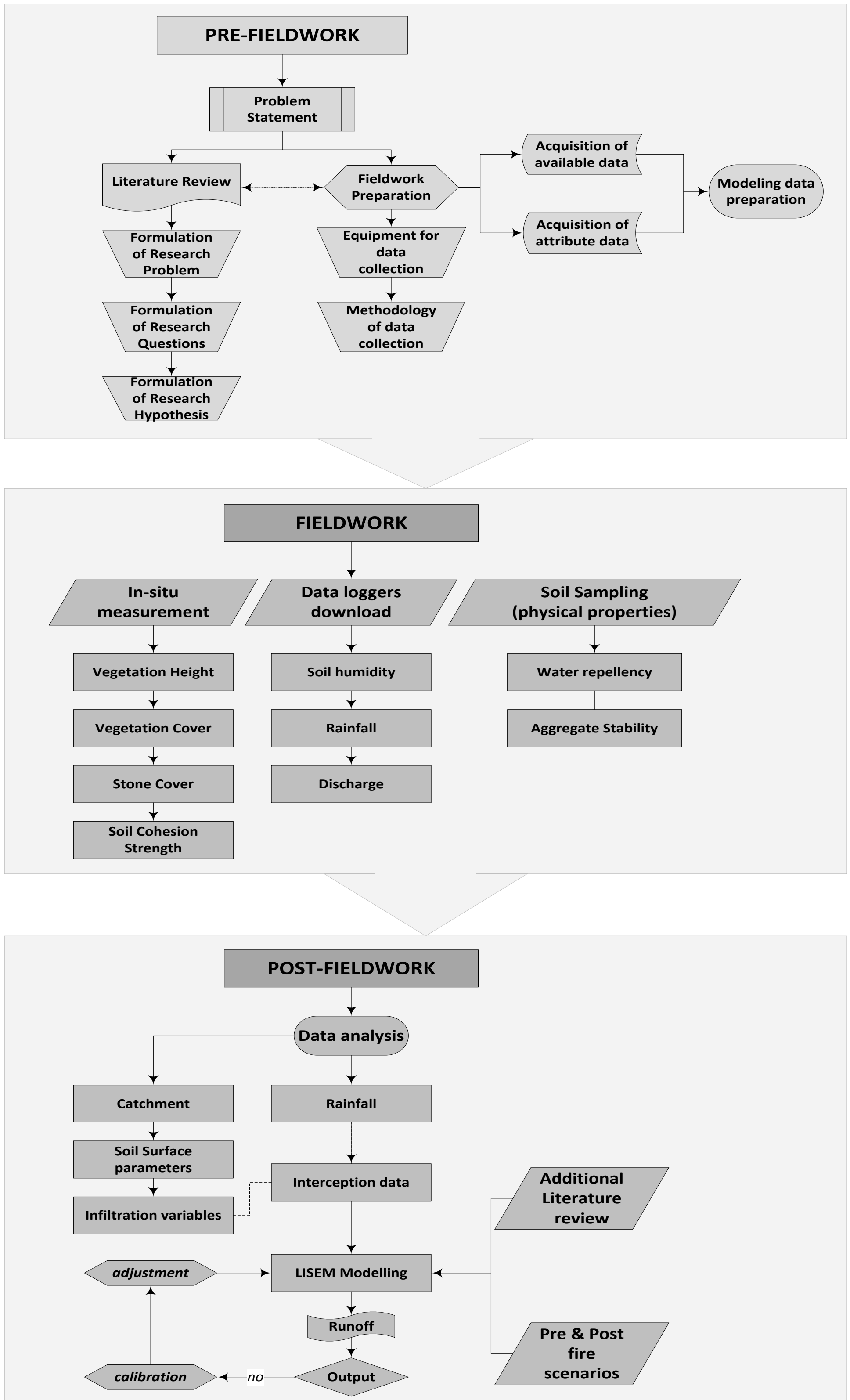


Figure 3.4 – Research Flowchart

3.3. Pre-fire observations and datasets (LISEM parametrization maps)

Usually, LISEM input maps are derived from 4 (four) base maps: Digital Elevation Map (DEM), Land Use Map, Soil Type, and Impermeable Area Maps, which are subsequently structured into different categories (Beskow et al., 2009; Jetten, 2002). However, in this particular research, except for the catchment maps, the required maps for vegetation, infiltration and soil surface were generated through use of data collected directly from field observations, by the research team lead Ir. Cathelijne Stoof.

3.3.1. Catchment Input Maps

The Digital Elevation Map (Figure 3.4) was derived by interpolation of contour lines, using ArcGIS software, and the 10 meter resolution gridcell was selected having into consideration the object of the study. Once derived it was used as a source for the generation of the 5 (five) maps that provide important information about the relief characteristics of the catchment. These maps were all derived through appropriate use of command scripts, which are run with PCRaster software.

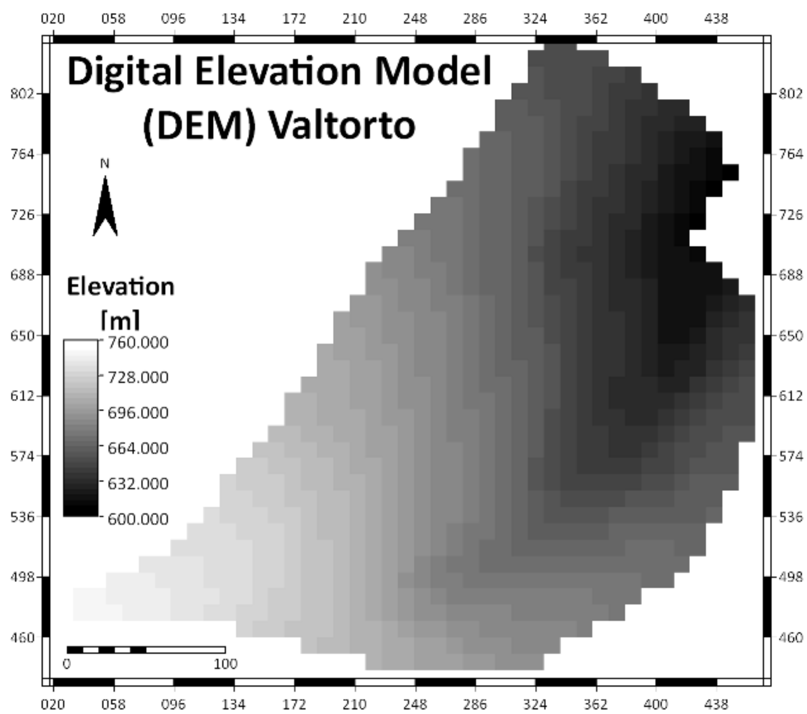


Figure 3.5 – LISEM model Digital Elevation Map of Valtorto

3.3.1.1. *Local Drain Direction*

This map determines the direction of the surface water flows in the catchment, and special attention must be taken to eliminate all the depressions, once the water should flow towards the outlet of the catchment (Figure 0.8, on Annex 11 below). Such procedure is taken into consideration while running the command script on PCRaster by using a high threshold value (Jetten, 2002):

```
pcrcalc ldd.map=lddcreate(dem.map,1e10,1e10,1e10,1e10)
```

3.3.1.2. *Area*

This map is of capital importance because all others will be verified against it for any missing values or differences of cell values.

3.3.1.3. *Slope Gradient*

This map (See Annex 11, Figure 0.9) retrieves the values of the gradient slope in the direction of the LDD map. It was generated through the command of script of DEM slope:

```
pcrcalc grad.map = slope (dem.map)
```

3.3.1.4. *Rain Gauges area*

This is the map that illustrates the number of rain gauges placed in the catchment. In our case, there are 4 (four) rain gauges placed within catchment boundaries, and they are delimited through a linkage made with the 4 classes of canopy heights: gauge 1 linked to canopy height from 0 to 40 cm, gauge 2 with canopy height from 41 to 80 cm, gauge 3 with canopy height from 81 to 120 cm, and gauge 4 with canopy height from 121 and higher. See illustration on Annex 11, Figure 0.10

3.3.2. Vegetation Maps

Only 3 (three) input maps are necessary to provide full information about vegetation status in the catchment. The values are a result of an exhaustive fieldwork, covering a considerable portion of the catchment so that the data could provide us an almost realistic overview of the actual vegetation status. The pre fire data was collected on the field by Ir. Cathelijne Stoof, who is the coordinator of the research related works on the catchment.

3.3.2.1. *Canopy Height*

This parameter was measured at random 205 (two hundred and five) locations within catchment boundary. The measurements were taken every 50 cm along a 2 meter transect, and then was averaged. Posteriorly, the canopy height was divided into 4 classes (0-40 cm, 41-80 cm, 81-120 cm, and 121 cm and higher. (See map shown on Figure 4.2, on page 31).

3.3.2.2. *Vegetation Cover Fraction*

The measurement of vegetation cover fraction was taken at 182 (one hundred and eighty two) randomly selected points in the catchment, using visual judgment. The location where they were taken, was georeferenced using a GPS (See map shown on Figure 4.4, on page 33).

3.3.2.3. *Leaf Area Index (LAI)*

The parameter is to calculated the parts of the gridcell that is vegetated, and together with the vegetation cover fraction they are extremely important to determine the amount of rainfall interception (Jong and Jetten, 2007). In this research, however, the rainfall interception and throughfall were measured on the field in 5 (five) locations in the catchment. The interception measuring devices were placed inside the catchment, according to classification of the vegetation height. Two sets of the improvised device, made of 5-liter plastic bottles, were placed on each measuring location (vegetation class); one underneath, and the other on top of the vegetation, and the readings were taken every 3-4 weeks. Then the interception calculations were done by comparing the difference in the volume of the water deposited in the bottles. Using such procedure, then the interception was directly subtracted from the rainfall, reason for which LAI map was produced with the value of 0 (zero).

According to the readings made on the interception measuring devices installed in the field, the values were much higher than expected, which could be explained by many reasons, including the measuring methodology used and the calibration of the device. The values of the field measured interception ranges from 16% to 70%, opposing the statement made by (Jong and Jetten, 2007) that the rainfall interception values ranges between 10% to 20% on an annual basis, and in function of the vegetation type cover, structure and potential evaporation. However, in this study, we decided to use the values measured on the field, certainly have significant effect on the results obtained.

3.3.3. Soil Surface Maps

3.3.3.1. ***Random Roughness***

The measurement of random roughness was taken in the field within a radius of 2 meters of each of the 42 sampling sites, using the pinmeter. This equipment, is consisted of 50 pins of equal length, placed vertically against a board (with the identification of the location), which will reproduce the shape of the ground - underneath, where it is placed, and then photographed (digital camera). (The cross board measurement was 56 cm, to which the width will be used on the image processing). Then, each photography was processed with a small software PMPPROJ – designed for the purpose. This software, when calibrated, read the tip of each pin, retrieving the results. The values retrieved were saved in format of **.txt* file and with the assistance of excel the standard deviation are calculated. (See Figure nr. 3.6)

Figure 3.6 – Pinmeter, showing the readings of the roughness of the soil (tip of the pins)

3.3.3.2. *Manning's n*

Roughness coefficient is a determining factor for the calculation of discharge. Meanwhile, due to the importance of the research outcome, the values of Manning's *n* were measured in the field, in detriment of simply making use of existent literature values. The decision was based upon Hessel's (2003b) assertion that the referred value, together with the values of hydraulic conductivity of the soils, are the most important calibration factors for LISEM model. However, maybe due to the soil's coverage condition of the catchment – grass, moss, shrubs – as well as different methodology of testing. The field measurements were undertaken before and right after the experimental fire by the field coordinator (see Table 0.5 and Table 0.6 on Annex 4)

3.3.3.3. *Stone Cover Fraction*

Stone cover fraction was taken at 189 (one hundred and eighty nine) randomly selected location in the catchment – using visual judgment criterion.

3.3.3.4. *Crust*

No crust formation was visible in the catchment, for the value of the map was considered to be 0 (zero).

3.3.3.5. *Roadwidth Map*

The catchment presents no (considerable impermeable) roads

3.3.4. Infiltration Maps

Although LISEM presents other alternatives of infiltration models, such as, among others, SWATRE, Morel and Seytoux, and Holtan, we opted to use Green and Ampt – 1 Layer model, due to availability of data. This model is based on the Darcy's equation to the wetted zone, assuming the existence of a distinct wetting front (Jetten, 2002). This is the simplified equation used in LISEM, in which *dI* must be a positive number greater then 0 (zero):

$$dI = \frac{1}{2}\left[-(2I - kdt) + \sqrt{(2I - kdt)^2 + 8kdt(\Omega + I)}\right]$$

where

I = rate of infiltration (m/s)

k = hydraulic conductivity in the wetted zone (m/s)

t = time (since the start of infiltration)

Ω = potential head parameter (m)

All field data as well as the laboratory tests required afterwards to produce the infiltration maps, were taken by the field research coordinator with assistance of some students that were working in field. This way, the following maps, are required to run this model of infiltration.

3.3.4.1. *Soil Water Tension at Wetting Front*

The water tension at the wetting front was calculated through averaging the literature values given for the catchment soil texture, once this parameter is directly dependent of the soil texture. The texture of the catchment soil lies between loam and sandy loam, whose water tension values at the wetting front are respectively 8.9 and 11.0 cm (Chow et al., 1988). Given the circumstances, it was taken the value of 9.95 cm, as the average depth, to produce the single value map of this physical parameter for the entire catchment.

3.3.4.2. *Saturated hydraulic conductivity*

The measurements of saturated hydraulic conductivity (K_{sat}) was taken on the field at 15 (fifteen) selected locations in the catchment, using the constant-head methods, on undisturbed soils.

3.3.4.3. *Saturated volumetric soil moisture content (Thetas) & Initial volumetric soil moisture content (Thetai)*

Both parameters were calculated from the bulk density and K_{sat} measurements (however, the post fire values used on the simulations were from literature).

3.3.4.4. *Soil depth*

Soil depth measurements was takes by probing the catchment with an auger over 256 selected locations. The augering took place at about every half meter along the 2 meters transects.

3.3.5. Erosion Deposition Maps

3.3.5.1. *D50 Soil texture value*

The test for D50 was carried out in the lab, through use of laser method, which provides a much accurate value of the median of the particle size of the soil, in micrometer (μm). The result of the test retrieved the D50 value of 284 μm.

3.3.5.2. *Cohesion*

The catchment has a good and homogeneous coverage of grass. This feature, by the fact that the vegetation roots keeps the cohesion of the soil, and consequently diminishes the detachment rate of the soil with the impact of the rainfall (Baets et al., 2008), is a very important component of the model. However, since the field values are not available, it was decided that we use literature values for similar type of soil texture and grass coverage. Baets, Torri al. (2008) presents a table with the value of 7.2 kPa for soil similar to the research catchment, value which was used on the model.

3.3.5.3. *Aggregate stability*

Soil samples were taken from the 42 main sampling sites in the catchment, for testing the soil aggregate stability using the water droplet test technique in the lab, mostly known as Lowe's test, which is determined by counting the number of water drops necessary to reduce the aggregates by 50% (Gumiere et al., 2009). However, on the LISEM model, splash detachment (Ds) is simulated as a function of aggregate stability, rainfall kinetic energy and the depth of the surface layer (Jetten, 2002), from which the following general equation had been derived:

$$D_s = \left[{2.82}/{A_s} \times K_e \times exp^{(-1.448h)} + 2.96 \right] \times P \times A$$

where = $\boldsymbol{D_s}$ is the splash detachment (g/s)

$\boldsymbol{A_s}$ is aggregate stability (median number of water drops – counts)

$\boldsymbol{K_e}$ is the kinetic energy of the rainfall or throughfall (J/m²)

h is the depth of surface water layer (mm)

P is the amount of rainfall or throughfall under vegetation in time steps (mm)

A is the surface of the splash event (m²)

The calibration of the software model LISEM was done using the above formula to determine the splash detachment, and the parameter aggregate stability value should be median of water droplet counts. However, due to some constraints to carry out this test on the lab, reliable literature source was used for the acquisition of this value. The results shown by Varela, Benito et al. (2009) the aggregates of loamy soils with similar properties similar to the catchment of Valtorto, using the values attributes of LISEM, should be approximately 140, in a scale that 200 is the highest value.

3.4. Fire event (short description)

The experimental fire occurred on February 20th 2009, after some failed attempts, due to weather conditions. If on one hand, the wind was too strong, on the other the humidity was too low to ignite and control the fire, in addition to the rain that also conditioned the event to be postponed.

Given the situation the crew to undertake the experimental fire, was forced to wait for the proper condition, so that the professional involved could get the maximum or total control of the fire. During the experimental fire, three teams of firefighters, whose main task was to ignite and monitor the event, assisted the research team. Many sensors and instruments were installed in the catchment, to take measurements of parameters affected by the fire. The data of temperatures – of the air and the soil – were registered, during the event. According to instructions, the catchment was burned from both sides, and the intensity was low. The registered temperature of the flames was about 550°C and the height of reached the 2 meters. Meanwhile the climax was reached when both fronts of fires crossed. At this point the temperature went up to 900°C and the height surpassed the 10 meter mark (___, 2009).

The fire took approximately 3 hours to consume the entire catchment. However, on the North slope, the soil temperature registered at different depth showed little change in comparison with the South slope.

The temperature registered at different soil depth (0 cm, 1 cm and 3 cm), with type K thermocouples (50 mm long, 1.5 mm in diameter) connected to data loggers (EL-USB-TC, Lascar electronics) installed at 12 cm depth. However, the temperature registered on the soil was not significant enough to lead to any changes on soils physical properties. At the depth of 3 cm the registered temperatures ranged from 6.5°C to 22.5°C, which is still within range of low to mild severity fire (Drooger, 2009). Many species can still survive such temperature.

3.5. Post-fire observations and field data collection

Post fire field observations e data collection was followed in the same pattern of the monitoring carried out before the fire event. However, additional data, such as the temperature (intensities) of the fire (in the surface and soil) was also collected. The reading of the soil temperatures, were taken from loggers, previously placed in various places of the catchment.

3.6. Statistical analysis techniques

The data and some results of the simulations for pre and post experimental fire, simulated with LISEM, were submitted to statistical analysis in order to verify the significance or not of the potentially occurred changes on the physical parameters of the soil. The statistical analysis used was ANOVA (**AN**alysis **O**f **VA**riance) t-Test: Two-Sample Assuming Unequal Variances, which allows us to compare and evaluate the parameters. Hence we were able to compare the values retrieved from the LISEM simulations with the three different rainfalls on pre and post fire conditions. This analysis was carried out with the assistance of the software Excel 2007.

3.7. Lisem erosion model

LISEM is a physically based model, completely incorporated in a raster Geographical Information System (GIS), using PCRaster language and environment (Mol and Linge, 2009). The incorporation into GIS makes the model adequate for simulation of event based storms in small catchments, with an area not greater than 100km² (De Roo and Jetten, 1999). The diverse processes incorporated in the model are rainfall, interception, surface storage in micro depressions, infiltration, vertical movement of water in the soil, overland flow, channel flow, detachment by rainfall and through fall, detachment by overland flow, and transport capacity of the flow. Also, small paved roads (smaller than the pixel size), and surface sealing on the hydrological and soil processes are taken into account (Eurochina, 1998).

PCRaster database uses four types of data, in which the data from 2D areas are represented by raster maps, and they have a special format that enables simple and structured manipulation of spatial data in the package. It is the most important data in the database. The remaining three types of data, which are the tables, time series and point data column files (de Jong, 2008). The first step is the creation of base map the exact study area, extent, and cell size.

Lisem soil erosion model is structured into hydrological and erosion processes, as illustrated bellow.

3.8. Calibration

Even though, Hessel, Jetten et al. (2003b) adverted that in theory physically based models should not necessarily be calibrated, it is always secure to undergo such procedure, once we know that the real world events are different. However, the inexistence of the outlet discharge data from the field , hampered procedure to be put in effect. Meanwhile the analysis of the value of the fraction of discharge versus rainfall (Q/P), specially in saturated soil conditions, seems to be reasonable to be taken into account (Jetten, 2006). Furthermore, through visual comparison between the hydrograph and the sedigraph, and taking into consideration the small size of the catchment, the peak time of both are almost coincident, and we consider that we should believe the model could be calibrated.

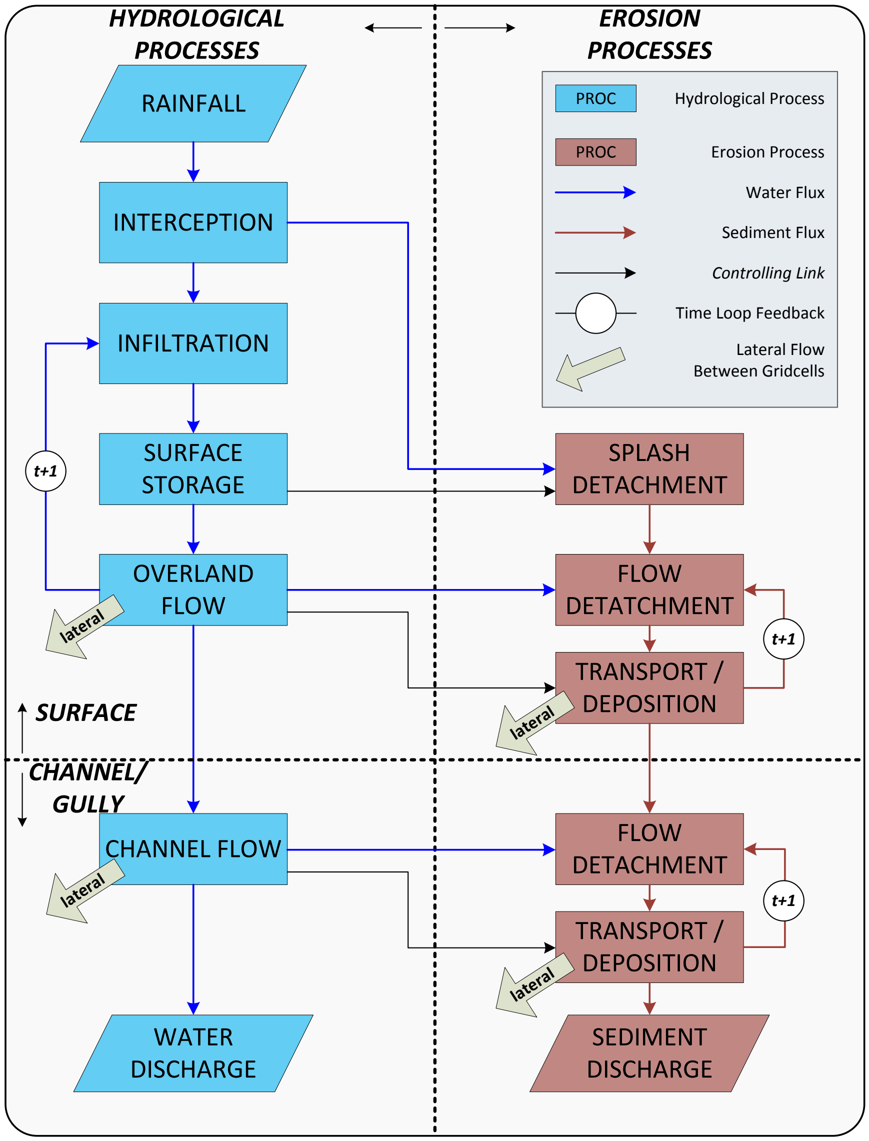


Figure 3.7 – Structure of the model LISEM (De Roo and Jetten, 1999)

LISEM input maps are described in details under sub-chapter nr 3.3 above (Pre-fire observations and datasets (LISEM parameterization maps))

Table 3.1 – Input data for LISEM version 2.58 BETA (using Green & Ampt infiltration Model)

Parameter	Name of the Map	Acquisition Method	Unit
Catchment			
Catchment boundaries	area.map	from DEM	-
Slope gradient	grad.map	from DEM	-
Local Drainage Direction (LDD)	ldd.map	from DEM	-
Rain gauges	id.map	mapping	-
Outlet location	outlet.map	from DEM	-
Reporting runoff points	outlet.map	from DEM	-

Parameter	Name of the Map	Acquisition Method	Unit
Rainfall	*.txt	field data	mm/hr
Vegetation			
LAI (Leaf Area Index)	lai.map	field data from rainfall	-
Percentage Vegetation Cover	per.map	field data	%
Canopy Height	ch.map	field data	m
Soil Surface			
Manning roughness (n)	n.map	field data	-
Random Roughness (RR)	rr.map	field data	cm
Stone Fraction (% Stone)	stonfrc.map	field data	%
Crusting	crustfrc.map	field data	-
Impermeable Roadwith	roadwit.map	field data	m
Erosion			
Cohesion	coh.map	literature	kPa
Aggregate stability	aggrstab.map	literature	-
D50	d50.map	lab	µm
Infiltration			
Saturated hydraulic conductivity	Ksat1.map	field	mm/hr
Saturated soil moisture content (Porosity)	Thetas1.map	literature	-
Initial soil moisture content	Thetai1.map	literature	-
Soil depth	soildep1.map		mm
Wetting front soil water potential	PSI1.map		

4. Comparative statistical analysis of pre & post fire soil and vegetation data

4.1. Vegetation data

The vegetation is one of the parameters, which at first sight, is most affected by the fire effects because its cells begins to be destroyed to the death, when they are exposed to a temperature between 50° C to 55° C, for some period of time, and according to Clark (2001) burning conditions and characteristics of the fire, provide us important information for a good understanding of the vegetation restoration after the fire. According to his statements, vegetation reacts differently among fires in different areas on the fire same fire. Such heat variability regime and the species of vegetation are decisive on post fire results and possible rehabilitation.

Statistical comparisons were carried out regarding the values registered pre and post experimental fire event of February 2009. For the vegetation data, we compared the vegetation height and the percentage covered. Throughout the research, the leaf area index (LAI) value, in spite of its importance on the calculation of the interception, was not taken into consideration because the interception measurement was directly taken on the field and subtracted on the rainfall.

4.1.1. Canopy Height (CH)

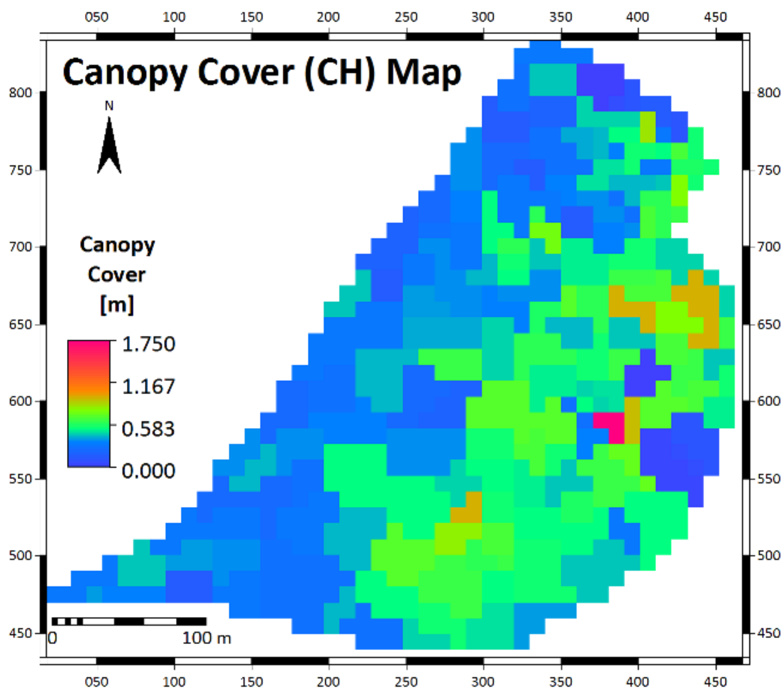


Figure 4.1 – Pre Fire Canopy Cover Map

The hypothesis tested did not discriminate the living species composition on the field (shrubs, and grasses), and we performed the t-Test: Two-Sample Assuming Unequal Variances (see Annex 2) to find evidence of the occurred changes.

Without a doubt, the differences of the canopy cover for the pre and post fire are situations are visibly significant, once we assumed complete destruction of the canopy cover. The mean values of the samples for pre and post fire are respectively 0.46 and 0, and likewise the variances are 0.05 and 0. The two tailed calculated t is 29.44, and the p-value of this test is equal to 0, which are certainly less than the selected $\alpha = 0.05$. Such result, induces us to reaffirm the high significance of the changes occurred (the hypothesis of equal means is most likely to be inexistent). The Figure 4.2 evidently illustrates the differences in the mean and standard deviation between the two situations.

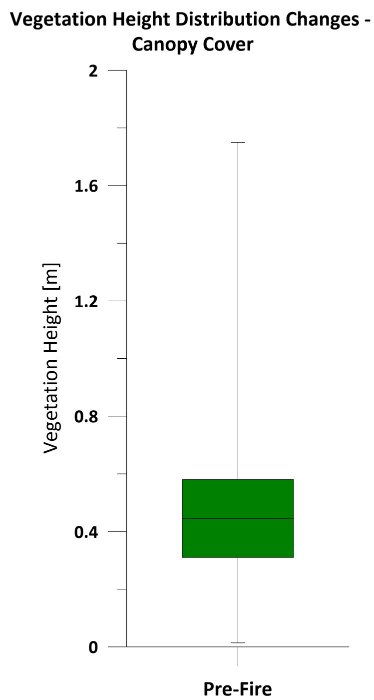


Figure 4.2 – Vegetation Distribution Changes – Canopy cover (pre fire)

4.1.2. Fraction of vegetation cover (Per)

Since this parameter and the previous (canopy height) are linked to each other, we decided to treat it the same way, by proceeding with the same approach of statistical analysis.

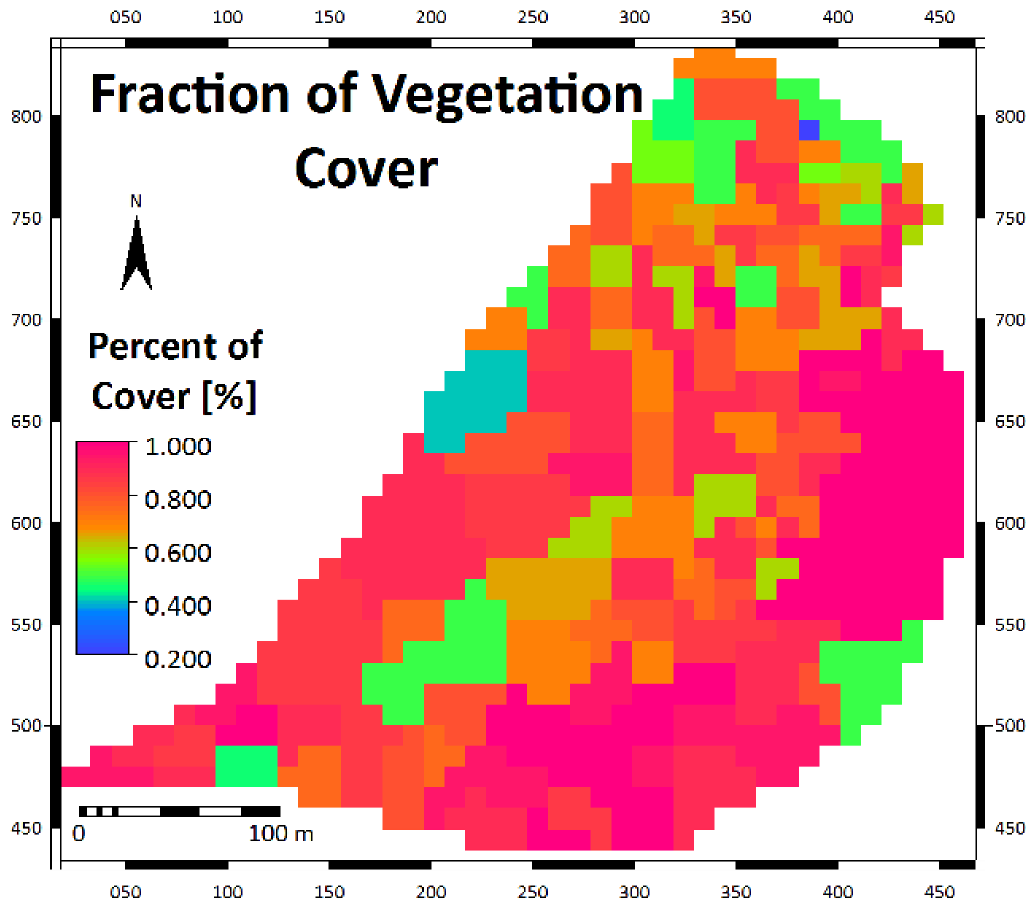


Figure 4.3 – Pre Fire fraction of vegetation Cover Map

As it was expected, the outcome of the analysis retrieved values that confirm the significance of the changes. The mean values of the samples for pre and post fire are respectively 0.81 and 0, and the variances are 0.03 and 0. The two tailed calculated t is 67.15, and the p-value of this test is equal to 0, which is less than the selected $\alpha = 0.05$, confirming the high significance of the changes occurred (the hypothesis of equal means is considerably low). The Figure 4.4 illustrates the box plot graph. (See Annex 3, Table 0.3 and Table 0.4)

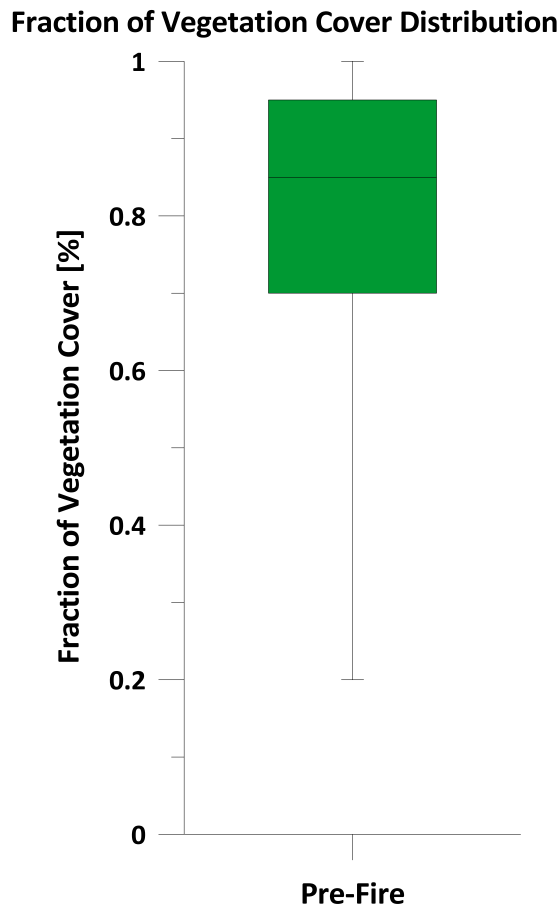


Figure 4.4 –Percentage Cover Distribution Changes (pre fire)

4.2. Surface Data

Except for the Manning's n, the remaining surface and erosion related parameters, such as D50, aggregate stability, cohesion, random roughness, and stone fraction, were assumed to remain constant for both pre and post fire.

4.2.1. Manning's n

Manning's n statistical analysis was undertaken using the overall average for each of the 6 experimental plots, for field measurements taken pre and post fire, by the research team, lead on the field by Ir. Cathelijne Stoof. The mean of both measurements are significantly different from each other (0.601 for pre fire, and 0.195 for post fire), however the variances have quite similar values (0.018 for pre fire, and 0.019 for post fire). Meanwhile, both p-values for one tail and two tail (2.37×10^{-4}, and 4.75×10^{-4} respectively) are significantly low compared to the selected α= 0.05, meaning that the effect of the fire was expressive. The change on this parameter will certainly reproduce effects on the hydrological process, in terms of increase in surface water velocity, which leading to an increase in soil erosion as well. The Figure 4.5 below shows the occurred change on the Manning's n value for pre and post fire situations.

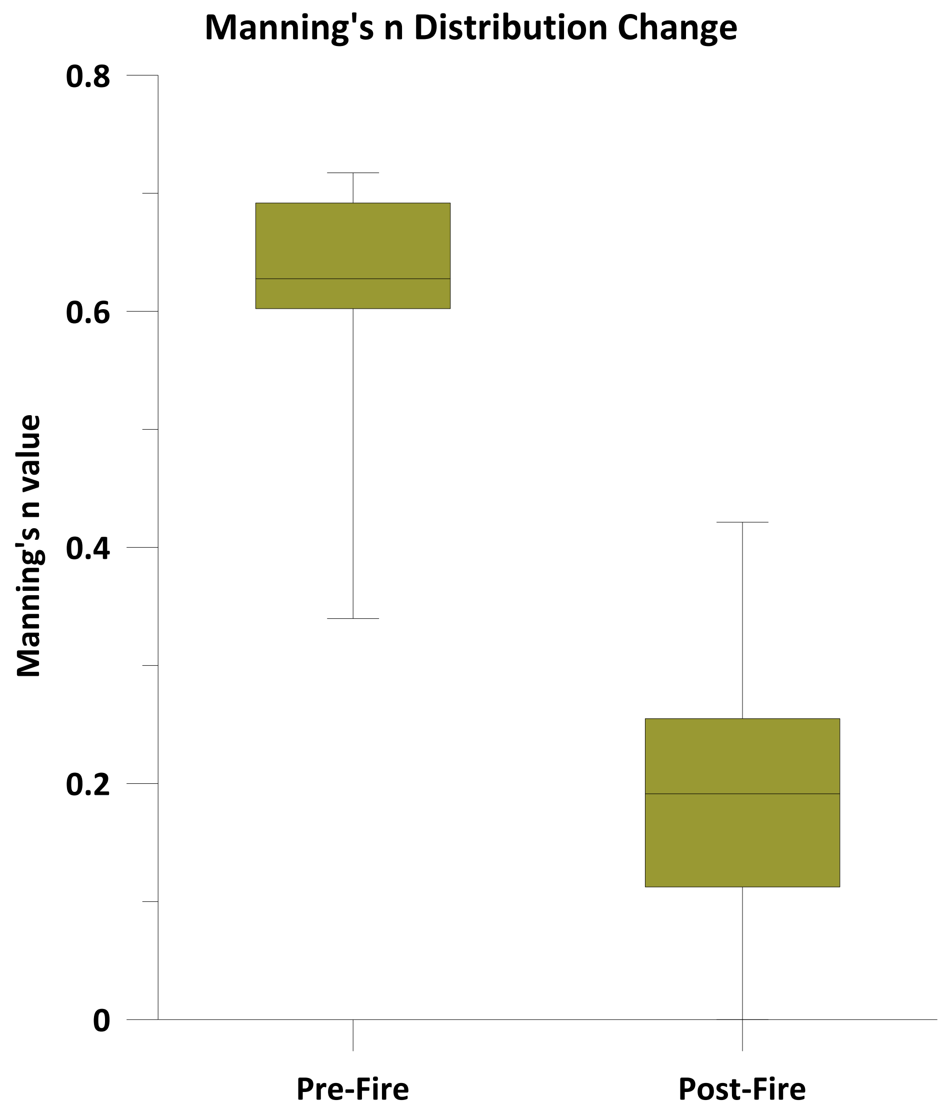


Figure 4.5 – Manning's n Distribution change – pre & post fire

4.3. Infiltration Data

In any study about surface runoff and soil's water erosion, it is necessarily required a reference on the process of infiltration, whereas water surface drainage is solely the discharge of the excess water, incapable of entering the soil to recharge the phreatic surface. However, this process is composed of different parameters, which with a minimum modification can favor it or constrain its progress. Induced forest fire, depending on its intensity duration, constitutes a factor that stimulates changes on some soil physical properties that directly affects the infiltration. According to Ekjnci (2006), parameters like hydraulic conductivity (K_{sat}), total porosity, and soil water (%) are negatively affected, through significant reduction levels when compared to the their values before the fire event, contributing directly to hydrological process.

On this study, the soil depth and soil water tension were assumed to remain constant for pre and post fire. Thus, the research concentrated mainly on other important infiltration parameters (see below), which were statistically analyzed so that we are able to observe their behavior, how they are linked to each other, and see how significant they might be in the whole process, through LISEM model.

4.3.1. Saturated Hydraulic Conductivity (K_{sat})

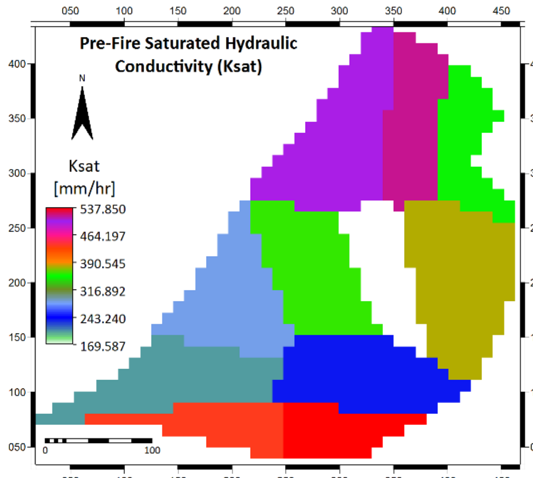


Figure 4.6 – Pre-Fire K_{sat} Map

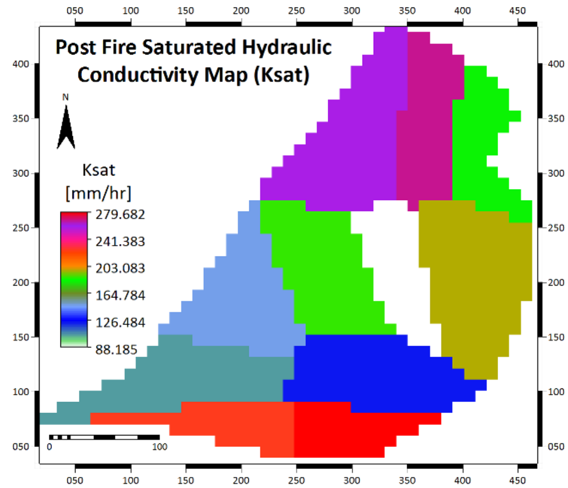


Figure 4.7 – Post-Fire K_{sat} Map

Hydraulic conductivity is the capacity of the soil of transmitting the water when submitted to hydraulic gradient, that is, it is responsible it for the flow of the water into the soil, and constitutes an important parameter in the process of infiltration, together with other soil properties. If fact, K_{sat} performance is, for instance, dependent of the dimension of the particles. Due to alterations that occur to the soil mineral constituent, when exposed to intense temperatures, K_{sat} value suffers some decrease because of the leaching of small ashes particles resulting from the fuel burned.

With the digits of this parameter obtained from pre and post fire situations, the statistical analysis (t-test) was undertaken, and it evidences the significance of the occurred alterations. The mean values of the samples dropped from 360.58 to 187.5 and the two tailed test performed selecting $\alpha = 0.05$, the p-value retrieved, on two-tail was significantly lower ($p = 1.74 \times 10^{-3}$). This value show that statistically the effect of the fire on K_{sat} was significant (see result on Annex 5, and Table 0.9). The Figure 4.8 illustrates the changes in K_{sat}, affected by fire.

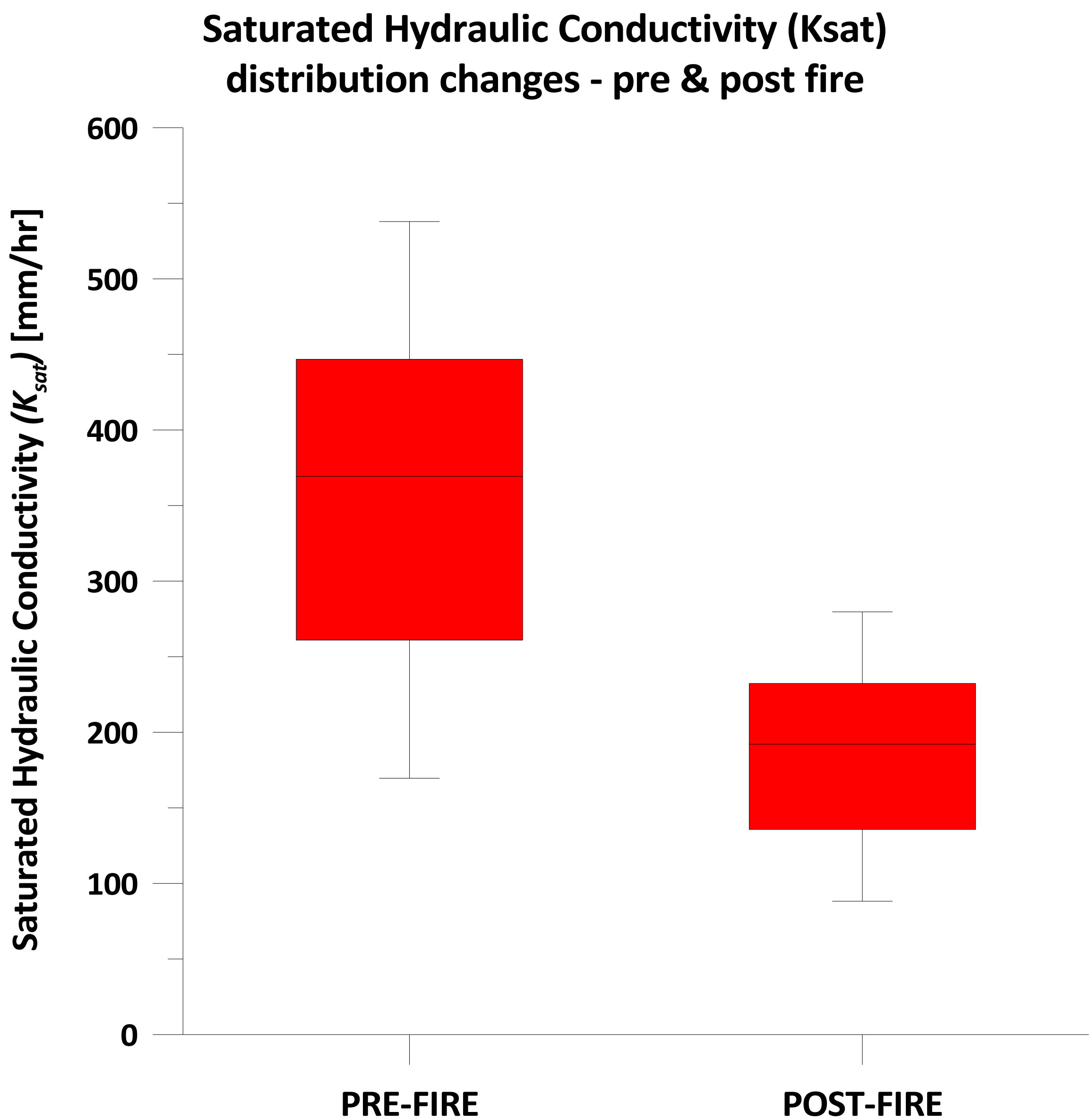


Figure 4.8 – Saturated Hydraulic Conductivity (K_{sat}) [mm/hr] Distribution change – pre & post fire

4.3.2. Thetai

The initial volumetric soil moisture content (Thetai) statistical analysis to observe the significance of the changes occurred pre and post fire was performed using the same method. As expected, the mean initial value of the 14 samples experienced changes, decreasing from 0.296 in pre-fire condition to 0.269 and the variances ranged from 9.91×10^{-4} to 8.21×10^{-4}. The t statistic value of the analysis is equal to 2.344, and two tail p = 0.027. The result of the test retrieve a value below the selected $\alpha = 0.05$, showing the there was significant changes of soil moisture affected by the fire. The significance of the occurred changes can be verified on the Table 0.10 on the Annex 5. The Figure 4.11 illustrates the change differences of pre and post fire.

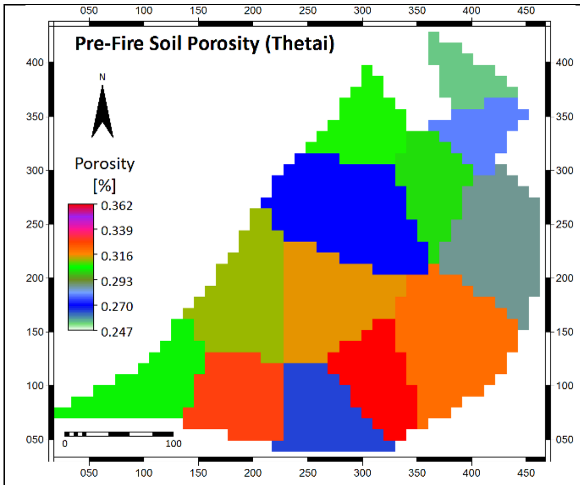


Figure 4.9 – Pre-Fire Thetai Map

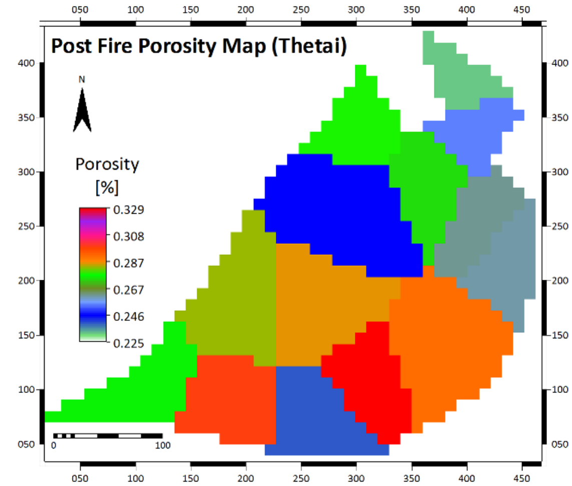


Figure 4.10 – Post-Fire Thetai Map

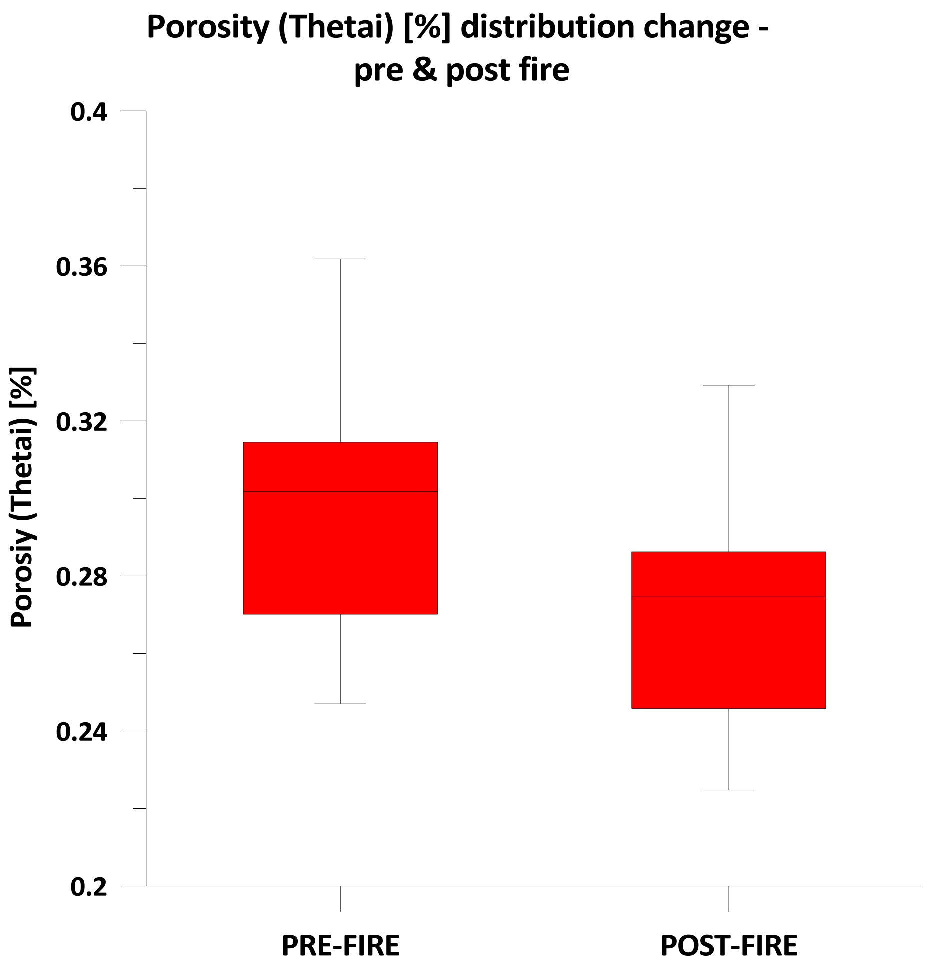


Figure 4.11 – Initial Soil Moisture (Thetai) Distribution change – pre & post fire

4.3.3. Saturated Soil Moisture (Thetas)

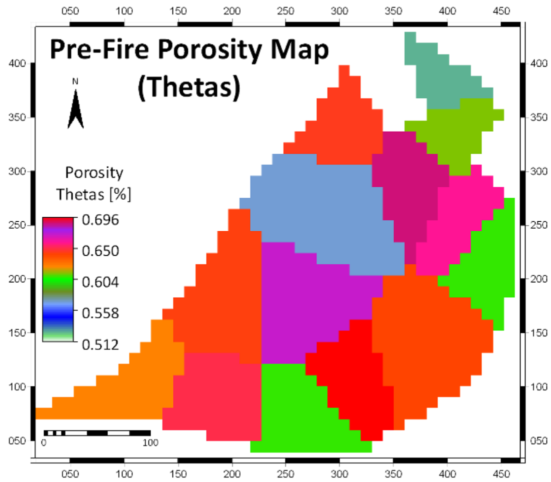


Figure 4.12 – Pre-Fire Porosity (Thetas) Map

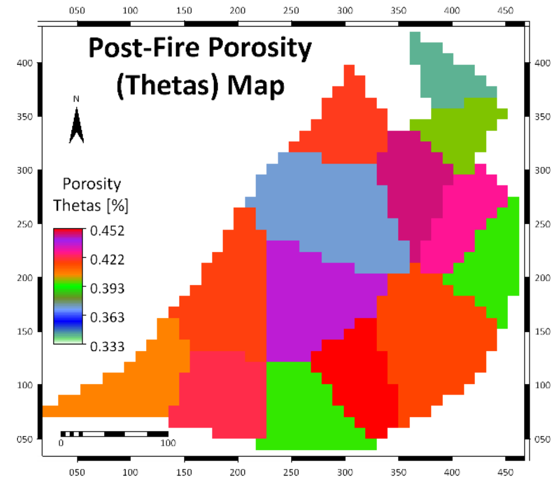


Figure 4.13 – Post-Fire Porosity (Thetas) Map

The performed statistical analysis, evidenced the significance of the changes occurred on saturated soil moisture (Thetas), due to the fire effect. The mean initial value (pre-fire) decreased more than 50% (from 0.6267 to 0.407), and the variances of the pre and post fire are 0.029 and 0.001 respectively. The t-value calculated was 13.76 and the p-values of the test are significantly below the selected $\alpha = 0.05$ ($p = 0$). Through the result of the test, we may confirm that the fire could significantly reduce the saturated volumetric soil moisture content (see results on Table 0.13, Annex 5). The Figure 4.14 shows the difference between the two situations.

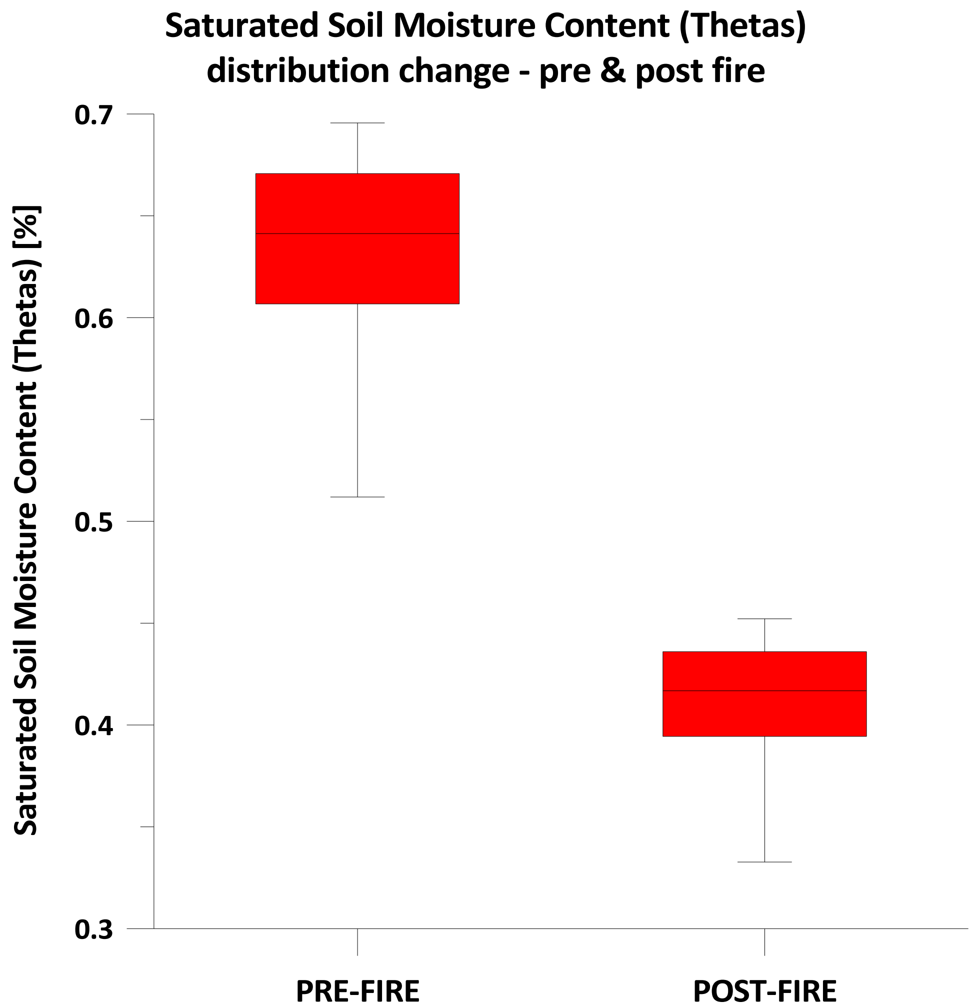


Figure 4.14 - Saturated Soil Moisture (Thetas) Distribution change – pre & post fire

5. Lisem modeling of induced fire effects

5.1. Design storm evaluation

For analyzing the impacts of fire incidence on runoff and erosion of the experimental catchment using a Lisem modeling approach, we first decided to use design storms, derived for the study region, Valtorto, close to Coimbra area and located in the Mondego river basin in Northern Portugal.

We adopted the US SCS (United States Soil Conservation Service) design storm types for setting the time distribution of the precipitation. Research findings of Renschler et al (1999) showed that a SCS Type I storm corresponded well to observed rainfall distributions in the southwestern Iberian Peninsula.

The design storm depths and maximum intensities for a specific duration were obtained from Brandão et al (2001), who analyzed and established I-D-F relationships (rainfall intensity-frequency-duration) for Portugal, based on recorded rainfall data from the Portuguese Meteorological Service and other instances.

The most nearby stations to the study area (Coimbra, etc.) were used for the purpose. We used a 6-hr duration rainfall depth, with a period of return of 2 years, which approximates the annual maximum storm event, and which has a high likelihood to occur in the year after a fire event. Combination of the I-D-F data and information, with the SCS Type I storm distribution (Annex 6), led to the following design storm characteristics:

> P = 36.1 mm (storm depth for a 6-hr duration 2-year return period or probability)
>
> I_{15max} = 42.6 mm/hr, when automatically derived from SCS Type I time distribution.
>
> I_{15max} = 41.4 mm/hr, when derived from the I-D-F short duration relationship for a 15’ duration of the location.

The intensity duration frequency relationships proposed by Brandão et al (2001) have the following equation form, with parameter values (a, b) varying for the different return periods. (Equation for $I_{15'max} = a\,D^b$ with a = 178.88 and b = -0.549).

We judged the two results for maximum intensity, obtained by two different methods as adequate for using the SCS Type I storms in the evaluation.

The Figure 5.1 shows the frequency and cumulative rainfall distribution of the design storm used, and the Table 0.14 on Annex 6 below, illustrates an Excel spreadsheet for computing the SCS Type storm time distributions and maximum intensities in 15 and 30 minutes.

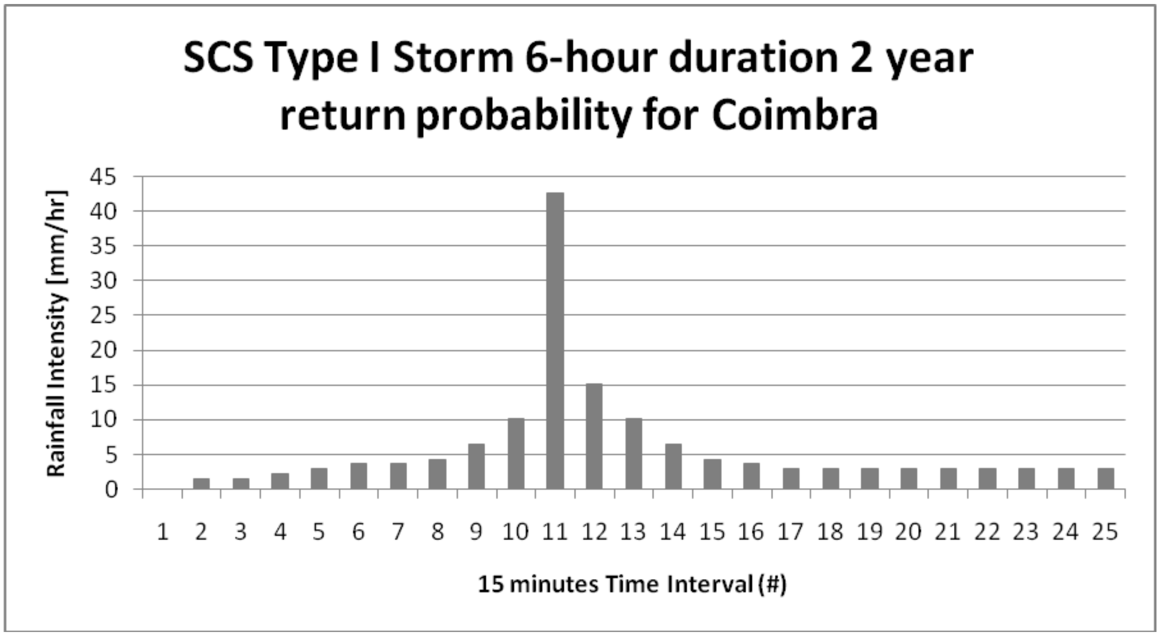


Figure 5.1 - SCS Type I storm 6-hour duration with 2-year return probability for Coimbra

As an example, a SCS Type II storm (of a 6-hour duration and with 2-yr return probability) was also evaluated. This storm type, typical for lower latitude sub-tropical areas, however contained a too high maximum intensity and was judged not adequate for the region, although its total rainfall depth was equal P=36.1 mm.

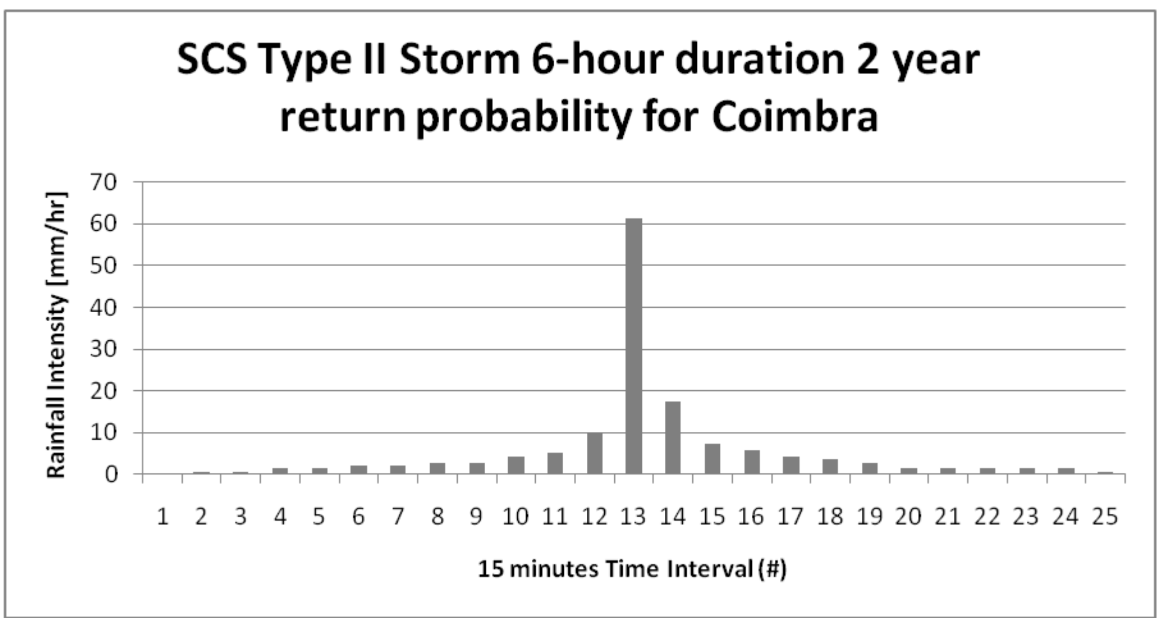


Figure 5.2 - SCS Type II storm 6-hour duration with 2-year return probability for Coimbra

The design storm data were converted to the LISEM format and further used in the modeling.

The rainfall distribution gauges map, as explained on the chapter 3.3.1.4 above, was made according to the canopy height.

5.2. LISEM modeling using design storm and pre-fire vegetation and soil conditions

The evaluation of the two storms allowed us to simulate and observe the behavior of surface runoff and consequent soil erosion, using the field data for surface vegetation cover and field capacity soil moisture. The SCS Type I storm was used, and the interception was directly subtracted (in this case the LAI Map used contains a single value of zero). The model setup for the infiltration method was Green & Ampt – 1 layer, with the additional option of impermeable subsoil, and K_{sat} factor at 100. The simulation time was 600 minutes (10 hours) with the time step of 60 seconds.

As previously mentioned, field values for rainfall interception was used in this research, even though acknowledging the high values obtained in comparison with previous studies. However, the interception devices were placed in the catchment in function of the canopy cover, in the same manner the rain gauges were linked to the canopy cover (see Table 0.16, Table 0.17, Table 0.18, and Table 0.19 on Annex 7 below). The interception values were obtained for each device (in percentage) was then deducted from the rainfall of each of the 4 location as shows the table below:

Table 5.1 – Throughfall & Interception percentage from each rain gauges

Raingauges (#)	Throughfall (%)	Interception (%)
1	53	47
2	45	55
3	37	63
4	29	71

When these values are inserted into the model, already subtracted from the rainfall data, we are able to verify a big drop on the amount of the net rainfall of each storm (see Table 5.2 of pre fire, and Table 5.3 – LISEM model output table using design storm on post fire conditions post fire), and consequently with a big effect on the results retrieved by the model.

The simulation produced the output presented on Table 5.2

Table 5.2 – LISEM model output table using design storm on pre fire conditions

Catchment area	[ha]	9.83
Total net rainfall	[mm]	15.91
Total discharge	[mm]	0.76
Total infiltration	[mm]	15.12
Total discharge	[m³]	74.58
Peak discharge	[l/s]	7.78

Peak time	[min]	182.00
Discharge/Rainfall	[%]	4.77
Splash detachment	[ton]	0.03
Flow detachment (land)	[ton]	2.79
Deposition (land)	[ton]	-1.19
Total soil loss	[ton]	1.63
Average soil loss	[kg/ha]	165.81

The results show that more than 95% of the rainfall infiltrates the soil, and certainly contributing for the insignificant amount of soil detachment and consequent erosion. The surface vegetation condition in pre fire situation is one of the factors to improve the rate of infiltration, firstly because the canopy cover reduces the energy of rainfall impact on the ground. Then the vegetation percentage cover distribution (see percentage cover map on Figure 4.3) on the catchment is relatively high (± 80%). The amount of vegetation soil cover, involves a greater volume of roots in the soil, causing an increase on Manning's n, which directly affects water surface runoff.

These facts can also be confirmed with the delays in the surface runoff, which starts at 30 minutes, and the peak runoff at 182 minutes (Figure 5.3).

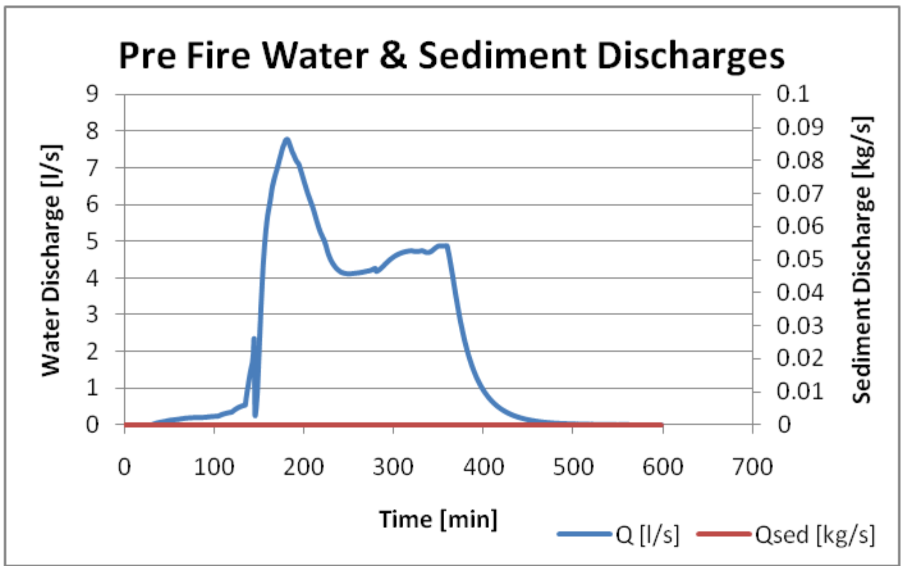


Figure 5.3 – Lisem output of pre fire discharges - Design Storm

5.3. LISEM modeling using design storm and post-fire vegetation and soil conditions

The SCS Type I storm was as well used to simulate and observe the behavior of surface runoff and soil erosion in post fire conditions. The model setup for infiltration was the same used to simulate the pre-fire conditions. However, a few assumptions were taken into consideration; no interception was subtracted from the rainfall, the vegetation height and percentage covers were considered inexistent after the experimental fire.

Table 5.3 – LISEM model output table using design storm on post fire conditions

Catchment area	[ha]	9.83
Total net rainfall	[mm]	33.02
Total discharge	[mm]	18.15
Total interception	[mm]	0.00
Total infiltration	[mm]	14.60
Total discharge	[m³]	1,784.57
Peak discharge	[l/s]	366.99
Peak time	[min]	157.00
Discharge/Rainfall	[%]	54.98
Splash detachment	[ton]	0.45
Flow detachment (land)	[ton]	599.52
Deposition (land)	[ton]	-215.02
Total soil loss	[ton]	384.95
Average soil loss	[kg/ha]	39,155.32

Through the results of this simulation, it can be evidenced that the registered infiltration was of only 45% of the rainfall, which could be, at first, explained by the absence of a vegetation cover. Notwithstanding the reduced infiltration registered, we may say that, although some damages were caused by the one of the experimental fire on the vegetation, it was not sufficient enough to destroy the roots in its totality, and disaggregate the soil. Even though, damaging a percentage of the existing roots in the soil, consequently reducing the value of the resistance to water flow (Manning's n), still some amount of water was restrained in the soil.

We may also observe that the runoff started much sooner (7 minutes), and the peak discharge was also reached in less time (± 150 minutes) than pre fire simulation (see Figure 5.4). The absence of the vegetation on the other hand, increased the effect of rainfall on the soil, in which the energy for soil detachment becomes higher, and consequently there will be a higher amount of soil erosion. It can be observed that the volume of soil loss on this simulation have considerably increased to 385 tons, which cannot be only explained by the absence of the vegetation, but also by the alterations of some physical properties of the soil, that are very important. The saturated hydraulic conductivity was affected by the fire, due to small particles of ash residues produced by the burned biomass, increasing the soil bulk density. These small particles, naturally decreases the soil porosity, hindering the soil water inflow. The referred changes, added with decrease of soil moisture content that steps in as a consequence of soil heating (by surface fire), and increase of evaporation (through absence of vegetation), explains the occurred increases of water surface runoff and soil erosion.

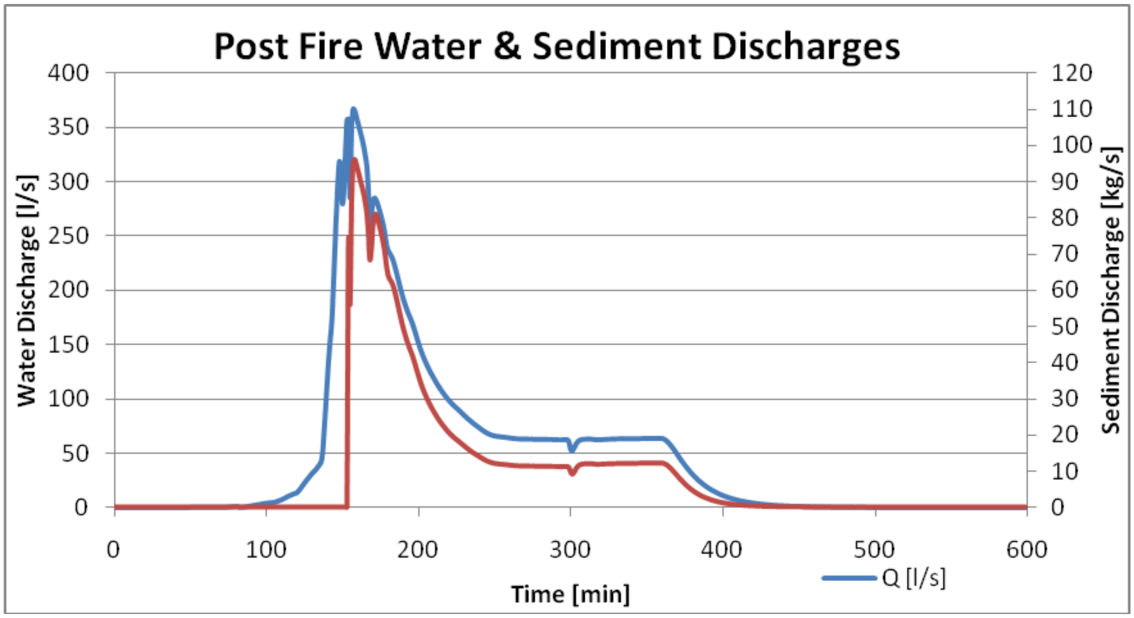


Figure 5.4 – Lisem output of post fire discharges - Design Storm

5.4. LISEM modeling using real storm and pre-fire vegetation and soil conditions

We used two different events of rainfall registered on the site, to simulate the scenarios. These two events have distinct characteristics. The event occurred on September 5th of 2008 (Figure 5.5), is of medium intensity, but with long duration, while the event of October 7th of 2008 (Figure 5.6) is of high intensity and with short duration.

The LISEM simulations set up for the pre-fire were the same as described on chapter 5.2 above.

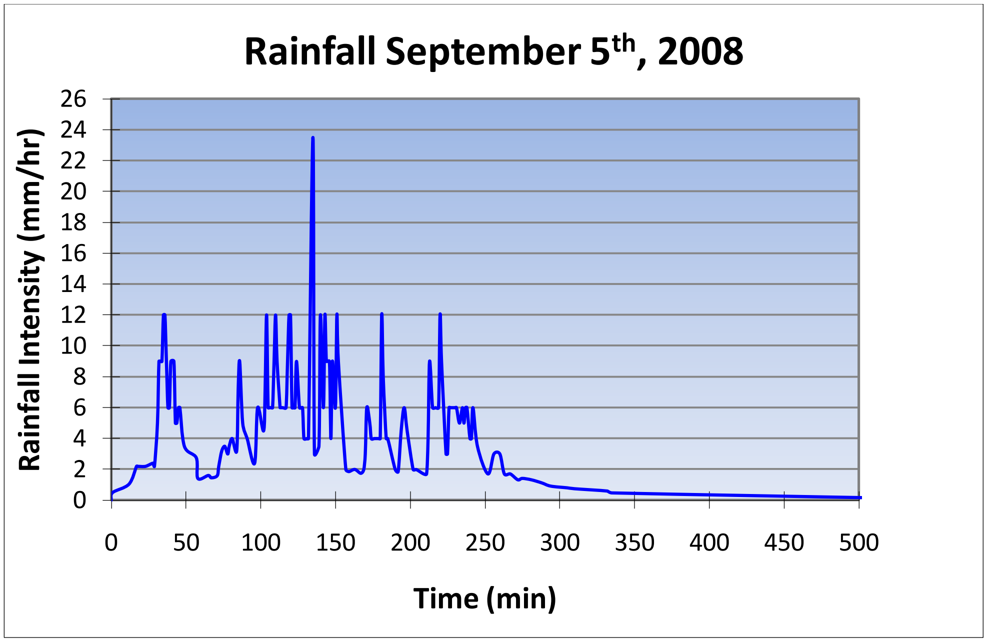


Figure 5.5 – Rainfall Intensity; event of September 5th, 2008

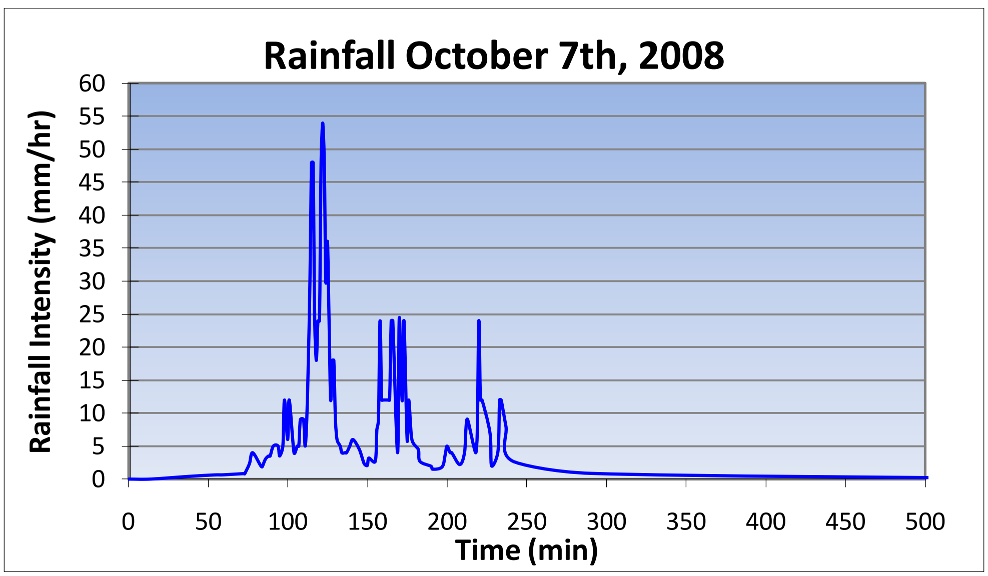


Figure 5.6 – Rainfall Intensity; event of October 7th, 2008

The LISEM model operated using the two field registered storms, returned results within our expectancy (see Table 5.4). Though the storms characteristics are different, the discharge rainfall rate (1.14% and 1.91%), and the total soil loss (0.20 and 0.35 tons) are insignificantly different. Through a statistical comparison of the retrieved results, the p-value for a two tail with a selected $\alpha = 0.05$, was equal to 0.93. This value evidences the insignificance of the differences between the two storms simulated on pre fire conditions.

Table 5.4 - LISEM model output table using two real storms on pre fire conditions

		PRE-FIRE	
		Sept 5th, 2008 Storm	**Oct 7th, 2008 Storm**
Total net rainfall	[mm]	9.07	10.86
Total discharge	[mm]	0.10	0.21
Total infiltration	[mm]	8.95	10.64
Total discharge	[m³]	10.15	20.39
Peak discharge	[l/s]	1.63	3.89
Peak time	[min]	245.00	241.00
Discharge/Rainfall	[%]	1.14	1.91
Splash detachment	[ton]	0.02	0.02
Flow detachment (land)	[ton]	0.32	0.65
Deposition (land)	[ton]	-0.14	-0.32
Total soil loss	[ton]	0.20	0.35
Average soil loss	[kg/ha]	19.89	35.95

5.5. LISEM modeling using real storm and post-fire vegetation and soil conditions

Table 5.5 - LISEM model output table using two real storms on post fire conditions

		POST-FIRE	
		Sept 5th, 2008 Storm	**Oct 7th, 2008 Storm**
Total net rainfall	[mm]	18.80	22.53
Total discharge	[mm]	6.33	9.16
Total interception	[mm]	0.00	0.00
Total infiltration	[mm]	12.21	13.11
Total discharge	[m³]	622.68	900.62
Peak discharge	[l/s]	81.15	153.89
Peak time	[min]	239.00	174.00
Discharge/Rainfall	[%]	33.69	40.67
Splash detachment	[ton]	0.15	0.23
Flow detachment (land)	[ton]	124.82	233.26
Deposition (land)	[ton]	-40.28	-81.47
Total soil loss	[ton]	84.69	152.02
Average soil loss	[kg/ha]	8614.72	15462.68

The LISEM model results for post fire simulations, reveals a scenario quite different from the previous (pre fire), which brings about the impact of higher intensity of rainfall. According to the values of the table, the more intense the storm, the lesser the infiltration, and the peak runoff time, and the higher total discharge, flow detachment, and consequently there is more soil erosion.

However, the storms intensity does not act in an isolated way. As we mentioned before, other parameters are also important. The vegetation cover (canopy and percentage), for instance, is of capital importance on reducing the energy of the rainfall, and consequently retarding the surface runoff in detriment of allowing more infiltration of water into the soil. Additionally, the vegetation roots into the soil helps the resistance to surface flow.

Even though the discharge rainfall rates differences are not so large between the storms, they are quantitatively very high (34 and 40%) when compared to the pre fire situation (1.14 and 1.91%). The same can be observed on the amount of the rainfall infiltration percentage regarding each of the storms. While on the pre fire situation more than 97% of the storms were infiltrated, on post fire simulation only 65% and 58% of rainfall were infiltrated, respectively for Sep 5th and Oct 7th rainfalls (see Table 5.5).

Soil loss on post fire simulation has enormously triggered. On the storm from Sept 5th it has risen from approximately 20 kg to 85 tons, while on the Oct 7th storm it has increased from 35 kg to 152 tons. Besides the effects of the vegetation, also the infiltration parameters of the soil play an important role on this increase. With the fire burning the biomass on the soil, there is an increase in bulk density of the soil, and consequently the porosity of the soil becomes lower. As previously explained the saturated hydraulic conductivity will also decrease, as there is a formation of a layer of ash particles on the soil, which hampers the movement of water into soil.

On the Figure 0.4 and Figure 0.5 of the Annex 9 below, we observe a delay of approximately 100 minutes between the peak water discharge, and the peak sediment flow. Such time delay could be, in part, explained by the soil moisture content. Since the moisture content of the soil decreases with the fire, and then due to lack of the vegetation cover, the soil becomes more exposed to the direct income of solar temperature. This exposure will surely increase the rate of evaporation of the moist. In this particular case, we may believe that the soil was initially dry, and during the initial period, it need to intake water until the saturation so that some particles would be disaggregated and be washed out. If we carefully observe the soil intakes the water since the beginning of the event, and during a period of approximately 10 minutes , towards the receding phase of the rainfall, it started being washed out for a relatively short period of time.

6. Discussion, Conclusions and recommendations

6.1. Discussion

The aim of this research was to estimate the changes that could have occurred on soils physical properties, post experimental fire, and the effects they might have on surface runoff and soils erosion, through simulations made with LISEM model.

To achieve our goal, we would first expect the experimental fire to be more intense, and with longer duration. As it was mentioned before, fire intensity and duration is of extreme importance to inflict changes in some physical soil properties (Certini, 2005), which could provide us means of researching in details which property is influential. However, the temperature reached between soil surface and the 3 cm depth of the soil, was not high enough (22.5°C) to inflict any changes (Drooger, 2009). With such fire intensity no irreversible changes may occur, however severe fires, have negative effects on soil, causing significant destruction of organic matter, deterioration of both structure and porosity, considerable loss of nutrients through volatilization, ash entrapment in smoke columns, leaching and erosion (Certini, 2005).

The results of statistical analysis carried out (Annex 2,Annex 3,Annex 4, and Annex 5) variance analysis for parameters used in LISEM model for pre and post fire, and they clearly illustrate the significance of the occurred changes.

However, the simulations that we carry through with LISEM model, using three types of different storms, we were capable to observe that the vegetation, soil surface, and infiltration parameters, and even the intensity of storms have all a great deal of influence in the surface runoff and soil erosion after fire. In all simulations run, the vegetation cover, and percentage cover was assumed to become absolute zero. The infiltration parameters (K_{sat}, initial soil moisture, and saturated soil moisture), are all lower in post fire conditions, due to the increase in bulk density which directly affects K_{sat} and porosity. As stated by Ekjnci (2006), low K_{sat}, means the infiltration becomes lower, and the soil moisture content as well becomes lower (Ekjnci, 2006).

The simulations for Valtorto, the designed storm rainfall, the infiltration decreased from pre fire 95% to 44% post fire, and the total discharge increased from 75m³ to 1,785m³ post fire. Furthermore, due to the changes occurred on the soil surface, the flow detachment increased from 2.8 ton in pre fire conditions to 600 ton post fire. These changes also triggered the total soil loss to jump from the 1.6 ton on pre fire condition to 385 ton post fire, over the entire catchment. Regarding the simulations carried out with the two field storms (moderate and high intensities) showed basically the same trend as the design rainfall, as the Table 6.1 illustrates.

Table 6.1 - Changes occured fron pre to post fire with field storms

	Infiltration [%]		Discharge [m³]		Flow Detachment [ton]		Soil loss [ton]	
STORMS	Pre	Post	Pre	Post	Pre	Post	Pre	Post

	Infiltration [%]		Discharge [m³]		Flow Detachment [ton]		Soil loss [ton]	
STORMS	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
September 5th	97	33	10	623	0.3	124	0.2	85
October 7th	98	41	20	900	0.7	233	0.4	152

Hessel et al. (2003a) said that hydraulic conductivity e Manning's n are the two most important factors on the model calibration, being the first of extreme sensitivity at deeper soils. The soil storage capacity, calculated through the use of hydraulic conductivity and soil depth, is also important for the generated amount of soil loss.

In the shallow areas of Valtorto catchment, soil depth should be considered important, because it determines the (low) storage capacity in those areas, and consequent increase in soil loss.

6.2. Conclusions and Recommendations

At the end of this research, we may not have reached every expected result, however, important conclusions were drawn regarding the response of the catchment post experimental fire. No irreversible changes in soils physical properties were reported to happen, because of the low fire intensity on soil. The changes that occurred was attributed to the changes occurred on soil surface, mainly destruction of the vegetation canopy, and soil cover percentage reduction.

Additionally it was possible to conclude that the fire caused a significant impact in the K_{sat} value, which reflects directly on the level of porosity of soil. Being the particle size distribution one of the important factors for the variation of K_{sat} value, the generation of ashes from the burnt biomass creates a layer on the soil surface that obstructs the entrance of the water into the soil. As a consequence, this phenomenon has a repercussion on the porosity of the soil. It is noticeable that the variation of the porosity value reduces almost in the same ratio of the reduction of K_{sat} value. Such fact can be verified on the significant increase of surface runoff on the result retrieved by the LISEM.

The results of the model was also generated by the value of interception used under pre fire condition, averaging around 10 mm from the total rainfall (representing a very high percentage – almost 50%), and the assumption of no interception on the post fire condition. This way the post fire condition experienced the effect of almost twice the amount of the rainfall on the soil, causing a much higher surface runoff and consequent soil erosion.

Meanwhile, the splash detachment ratio is practically zero, which is due to the high value of stone cover fraction. (see Figure 0.12 on Annex 11 below).

If the expected results were not totally achieved, regarding soil property changes, LISEM model behavior was quite satisfactory. Although it is a software designed, without the purpose of handling forest fire effects on soils, it showed to be an effective software to produce acceptable results, about runoff and erosion. It is a very versatile software, once it allows the parameters changes of values, and make as many simulations as is possible.

The recommendations we might leave here are the following:

- Rely more on field data collection
- All literature values used in the study must be eliminated, giving way to actual field information
- Since the catchment is small, single value maps should be reduced to the minimum;
- Calibration using field discharge measurements must be done, so that the study could be qualitatively upgraded, in terms of results accuracy;

Values used should all be taken from the field

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Annexes

Annex 1. Valtorto Sampling Sites

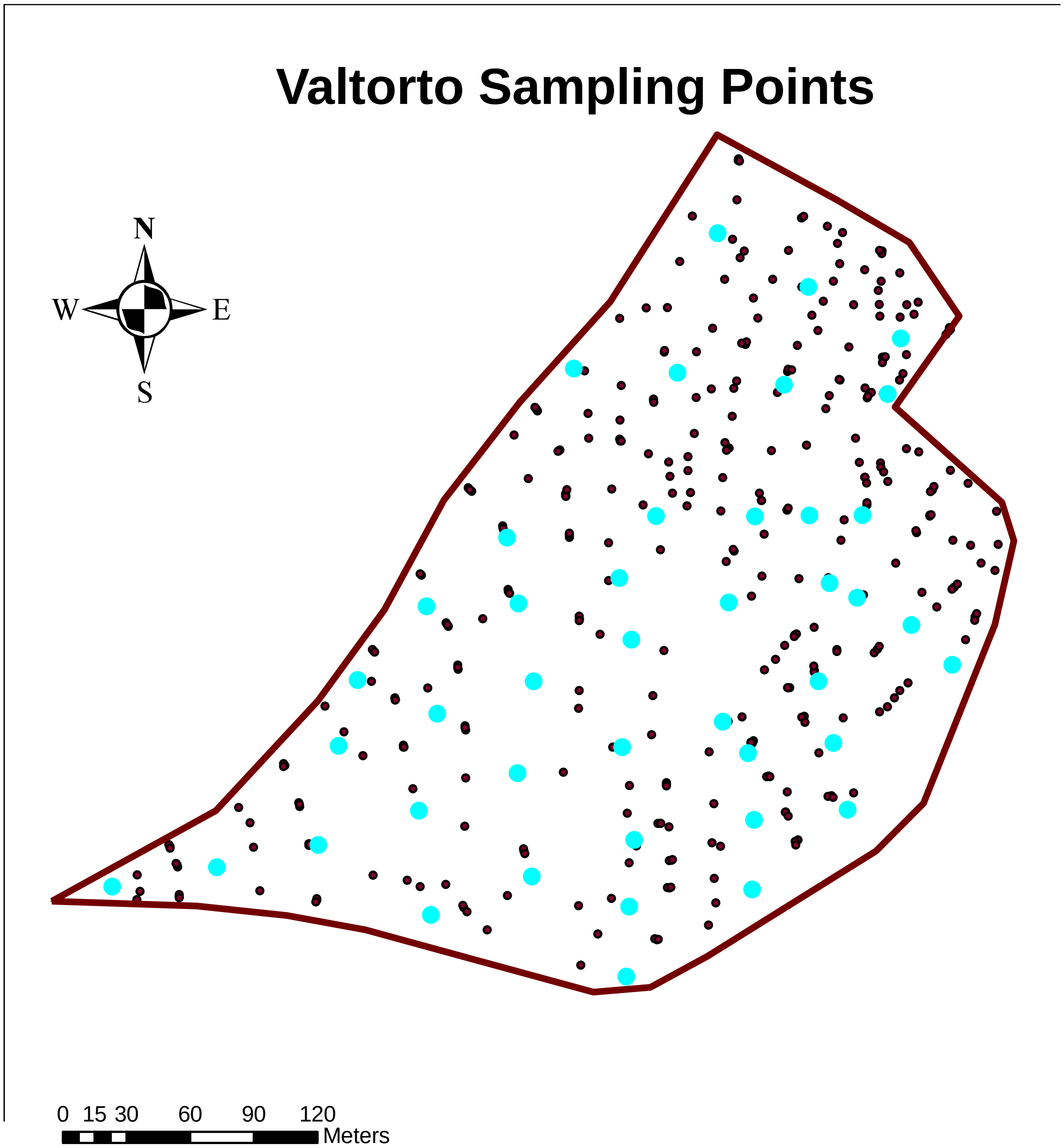

Figure 0.1 - Sampling Sites at Valtorto Catchment

OBS.: *The bigger cyan points, are the official 42 sampling sites, and the remaining are the sampling spots where data were taken by other students, according to their field of studies. For reasons beyond our control, it was not possible to separate them.*

Annex 2. Table of Vegetation Cover & Parameter Statistical Analisys

Table 0.1 - Pre & Post Fire Field Data of Canopy Cover

Location	Veg. Height		Location	Veg. Height		Location	Veg. Height		Location	Veg. Height		Location	Veg. Height	
	Pre-Fire	Post-Fire		Pre-Fire	Post-Fire		Pre-Fire	Post-Fire		Pre-Fire	Post-Fire		Pre-Fire	Post-Fire
L602	0.590	0.000	L903	0.320	0.000	L824	0.530	0.000	L502	0.460	0.000	L1011	0.360	0.000
L603	0.680	0.000	L904	0.320	0.000	L825	0.690	0.000	L503	0.490	0.000	L1012	0.640	0.000
L604	0.650	0.000	L905	0.360	0.000	L826	0.460	0.000	L504	0.259	0.000	P3	0.523	0.000
L605	0.300	0.000	L906	0.400	0.000	L827	0.540	0.000	L506	0.550	0.000	P4	0.435	0.000
L606	0.520	0.000	L907	0.650	0.000	L828	0.650	0.000	L508	0.514	0.000	P5	0.178	0.000
L607	0.310	0.000	L908	0.180	0.000	L829	0.650	0.000	L509	0.550	0.000	P6	0.426	0.000
L608	0.860	0.000	L909	0.230	0.000	L830	0.610	0.000	L510	0.960	0.000	P7	0.392	0.000
L609	0.540	0.000	L911	0.390	0.000	L831	0.660	0.000	L511	0.830	0.000	P102	0.438	0.000
L611	0.530	0.000	L912	0.330	0.000	L832	0.650	0.000	L512	0.560	0.000	P105	0.310	0.000
L612	0.460	0.000	L914	0.180	0.000	L833	0.520	0.000	L513	0.520	0.000	P108	0.434	0.000
L613	0.090	0.000	L915	0.170	0.000	L834	0.480	0.000	L514	0.476	0.000	P202	0.312	0.000
L614	0.130	0.000	L916	0.240	0.000	L836	0.560	0.000	L516	0.362	0.000	P205	0.284	0.000
L615	0.140	0.000	L917	0.290	0.000	L838	0.530	0.000	L610	0.340	0.000	P208	0.344	0.000
L615-1	0.100	0.000	L918	0.360	0.000	L407	0.358	0.000	L619	0.440	0.000	P211	0.524	0.000
L616	0.800	0.000	L701	0.310	0.000	L408	0.366	0.000	L628	0.000	0.000	P213	0.294	0.000
L617	0.640	0.000	L702	0.650	0.000	L409	0.536	0.000	L910	0.400	0.000	P215	0.424	0.000
L618	0.620	0.000	L703	0.640	0.000	L410	0.550	0.000	L705	0.340	0.000	P216	0.260	0.000
L620	0.420	0.000	L704	0.730	0.000	L411	0.600	0.000	L913	0.200	0.000	P218	0.566	0.000
L621	0.280	0.000	L707	1.750	0.000	L412	0.326	0.000	L808	0.300	0.000	P221	0.622	0.000
L622	0.370	0.000	L708	0.450	0.000	L413	0.618	0.000	L811	0.140	0.000	P224	0.668	0.000
L623	0.350	0.000	L709	0.580	0.000	L414	1.290	0.000	L815	0.440	0.000	P301	0.472	0.000
L624	0.174	0.000	L710	0.530	0.000	L415	0.744	0.000	L817	0.340	0.000	P302	0.472	0.000
L625	0.370	0.000	L711	0.450	0.000	L416	0.450	0.000	L823	0.290	0.000	P304	0.472	0.000
L626	0.490	0.000	L801	0.240	0.000	L417	0.370	0.000	L835	0.390	0.000	P303	0.472	0.000
L627	0.480	0.000	L802	0.360	0.000	L418	0.590	0.000	L837	0.550	0.000	P305	0.472	0.000
L629	0.460	0.000	L803	0.254	0.000	L419	0.616	0.000	L424	0.610	0.000	P306	0.410	0.000
L630	0.410	0.000	L804	0.230	0.000	L420	0.618	0.000	L433	0.500	0.000	P307	0.968	0.000
L631	0.260	0.000	L805	0.420	0.000	L421	0.432	0.000	L505	0.690	0.000	P325	0.014	0.000
L632	0.340	0.000	L806	0.360	0.000	L422	0.696	0.000	L507	0.670	0.000	P325	0.014	0.000
L633	0.320	0.000	L807	0.250	0.000	L423	0.498	0.000	L515	0.520	0.000	P337	0.930	0.000
L634	0.300	0.000	L809	0.370	0.000	L425	0.554	0.000	L601	0.550	0.000	P353	0.020	0.000
L635	0.160	0.000	L810	0.300	0.000	L426	0.630	0.000	L636	0.268	0.000	P354	0.050	0.000
L637	0.210	0.000	L812	0.380	0.000	L427	0.660	0.000	L1001	0.496	0.000	P355	0.060	0.000
L638	0.440	0.000	L813	0.300	0.000	L428	0.680	0.000	L1002	0.670	0.000	P356	0.040	0.000
L639	0.300	0.000	L814	0.450	0.000	L429	0.950	0.000	L1003	0.650	0.000	P357	0.120	0.000
L640	0.280	0.000	L816	0.340	0.000	L430	0.440	0.000	L1004	0.670	0.000	P373	0.518	0.000
L641	0.160	0.000	L818	0.308	0.000	L431	0.650	0.000	L1005	0.790	0.000	L505	0.690	0.000
L642	0.226	0.000	L819	0.330	0.000	L432	0.540	0.000	L1006	0.960	0.000	L610	0.340	0.000
L644	0.530	0.000	L820	0.290	0.000	L434	0.690	0.000	L1007	0.960	0.000	L622	0.370	0.000
L901	0.360	0.000	L821	0.260	0.000	L435	0.460	0.000	L1009	0.450	0.000	L637	0.210	0.000
L902	0.350	0.000	L822	0.430	0.000	L501	0.520	0.000	L1010	0.560	0.000	P341	0.686	0.000

	Pre-Fire	Post Fire
Count	205	205
Minimum	0	0
Maximum	1.75	0
Average	0.456	0
Std Deviation	0.224	0

Table 0.2 – t-Test: Two-Sample Assuming Unequal Variances (Canopy Cover pre & post fire)

t-Test: Two-Sample Assuming Unequal Variances

	Pre-Fire	*Post-Fire*
Mean	0.457319	0
Variance	0.049224	0
Observations	204	204
Hypothesized Mean Difference	0	
df	203	
t Stat	29.44055	
P(T<=t) two-tail	3.4E-75	
t Critical two-tail	1.971719	

Annex 3. Table of Ground Percentage Cover & Statistical Analysis

Table 0.3 – Pre & Post Fire Field Data of Percentage Cover

Location	Ground Cover		Location	Ground Cover		Location	Ground Cover		Location	Ground Cover		Location	Ground Cover	
	Pre-Fire	Post-Fire		Pre-Fire	Post-Fire		Pre-Fire	Post-Fire		Pre-Fire	Post-Fire		Pre-Fire	Post-Fire
L602	0.85	0	**L902**	0.6	0	**L821**	0.8	0	**L432**	0.8	0	**L1005**	1	0
L603	0.9	0	**L903**	0.75	0	**L822**	0.95	0	**L434**	0.7	0	**L1006**	1	0
L604	0.85	0	**L904**	0.65	0	**L824**	0.95	0	**L435**	0.75	0	**L1007**	1	0
L605	0.5	0	**L905**	0.9	0	**L825**	1	0	**L501**	0.7	0	**L1009**	1	0
L606	0.6	0	**L906**	0.9	0	**L826**	1	0	**L502**	0.9	0	**L1010**	1	0
L607	0.6	0	**L907**	0.95	0	**L827**	0.85	0	**L503**	0.75	0	**L1011**	0.9	0
L609	0.65	0	**L908**	0.6	0	**L828**	1	0	**L504**	0.8	0	**L1012**	1	0
L611	0.55	0	**L909**	0.85	0	**L829**	1	0	**L506**	0.8	0	**P213**	0.5	0
L612	0.7	0	**L911**	0.9	0	**L830**	1	0	**L508**	0.85	0	**P214**	0.5	0
L613	0.2	0	**L912**	0.85	0	**L831**	1	0	**L509**	0.7	0	**P215**	0.8	0
L614	0.5	0	**L914**	0.7	0	**L832**	1	0	**L510**	0.95	0	**P216**	0.75	0
L615	0.5	0	**L915**	0.4	0	**L833**	0.95	0	**L511**	0.95	0	**P218**	0.6	0
L615-1	0.5	0	**L916**	0.75	0	**L834**	1	0	**L512**	0.9	0	**P221**	0.9	0
L616	0.95	0	**L917**	0.9	0	**L836**	0.9	0	**L513**	0.8	0	**P224**	1	0
L617	0.85	0	**L918**	0.9	0	**L838**	1	0	**L514**	0.75	0	**P301**	0.9	0
L618	0.85	0	**L701**	0.8	0	**L404**	0.7	0	**L516**	0.65	0	**P306**	0.9	0
L620	0.75	0	**L702**	0.9	0	**L405**	0.7	0	**L610**	0.7	0	**P307**	1	0
L621	0.65	0	**L703**	1	0	**L406**	0.7	0	**L619**	0.75	0	**P325**	1	0
L622	0.65	0	**L704**	1	0	**L409**	0.95	0	**L910**	0.8	0	**P325**	1	0
L623	0.8	0	**L707**	1	0	**L410**	0.9	0	**L705**	0.6	0	**P337**	1	0
L624	0.5	0	**L708**	0.85	0	**L412**	0.6	0	**L913**	0.5	0	**P373**	0.5	0
L625	0.75	0	**L709**	0.9	0	**L413**	0.95	0	**L808**	0.85	0	**L505**	0.9	0
L626	0.8	0	**L710**	0.9	0	**L414**	1	0	**L811**	0.45	0	**L610**	0.7	0
L627	0.85	0	**L711**	0.95	0	**L415**	1	0	**L815**	0.85	0	**L622**	0.65	0
L629	0.8	0	**L801**	0.9	0	**L416**	0.8	0	**L817**	0.95	0	**L637**	0.5	0
L630	0.9	0	**L802**	0.9	0	**L417**	0.8	0	**L823**	0.9	0	**P341**	1	0
L631	0.7	0	**L803**	0.75	0	**L418**	0.9	0	**L835**	0.9	0			
L632	0.85	0	**L804**	0.85	0	**L419**	0.9	0	**L837**	0.95	0			
L633	0.65	0	**L805**	0.85	0	**L420**	0.9	0	**L424**	0.85	0			
L634	0.75	0	**L806**	0.85	0	**L421**	0.7	0	**L433**	0.6	0			
L635	0.65	0	**L809**	0.9	0	**L422**	0.9	0	**L505**	0.9	0			
L637	0.5	0	**L810**	0.75	0	**L423**	0.7	0	**L507**	0.75	0			
L638	0.8	0	**L812**	1	0	**L425**	0.65	0	**L515**	0.7	0			
L639	0.7	0	**L813**	0.95	0	**L426**	1	0	**L601**	0.65	0			
L640	0.45	0	**L814**	0.9	0	**L427**	0.95	0	**L636**	0.5	0			
L641	0.55	0	**L816**	0.9	0	**L428**	1	0	**L1001**	1	0			
L642	0.7	0	**L818**	0.9	0	**L429**	1	0	**L1002**	1	0			
L644	0.9	0	**L819**	0.95	0	**L430**	0.8	0	**L1003**	1	0			
L901	0.8	0	**L820**	0.85	0	**L431**	0.9	0	**L1004**	1	0			

	Pre-Fire	Post Fire
Count	**37**	**37**
Minimum	**0.2**	**0**
Maximum	**0.95**	**0**
Average	**0.6778**	**0**
Std Deviation	**0.1606**	**0**

Table 0.4 – t-Test: Two-Sample Assuming Unequal Variances (Canopy Cover pre & post fire)

t-Test: Two-Sample Assuming Unequal Variances

	Pre-Fire	*Post Fire*
Mean	0.811878	0
Variance	0.026455	0
Observations	181	181
Hypothesized Mean Difference	0	
df	180	
t Stat	67.15427	
P(T<=t) two-tail	2.3E-129	
t Critical two-tail	1.973231	

Annex 4. Manning's n Data

Table 0.5 – Experimental Field data for Manning's n for Unburned plots

	UNBURNED							
	Run 1		Run 2		Run 3		Overall	
	Average	Stdev	Average	Stdev	Average	Stdev	Average	Stdev
Plot 1	0.598	0.056	0.618	0.312	0.654	0.082	0.624	0.177
Plot 2	0.521	0.103	0.579	0.035	0.761	0.199	0.631	0.173
Plot 3	0.290	0.038	0.396	0.061	0.333	0.044	0.340	0.064
Plot 4	0.721	0.332	0.655	0.291	0.795	0.638	0.692	0.379
Plot 5	0.660	0.346	0.720	0.385	0.772	0.409	0.717	0.361
Plot 6	0.450	0.287	0.574	0.287	0.624	0.325	0.602	0.317
Total	***0.540***	***0.143***	***0.590***	***0.144***	***0.657***	***0.223***	***0.601***	***0.126***

Table 0.6 – Experimental Field data for Manning's n for Burned plots

	BURNED							
	Run 1		Run 2		Run 3		Overall	
	Average	Stdev	Average	Stdev	Average	Stdev	Average	Stdev
Plot 1	0.220	0.000	0.604	0.000	0.431	0.019	0.421	0.158
Plot 2	0.214	0.135	0.002	0.003	0.125	0.098	0.112	0.128
Plot 3	0.242	0.094	0.191	0.109	0.128	0.013	0.187	0.093
Plot 4	0.231	0.223	0.172	0.105	0.358	0.040	0.255	0.149
Plot 5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Plot 6	0.199	0.049	0.229	0.049	0.158	0.110	0.196	0.075
Total	***0.184***	***0.086***	***0.199***	***0.052***	***0.200***	***0.046***	***0.195***	***0.059***

Table 0.7 - t-Test: Two-Sample Assuming Unequal Variances (Manning's n)

t-Test: Two-Sample Assuming Unequal Variances

	Pre-Fire Average	*Post-Fire Average*
Mean	0.601060296	0.19526125
Variance	0.018286459	0.019949537
Observations	6	6
Hypothesized Mean Difference	0	
df	10	
t Stat	5.083355047	
P(T<=t) two-tail	0.000475448	
t Critical two-tail	2.228138842	

Annex 5. Infiltration Data

Table 0.8 - Saturated Hydraulic Conductivity Data (Ksat)

Location	PRE-FIRE	POST-FIRE
T21	349.154	181.560
T22	516.663	268.665
T23	495.813	257.823
T41	378.317	196.725
T42	169.588	88.186
T43	360.363	187.389
T45	283.979	147.669
T54	203.725	105.937
T62	435.196	226.302
T71	235.783	122.607
T72	537.850	279.682
TN1	435.496	226.458
TN2	658.017	342.169
TN3	446.763	232.316
TS1	260.979	135.709

Table 0.9 - t-Test: Two-Sample Assuming Unequal Variances (K_{sat})

t-Test: Two-Sample Assuming Unequal Variances

	PRE-FIRE	*POST-FIRE*
Mean	384.5122	199.9464
Variance	18960.56	5126.936
Observations	15	15
Hypothesized Mean Difference	0	
df	21	
t Stat	4.605759	
P(T<=t) two-tail	0.000153	
t Critical two-tail	2.079614	

Table 0.10 - Initial Soil Moisture Data (Thetai)

	THETAI [%]	
Location	**PRE-FIRE**	**POST-FIRE**
A1	0.303	0.276
A2	0.311	0.283
A3	0.329	0.299
A4	0.264	0.240

	THETAI [%]	
Location	**PRE-FIRE**	**POST-FIRE**
B1	0.315	0.286
B2	0.270	0.246
B3	0.306	0.278
C1	0.247	0.225
C2	0.255	0.232
C3	0.280	0.254
D1	0.301	0.274
D2	0.321	0.292
D3	0.287	0.261
E1	0.362	0.329

Table 0.11 – t-Test: Two-Sample Assuming Unequal Variances (Thetai)

t-Test: Two-Sample Assuming Unequal Variances

	PRE-FIRE	*POST-FIRE*
Mean	0.296357	0.269685
Variance	0.000991	0.000821
Observations	14	14
Hypothesized Mean Difference	0	
df	26	
t Stat	2.344802	
P(T<=t) two-tail	0.026948	
t Critical two-tail	2.055529	

Table 0.12 - Saturated Volumetric Soil Moisture Data (Thetas)

	THETAS [%]	
Location	**PRE-FIRE**	**POST-FIRE**
A1	0.644	0.418
A2	0.614	0.399
A3	0.512	0.333
A4	0.526	0.342
B1	0.686	0.446
B2	0.671	0.436
B3	0.571	0.371
C1	0.659	0.428
C2	0.696	0.452
C3	0.683	0.444
D1	0.624	0.406
D2	0.643	0.418
D3	0.650	0.422

	THETAS [%]	
Location	**PRE-FIRE**	**POST-FIRE**
E1	0.608	0.395
E2	0.607	0.394
E3	0.640	0.416

Table 0.13 – t-Test: Two-Sample Assuming Unequal Variances (Thetas)

t-Test: Two-Sample Assuming Unequal Variances

	PRE-FIRE	*POST-FIRE*
Mean	0.626987	0.407542
Variance	0.002863	0.001209
Observations	16	16
Hypothesized Mean Difference	0	
df	26	
t Stat	13.75584	
P(T<=t) two-tail	1.92E-13	
t Critical two-tail	2.055529	

Annex 6. Storm Evaluation

Table 0.14 – SCS Type I storm distribution (source: C. Mannaerts)

Filename	EI_SCS_T1	Water Erosion Prediction
Description	EI computation spreadheet for a SCS Type I storm distribution	
Description	Example duration: 06 hr.	
STATION NAME:	Coimbra -Treturn=2yr	
STORM DATE:	design storm data	

Storm Distribution in fraction	**Cumulative Rainfall depth in [mm]**	**Rainfall increment in [mm]**	**Kinetic Energy/mm [MJ/ha*mm]**	**Energy per /increment [MJ/ha]**		**15-min Rain Intensity I15 in [mm/h]**	**30-min Rain Intensity I30 in [mm/h]**
0.010	0.4	0.36	0.10	0.03		1.4	
0.010	0.7	0.36	0.10	0.03		1.4	1.4
0.015	1.3	0.54	0.10	0.06		2.2	1.8
0.020	2.0	0.72	0.11	0.08		2.9	2.5
0.025	2.9	0.90	0.12	0.10		3.6	3.2
0.025	3.8	0.90	0.12	0.10		3.6	3.6
0.030	4.9	1.08	0.12	0.13		4.3	4.0
0.045	6.5	1.62	0.14	0.23		6.5	5.4
0.070	9.0	2.53	0.16	0.41		10.1	8.3
0.295	19.7	10.65	0.27	2.82		42.6	26.4
0.105	23.5	3.79	0.19	0.73		15.2	28.9
0.070	26.0	2.53	0.16	0.41		10.1	12.6
0.045	27.6	1.62	0.14	0.23		6.5	8.3
0.030	28.7	1.08	0.12	0.13		4.3	5.4
0.025	29.6	0.90	0.12	0.10		3.6	4.0
0.020	30.3	0.72	0.11	0.08		2.9	3.2
0.020	31.0	0.72	0.11	0.08		2.9	2.9
0.020	31.8	0.72	0.11	0.08		2.9	2.9
0.020	32.5	0.72	0.11	0.08		2.9	2.9
0.020	33.2	0.72	0.11	0.08		2.9	2.9
0.020	33.9	0.72	0.11	0.08		2.9	2.9
0.020	34.7	0.72	0.11	0.08		2.9	2.9
0.020	35.4	0.72	0.11	0.08		2.9	2.9
0.020	36.1	0.72	0.11	0.08		2.9	2.9
Rain depth	36.1	[mm]	Energy=	6.324	Imax30=	42.6	

			UNIT SYSTEMS
RAINFALL STORM EROSIVITY ESTIMATE =	EI30-SI(1)	269.41	[MJ/ha*mm/hr]
CONVERSION TO OTHER UNITS	EI30-SI	26.94	[KJ/m2*mm/hr]
Conventional US.rainfall erosivity units -->	R-usa	15.83	100[ft.UStonf/acre*inch/hr]
	EI30-usa	1582.88	[ft.UStonf/acre*inch/hr]
(old) Eur. rainfall erosivity units -->	R-mks	27.43	100[m.tonf/ha*cm/hr]
	EI30-mks	2743.44	[m.tonf/ha*cm/hr]

INPUT DATA RANGE		
FILENAME:	**EI_SCS_T1**	
STATION NAME:	**Coimbra -Treturn=2yr**	
STORM DATE:	**design storm data**	
RAINFALL DEPTH:	**36.1**	[mm]

Table 0.15 – SCS Type II storm distribution (source: C. Mannaerts)

Filename	EI_T2_Coimbra_15	Water Erosion Prediction
Description	EI computation spreadheet for a SCS Type II storm distribution	
Description	Example duration: 06 hr.	
STATION NAME:	Coimbra (return period 2yrs)	
STORM		
DATE:	design criteria ref. precipitacoes intensas portugal	

Storm Distribution in fraction	**Cumulative Rainfall depth in [mm]**	**Rainfall increment in [mm]**	**Kinetic Energy/mm [MJ/ha*mm]**	**Energy per /increment [MJ/ha]**		**15-min Rain Intensity I15 in [mm/h]**	**30-min Rain Intensity I30 in [mm/h]**
0.005	0.2	0.18	0.09	0.02		0.7	
0.005	0.4	0.18	0.09	0.02		0.7	0.7
0.010	0.7	0.36	0.10	0.03		1.4	1.1
0.010	1.1	0.36	0.10	0.03		1.4	1.4
0.015	1.6	0.54	0.10	0.06		2.2	1.8
0.015	2.2	0.54	0.10	0.06		2.2	2.2
0.020	2.9	0.72	0.11	0.08		2.9	2.5
0.020	3.6	0.72	0.11	0.08		2.9	2.9
0.030	4.7	1.08	0.12	0.13		4.3	3.6
0.035	6.0	1.26	0.13	0.16		5.1	4.7
0.070	8.5	2.53	0.16	0.41		10.1	7.6
0.425	23.8	15.34	0.28	4.30		61.4	35.7
0.120	28.2	4.33	0.20	0.88		17.3	39.3
0.050	30.0	1.81	0.14	0.26		7.2	12.3
0.040	31.4	1.44	0.13	0.19		5.8	6.5
0.030	32.5	1.08	0.12	0.13		4.3	5.1
0.025	33.4	0.90	0.12	0.10		3.6	4.0
0.020	34.1	0.72	0.11	0.08		2.9	3.2
0.010	34.5	0.36	0.10	0.03		1.4	2.2
0.010	34.8	0.36	0.10	0.03		1.4	1.4
0.010	35.2	0.36	0.10	0.03		1.4	1.4
0.010	35.6	0.36	0.10	0.03		1.4	1.4
0.010	35.9	0.36	0.10	0.03		1.4	1.4
0.005	36.1	0.18	0.09	0.02		0.7	1.1
Rain depth	36.1	[mm]	Energy=	7.212	Imax30=	61.4	
						UNIT SYSTEMS	

RAINFALL STORM EROSIVITY ESTIMATE =	EI30-SI(1)	442.61	[MJ/ha*mm/hr]
CONVERSION TO OTHER UNITS	EI30-SI	44.26	[KJ/m2*mm/hr]
Conventional US.rainfall erosivity units -->	R-usa	26.01	100[ft.UStonf/acre*inch/hr]
	EI30-usa	2600.53	[ft.UStonf/acre*inch/hr]
(old) Eur. rainfall erosivity units -->	R-mks	45.07	100[m.tonf/ha*cm/hr]
	EI30-mks	4507.23	[m.tonf/ha*cm/hr]

INPUT DATA RANGE		
FILENAME:	**EI_T2_Coimbra_15**	
STATION NAME:	**Coimbra (return period 2yrs)**	
STORM		
DATE:	**design criteria ref. precipitacoes intensas portugal**	
RAINFALL DEPTH:	**36.1**	[mm]

Annex 7. Interception field data

Table 0.16 – Rainfall readings on the installed interception devices on the field

		23-Oct				**17-Nov**				**2-Dec**		
Rain		**ml**	**mm**	**cover**		**ml**	**mm**	**cover**		**ml**	**mm**	**cover**
	metal	353	26.7	0	**metal**				**metal**	1125	85.2	0
	I6X	1160	63.6	0.0	**I6X**	630	34.6	0.0	**I6X**	1175	64.5	0.0
	I12X	1235	62.8	0	**I12X**	595	30.3	0	**I12X**	1192	60.7	0
	I18X	1195	60.8	0	**I18X**	615	31.3	0	**I18X**	1202	61.2	0
		average	62.4	0.0		average	32.0	0.0		average	62.1	0.0
		stdev	1.5	0.0		stdev	2.2	0.0		stdev	2.1	0.0
		5-Dec				**12-Dec**				**15-Dec**		
		ml	**mm**	**cover**		**ml**	**mm**	**cover**		**ml**	**mm**	**cover**
	metal	690	52.3	0	**metal**	770	58.3	0	**metal**	640	48.5	0
	I6X	1085	59.5	0.0	**I6X**	1130	62.0	0.0	**I6X**	980	53.8	0.0
	I12X	1070	54.5	0	**I12X**	1295	65.9	0	**I12X**	1040	52.9	0
	I18X	1030	52.4	0	**I18X**	1290	65.6	0	**I18X**	1000	50.9	0
		average	55.5	0.0		average	64.5	0.0		average	52.5	0.0
		stdev	3.7	0.0		stdev	2.2	0.0		stdev	1.5	0.0
		7-Jan				**16-Jan**				**21-Jan**		
		ml	**mm**	**cover**		**ml**	**mm**	**cover**		**ml**	**mm**	**cover**
	metal	1440	109.1	0	**metal**	630	47.7	0	**metal**	670	50.8	0
	I6X	1940	106.4	0.0	**I6X**	770	42.2	0.0	**I6X**	1043	57.2	0.0
	I12X	2260	115.0	0	**I12X**	940	47.8	0	**I12X**	1120	57.0	0
	I18X	2310	117.6	0	**I18X**	950	48.3	0	**I18X**	1050	53.4	0
		average	113.0	0.0		average	46.1	0.0		average	55.9	0.0
		stdev	5.8	0.0		stdev	3.4	0.0		stdev	2.1	0.0
		1-Feb				**6-Feb**				**10-Feb**		
		ml	**mm**	**cover**		**ml**	**mm**	**cover**		**ml**	**mm**	**cover**
	metal	3425	259.5	0	**metal**	950	72.0	0	**metal**	290	22.0	0
	I6X	3930	215.6	0.0	**I6X**	1320	72.4	0.0	**I6X**	460	25.2	0.0
	I12X	3600	183.2	0	**I12X**	1460	74.3	0	**I12X**	450	22.9	0
	I18X	3760	191.3		**I18X**	1440	73.3	0	**I18X**	460	23.4	0
		average	196.7	0.0		average	73.3	0.0		average	23.9	0.0
		stdev	16.9	0.0		stdev	0.9	0.0		stdev	1.2	0.0

Table 0.17 – Interception and throughfall (mm & %) measured in the field – lower South facing slope

	23-Oct				17-Nov				2-Dec		
South low	ml	mm	cover	South low	ml	mm	cover	South low	ml	mm	cover
I1	685	37.6	10	**I1**	365	20.0	30	**I1**	780	42.8	20
I2	850	46.6	5	**I2**	300	16.5	85	**I2**	320	17.6	100
I3	625	34.3	25	**I3**	300	16.5	20	**I3**	480	26.3	95
I4	470	25.8	35	**I4**	350	19.2	30	**I4**	100	5.5	90

I5	370	20.3	70	**I5**	245	13.4	90	**I5**	130	7.1	90
	average	32.9	29.0		average	17.1	51.0		average	19.9	79.0
	stdev	10.3	25.8		stdev	2.6	33.6		stdev	15.3	33.2
Throughfall			53 %	Throughfall			53 %	Throughfall			32 %
stdev			16 %	stdev			8 %	stdev			25 %
Rain intercepted			47 %	Rain intercepted			47 %	Rain intercepted			68 %
	5-Dec				12-Dec				15-Dec		
South low	ml	mm	cover	South low	ml	mm	cover	South low	ml	mm	cover
I1	680	37.3	25	**I1**	748	41.0	25	**I1**	700	38.4	10
I2	440	24.1	65	**I2**	435	23.9	60	**I2**	600	32.9	20
I3	595	32.6	40	**I3**	805	44.2	50	**I3**	380	20.9	95
I4	610	33.5	50	**I4**	450	24.7	50	**I4**	730	40.1	65
I5	610	33.5	40	**I5**	475	26.1	50	**I5**	520	28.5	95
	average	32.2	44.0		average	32.0	47.0		average	32.2	57.0
	stdev	4.9	14.7		stdev	9.8	13.0		stdev	7.8	40.4
Throughfall			58 %	Throughfall			50 %	Throughfall			61 %
stdev			9 %	stdev			15 %	stdev			15 %
Rain intercepted			42 %	Rain intercepted			50 %	Rain intercepted			39 %
	7-Jan				16-Jan				21-Jan		
South low	ml	mm	cover	South low	ml	mm	cover	South low	ml	mm	cover
I1	1395	76.5	10	**I1**	590	32.4	15	**I1**	785	43.1	15
I2	1065	58.4	35	**I2**	375	20.6	15	**I2**	700	38.4	40
I3	1750	96.0	30	**I3**	940	51.6	35	**I3**	610	33.5	40
I4	625	34.3	40	**I4**	260	14.3	75	**I4**	575	31.6	30
I5	710	39.0	50	**I5**	330	18.1	50	**I5**	520	28.5	65
	average	60.9	33.0		average	27.4	38.0		average	35.0	38.0
	stdev	25.9	14.8		stdev	15.1	25.4		stdev	5.8	18.2
Throughfall			54 %	Throughfall			59 %	Throughfall			63 %
stdev			23 %	stdev			33 %	stdev			10 %
Rain intercepted			46 %	Rain intercepted			41 %	Rain intercepted			37 %
	1-Feb				6-Feb				10-Feb		
South low	ml	mm	cover	South low	ml	mm	cover	South low	ml	mm	cover
I1	3395	186.3	20	**I1**	980	53.8	10	**I1**	275	15.1	25
I2	3300	181.1	20	**I2**	880	48.3	10	**I2**	270	14.8	40
I3	3640	199.7	25	**I3**	1010	55.4	30	**I3**	245	13.4	50
I4	2545	139.6	10	**I4**	400	21.9	75	**I4**	210	11.5	70
I5	2250	123.5	50	**I5**	570	31.3	20	**I5**	200	11.0	70
	average	166.0	25.0		average	42.1	29.0		average	13.2	51.0
	stdev	32.7	15.0		stdev	14.8	27.0		stdev	1.9	19.5
Throughfall			84 %	Throughfall			57 %	Throughfall			55 %
stdev			17 %	stdev			20 %	stdev			8 %
Rain intercepted			16 %	Rain intercepted			43 %	Rain intercepted			45 %

Table 0.18 – Interception and throughfall (mm & %) measured in the field – lower North facing slope

	23-Oct				17-Nov				2-Dec		
North low	**ml**	**mm**	**cover**	**North low**	**ml**	**mm**	**cover**	**North low**	**ml**	**mm**	**cover**

I7	510	26.0	75	**I7**	235	12.9	95	**I7**	460	25.2	95
I8	475	24.2	50	**I8**	225	12.3	85	**I8**	270	14.8	95
I9	550	28.0	90	**I9**	160	8.8	100	**I9**	555	30.5	100
I10	380	19.3	70	**I10**	175	9.6	95	**I10**	705	38.7	95
I11	730	37.2	40	**I11**	350	19.2	35	**I11**	420	23.0	75
	average	26.9	65.0		average	12.6	82.0		average	26.4	92.0
	stdev	6.6	20.0		stdev	4.1	26.8		stdev	8.9	9.7
Throughfall		43 %		Throughfall		39 %		Throughfall		43 %	
stdev		10 %		stdev		13 %		stdev		14 %	
Rain intercepted		57 %		Rain intercepted		61 %		Rain intercepted		57 %	

	5-Dec				12-Dec				15-Dec		
North low	**ml**	**mm**	**cover**	**North low**	**ml**	**mm**	**cover**	**North low**	**ml**	**mm**	**cover**
I7	405	22.2	40	**I7**	530	29.1	50	**I7**	480	26.3	40
I8	190	10.4	40	**I8**	310	17.0	80	**I8**	260	14.3	95
I9	535	29.4	40	**I9**	690	37.9	40	**I9**	580	31.8	100
I10	975	53.5	90	**I10**	965	52.9	95	**I10**	960	52.7	75
I11	580	31.8	50	**I11**	665	36.5	60	**I11**	580	31.8	50
	average	29.5	52.0		average	34.7	65.0		average	31.4	72.0
	stdev	15.8	21.7		stdev	13.1	22.4		stdev	13.9	26.6
Throughfall		53 %		Throughfall		54 %		Throughfall		60 %	
stdev		28 %		stdev		20 %		stdev		26 %	
Rain intercepted		47 %		Rain intercepted		46 %		Rain intercepted		40 %	

	7-Jan				16-Jan				21-Jan		
North low	**ml**	**mm**	**cover**	**North low**	**ml**	**mm**	**cover**	**North low**	**ml**	**mm**	**cover**
I7	960	52.7	20	**I7**	390	21.4	40	**I7**	570	31.3	25
I8	875	48.0	90	**I8**	320	17.6	95	**I8**	205	11.2	50
I9	1075	59.0	75	**I9**	440	24.1	90	**I9**	540	29.6	70
I10	1375	75.4	80	**I10**	575	31.6	95	**I10**	860	47.2	95
I11	1425	78.2	60	**I11**	485	26.6	90	**I11**	540	29.6	50
	average	62.7	65.0		average	24.3	82.0		average	29.8	58.0
	stdev	13.5	27.4		stdev	5.3	23.6		stdev	12.7	26.1
Throughfall		55 %		Throughfall		53 %		Throughfall		53 %	
stdev		12 %		stdev		11 %		stdev		23 %	
Rain intercepted		45 %		Rain intercepted		47 %		Rain intercepted		47 %	

	1-Feb				6-Feb				10-Feb		
North low	**ml**	**mm**	**cover**	**North low**	**ml**	**mm**	**cover**	**North low**	**ml**	**mm**	**cover**
I7	3040	166.8	30	**I7**	600	32.9	70	**I7**	255	14.0	65
I8	1790	98.2	50	**I8**	680	37.3	30	**I8**	115	6.3	60
I9	3200	175.6	30	**I9**	640	35.1	60	**I9**	190	10.4	80
I10	3600	197.5	90	**I10**	1010	55.4	90	**I10**	325	17.8	60
I11	2900	159.1	50	**I11**	950	52.1	30	**I11**	205	11.2	75
	average	159.5	50.0		average	42.6	56.0		average	12.0	68.0
	stdev	37.1	24.5		stdev	10.4	26.1		stdev	4.3	9.1
Throughfall		81 %		Throughfall		58 %		Throughfall		50 %	
stdev		19 %		stdev		14 %		stdev		18 %	
Rain intercepted		19 %		Rain intercepted		42 %		Rain intercepted		50 %	

Table 0.19 – Interception and throughfall (mm & %) measured in the field - upper North facing slope

	23-Oct				17-Nov				2-Dec		
North high	**ml**	**mm**	**cover%**	**North high**	**ml**	**mm**	**cover%**	**North high**	**ml**	**mm**	**cover%**
I13	665	36.5	95	**I13**	220	12.1	95	**I13**	430	23.6	100
I14	220	12.1	95	**I14**	90	4.9	100	**I14**	635	34.8	100
I15	380	19.3	90	**I15**	215	11.8	100	**I15**	445	24.4	95
I16	300	15.3	75	**I16**	240	13.2	80	**I16**	240	13.2	100
I17	345	17.6	95	**I17**	125	6.9	100	**I17**	425	23.3	100
	average	20.1	90.0		average	9.8	95.0		average	23.9	99.0
	stdev	9.5	8.7		stdev	3.6	8.7		stdev	7.7	2.2
Throughfall			32 %	Throughfall			30 %	Throughfall			38 %
stdev			15 %	stdev			11 %	stdev			12 %
Rain intercepted			68 %	Rain intercepted			70 %	Rain intercepted			62 %

	5-Dec				12-Dec				15-Dec		
North high	**ml**	**mm**	**cover%**	**North high**	**ml**	**mm**	**cover%**	**North high**	**ml**	**mm**	**cover%**
I13	385	21.1	70	**I13**	335	18.4	50	**I13**	430	23.6	95
I14	390	21.4	90	**I14**	547	30.0	100	**I14**	440	24.1	100
I15	385	21.1	50	**I15**	490	26.9	60	**I15**	425	23.3	100
I16	230	12.6	80	**I16**	285	15.6	50	**I16**	280	15.4	100
I17	375	20.6	100	**I17**	447	24.5	100	**I17**	680	37.3	100
	average	19.4	78.0		average	23.1	72.0		average	24.7	99.0
	stdev	3.8	19.2		stdev	6.0	25.9		stdev	7.9	2.2
Throughfall			35 %	Throughfall			36 %	Throughfall			47 %
stdev			7 %	stdev			9 %	stdev			15 %
Rain intercepted			65 %	Rain intercepted			64 %	Rain intercepted			53 %

	7-Jan				16-Jan				21-Jan		
North high	**ml**	**mm**	**cover%**	**North high**	**ml**	**mm**	**cover%**	**North high**	**ml**	**mm**	**cover%**
I13	775	42.5	50	**I13**				**I13**	440	24.1	100
I14	665	36.5	90	**I14**	265	14.5	100	**I14**	440	24.1	90
I15	835	45.8	70	**I15**	350	19.2	80	**I15**	425	23.3	90
I16	685	37.6	70	**I16**	335	18.4	20	**I16**	430	23.6	10
I17	760	41.7	80	**I17**	315	17.3	95	**I17**	475	26.1	90
	average	40.8	72.0		average	17.4	73.8		average	24.3	76.0
	stdev	3.8	14.8		stdev	2.0	36.8		stdev	1.1	37.1
Throughfall			36 %	Throughfall			38 %	Throughfall			43 %
stdev			3 %	stdev			4 %	stdev			2 %
Rain intercepted			64 %	Rain intercepted			62 %	Rain intercepted			57 %

	1-Feb				6-Feb				10-Feb		
North high	**ml**	**mm**	**cover%**	**North high**	**ml**	**mm**	**cover%**	**North high**	**ml**	**mm**	**cover%**
I13	2150	118.0	80	**I13**	470	25.8	90	**I13**	935	51.3	100
I14	2000	109.7	90	**I14**	480	26.3	100	**I14**	200	11.0	100
I15	2025	111.1	70	**I15**	580	31.8	50	**I15**	160	8.8	80
I16	3230	177.2	60	**I16**	1440	79.0	20	**I16**	140	7.7	60
I17	2085	114.4	100	**I17**	855	46.9	100	**I17**	180	9.9	90
	average	126.1	80.0		average	42.0	72.0		average	9.3	86.0
	stdev	28.8	15.8		stdev	22.4	35.6		stdev	18.8	16.7

Throughfall	64 %	Throughfall	57 %	Throughfall	39 %
stdev	15 %	stdev	31 %	stdev	79 %
Rain intercepted	36 %	Rain intercepted	43 %	Rain intercepted	61 %

Annex 8. Lisem output for pre fire simulations with real storms

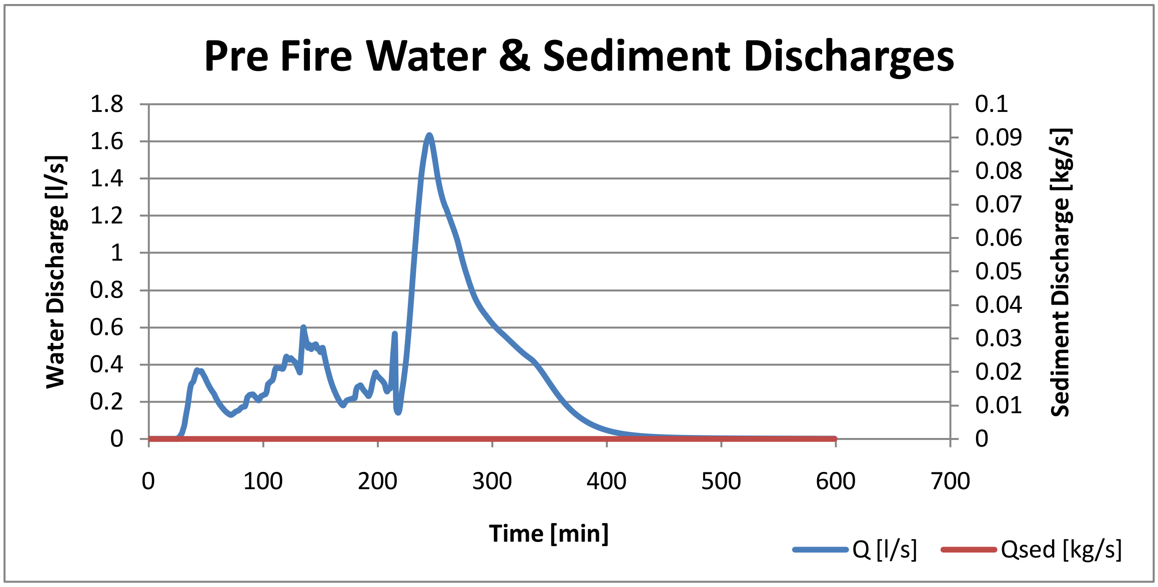

Figure 0.2 – Lisem output of pre fire discharges – September 5th Storm

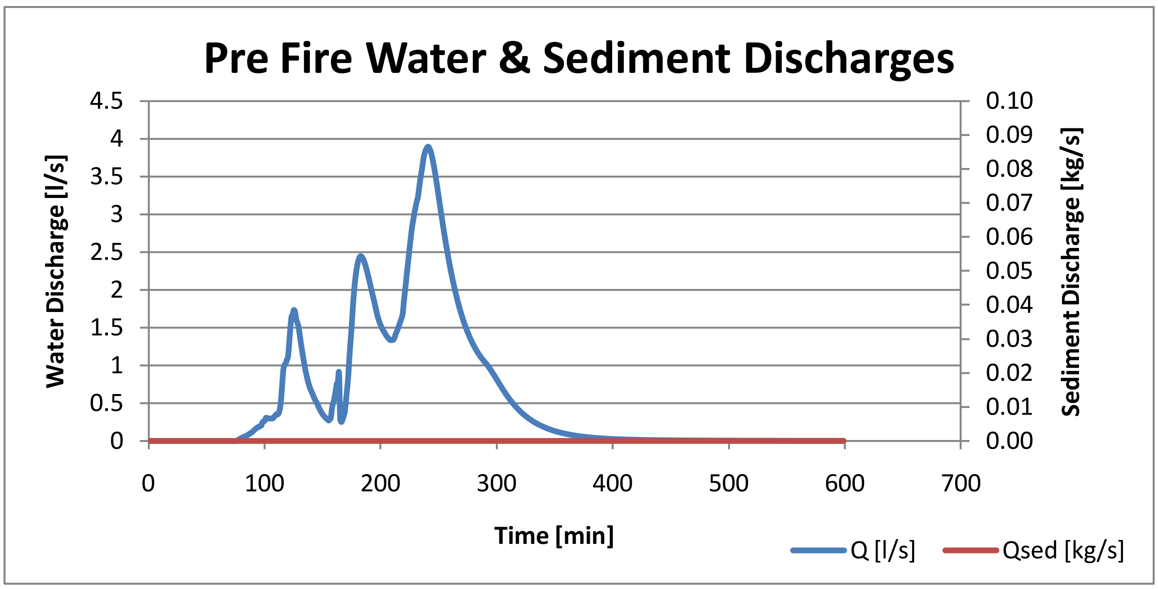

Figure 0.3 – Lisem output of pre fire discharges – October 7th Storm

Annex 9. Lisem output for post fire simulations with real storms

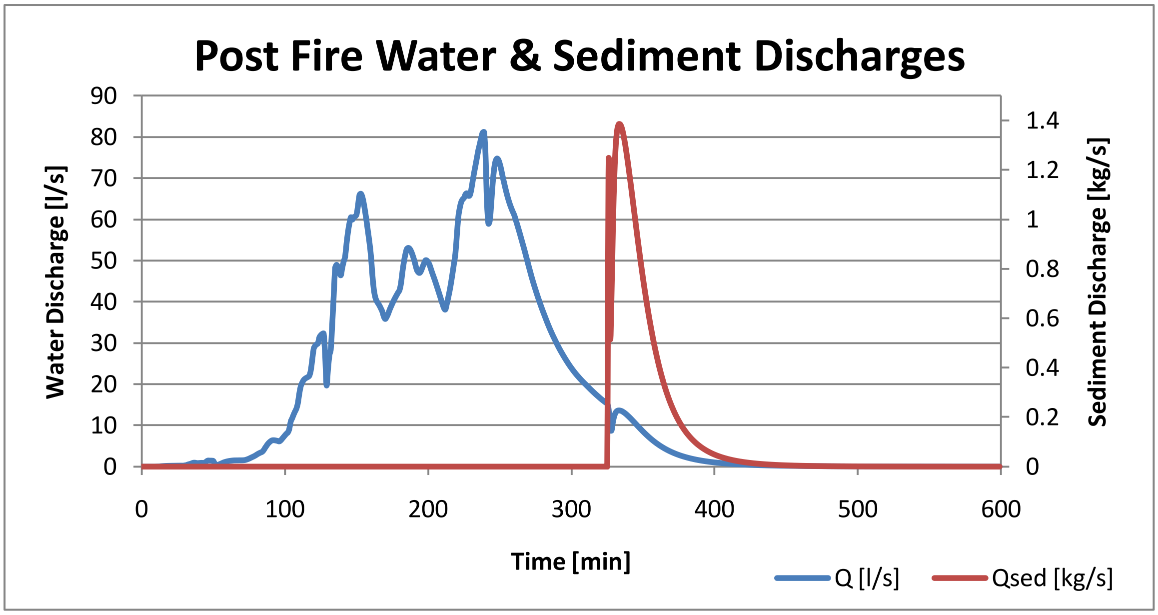

Figure 0.4 – Lisem output of post fire discharges – September 5th Storm

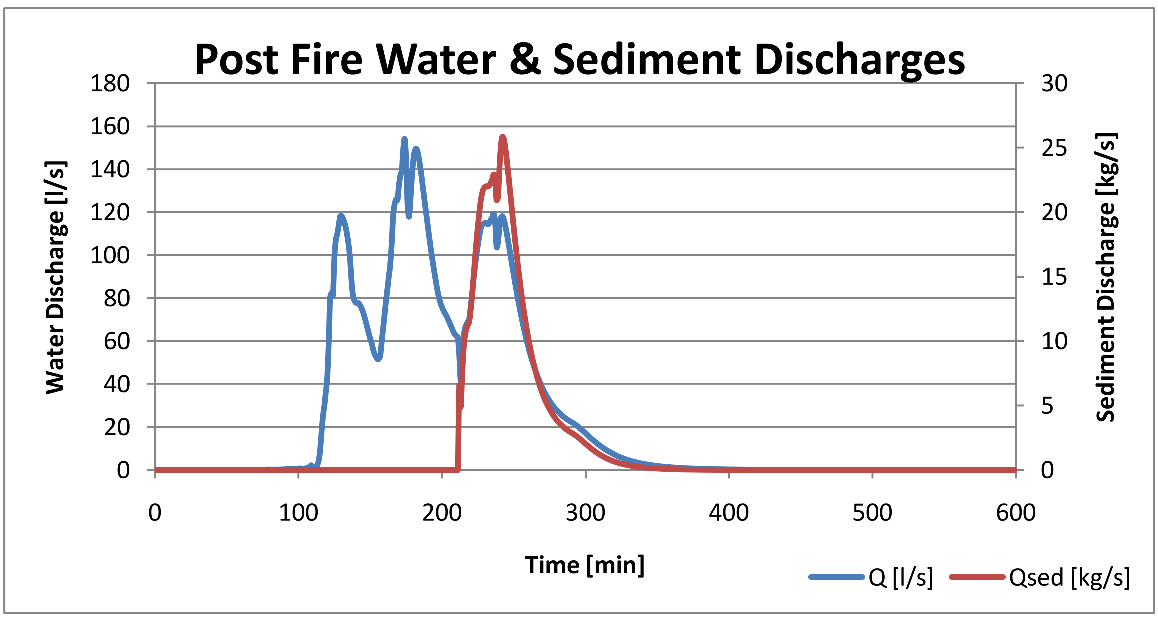

Figure 0.5 – Lisem output of post fire discharges – October 7th Storm

Annex 10. Pictures (fieldwork & lab works)

Figure 0.6 – Soil sampling for lab testing

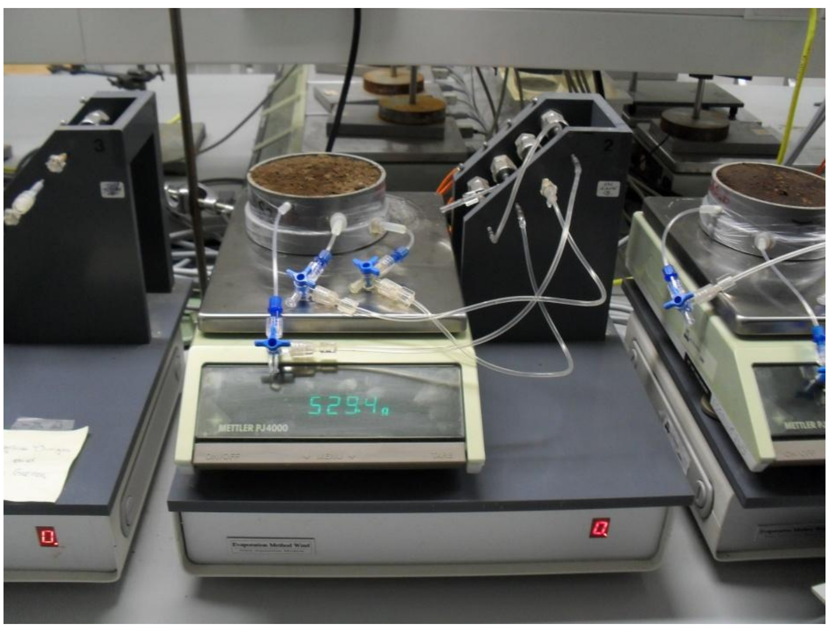

Figure 0.7 – Lab testing (K_{sat}), and moisture

Annex 11. Some LISEM Input Maps

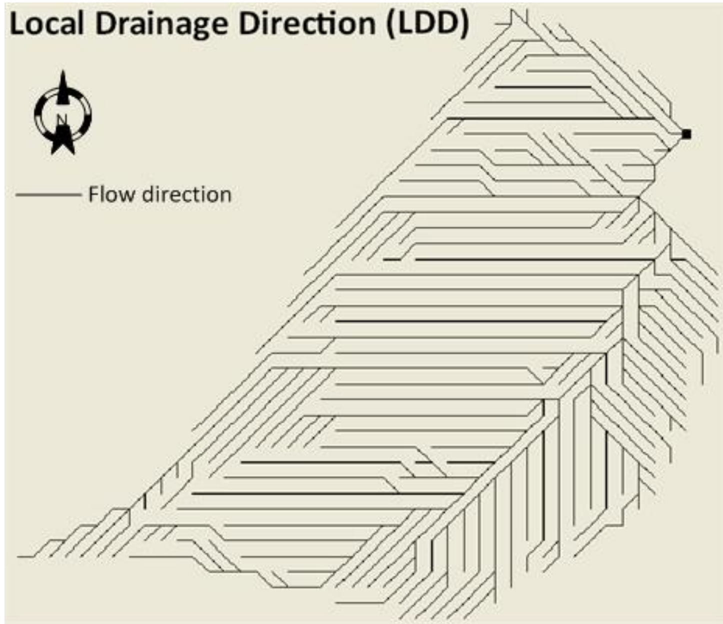

Figure 0.8 – Local Drainage Direction Map (LDD) Map

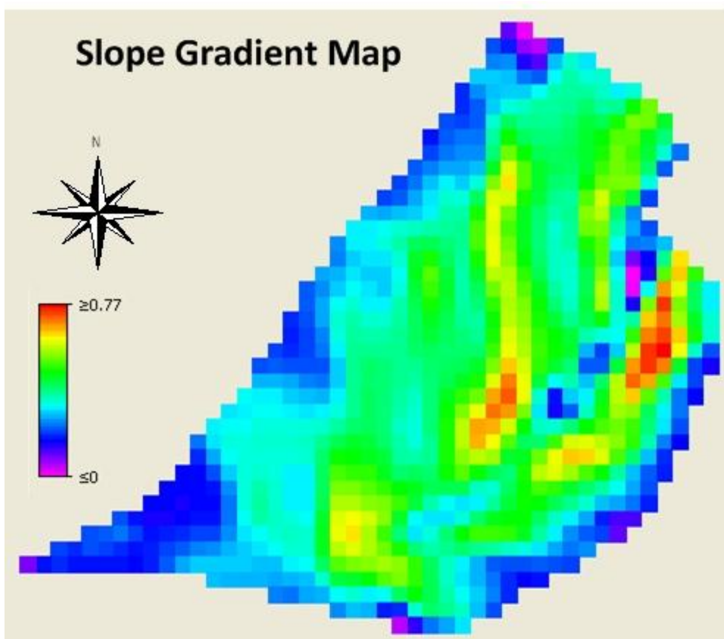

Figure 0.9 - Slope gradient Map

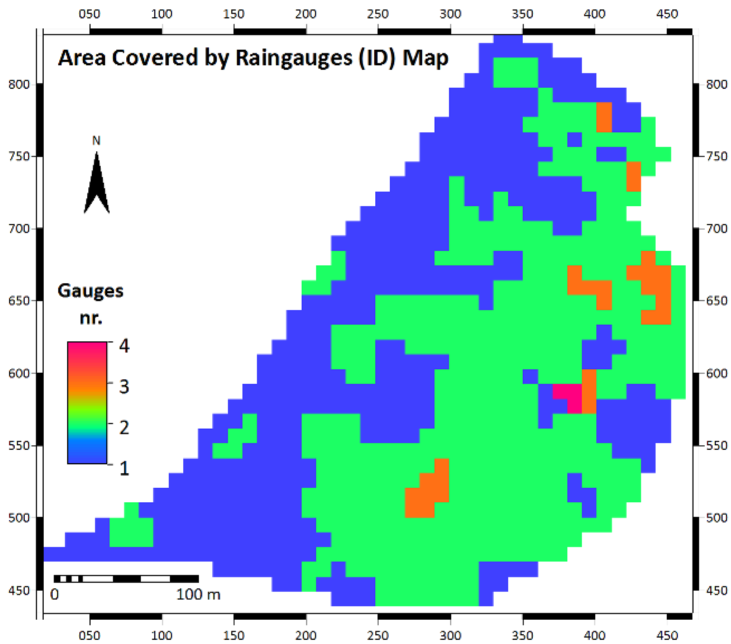

Figure 0.10 – Rain Gauges Area Map

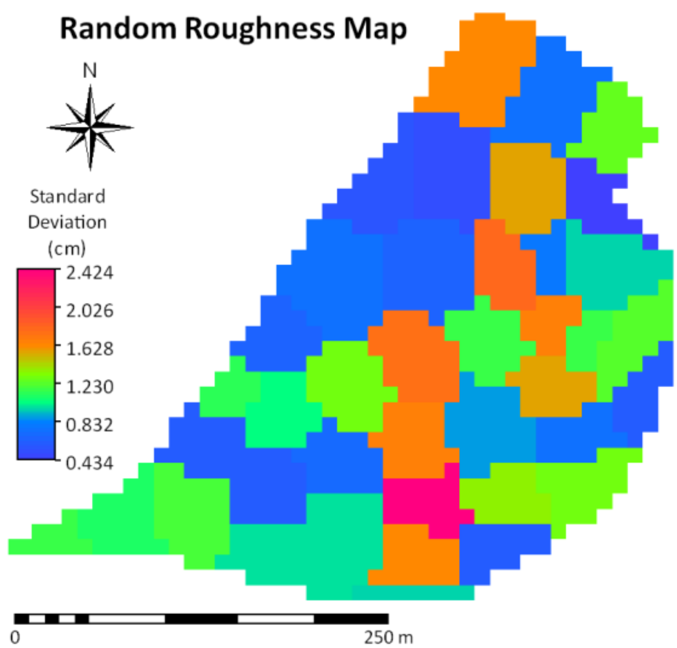

Figure 0.11 – Random Roughness Map

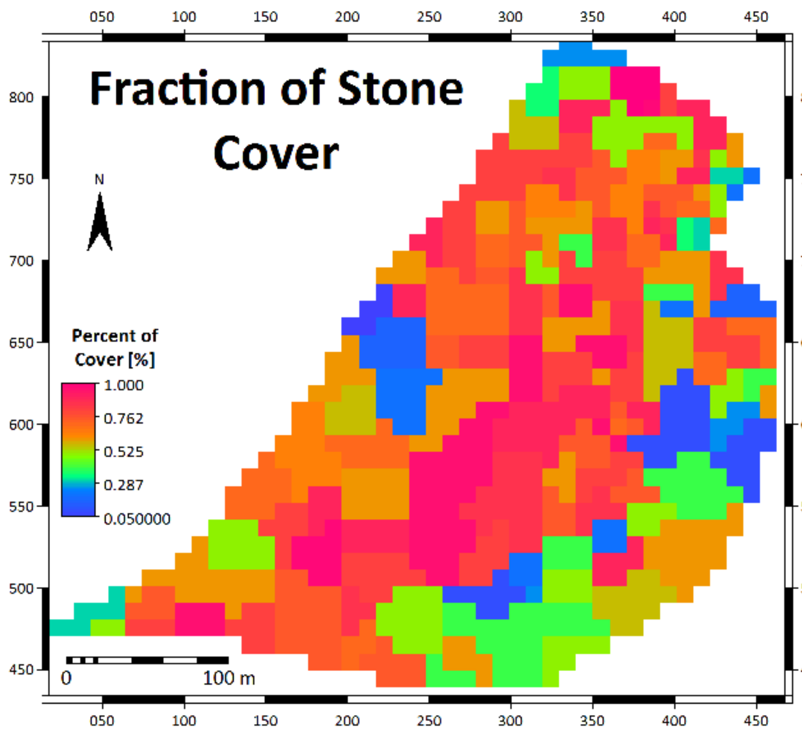

Figure 0.12 – Stone Fraction Map

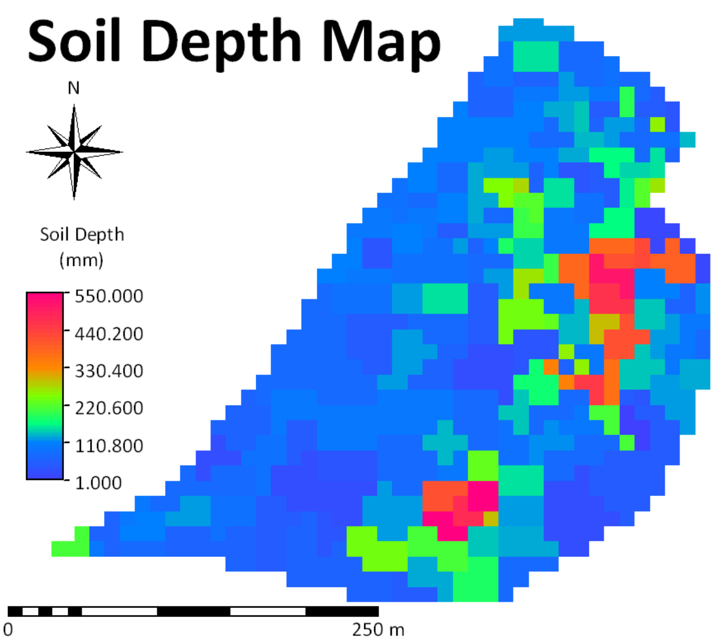

Figure 0.13 – Soil Depth Map