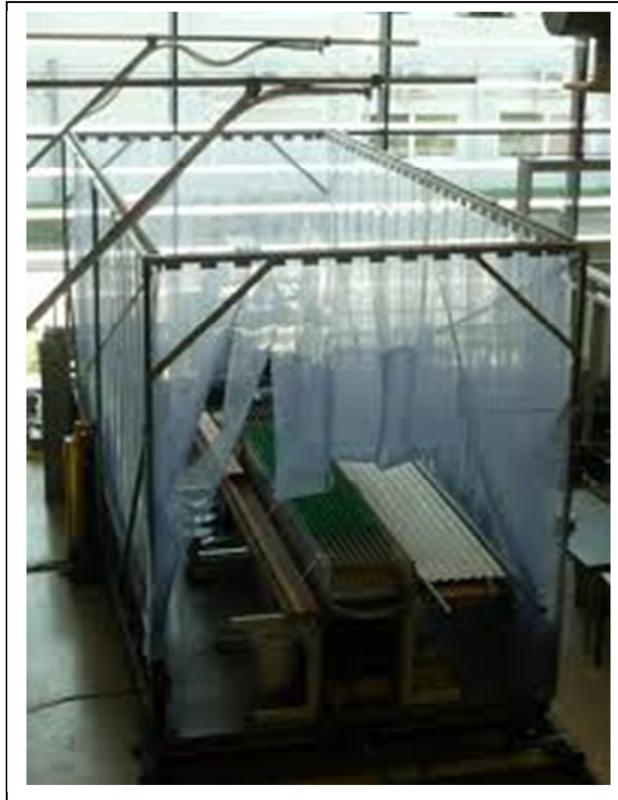Land Degradation & Development Group

RELATIONSHIP BETWEEN RAINFALL INTENSITIES, AGGREGATE STABILITY AND SHEAR RESISTANCE AS PARAMETERS TO EVALUATE SOIL EROSION BY WATER: AN EXPERIMENTAL STUDY

MSc thesis by A.I Marruedo Arricibita

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WAGENINGEN UNIVERSITY
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Relationship between rainfall intensities, aggregate stability and shear resistance as parameters to evaluate soil erosion by water: an experimental study

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Preface & Acknowledgements

During the 4 months of this experimental research I have learnt how to work and proceed in laboratory work conditions. I have learnt how to design and think about the setup of the experiments and deal with the problems that might appear during the preparation of the rainfall experiments set up and measurements.

First of all, I would like to thanks my family for the emotional, moral and economical support that they always gave to me in order to complete my academic education and my personal goals. Secondly, I also would like to thanks my friends in my home country (Spain) as well as to my good friends in Wageningen and Firehouse, that always have been there supporting me during the realization of this thesis research.

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A.I. Marruedo Arricibita

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Abstract

It is generally assumed there is a relation between raindrop impact on soil surface, aggregate stability and shear stress. Since this relationship is of importance to understand the influence of raindrops on the detachment rate and the aggregate stability and shear strength; this study attempts to understand the influence of different rainfall intensities on aggregate stability and shear strength of a loamy texture soil from arable land. Furthermore, suspended sediment delivery and runoff water was monitored to assess the hydrology and erosion dynamics. Finally, we monitored soil surface development (soil crusting and small rill development) to assess soil particle detachment as well as runoff processes (hortonian overland flow conditions). This information enabled understanding of temporal thresholds depending on the different rainfall intensities applied of the arable loamy soil surface studied in this experimental research. The experimental set up consisted of two experiments in a laboratory rainfall simulator. The experiments comprised of 4 boxes (100cm x 49.5cm) which were put on an angle of 2.5 and 10-12 degrees respectively. As the rainfall intensities vary in the rainfall simulator, simultaneously the impact of rainfall intensities could be assessed. The different rainfall intensities influenced the runoff amount and suspended sediment amount in runoff water. Furthermore, the different slopes also influenced the amount of runoff water and suspended sediment amount in runoff water. Moisture content and the Ca cohesive component (horizontal force of shear strength) increased significantly after 75 minutes of rainfall but there were no significant differences between the different rainfall intensities applied. Aggregate stability increased with the slope of 2.5º and decreased with 10-12º slope. The roughness coefficient of soil surface did not change significantly when assessed with the chain method. However, the different rainfall intensities as well as the slope change did clearly influence the runoff erosion processes (runoff amount and suspended sediment amount). Yet, these changes were not reflected by the variables measured in this research: Moisture content, Ca cohesive component and aggregate stability. The soil surface roughness clearly changed due to the rainfall experiments, yet the chain method was not able to detect these changes. This shows that this methodology is too coarse to assess these small scaled differences. More suitable methodologies that will help to find and describe the complex relationship between the different rainfall intensities and: Moisture content, Ca cohesive component and aggregate stability is suggested; as well as the soil surface roughness changes in time. Finally, further research on the influence of different rainfall intensities, slope, soil textural type and crusting processes on the studied variables: Ca cohesive component, moisture content and aggregate stability is recommended.

Key words: Rainfall intensities, slope, soil textural type, moisture content, aggregate stability, shear strength, Ca cohesive component, roughness coefficient, rainfall simulator, surface test shear apparatus, wet sieving, chain method, laboratory, loamy soil.

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Introduction

Awareness of the influence of modern arable farming over the agricultural ecosystems as well as over the sustainability of these systems has been increasing during the second part of the twentieth century. Deterioration of soils and its structure, apart from other changes in farming ecosystems (landscape, flora, fauna, water and air quality), is now being associated with the use of modern arable farming as an environmental problem. Consequently, agricultural policies are beginning to include environmental considerations in the EU member countries (Stoate et al. 2001).

The method, timing and frequency of cultivation; soil type, rainfall amount and intensity, as well as the topography affect the soil itself. Changes in agricultural activities such as the increase of the field size or the use of heavy machinery led to an increase of the soil erosion; estimated mean annual soil loss according to the European Union Environment Directorate (DGXI) in northern Europe is 8 t ha^{-1} (Stoate et al 2001).

Apart from the environmental damage caused by soil erosion due to the use of modern arable farming (conventional farming techniques), damages in off farm infrastructures (roads, properties, communications and water ways) and pollution of drinking water, sedimentation of reservoirs and so on, must be taken into consideration which have influence in the society and economy of a region; which are higher than on-farm costs overcame by farmers (Stoate et al 2001).

As it is mentioned in the article by Boardman et al (1996), erosion problems and property damages by runoff from agricultural lands became frequent in The Netherlands in the 80s and 90s. As an example in 1985, the annual cost of the maintenance and repair of damage to private properties by erosion and flooding to seven communities in South-Limburg and to the Waterboard were almost US$ 800,000 (Boardman et al. 1996). The use of crops such as sugar beet and maize in this country have been increasing since 1960; which are 15 and 20 times more sensitive to erosion than cereals (Boardman et al. 1994). This is due to the fact that soils are exposed to rain during the autumn and winter (Stoate et al 2001). According to Boardman et al (1996), experimental works in the region of South-Limburg, in The Netherlands, suggested that rainfall intensities were leading to generation of Hortonian overland flow during summer. Furthermore, Hortonian overland flow also occurs during winter periods due to soil crusting of the soil surface in arable lands.

Thus, the influence of raindrop impact and rainfall intensity over the arable soils in the agricultural farming ecosystems in The Netherlands is of importance regarding soil erosion and runoff by water in terms of generation of Hortonian overland flow. According to several articles (Nearing et al. 1991, Le Bissonais 1996, Barthès et al 2002, Cantón et al. 2009, Boix-Fayos et al 2001 and Léonard et al. 2004), soil detachment of soil particles, is thought to be one of the main influencing parameters on water erosion and runoff. On the other hand, raindrop impact is suggested as an influencing parameter of soil detachment as well as soil aggregate stability and shear resistance (Nearing et al. 1991, Le Bissonais 1996, Barthès et al 2002, Cantón et al. 2009, Boix-Fayos et al 2001 and Léonard et al. 2004).

The influence of raindrop impact on detachment rate is also mentioned in Barthès et al (2002) and Le Bissonais (1996). Barthés et al. (2002) argue that apart from aggregate disintegration (aggregate stability and aggregate size); particle detachment due to raindrop shearing, overland flow and transport by rain splash and runoff also contribute to soil erosion by water. In addition, Le Bissonais (1996) mentions the influence of wet conditions regarding the impact of raindrops. The raindrop impact produces lateral shear stress causing the detachment and projection of the aggregate fragments. According to this, raindrops detach and displace the previously fragments detached. In addition, the size of the detached fragments determine the physical characteristics of the crust and their transportability (Le Bissonaiss 1996).

Léonard et al. (2004) highlighted the importance of hydraulic shear stress as the main parameter controlling the incipient motion of particles in flowing water. However, several studies (Nearing et al. 1991, Le Bissonais 1996, Barthès et al 2002, Cantón et al. 2009, Boix-Fayos et al 2001 and Léonard et al. 2004) have shown that soil particle detachment might not be mainly depending on shear resistivity of soil particles. In fact, they mention the influence of more parameters such as aggregate stability, aggregate sizes, bonding between these aggregates and raindrop impact, as it has been mentioned before (Nearing, Bradford et al. 1991).

In the studies mentioned by Le Bissonaiss (1996) of Hairsine & Hook (1995) the aggregate stability was also suggested as an influencing factor in soil erosion and water infiltration. Furthermore, they mentioned that erosion rates were mainly influenced by the aggregate breakdown of soil aggregates, contrary to the idea of Léonard et al. (2004).

Cantón et al. (2009) also argues that soil aggregate stability is one of the main parameters that influence soil erodibility and runoff. Furthermore, Boix-Fayos et al (2001) and Barthés et al. (2002) mention aggregate size distribution apart from aggregate stability as important parameter explaining soil degradation.

It may be of importance to understand the influence of raindrops over the detachment rate and aggregate stability and shear resistance due to the suggested relationships between these parameters. Therefore, the knowledge gap about the influence of different rainfall intensities on the aggregate stability and shear resistance of a loamy texture soil from arable land as well as the suspended sediment delivery and runoff water amount is of interest to fulfill. Furthermore the knowledge gaps of:

- soil surface development (soil crusting and small rill development) in time, regarding soil particle detachment as well as,
- runoff processes (hortonian overland flow conditions) in terms of temporal thresholds depending on the different rainfall intensities applied over the arable loamy soil surface,

are of interest to fulfill.

Problem statement

The relationship between different rainfall intensities with aggregate stability and shear resistance in arable soil with loamy texture is unknown, as well as the soil detachment rate by raindrops in such conditions.

This study attempts to understand:

- The influence of different rainfall intensities on:
  - the soil surface erosion processes
  - the studied variables: volumetric moisture content (v.m.c), Ca cohesive component (horizontal force component of the shear resistance) and aggregate stability.
  - the soil surface roughness
- The relationship between: volumetric moisture content, Ca cohesive component, aggregate stability and soil surface roughness.
- Soil surface roughness changes in time.

Therefore, assessment of the impact of different rainfall intensities on soil surface processes in terms of soil erosion mechanisms and threshold values in time was done. Furthermore, the influencing variable network of soil erosion by runoff regarding all measured variables: aggregate stability, shear resistance, soil detachment rate, rainfall intensities and soil moisture was studied.

Research questions

This experimental study aims to answer the following research questions:
- How do the values of aggregate stability and shear resistivity change after rainfall with different intensities?
- What is the impact of different rainfall intensities on runoff and suspended sediment delivery?

Research sub-questions

In order to answer the main research questions, the following research sub-questions are going to be answered:
- How do aggregate sizes on the soils surface change after rainfall of different intensities?
- Which is the aggregate stability of a loamy soil after different rainfall intensities?
- What are the critical shear stress values after different rainfall intensities?

- How does rainfall intensity influence the suspended sediment and runoff volume values?

Concepts and theories

Soil aggregates and soil aggregate stability

Soil aggregates are conformed by groups of soil particles that more strongly linked between them than to other soil particles (Martin, Martin et al. 1955). Aggregate stability refers to the ability of these aggregates to resist the separation of them when outside forces are applied. When soil aggregates are broken by raindrops, the soil particles portion of aggregates are released and can seal the soil pores forming soil crusts and enabling the flow of water or air or the emergence of seedlings through this soil pores. The decrease of aggregate stability affect erosion and water flow over the soil surface (NSSC, SQI et al. 1996). Some of the variables influencing aggregate stability are: soil texture, predominant type of clay, amount and type of organic matter (NSSC, SQI et al. 1996).

Soil aggregate breakdown

The breakdown of aggregates by water can be provoked by different physico-chemical and physical mechanisms. These mechanisms can effect the microscopic clay particles, to the macroscopic soil aggregates. Four main mechanisms are identified according to BISSONAIS (1996):

    i)   slaking
    ii)   breakdown by differential swelling;
    iii)   breakdown by raindrop impact;
    iv)   physic-chemical dispersion due to osmotic stress

Bissonais et al (1996) mentioned that according to Panabokke & Quirk (1957), Le Bissonais (1988) and Truman et al (1990), the slaking mechanism decreases with increase in moisture content until the saturation conditions are reached. Furthermore, in the case of breakdown, when the clay content increases this mechanisms decreases (BISSONNAIS 1996).

Regarding the formation of crusts, two different formations are mentioned by Bissonnais (1996). Structural crusts are formed in the pre-ponding phase. In contrary, depositional crust are formed at the same time as the erosion is happening.

Soil particle detachment

The detachment of soil particles by water occurs mainly by splash mechanisms due to raindrop impact on soil surface and by erosion of overland water flow of surface runoff (Nearing, Bradford et al. 1991). In addition, depending on the soil characteristic the resistance to soil detachment will vary, which is known as soil detachability (Nearing, Bradford et al. 1991).

When a soil particle is detached, they must be separated against the bonding forces of the soil aggregates. According to Nearing, Bradford et al. (1991) the force responsible for this detachment is a turbulent event that develops in the water soil interface. The detachment of a particle from a soil aggregate will take place when this turbulent event is bigger than the bonding force between aggregates (Nearing, Bradford et al. 1991).
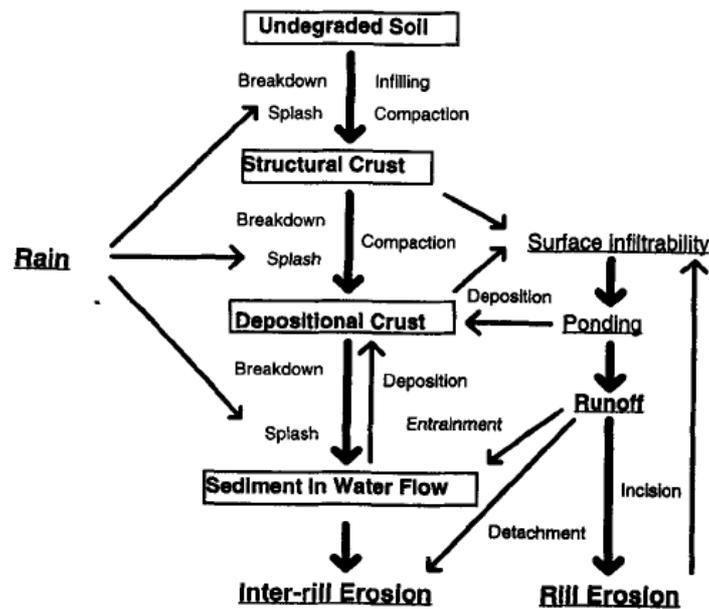
Figure 1 *Scheme of the relationships between aggregate breakdown, crusting and erosion mechanisms (BISSONNAIS 1996).*

Shear stress and soil critical shear stress

Léonard and Richard et al. (2004) mentioned that shear stress is composed of two shear stress components:

1. Grain shear stress which is the friction between water and soil surface and
2. Form shear stress which is the pressure difference between the upper part and lower part of the roughness elements, for instance when roughness elements are present such as stones, vegetation and similar.

Furthermore, it is also mentioned the influence of roughness on shear stress as an influential factor on the estimation of shear stress.

According to Léonard and Richard (2004) and Julien and Simons (1985) when the detachment of soil particles from the soil aggregates is first observed, the value of shear stress that corresponds to that moment is called critical shear stress.

Julien and Simons (1958) explained that the critical shear stress depends on the size of the soil particle size and "the specific masses of water and sediment" (Julien and Simons 1985). Eijkelkamp (2011) mentions that soil shear stress increases when increasing the organic carbon content within the soil. In addition, when the soil samples are air dried, soil shear stress values will be the lowest in comparison with higher moisture contents in the soil sample.

Kinetic energy of raindrops

The rain kinetic energy is the sum of the kinetic energy of each individual raindrop that hits the soil. The information from drop size distribution (DSD) measurements combined with fall velocity measurements or empirical laws linking terminal fall velocity (Vf), and drop diameter (D) allow the computation of the kinetic energy (Salles C. et al. 2002).

Drop size is related to terminal velocity, and also with kinetic energy. The kinetic energy, $E_{K,D}$ (in J) of a raindrop of size D is the product of its mass, m_D (in kg) and the square of its terminal velocity v_D (in m s^{-1}) (Dijk A.I.J.M et al. 2002).

The kinetic energy of a raindrop is calculated as follows (Fox N.I., 2004):

$$E_{K,D} = \frac{1}{2} \times m_D \times v_D^2$$

Where m_D is the mass of the drop:

$$m_D = \frac{\pi}{6} \times \rho \times D^3$$

According to Bissonnais (1996) one of the aggregate breakdown mechanisms is due to the impact of raindrops in the soil aggregates. Dijk, Zijp et al. (1996) argue that splash erosion by raindrops is mainly in function of the kinetic energy of rainfall, the soil shear strength and the aggregate stability between other influencing factors.

Runoff and sheet flow

When the infiltration of water over the soil surface is less than the rain fall amount, runoff will occur. In addition, if the soil aggregates are disintegrated and therefore the pores are filled of smaller soil aggregates or soil particles, the water of rainfall will not flow through them increasing the water flow over the soil surface, in other words the runoff mechanisms. This processes will enhance soil erosion by water flow (Barthès and Roose 2002).

The relation between the viscous forces and inertia forces defines the Reynolds number. Depending on the Reynolds number water flow can be classified as laminar or turbulent. When the viscous forces are higher than the inertia forces the flow is laminar and the Reynold´s number will be low. This is the case of sheet flows (Julien and Simons 1985). Sheet flow in general is classified as laminar flow. However, most of the sediment transport equations are derived from turbulent flow conditions; therefore, according to Julien and Simons (1985) the use of these equations in order to calculate the sediment transport by overland flow should be analyzed again.

In sheet flow, due to the high values of viscous forces with low values of Reynold´s number, the impact of raindrop and roughness are not so strong. The high values of viscous forces decrease the influence of perturbations of raindrops and roughness on the flow velocity, and the flow keeps being laminar until the critical value of Reynold´s number is reached (Julien and Simons 1985).

If the inertia forces are higher than the viscous forces, the Reynold´s number will be high and the flow will be turbulent (Julien and Simons 1985).
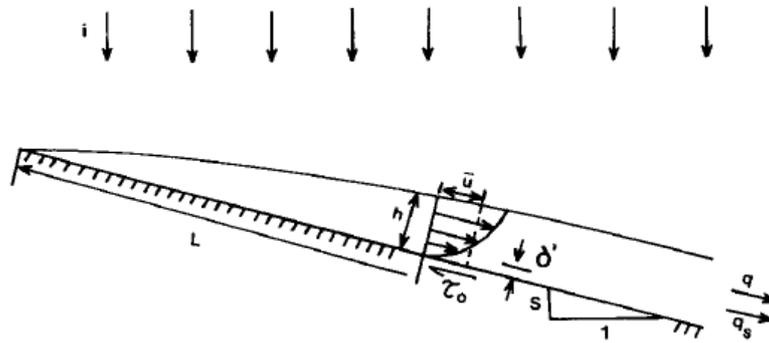
Figure 2 *Overland flow variables (Julien and Simons 1985).*

The main variables that describe overland flow are define as follows (Julien and Simons 1985):

1. Geometric variables: "L" slope length and gradient S.
2. Hydraulic variables: "I" rainfall intensity, "h" flow depth, "u" mean velocity, "q" unit water discharge and "δ'" thickness of the laminar sub-layer.

Bed shear stress is generally linked to sediment discharge, "q_s".

3. Other variables: "g" gravitational acceleration, "v" kinematic viscosity and "p" specific mass of water.

According to Julien and Simons (1985) the erosion rate is mainly function of the detachment of the soil particles and the transporting capacity of the runoff water. Furthermore, "sheet erosion is the result of the detachment of soil particles by raindrop impact and transport by overland flow" (Julien and Simons 1985).

Methodology

Rainfall simulations

In order to observe the influence of four different rainfall intensities on runoff and suspended sediments in runoff water, four boxes full of soil loamy material were tested in a rainfall simulator, composed by two big nozzles and two small nozzles.

The boxes were 100 cm length x 49.5 cm width and x 30 cm depth. Each box was situated in an specific place in the rainfall simulator depending on the range of rainfall intensity that were representing. It has been determined beforehand (Lassu, T. 2012). The four intensity ranges were:

Table 1 Rainfall intensity ranges.

Box nº	Intensity (mm/h)
1	40-50
2	>60
3	50-60
4	30-40

Position of the soil boxes in the Rainfall Simulator:
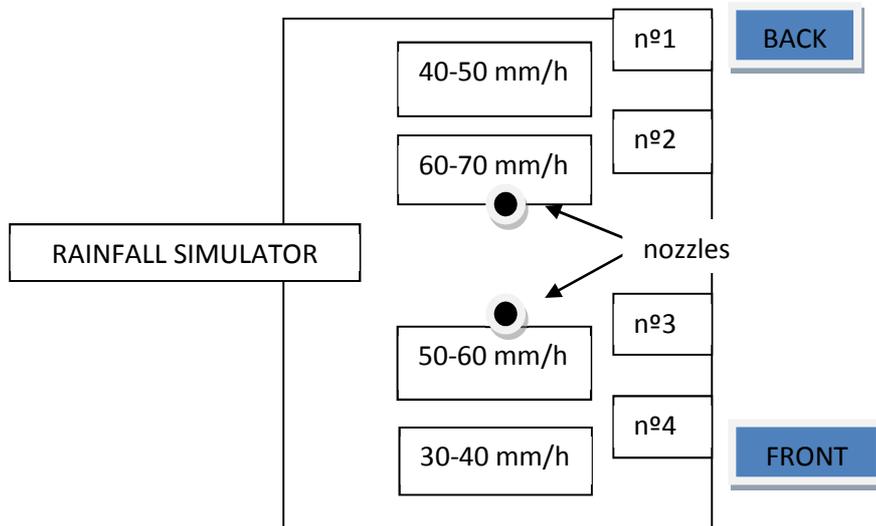
Figure 3 Set up of the rainfall experiment.

For each test box, 5 rainfall events (that conform one rainfall experiment: repetition or run) of 15 minutes were performed. Between the events, the water runoff was collected in buckets, in order to weight the runoff water and measure the suspended sediment concentration and load. The roughness of the soil surface was measured as well every 15 minutes.

The intensity of the rainfall was 4.5 l/h. After every event (15 minutes) the rainfall intensity values were checked by reading the rainfall volume of the green pots on each soil box.

Two groups of experiments were done: 5 rainfall experiments (repetitions or runs) with an inclination of the boxes of 2.5 º and 5 rainfall experiments (repetitions or runs) with an inclination of 10-12º.

Aggregate stability by wet sieving device
Wet sieving was done in order to see the aggregate stability of the soil before and after each rainfall simulation experiment (5x15 minutes events). The soil samples were air dried and then the soil samples were sieved with a sieve of >2mm. Using wet sieving apparatus, the weighted (4 grames) and dried soil samples were separated into the unstable part (collapsed in distilled water in the first run during 3 minutes) and stable part (collapsed in the last run caused by the dispersing solution). After separating both parts, they were dried at 105ºC for 24 hours and weighted.

Aggregate stability index = Wds/(Wds + Wdw)

with: Wds = aggregates dispersed in dispersing solution (g)
Wdw = aggregates dispersed in distilled water (g)

Supplier:	Eijkelkamp Agrisearch Equipment – Giesbeek NL
Duration of the sieving	3 min
Weight sample (< 2 mm)	4 g
Stainless steel can	diam. 64 mm h 45 mm
Sieve can	diam. 39 mm h 39 mm
Sieve size	250 µm
Sieve surface	10,2 cm²
Number of cans	8
Dispersing solution	2 g $(NaPO_3)_6$/L with pH>7
	2 g NaOH/L with pH<7
	or Ultrasonic probe

(4)   (5)

Figure 4 *Specification of the aggregate stability apparatus.*

Figure 5 *Aggregate stability apparatus.*

Shear resistance by Surface shear stress apparatus

The value of shear strength was calculated using Mohr-Coulomb´s equation:
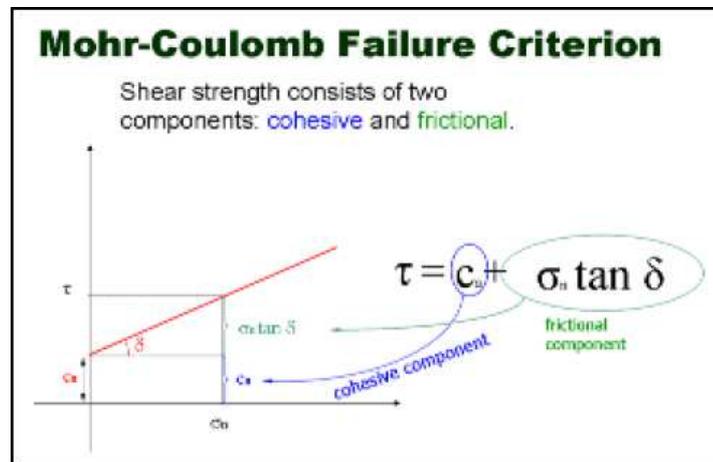
***Figure 6** Mohr-Coulomb´s equation.*

$$\tau = c_a + \sigma_n \tan \delta$$

with:

τ = soil shear strength (hPa),
c_a = adhesion between sandpaper and soil (hPa or 10^2 Pa),
σ_n = normal stress applied on the soil surface (hPa or 10^2 Pa),
δ = surface angle of internal friction (°).

Small vertical shear stresses between 1 and 30 hPa are applied to cylindrical soil samples (diameter 100 mm/ height 30 mm). This soil sample is fixed in the apparatus and the vertical shear stresses are applied over the sample using a "cylindrical shear container" ($\emptyset$ = 68mm). Into the "cylindrical shear container", different weights are placed (different weights are available, in our case 100 grames) in order to apply the mentioned vertical shear stress. At the bottom of the shear container there is a highly abrasive material in order to generate a rough-shear surface.

***Figure 7** Shear stress apparatus.*

The horizontal shear stress force is reproduced by slowly turning (for about max. 1 turn/sec.) the hand wheel of a precision-winding mechanism. "The spring construction transfers distance to force and damps for force increments" (Eijkelkamp 2011).

"The surface shear load (= slowly applied max. load to create a movement of the shear container with vertical load) is measured by a digital balance. This balance logs the max. applied force until movement for 5 seconds" (Eijkelkamp 2011). This test is a comparison test. Therefore it is important to maintain the initial conditions in every measurement in order to get reliable values of the shear stress of the soil samples. It is necessary to have three repetitions of shear stress measurement, per soil sample and per vertical load (Eijkelkamp 2011). The measurements are done in two different orientations per soil samples: 0º and 45º.

Surface roughness coefficient by chain method

Surface roughness coefficient was calculated using the chain method described by Saleh (1996). The only difference was in the type of chain used. In this case, the chain was composed by small balls bonded one to each other.

Figure 8 Chain method device described by Saleh (1996), (Jester et al. 2005).

Roughness coefficient was computed following the formula below:

$$RC=100*(1-L2/L1) \text{ (Saleh, 1996)}$$

where:

RC: Roughness Coefficient
L2: Length of the chain
L1: Length of the measured surface

Results

In the following paragraphs a general overview of the main findings will be presented as well as the more detailed results obtained in this experimental research:

1. Runoff and suspended sediment amount values after the rainfall experiments will be presented and described.
2. The most meaningful behaviors and values of the following studied variables: moisture content, Ca cohesive component and aggregate stability are going to be described.
3. Surface roughness coefficient values after the rainfall experiments will be explained.
4. Finally, the statistical analysis of all the data gathered in the laboratory work will be presented and described.

General overview of the results

The highest values of runoff and suspended sediment amount were registered in rainfall experiments with slope 10-12º (see table 2 and table 3).

The most influencing rainfall intensity in slope 10-12º is 50-60mm/h where the runoff and suspended sediment amount show maximum values (see table 2).
In the contrary, in slope 2.5º the maximum value of runoff was at intensity >60mm/h. But the maximum values of suspended sediment amount where registered for intensity of 40-50mm/h (see table 3).

The moisture content increased for both slopes. However, the highest increase was registered in slope 2.5º. Maximum values of moisture content were registered at 30-40mm/h (slope 10-12º) and at 40-50mm/h (slope 2.5º) intensities (see tables 2 and 3).
Ca cohesive component also increased in both slopes. The increase of Ca cohesive component was higher with slope 2.5º. Maximum values of Ca cohesive component were registered at intensity >60mm/h (see tables 2 and 3).
Aggregate stability increased in slope 2.5º and decreased in slope 10-12º. The biggest change in this variable for both slopes was registered at intensity 50-60mm/h (see tables 2 and 3).

In slope 10-12º, roughness coefficient decreased when applying intensities: 40-50mm/h, 50.60mm/h and >60mm/h. In slope 2.5º the roughness coefficient only decreased at intensity 40-50mm/h (see table 4).

Table 2 *Average runoff, suspended sediment concentration [] ([]= concentration) and load, Ca cohesive component, aggregate stability and moisture content values of rainfall experiments done, with different rainfall intensities and slope 10-12º. In yellow: Maximum values of the studied variables (for aggregate stability is minimum value).*

SLOPE 10-12º	runoff(l)	suspended sediment [] (g/l)	suspended sediment load(g/m2)	Ca cohesive component	aggregate stability	moisture content
Before	0	0	0	0,194	0,551	0,167
30-40mm/h	4,884	11,387	104,504	0,255	0,317	0,361
40-50mm/h	8,980	11,904	210,948	0,258	0,367	0,358
50-60mm/h	17,700	14,369	480,492	0,263	0,303	0,335
>60mm/h	16,611	12,986	433,280	0,315	0,322	0,344

Table 3 *Average runoff, suspended sediment concentration [] and load, Ca cohesive component, aggregate stability and moisture content values of rainfall experiments done, with different rainfall intensities and slope 10-12º. In yellow: Maximum values of the studied variables.*

SLOPE 2.5	runoff(l)	suspended sediment [] (g/l)	suspended sediment load(g/m2)	Ca cohesive component	aggregate stability	moisture content
Before	0	0	0	0,175	0,238	0,134
30-40mm/h	0,478	0,617	0,2948	0,293	0,228	0,351
40-50mm/h	2,140	1,221	9,364	0,296	0,259	0,372
50-60mm/h	4,546	0,338	11,044	0,281	0,295	0,361
>60mm/h	8,627	0,819	17,252	0,311	0,274	0,364

Table 4 *Roughness coefficient values for each rainfall intensity and both slopes: 2.5º and 10-12º. L= roughness measured along the box, W= roughness measurement across the width of the box.*

SLOPE 2.5	L0	L	W0	W	SLOPE 10-12º	L0	L	W0	W
30-40mm/h	0,793	0,693	1,392	1,490	**30-40mm/h**	0,793	1,085	1,971	2,069
40-50mm/h	1,184	0,793	2,072	1,490	**40-50mm/h**	1,282	1,667	2,351	1,974
50-60mm/h	0,891	0,891	0,498	0,698	**50-60mm/h**	0,987	1,280	0,798	0,771
>60mm/h	1,573	1,379	0	0,692	**>60mm/h**	1,960	1,474	2,363	0,690

This is an overall review of the average results obtained from ten rainfall experiments done in the laboratory. Therefore, in the next paragraphs more detailed results will be described where the most interesting findings and outstanding results will be presented in graphs.

Rainfall experiments

10 rainfall experiments have been done split in two groups. One group of the experiments had a slope of 10-12ºwhile the other group of experiments had a slope of 2.5º. The amount of runoff, suspended sediment load and concentration and the amount of rainfall applied has been computed and represented (see annex 1). In figures 9 and 10 the most representative rainfall experiment graphs are shown and explained.

The amount of runoff water and sediment in water runoff is increasing when the experiment is running. Regarding the influence of different rainfall intensities, 50-60mm/h and >60mm/h intensities seem to be the most impacting ones due to the higher values of runoff and sediments in runoff water (see figure 9).

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2012

Slope 2.5
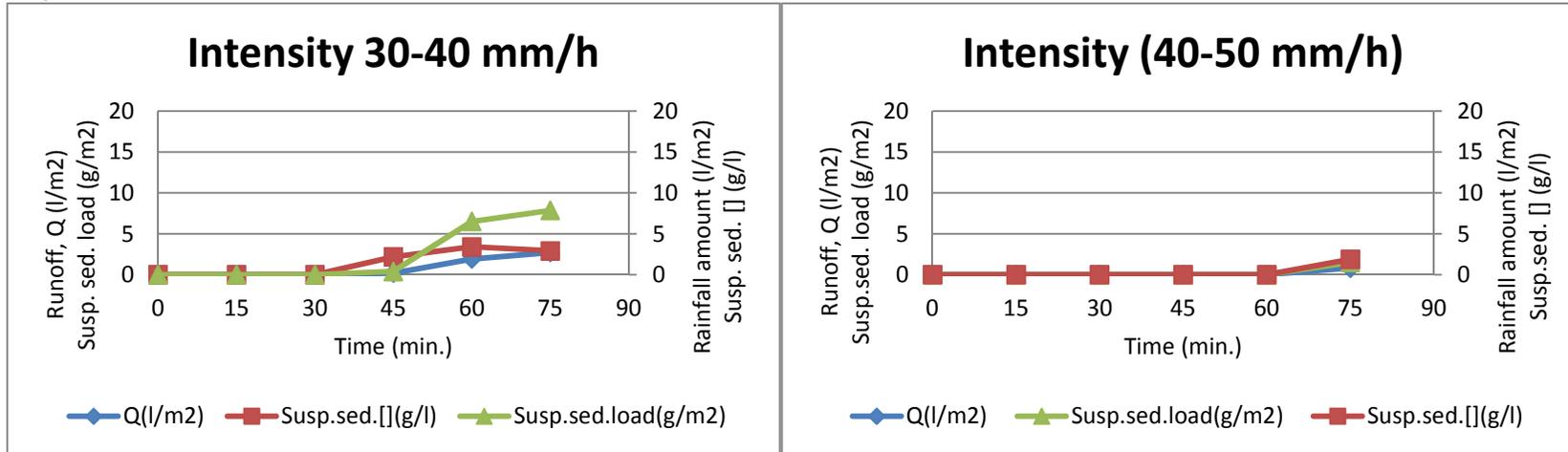
(9 a)

(9 b)
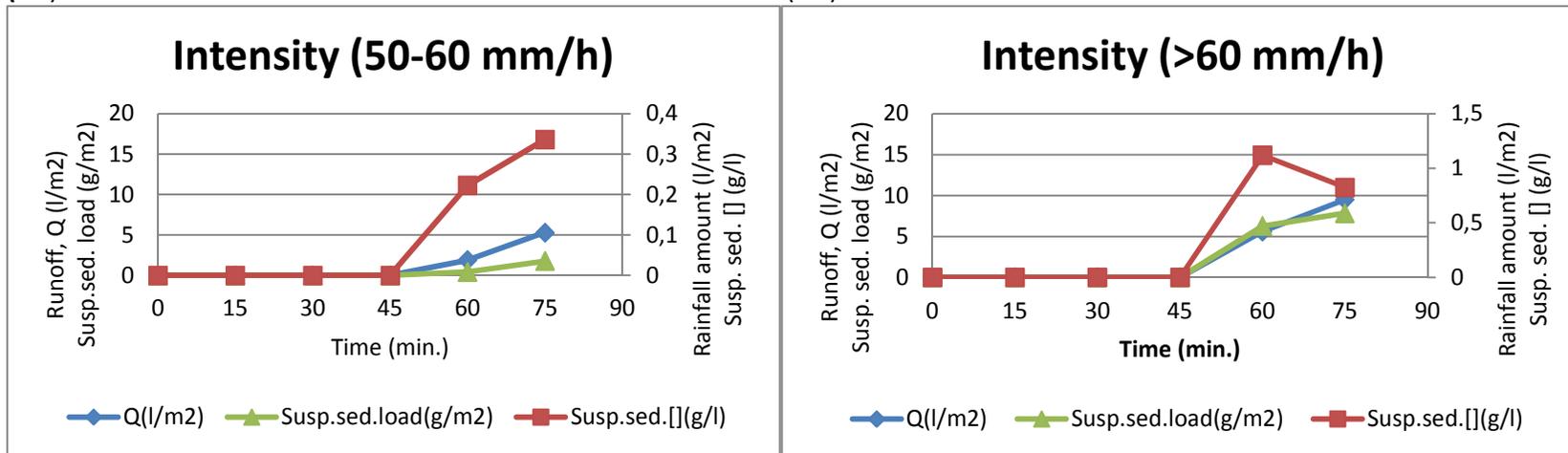
(9 c)

(9 d)

Figure 9 *Impact of rainfall intensity on runoff on a slope of 2.5º. Rainfall intensities vary from 30-40mm/h (9a) in run 1, 40-50mm/h(9b) in run 2, 50-60mm/h (9c) in run 2 and >60mm/h (9d) in run 3.*

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Slope 10-12º

(10 a)

(10 b)

(10 c)

(10 d)

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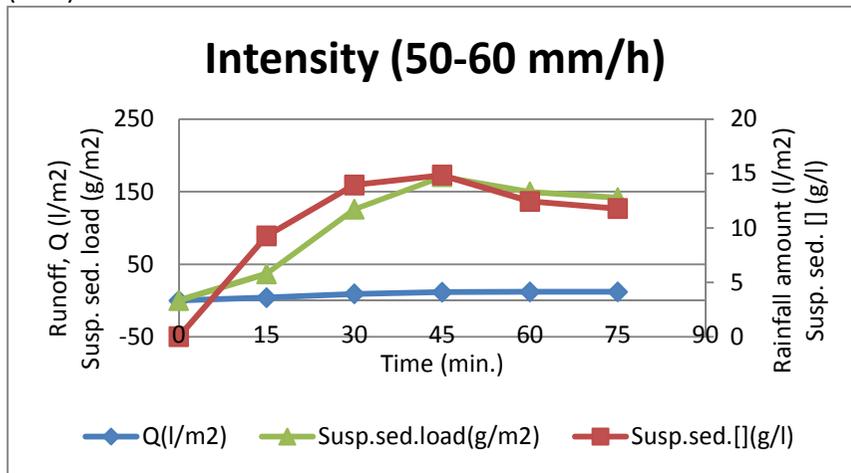
(10 e)

(10 f)

Figure 10 *Impact of rainfall intensity in runoff on a slope of 10-12º. Rainfall intensities vary from 30-40mm/h (10 a) in run x, 40-50mm/h (10 b) in run x, 50-60mm/h (10 c) and (10 d) in runs 3 and 4 respectively and >60mm/h (10 e) and (10 f) in runs 1 and 4 respectively.*
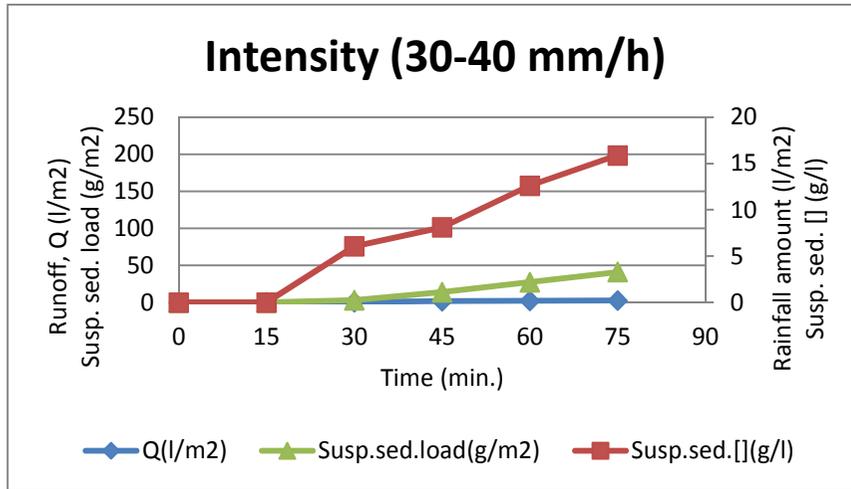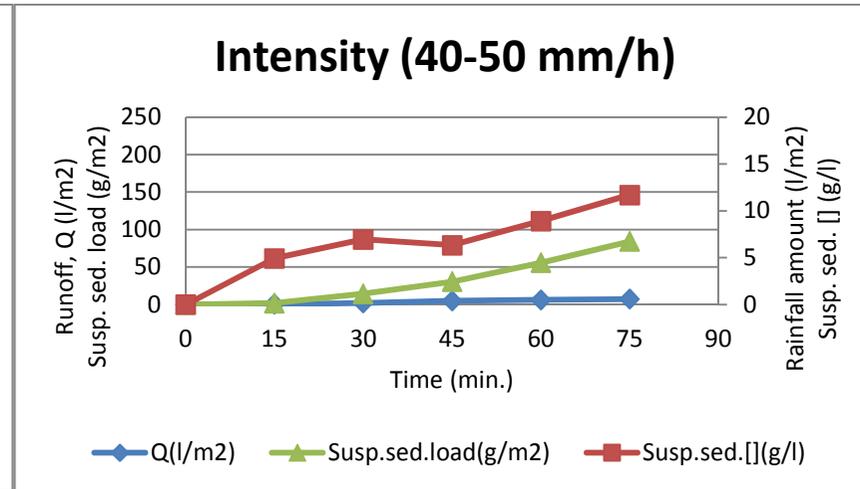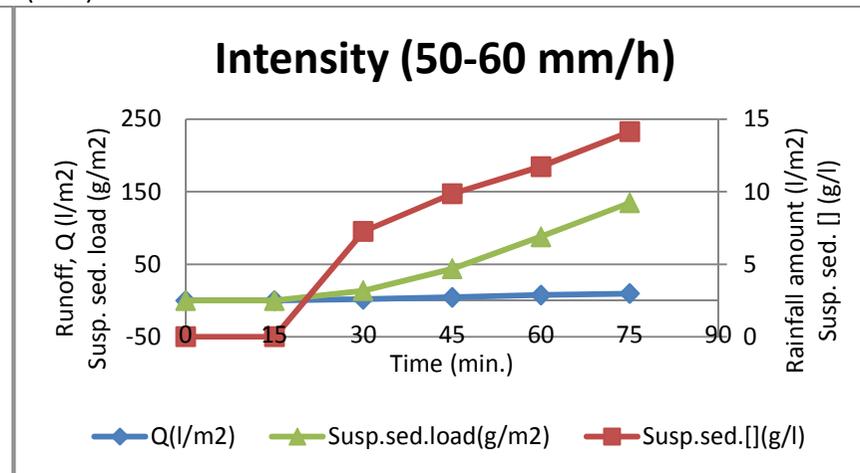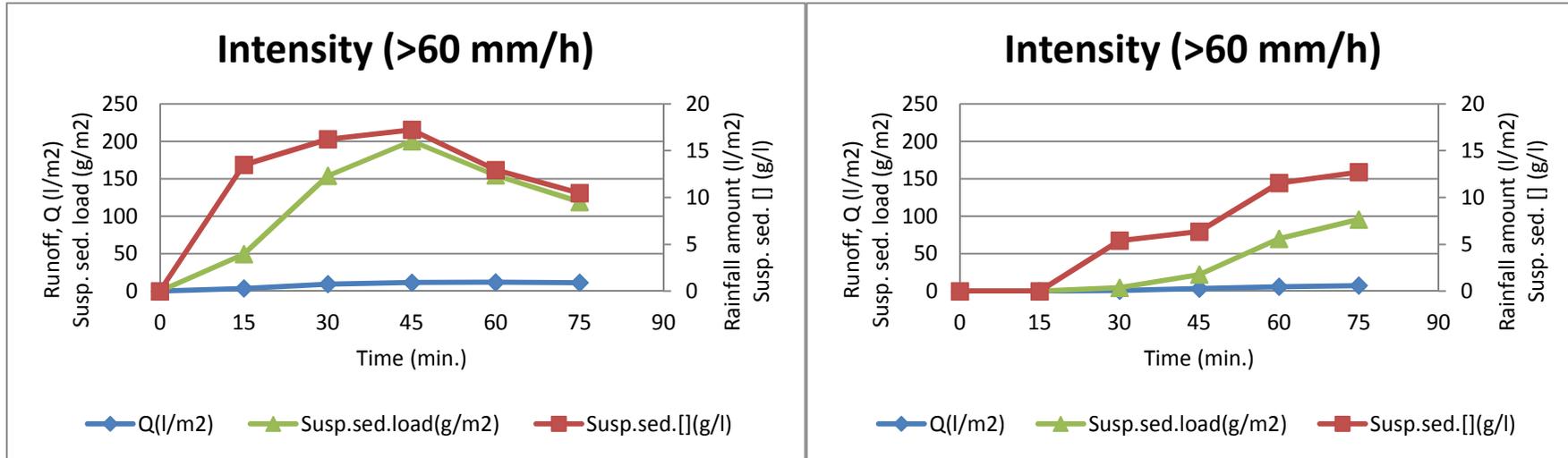
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The experiments with 10-12º slope showed the same trend for the runoff and suspended sediment amount in runoff water; runoff and the amount of suspended sediments in runoff water increased in time. These values were higher than in the experiments with 2.5 degrees of slope (see table 2 and figure 10).

However, for rainfall intensities of 50-60 mm/h and >60 mm/h different behavior of the measured variables were observed (see figures 10c, 10d, 10e and 10f). In most of the experiments, the increase of the runoff water and sediment amount in water runoff was linear. But for the intensities 50-60mm/h and >60mm/h a maximum of suspended sediment amount in water runoff is reached after 45 minutes of rain. These values decreased during the last 30 minutes of the experiments.

Shear resistance (C$_a$: cohesive component), aggregate stability and moisture content

The Ca cohesive component (horizontal force of shear stress), aggregate stability and moisture content of the tested soil were measured at the before and after conditions of the experiments. In figures 11 and 12 the <u>average values</u> (after 75 minutes of rain) of the 5 repetitions done for each slope have been represented in order to see changes between the before and after conditions of each variable.
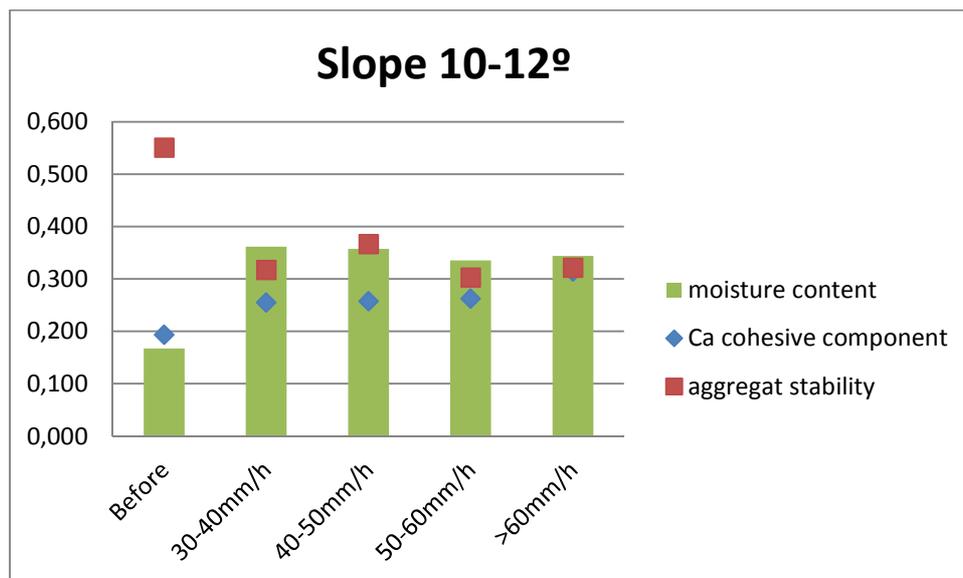
Figure 11 *Ca Cohesive component (horizontal force of shear resistance), aggregate stability and moisture content values at the before and after conditions of the rainfall experiment for each rainfall intensity, slope 10-12º.*

When applying slope 10-12º (see figure 11), Ca and moisture content values increased after the rainfall experiment. But there were no relevant differences between the different rainfall intensities applied regarding Ca cohesive component and moisture content values. On the other hand, aggregate stability values decreased after the rainfall experiment. There were no relevant differences between the different rainfall intensities applied.

Ca component of the shear resistance showed the highest value at intensity of >60mm/h. Regarding the moisture content variable, its values are more or less similar on each rainfall intensity applied. Finally, aggregate stability values are highest for the 40-50mm/h rainfall intensity.
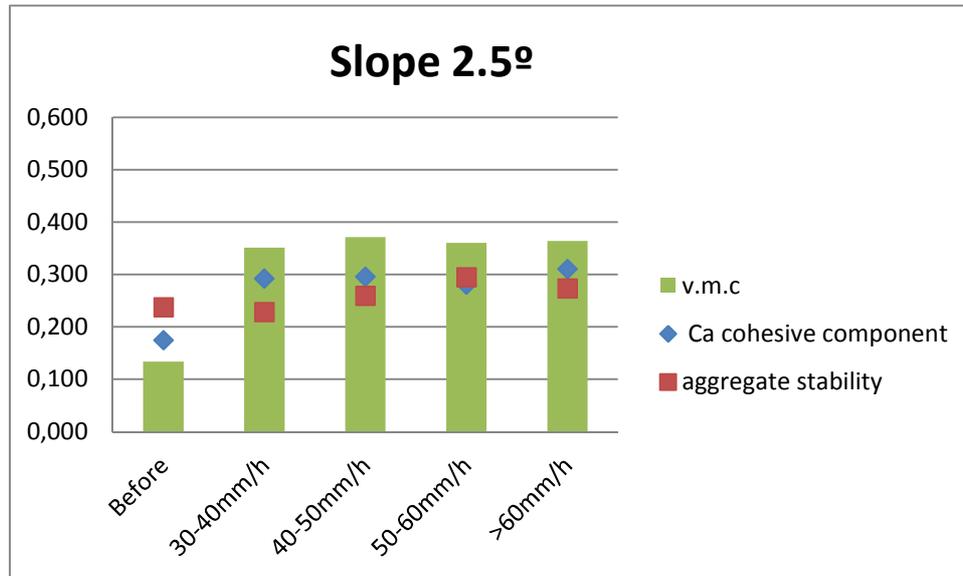
Figure 12 *Shear stress, aggregate stability and moisture content values at the before and after conditions of the rainfall experiment for each rainfall intensity, slope 2.5º.*

When applying slope 2.5º (see figure 12), Ca component, moisture content and aggregate stability variables showed higher values after the rainfall experiments. The highest value of shear resistance was registered at rainfall intensity of >60mm/h whereas the highest value of aggregate stability was measured at intensity of 50-60mm/h.

Moisture content values did not show clear differences between the different rainfall intensities applied.

Despite of the maximum values of Ca cohesive component (for >60mm/h) and aggregate stability (50-60mm/h), qualitatively there are no clear relevant differences observed between the different rainfall intensities.

Regarding the different slopes, moisture content values were not significantly different. Final aggregate stability values were slightly lower in slope 2.5º and final Ca cohesive component values were slightly higher in slope 2.5º.

On the other hand, the different slope influenced on the before and after values of aggregate stability. With slope 10-12 º the values decreased importantly but with the slope of 2.5º aggregate stability values increased.

Figures 11 and 12 represent the average values of the Ca cohesive component, moisture content and aggregate stability of all the rainfall experiments done. Nevertheless, the values of the Ca cohesive component, moisture content and the aggregate stability have been represented for each of the repetitions done. In general terms, there is no general trend observed for the Ca cohesive component either for aggregate stability, regarding the values observed on each of the rainfall simulation repetitions or runs. In some of the repetitions, both variables are changing in a parallel way (see figure 13), as it would be expected. But in other rainfall experiment repetitions this is not happening (see figure 14).
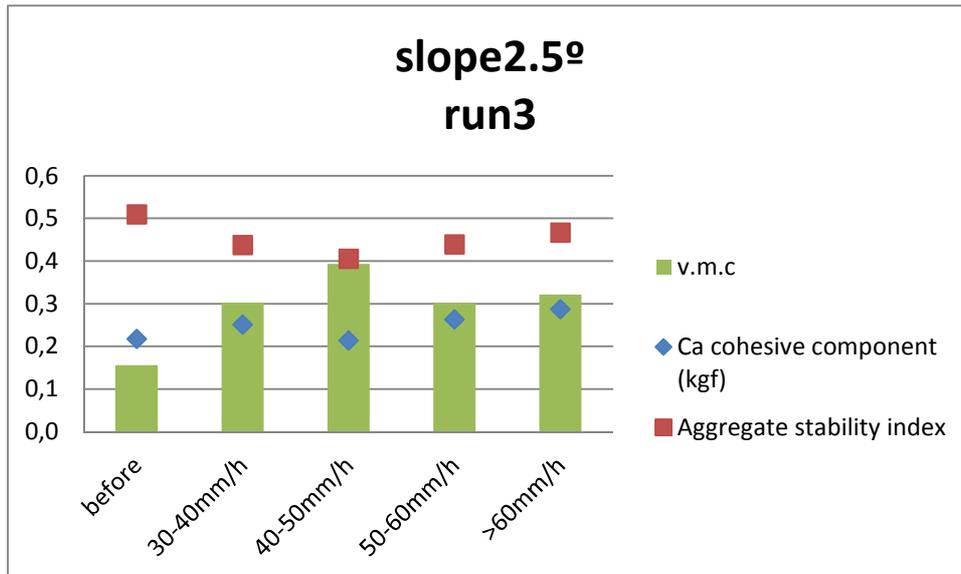
Figure 13 *Ca component, aggregate stability and moisture content values at the before and after conditions of the rainfall experiment for each rainfall intensity, slope 2.5º.*

In figure 13 is possible to observe certain symmetry on the Ca cohesive component and aggregate stability values when rainfall intensity increases. However, this case is not generalized. Figure 14, represents the most common case observed in this experimental study; where is possible to observe that when Ca cohesive component decreases, the aggregate stability values increased but without any dependency from the rainfall intensity applied.

Figure 14 *Ca component, aggregate stability and moisture content values at the before and after conditions of the rainfall experiment for each rainfall intensity, slope 10-12º.*

In summary, observing the data represented for each repetition (figures 13 and 14) and for all repetitions (figures 11 and 12), is possible to say that moisture content as well as the Ca cohesive component increased after 75 min. of rainfall simulation. On the other hand, aggregate stability behaviour changed regarding the different slopes applied. With slope 10-12º, the aggregate stability values decreased after the rainfall experiment, while in slope 2.5º, the aggregate stability values increased. In addition, in the slope 2.5º it is possible to see some

symmetry between Ca component and aggregate stability for some of the rainfall experiments done (see figure 13), but not in any rainfall experiment done with the slope 10-12º.

Regarding the maximum values of suspended sediment amount in water runoff observed for the intensities of 50-60mm/h and >60mm/h in the slope 10-12º (see figures 10c, 10d, 10e and 10f), the Ca cohesive component, moisture content and aggregate stability did not show any trend in common in any of the rainfall experiments done (for instance see figures 14, 15 and 16).
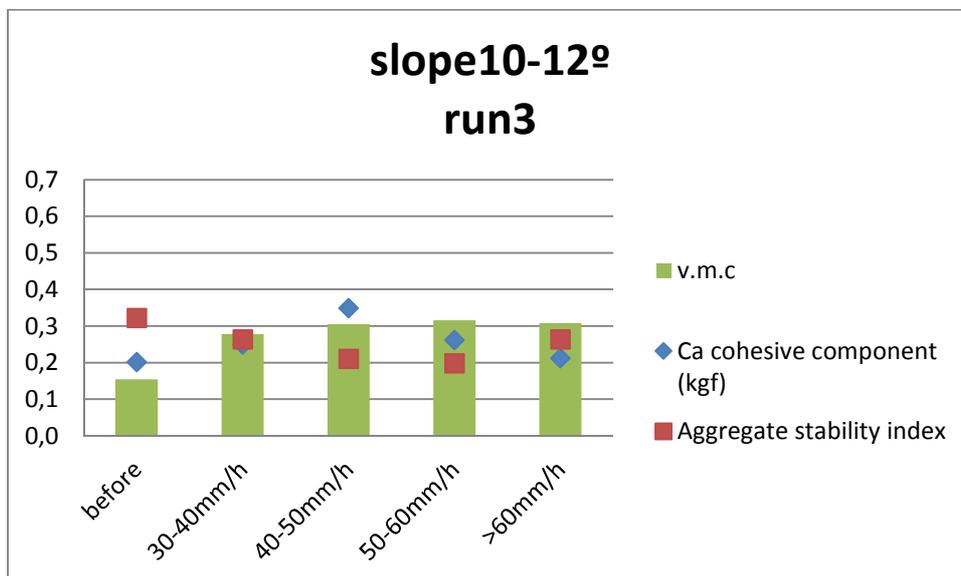

Figure 15 *Ca component, aggregate stability and moisture content values at the before and after conditions of the rainfall experiment for each rainfall intensity, slope 10-12º.*
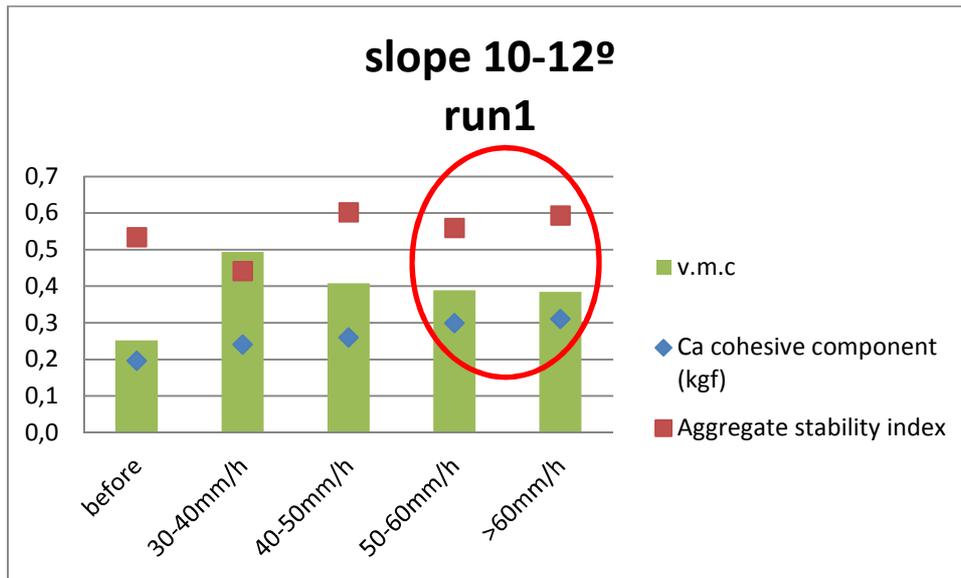

Figure 16 *Ca component, aggregate stability and moisture content values at the before and after conditions of the rainfall experiment for each rainfall intensity, slope 10-12º.*
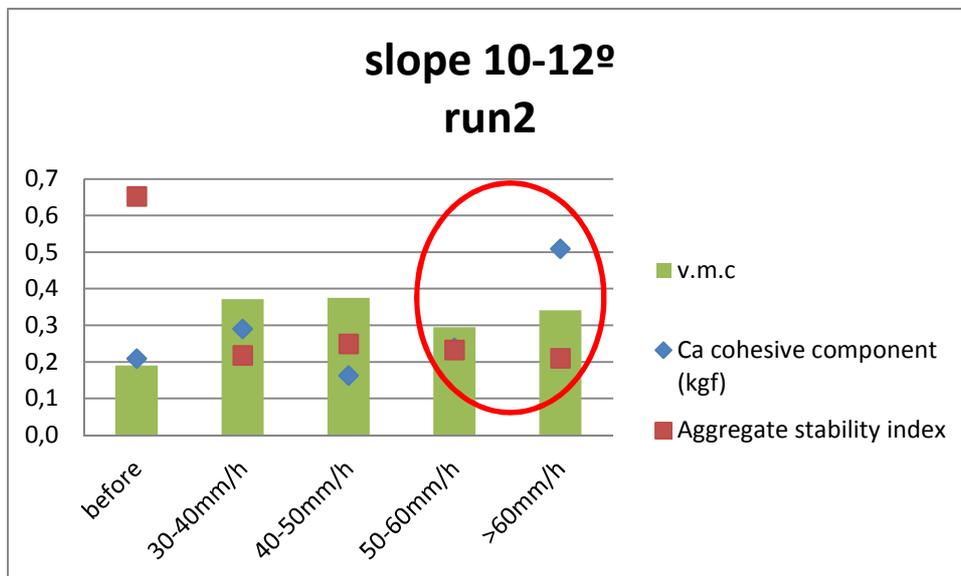
Roughness coefficient

Roughness changes in time were measured for every rainfall experiment (repetition or run) and different rainfall intensity boxes every 15 minutes. Roughness coefficient was computed in order to see differences in terms of time threshold values. The roughness coefficient was measured in two directions: along the box, named as "L" and across the width of the box at 30 cm and at 60 cm length named "W1" and "W2" respectively.

It was not possible to observe an important change in the surface roughness in time. A decrease in roughness coefficient was observed in few cases (see figures 17, 18 and 19). In most of the cases, the roughness coefficient increased or did not vary in a relevant way (see figures 20 and 21 and annex 2). Opposite to what has been observed in the average roughness coefficient values (see table 4) as well as in the pictures taken in the laboratory after the rainfall experiments (see figures 22 and 23).
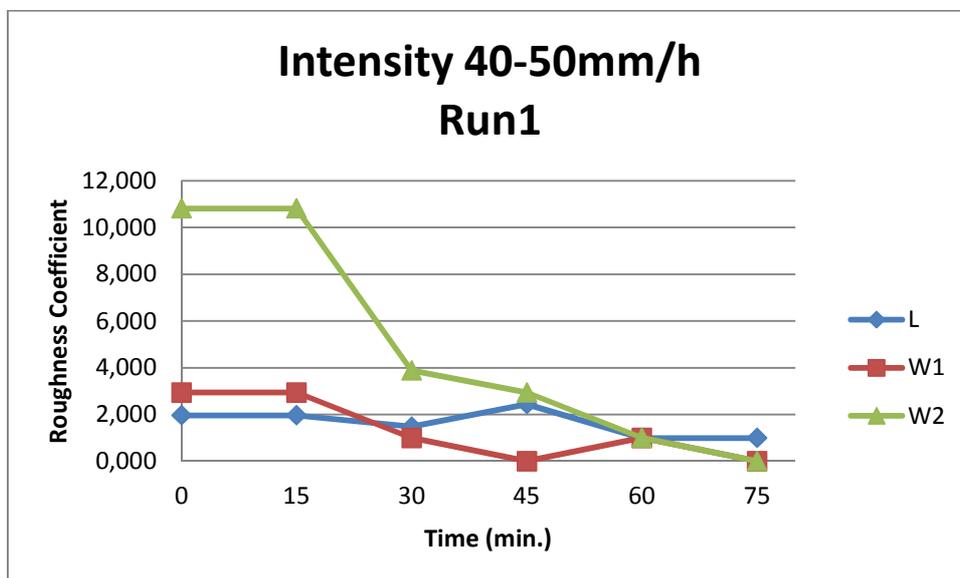
Figure 17 *Roughness change in time for intensity of 40-50mm/h, slope 10-12º.*
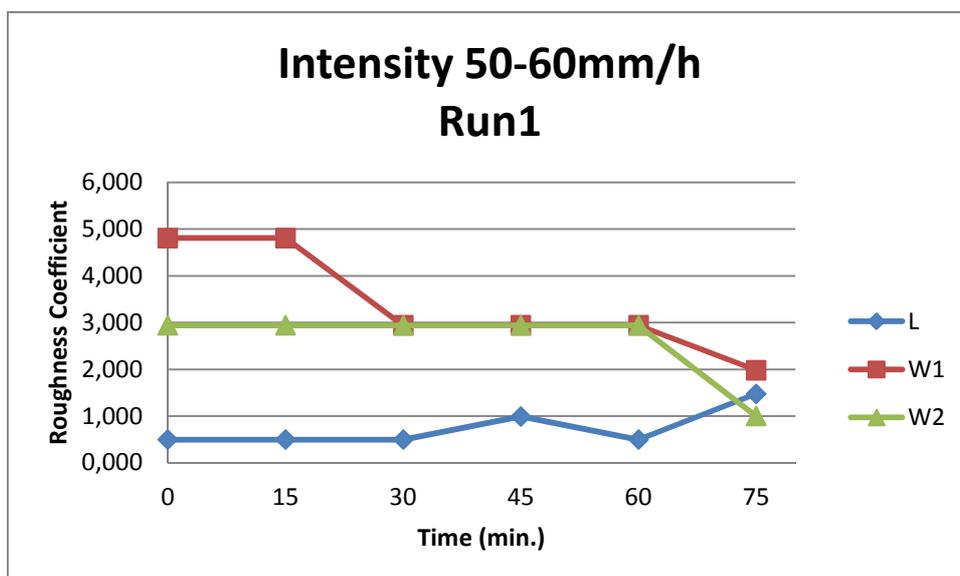
Figure 18 *Roughness change in time for intensity of 50-60mm/h, slope 10-12º.*
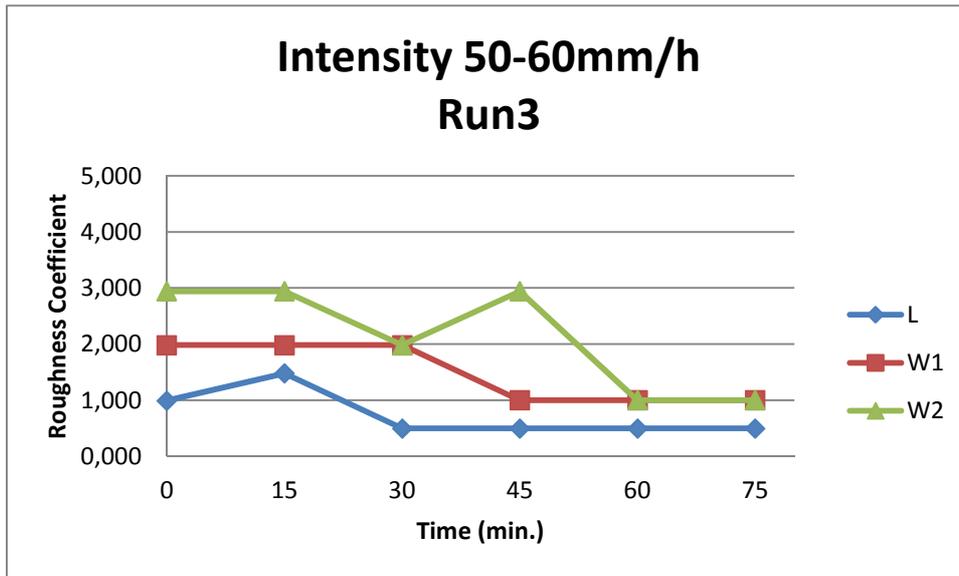
Figure 19 *Roughness change in time for intensity of 50-60mm/h, slope 2.5º.*
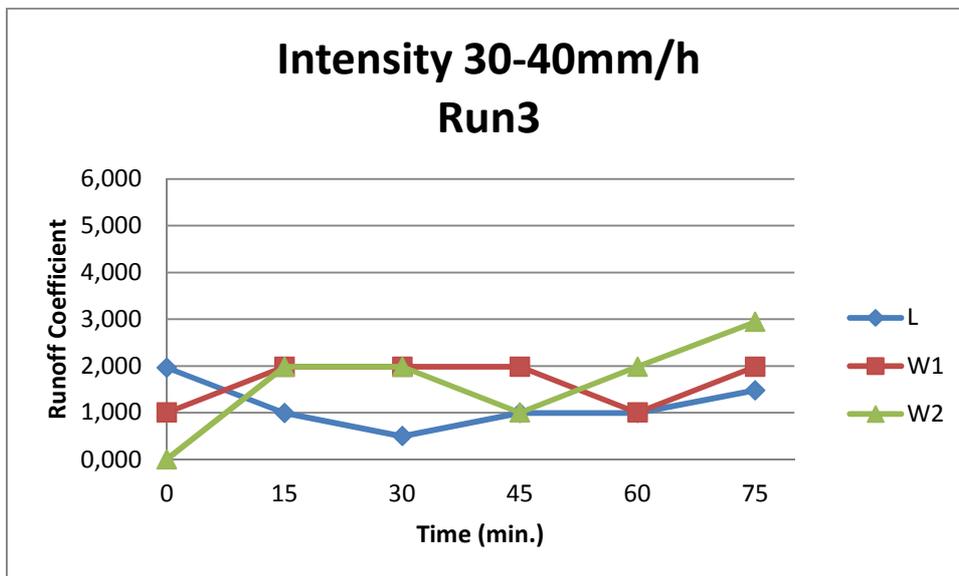
Figure 20 *Roughness change in time for intensity of 30-40mm/h, slope 10-12º.*

Figure 21 Roughness change in time for intensity of >60mm/h, slope 2.5º.

(22)   (23)
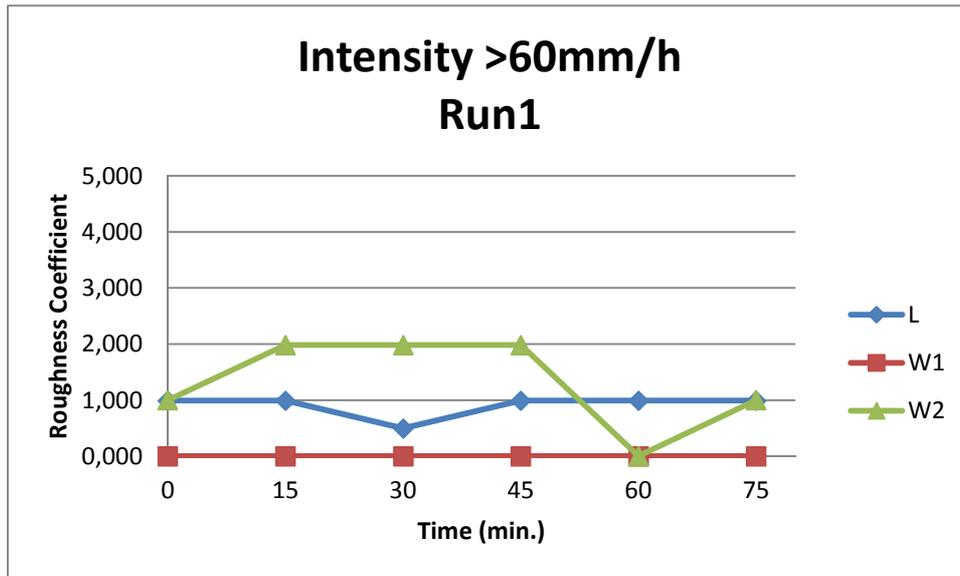
Figure 22 Initial soil surface roughness before a rainfall of 75 min. with intensity of 50-60mm/h (Cook, W. 2012).

Figure 23 Final soil surface roughness after a rainfall of 75 min. with intensity of 50-60mm/h (Cook, W. 2012).

Statistical analysis

In order to see more in detail some of the qualitative observations done in the previous data and graph analysis, an statistical analysis was done.

Significant differences between different rainfall intensities

Rainfall experiment variables
Slope 10-12º
Significant differences were found for most of the rainfall experiment variables (see table 5):

Rainfall amount MEAN: except for the 50-60 mm/h and >60mm/h intensities
Rainfall amount SUM: except for the 50-60 mm/h and >60mm/h intensities

Rainfall intensity values noted from the green pots showed similar values of rainfall intensities for box nº 3 and box nº 2. Both of them showed values close to 60 mm/h. As the statistical analysis also shows us, the boxes were not well situated in the rainfall simulator, because there was not a clear separation between the intensity ranges defined in the set up of the experiment: Box nº3=50-60mm/h and Box nº4=>60mm/h.
This fact, influenced in the significant differences observed by the statistical analysis, regarding the other studied variables:

Runoff SUM
Runoff MAX
Q mean
Q max

The maximum values of runoff water were significantly different in all the rainfall intensities applied except from the comparison between 50-60mm/h and >60mm/h due to the reasons mentioned above.
Mean values of runoff were significantly different except for the 30-40mm/h and 40-50mm/h intensities comparison and 50-60mm/h and >60mm/h intensities comparison.

Susp. Sed. Concentration mean: Significant differences were found between the lowest rainfall intensity applied (30-40mm/h) and the 40-50mm/h and 50-60mm/h rainfall intensities.
Susp. Sed. Load mean: Significant differences were found between the lowest (30-40mm/h) and the highest (>60mm/h) intensities applied.

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Significant differences: for different rainfall intensities

Slope 10-12º

Table 5 Significant differences for different rainfall intensities applied, slope 10-12º.

	RunoffSUM	RunoffMAX	Qmean	Qmax	SuspSedConc MEAN	SuspSedConc MAX	SuspSedLoad MEAN	RainfallAmount MEAN	StartRunoff Sec
Asymp. Sig.	0,005	0,001	0,003	0,002	0,037	0,373	0,004	0,001	0,072
	RunoffCoeff	**Rainfall AmountSUM**	**CaCohesive Conponent**	**Aggregate Stab**	**MoistContent**	**RoughnessL**	**RoughnessW1**	**RoughnessW2**	**RoughnessL0**
Asymp. Sig.	0,107	0,001	0,751	0,833	0,929	0,526	0,007	0,127	0,017
	RoughnessW10	**RoughnessW20**	**CaCohesive Conponent 0**	**Aggregate Stability0**	**MoistContent 0**				
Asymp. Sig.	0,027	0,432	1,000	1,000	0,770				

a. slope = 1

b. Kruskal Wallis Test

c. Grouping Variable: IntensityBOX

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Slope 2.5º

Table 6 *Significant differences for different rainfall intensities applied, slope 2.5º.*

	RunoffSUM	RunoffMAX	Qmean	Qmax	SuspSed ConcMEAN	SuspSedConc MAX	SuspSed LoadMEAN	RainfallAmount MEAN	StartRunoff Sec
Asymp. Sig.	0,245	0,156	0,245	0,156	0,459	0,460	0,337	0,001	0,661
	RunoffCoeff	**Rainfall AmountSUM**	**CaCohesive Conponent**	**Aggregate Stab**	**Moist Content**	**RoughnessL**	**Roughness W1**	**RoughnessW2**	**Roughness L0**
Asymp. Sig.	0,477	0,001	0,802	0,730	0,883	0,120	0,035	0,288	0,054
	Roughness W10	**Roughness W20**	**CaCohesive Conponent 0**	**Aggregate Stability0**	**Moist Content0**				
Asymp. Sig.	0,035	0,015	1,000	1,000	0,770				

a. slope = 2

b. Kruskal Wallis Test

c. Grouping Variable: IntensityBOX

Slope 2.5º

According to the statistical analysis, there were not significant differences between the different rainfall intensities applied (see table 6). However, the qualitative analysis showed us that there might be differences between the different rainfall intensities (see figure 8).

Ca cohesive component, moisture content and aggregate stability

In any of the slopes applied in the rainfall experiments, significant differences between the different rainfall intensities applied were detected regarding Ca cohesive component, moisture content and aggregate stability (see table 5 and 6).

Roughness coefficient

For both type of slopes applied, the statistical analysis showed significant differences for the roughness W1 variable (see table 5 and 6).

Significant differences between slopes for each rainfall intensity applied

This analysis was not possible to perform due to the lack of enough data. On the other hand, for the rainfall experiment variables was already possible to see that there may be differences between both slopes when observing the rainfall experiment graphs.
The other studied variables did not show clear differences regarding the qualitative analyisis.

Significant differences at the before and after conditions: Ca cohesive component, aggregate stability and moisture content: Wilcoxon test: non-parametric.

Ca cohesive component was tested in order to see if there were significant differences between the before and after values of this variable. According to the Wilcoxon test, there were relevant differences for each of the rainfall intensities applied. The Ca cohesive component values after the experiment increased significantly (see annex 4: table 4.1-table4.4).

Aggregate stability index decreased after the rainfall experiments but only in a significant way for the intensity 30-40mm/h (see annex 4: table 4.5-table 4.8). Opposite to these results, aggregate stability increased or did not present a relevant change in slope 2.5º according to the qualitative analysis (see annex 3 and table 3).

Finally, moisture content change significantly in all the rainfall intensities applied and its values increased after the rainfall experiment (see annex 4: table 4.9-4.12).

Roughness time threshold

In slope 2.5º there were not significant differences in time for any of the different rainfall intensities. In slope 10-12º, the only significant difference observed was for roughness W1 for the >60mm/h rainfall intensity.

Table 7 *Significant differences in time of surface roughness for intensity >60mm/h and slope 12º.*

Test Statistics[a,b]

	RoughnessI2L	RoughnessI2W 1	RoughnessI2W 2
Chi-Square	10,912	11,600	0,827
df	5	5	5
Asymp. Sig.	0,053	0,041	0,975

a. Kruskal Wallis Test

b. Grouping Variable: event2

As in the previous analysis regarding the significant differences between the different rainfall intensities applied, roughness W1 variable is significantly different (see tables 5 and 6). However, these differences are not reflected in the qualitative representation of the roughness coefficient data; where was not possible to describe any clear trend in roughness surface changes in time.

Correlation analysis

Correlation analysis of the studied variables was done in order to see if there were any correlations between rainfall experiment variables, Ca cohesive component, aggregate stability and roughness coefficient (see annex 4: table 4.21 and 4.22). The most meaningful correlations for this research were represented in figure 24.

Slope 10-12º

Rainfall experiment variables

Most of the rainfall experiment output variables: Q, Suspended sediment concentration and load are positively related to rainfall amount applied in the rainfall experiment (see figure 24).

Moisture content, Ca cohesive component and aggregate stability

Final Aggregate stability is positively related to moisture content at the end of the experiment. When there are high values of moisture content, high values of aggregate stability were found. However, after rainfall experiment, due to the raindrop impact, the aggregate stability index should have decreased because the soil aggregates should have been broken by raindrops.
Final aggregate stability is also related to Ca cohesive component, but in a negative way. Here again, instead of having a positive correlation as expected, the correlation is negative.

Furthermore, aggregate stability is also related to roughness coefficient. In one hand, the initial aggregate stability is positively related to roughness coefficient "L". On the other hand, final roughness coefficient is negatively related to roughness coefficient "L". A positive relationship would make sense, while the negative relationship not.

Finally, initial aggregate stability and moisture content seem to be related to "start runoff" variable; both of them in a positive way. This means that when low values of initial aggregate stability are present, the runoff will start earlier and when low values of final moisture content are present as well, the runoff would have started earlier.

Roughness Coefficient

According to the correlation analysis, roughness coefficient variables are mostly negatively related to rainfall experiment output variables; when high values of roughness coefficient are present, low values of runoff water occurred. Rainfall amount applied over the soil surface is also negatively related to roughness coefficient. When high values of rainfall, low values of roughness coefficient.

Slope 2.5º

In this case, seems to be that all the rainfall experiment output variables are positively related to moisture content. In addition, rainfall amount influenced positively the runoff water amount (see figure 24).

Ca cohesive component, aggregate stability and moisture content

Ca cohesive component and aggregate stability appear to be positively related as expected; opposite to the correlation observed for the slope 10-12º. On the other hand, any correlation regarding moisture content and the other two variables was observed.

Roughness coefficient

Few significant correlations were observed. Roughness coefficient seems to be related in a negative way with the amount of sediments in runoff water. However, this correlation makes sense, when there are high values of sediment amount in water runoff, the final roughness coefficient is low.
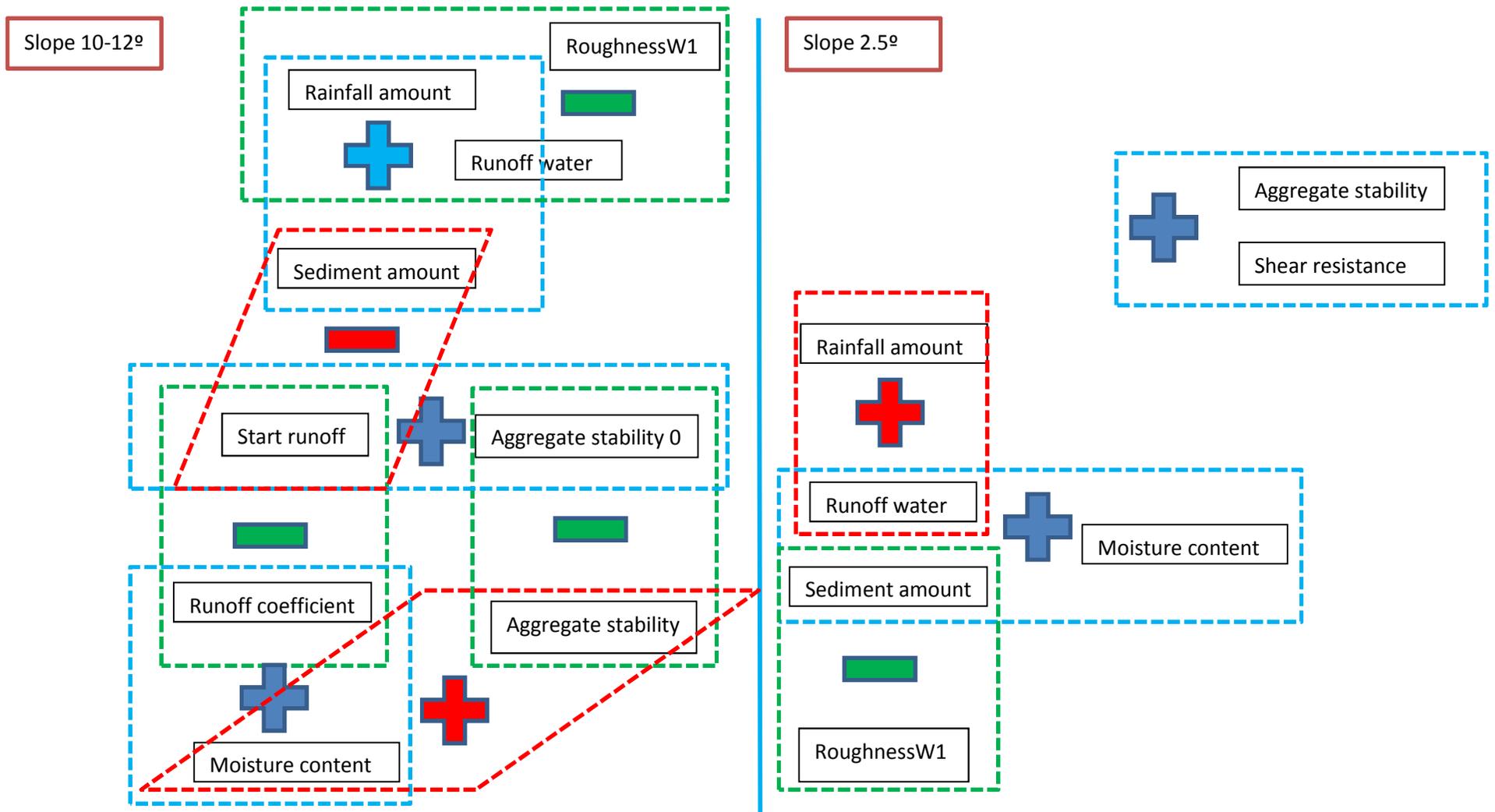
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Figure 24 *Most meaningful significant correlations observed in the statistical analysis.*

Discussion

Discussion of the methodology

In this experimental research an attempt to use easy, simple and fast methodology has been done. Rainfall experiment set up with different rainfall intensities and measurements of aggregate stability, Ca cohesive component and roughness coefficient as assessment parameters for water runoff erosion features have been done. Thus, apart from the possible discussion of the results obtained, the relationships between them, trends of the variables and rainfall experiment´s behavior; the discussion of the way by which this data has been obtained it may be of importance; in order to assess the suitability of these methods with the rainfall experiment set up and the conditions of the soil samples (see figure 27).

Rainfall simulator

Differences between the intensities 30-40 and 40-50mm/h were not clear, as well as for the higest intensities: 50-60mm/h and >60mm/. It seems that the boxes in the rainfall simulator were not in the best situation in order to define clear different rainfall intensity ranges. These conclusion is possible to see in the statistical analysis, where is shown that between the highest rainfall intensities applied there was no significant differences. Thus, it could be thought that this fact would have influenced the results obtained from the rainfall experiments. On the contrary, through qualitative analysis it was possibe to observe that there were differences in suspended sediment load and runoff amount between the different rainfall intensities applied.

In the other hand, it was not possible to describe any trend regarding the different rainfall intensities applied in the rainfall experiments in terms of moisture content, Ca cohesive component and aggregate stability. Thus, better positioning of the boxes it might be suggested in order to make clearer the possible differences between rainfall intensities regarding the already mentioned three variables as well as the roughness coefficient.

In addition, each repetition done on each slope applied showed different behavior in terms of moisture content, Ca cohesive component and aggregate stability. Therefore, here again, it was not possible to think about any trend of the variables mentioned.

The influence of the initial conditions of the soil should be discussed in order to figure out which variables would be influencing these rainfall experiments, to avoid large deviations behaviors of the studied variables on each repetition.

Shear resistance by Surface shear test apparatus

The methodology applied in this experimental study requires a preparation of soil samples before using the surface shear test apparatus that is mentioned and explained in the article by Zhang et al (2001). The soil samples must have the same moisture content and same conditions. However, the conditions of the soil after the rainfall experiment did not allow this procedure. The measures were done without any preparation of the soil samples and different moisture content. If the moisture content is changed, the influence of the moisture content after the rainfall experiment over the aggregate stability and shear resistance also changes. Therefore the Ca cohesive component values will not be the corresponding ones for those

conditions, and it will not be possible to describe an influence network of these variables and the different rainfall intensities.

In addition, the loamy texture of the soil made difficulties in measuring the Ca cohesive component of the soil. The soil was attached to the rough yellow surface of the device. Therefore, the reliability of the data measured by the device decreased. The same suggestion is mentioned in the article by Zhang et al (2001) which explains that the sand paper might influence the results. Taking into account the conditions of the soil after 75 minutes of rainfall, a different method may be suggested that could measure the shear resistance of the soil material in those conditions as it is also mentioned in the article by Zhang et al (2001). Further research might be needed in order to improve the device properties to adapt it to these measurement conditions.

Moisture content by cylinder method

Due to the loamy texture of the soil, the final conditions of the soil made it difficult to take proper soil samples for the moisture content measurements. The conditions of the soil might influence on the kind of method selected, that could fit better than the methods used in this experimental research. The pore presence added some constrains when selecting the proper method. Sensor measuring devices were refused due to this fact. The cylinder method was used due to its easy and fast use as well as for the lack of problems taking into account the soil pores.

In addition, due to the influence of the moisture content of the soil on the other variables (Ca and aggregate stability) and the rainfall experiment output variables (especially when applying a slope of 2.5º) the measurement of the moisture content should be as reliable as possible.

Aggregate stability by wet sieving

A wet sieving apparatus was used in order to measure the aggregate stability index. According to Le bissonaiss (1996) this apparatus combines most of the breakdown mechanisms; however, it is thought to overemphasize slaking mechanism compared with rainfall conditions. This fact could have influence in the data gathered in the experimental research.

Roughness coefficient by chain method

No changes in roughness were observed in the qualitative analysis with the chain method. On the other hand, the statistical analysis suggested possible relationships between the roughness coefficient, rainfall intensities and rainfall experiment output variables. Taking into account some pictures taken at the beginning conditions and at after conditions that showed the significant change in surface roughness after the rainfall experiment, it may be possible to suggest the unaccuracy of the chain method in this experimental study (see figures 22 and 23, see annex 5).
Changes in surface could be so small that the chain method would not be able to describe them (Jester et al. 2005 and Merrill et al. 2001). Different method in order to improve the measurement might be suggested, such us: pin roughness meter and chain set method (Jasper et al. 2005 and Merrill et al. 2001). Another possibility could be the improvement of the method already used such a thinner chain composed by a metal wire that would fit perfectly to the surface aggregates. Further research is needed in orther to study other methods that

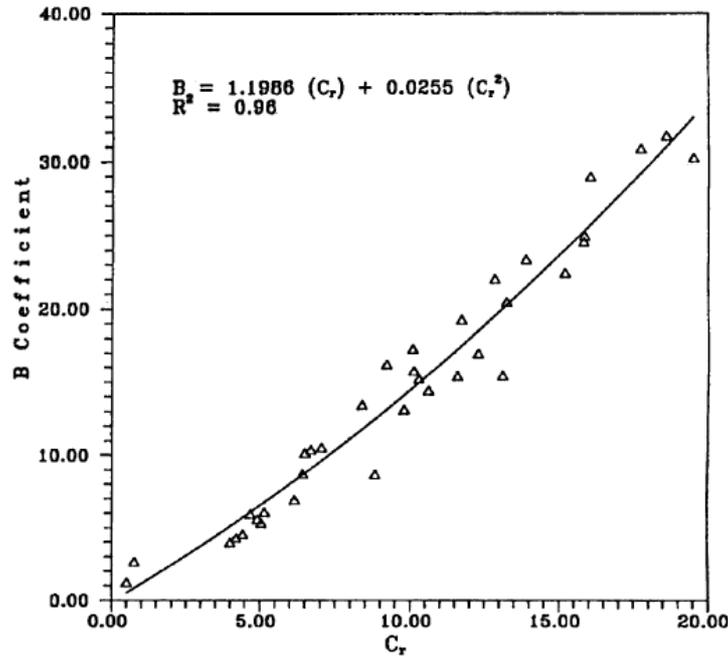would fit better in this case, or develop an alternative method like the possibility of a thiner metal wire.

Figure 25 *Relationship between the C, obtained by chain method and B coefficients computed from pin-roughness meter technique (Saleh 1993).*

In the article by Saleh (1993) the chain method was compared with the pin meter. In figure 25 is possible to see that significant correlations were found between both methods. When applying these methods over soil surface with smaller soil aggregates the difference between data obtained with each of the devices was higher. Saleh (1993) suggested that in the presence of smaller aggregates the pin meter was not accurate enough (less than 0.025-m in diameter).

On the contrary, Jester et al. (2005) compared different surface roughness measurement devices. Rainfall experiments were carried out in laboratory conditions. The rainfall experiments lasted 90 minutes. Two of the methods studied were: chain method and pin meter (see figure 26).
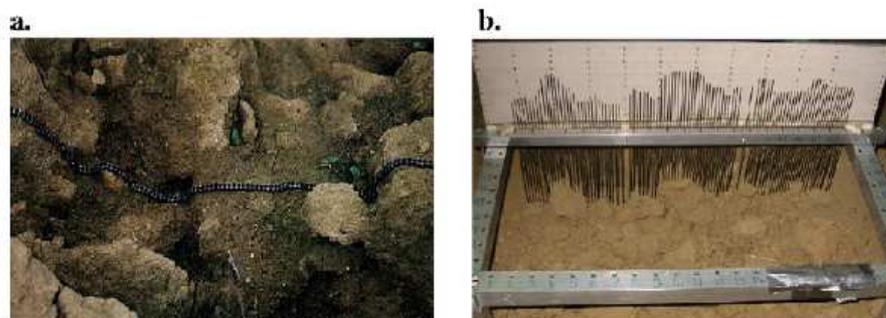
Figure 26 *a) chain method device and b) pin meter device (Jester et al. 2005).*

The measurement time needed using the chain methods was lower than for the pin method. However, the error or measurement uncertainty for the profile length was 5mm for the chain method, while for the pin method was 2 mm in height and position (Jester et al. 2005).

Table 8 Measurement uncertainty and time for the compared devices (Jester et al. 2005).

Device	Source of error	Vertical/horizontal error[a] (mm)	Time for measurement/data preparation (min)
Roller chain	Fit to roughness elements measure chain length	5 (for profile length)	25/–
Pin meter	Meeting surface with pins, reading from graph paper, straightness of pins	2/2	90/–

Differences between both methods were higher when the surface soil was rougher. After rainfall experiments, the soil surface was smoother and the differences were not so clear between both methods. It is suggested that when the soil surface is rough the chain could not follow the gaps between the aggregate, while the pin method fit well to each gap of the surface. When the rainfall effect smoothed the soil surface the chain fit much better than in the previous case (Jester et al 2005).

The pin meter could be suggested as an alternative method due to its higher accuracy (Jester et al. 2005) and applicability in laboratory conditions. Furthermore, chain method should be recommended in filed measurements as it is also suggested in Saleh (1993) and in Jester et al. (2005).

Finally, another alternative to the chain method explained by Merrill et al. (2001) is the chain set method. It is composed of a "6 member chain with link lengths in a geometric progression ranging from 0.48 to 15.2 cm" (Merrill et al. 2001). Merrill et al. (2001) showed in his research that this method could overcome the scale-uncertainty found using a single chain method and mentioned by Skidmore (1997): "very fine chain could yield the same CR value for a surface with many small roughness elements (RE´s) as for a surface with a smaller number of larger RE´s of the same shape".

This method could be able to give a quantitative value of scale-sensitive qualitative changes that could occur when soil surface roughness is changing due to wind or water erosion (Merrill et al 2001).
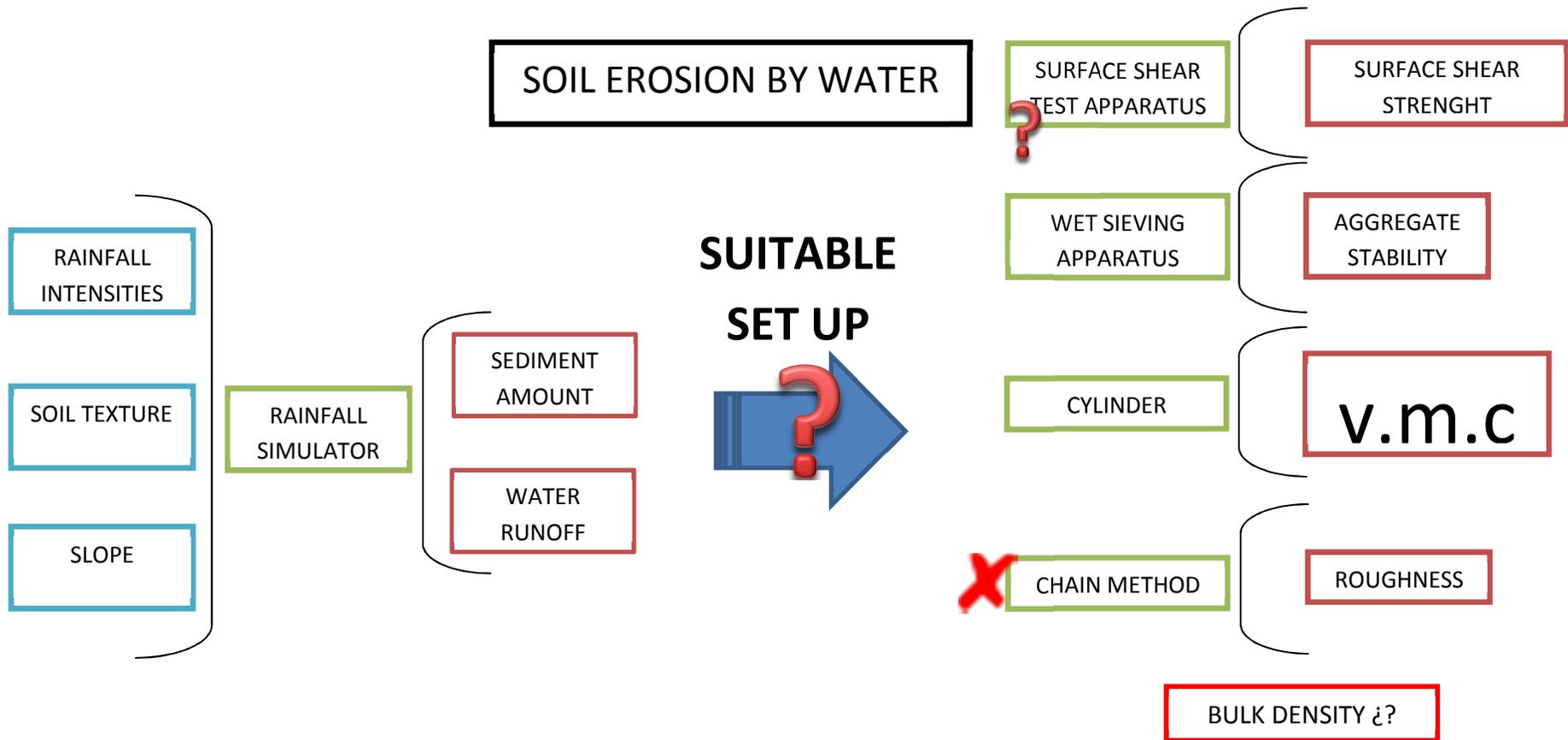
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Figure 27 *Methodology used in order to measure the parameters in brown squares.*

Discussion of the results

Data obtained from the used methodology in this experimental research is discussed in the coming paragraphs;

>   Firstly, influence of the different rainfall intensities on soil surface and the studied variables (Ca cohesive component, moisture content and aggregate stability) is discussed.

>   Secondly, the possible relationships between moisture content, Ca cohesive component and aggregate stability are discussed.

>   Thirdly, the consideration of other influencing variables in this experimental research: soil texture and bulk density is discussed.

>   Finally, roughness coefficient values will be discussed.

Rainfall experiments and the influence of different rainfall intensities on runoff water and suspended sediment amount in runoff water

Slope plays an important role on the runoff surface processes. When the slope was increased the runoff water and suspended sediment values increased considerably as shown in figures 10 and 11.

Furthermore, the amount of sediments and runoff water increased when increasing the rainfall intensity. Therefore it would be possible to argue that there is a difference between the different rainfall intensities in terms of suspended sediment amount and runoff water, thinking about erosion features.

In the research of Barthés et al (2002) it is showed that in field conditions, taking into account climate aggressiveness (in this case, rainfall aggressiveness) and slope, apart from the topsoil aggregation conditions, improved the relationship with the susceptibility to runoff and erosion, instead of considering only the topsoil aggregation as individual parameter to assess erosion processes.

In addition, apart from the influence of the slope and rainfall intensities observed regarding the runoff and suspended sediment amount in water runoff, there is also an increase on both of mentioned variables in time.

Slope, time and rainfall intensity variables seems to be clearly influencing the surface runoff processes, in terms of runoff and suspended sediment amount in water runoff. Statistically is also supported the idea about the influence of different rainfall intensities on the runoff water and suspended sediment amount in runoff water (see annex 4: table 4.1).

It could be suggested that taking into account the influence of these variables could improve the relationship of aggregate stability variable with runoff water and suspended sediment amount in runoff water as mentioned in Barthés et al. (2002).

On the other hand, values registered in the first run for most of the rainfall experiments done were higher than in the rest of the experiments or runs. This might lead to a discussion about

the setup of the rainfall experiments because the deeper material put in the boxes was never changed. It could be that the moisture content increased with the number of experiments done. In that case, the initial moisture values would have increased with every run or repetition. This suggestion would be consistent with the findings of Gover G. et al (1993) that conclude that the higher initial water contents increase the erosion resistance. Rainfall experiments done after the first repetition of the rainfall simulations showed lower values of water runoff as well as suspended sediment amount in water runoff (see figure 9).

Are the changes after the rainfall experiments reflected in: Shear resistance (C_a : cohesive component), aggregate stability and moisture content?

Influence of different rainfall intensities on Ca and moisture content:

Although rainfall experiments with slope of 10-12º showed the highest values of runoff water and sediment release for the intensities of 50-60mm/h and >60mm/h, moisture content and Ca cohesive component did not show big differences between the different rainfall intensities applied as it is shown in figures 12, 14, 15 and 16).

In most of the rainfall experiments, the final moisture content is similar in all the rainfall intensities applied, as well as the Ca cohesive component (see figure 11 and 12). Furthermore, there was no general trend observed depending on the rainfall intensities applied that would be influencing the behavior of the final amount of moisture content and Ca cohesive component in the applied two slopes: 2.5º and 10-12º.

Influence of different rainfall intensities on aggregate stability:

Figure 11 (graph with the average values of aggregate stability) shows a slight decrease in aggregate stability for the two highest intensities when applying slope 10-12º. However, observing the individual repetitions of each rainfall experiment, this slight decrease is not really clear. Therefore it is not possible to argue that an increase in rainfall intensities would be influencing the final aggregate stability values.

On the other hand, in the rainfall experiment results with slope of 10-12º (figures 10c, 10d, 10e and 10f), for the intensities of 50-60 mm/h and >60mm/h a different behavior was observed in some of the repetitions. At minutes 45 and 60 a maximum value of sediment amount in runoff water was reached and started decreasing in time. It may be that at the beginning of the experiment the soil aggregates are destroyed by the raindrops; disappearing the bond between these soil particles. The crusting process starts and the free soil particles start to reorganize over the soil surface. In the meanwhile due to the runoff processes, these soil particles are also being dragged. It seems to be that there is a point around the 45 min and 60 min. where the amount of dragged particles decreases while these are being sediment and reorganized over the soil surface. According to Morin J. et al. (1996) this process could have happened due to the "interface suction force acting on the entrained suspension flowing in the runoff" which might have attracted the clay soil particles in runoff to the clay particles already in the soil crust.
In addition, Moore D.C et al (1990) explains that a lower permeability due to the crusting processes could promote erosion, while higher soil strength (in this case: Ca cohesive component of shear strength) might decrease detachment and erosion. Moore D.C. et al (1990) argued that the crust layer is more cohesive than the soil layer that is not crusted, and therefore less susceptible to erosion.

Furthermore, Moldenhuer and Koswera (1968), Norton (1987) and Epstain and Gant (1973) found that soil erodibility depends on the rate and level of crust formation. Also, the soil loss decreases with crust formation. Epstain and Gant (1973) point out that soil loss reached a maximum value at the 10th minute of rainfall. Afterwards, the soil loss decreased to a constant rate.

The aggregate stability is lower due to loss of links between the particles. However, these particles are crusted over the soil surface and are part of a high dense soil layer, with compacted low pore amount. This explanation would fit with the aggregate stability values observed when applying a slope of 10-12º (see annex 3 and figure 11).

For the case of slope 2.5º, the behavior described above was not observed (see figures 9a, 9b, 9c, 9d and figure 12). It is suggested that, due to the lower slope applied, this process did not occur. It could be possible that more time would be needed in order to observe the same behavior of suspended sediment sedimentation and possible influences of the maximum rainfall intensities applied on aggregate stability.

Is the slope influencing on Moisture content, Ca cohesive component and aggregate stability values?

When applying a slope of 2.5º, the sediment amount and runoff water released was lower than when applying a slope of 10-12º (see figures 9 and 10). The Increase of the Ca cohesive component values from the initial conditions until the end of the rainfall experiment was slightly smaller for the slope 10-12º than for the slope 2.5º (see figure 11). This fact would fit with the higher release of sediment amount in runoff water when applying a slope of 10-12º (lower shear resistance, higher detachment rate of soil particles). On the other hand, the change of moisture content values were not so different between both different slopes applied for all the intensities applied (see figures 11 and 12).

Furthermore, in the correlation analysis for slope 2.5º, the moisture content seems to play the major role in the runoff and sediment amount in runoff water. In contrast, aggregate stability also seems to play a major role in slope 10-12º (see figure 24).

The ponding phenomena could be the main reason for this difference between slopes. Once the water starts ponding over the soil, the moisture content will increase and pond until a saturation point. Therefore, it seems to be that Ca cohesive component increase would be mainly depending on the moisture content of the soil when applying slope of 2.5º.

Moore D.C. et al (1990) mentioned the combined processes that might happen during soil crusting. On the one hand, decreased permeability may increase the water runoff, while on the other hand the increased soil strength (Ca cohesive component of shear strength) might decrease detachment and erosion.

Although runoff water values were registered in rainfall experiments with slope 2.5º, ponding of water runoff was observed. Consequently, water runoff flow was lower than in slope 10-12º, increasing the water runoff level on soil surface. Raindrop impact on soil surface dumped on water runoff. Raindrop impact might not have influenced on soil aggregate breakdown (only detachment of soil particles) as it might have done in slope 10-12º (detachment and displacement of soil particles). Therefore, aggregate stability of soil particles might not be responding in the same way as in slope 10-12º, where different erosion processes may have occurred.

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On the contrary, with higher slopes, this saturation point is not reached so easily and moisture content might not be the only variable playing the main role in runoff and sediment release processes. Thus, in the case of slope 10-12º, <u>aggregate stability</u> and <u>moisture content</u> are the ones which might play the major role in water runoff process according to the correlation analysis; which at the same time was influenced by the rainfall amount applied. It might be suggested a rainfall intensities influence on aggregate stability and moisture content through their influence in runoff processes (see figure 24). Ca cohesive component might not be mainly influenced by moisture content when applying slope of 10-12º regarding the qualitative observations (see figure 11).

When:

slope 2.5º → changes in Ca cohesive component= f(moisture content)
slope 10-12º → changes in Ca cohesive component= f(moisture content, aggregate stability)

The slope seems to play an important role on the behavior of these variables (moisture content, Ca cohesive component and aggregate stability) and relationships established between them. Thus, the next question would be of interest to respond:

Are there any correlations between the studied variables: moisture content, shear resistance (Ca: cohesive component) and aggregate stability?

Ca cohesive component and moisture content

Focusing in figure 12 (slope 2.5º), Ca cohesive component values seems to be slightly higher. Despite the lower slope applied, water amount in the soil was the same or slightly higher. It might be that the presence of higher water amount may be influencing the Ca cohesive component of the soil, increasing these values or not changing too much despite of the lower slope applied as it is also mentioned in Moore D.C. et al. (1990). But, opposite to what is explained in the article by Zimbone et al. (1996), when moisture content decreased soil shear strength increased.

In the research done by Zimbone et al. (1996) four different devices were used (two torvanoes, one hand vane tester and one pocket penetrometer) in order to measure the shear strength and establish a relationship with moisture content. As a conclusion of this research it was suggested that although in general it was found that high moisture content values were related to low values of shear strength, further research was needed in order to establish this relationship in terms of soil type. Thus, although this article says that there may be a negative relationship between both variables, it might be possible that the texture soil type in this case is playing a major role. In addition, the slope is also determining whereas the moisture content is playing a major role or not in the soil erosion processes studied (see figure 24). Therefore, loamy soil texture and slope could influence the relationship of moisture and the Ca cohesive component. Furthermore, crusting processes also might have influence on Ca cohesive component values and moisture content. According to Moore D.C. et al. (1990) the crust layer is more cohesive than the non-crusted layer. Therefore the shear strength values should be higher as it is observed in this experimental research (see figures 11 and 12).

Finally, significant differences were found in the statistical analysis between the before and after conditions of the Ca cohesive component and moisture content values. These results are in accordance with the qualitative observations done above, regarding the increase of moisture content and Ca cohesive component at the before and after conditions.

Aggregate stability and Ca cohesive component

Aggregate stability decreased from the before conditions to after conditions of the rainfall experiment when applying slope 10-12º. Due to the lower final aggregate stability values, Ca final cohesive component values should have decreased due to the lower degree of stable aggregates. However, this behavior was not observed in rainfall experiments with slope of 10-12º, where Ca cohesive component values increased.

Therefore, a positive correlation of Ca cohesive component and aggregate stability is not possible to consider in this case, despite the data registered in the rainfall experiments with slope of 2.5º.

It could be suggested the presence of a slope threshold value, where from a certain point of slope value, negative correlation between both variables is not possible to be explained by a linear behavior. In addition, the importance of the crusting processes during the rainfall experiments should be considered. For both slopes, Ca cohesive component values and moisture content values increased. The difference is that in slope 2.5º ponding processes were observed while in slope 10-12º not. It might be suggested that depending on the water runoff amount on soil surface and moisture content, the influence of raindrops on aggregate stability might change. Thus, moisture content variable could be between the correlation of aggregate stability variable and Ca cohesive component.

As it is mentioned in some articles (Boix-Fayos et al 2001, Le Bissonaiss 1996) the aggregate stability should not be considered as the only parameter predicting the soil condition and degradation. In the mentioned results is possible to observe that aggregate stability as a unique parameter does not give us a trend or an idea about the erosion processes occurred in the rainfall experiments.

Barthés et al. (2002) also argues that the importance of this variable regarding soil erosion processes remains questionable because first, this fact has been argued through laboratory experiments like this one, and second the behavior of sieved and manipulated samples is not in most of the cases representative of the field processes. However, according to the results of Barthés et al. (2001), a close negative relationship is suggested between aggregate stability and runoff erosion process. This fact is opposite to what this research found in laboratory conditions. Therefore two options could be suggested as possible explanations: 1) Laboratory conditions as Barthés et al. (2001) argued are questionable and not realistic 2) Not always there is a negative relationship between both variables and it may depend on the slope of soil surface and crusting processes.

It should be considered other influencing variables: soil texture and bulk density?

Regarding the suggested influence of soil texture, the results of the research of Zhang et al. (2001) also showed the influence of bulk density over the different soil types. Furthermore, every different behavior observed for the bulk density values regarding all the soil textural types, correspond to the soil type Pp with soil texture of silty loam, the same soil texture type as in our experimental study. It might be suggested that textural type related to bulk density is of importance; influencing Ca cohesive component values in a different way than in other textural types of soil. This issue it has been also highlighted by Zimbone et al (1996). Soil textural type as a highly influencing variable which depending on the soil textural type might could change the relationship between the studied variables in this research.
In the same article by Zhang et al. (2001) bulk density as influencing variable was studied as well. It was found that although the difference in bulk density values was small, there were

effects of bulk density observed over shear strength of the soil samples studied, apart from the influence of moisture content and soil type. Therefore, influence of bulk density could have been taken into account apart from the variables already studied, in order to understand the data obtained and try to establish better relationships between the different variables.

Roughness coefficient

According to the statistical analysis, the roughness coefficient seems to be significantly different regarding the different rainfall intensities applied, for both of the slopes; opposite to the qualitative analysis done with the chain method.

Significant changes in roughness in time were not found with the chain method, neither in the statistical analysis.

When applying slope 10-12º, the correlation analysis shows a relationship between the roughness coefficient and the runoff water and rainfall amount; opposite to the qualitative analysis of the roughness coefficient done. This correlation also showed negative significant correlations with the rainfall amount applied. Thus, the roughness coefficient would be influenced by the rainfall intensity applied and this would be related to runoff and sediment release. Consequently, at the end of the experiment the roughness coefficient might have decreased.

These results are opposite to what it has been explained in the qualitative analysis. Two main reasons could be argued: 1) Statistical analysis is not good enough. 2) Chain method is not the best methodology. Regarding the pictures taken before and after the rainfall experiments that showed us the change in roughness surface, it may be suggested that the chain method was not the best method (see figures 22 and 23).

For the slope 2.5º, the roughness coefficient is negatively correlated to suspended sediment amount in water runoff. This might suggest that when high values of sediment in water runoff, roughness coefficient might decrease. The qualitative analysis did not show these correlations. As for the slope of 10-12º, it may be suggested that the method used to measure the roughness changes in time was not the best one (see figures 22 and 23).

Conclusion

This study aimed to discover the relationship between rainfall intensities, aggregate stability and shear resistance as parameters to evaluate soil erosion by water in laboratory conditions.

Ten rainfall experiments in laboratory conditions have been done, split in two groups depending on the set slopes: 5 rainfall experiments with slope 2.5º and 5 rainfall experiments with slope 10-12º. The rainfall experiments lasted 75 minutes each. Rainfall amount, water runoff amount, suspended sediment concentration and load were measured for each experiment.

Soil samples of the tested soil material were taken at the before and after conditions of the rainfall experiments, in order to measure aggregate stability index, the Ca cohesive component of the shear resistance and moisture content. The soil samples at the after conditions were taken from each of the boxes in order to take representative samples of applied different rainfall intensities.

The observed results suggest:

Rainfall simulator
- Better position of the boxes it is suggested in order to better observation of differences between the different rainfall intensities over the soil surface.

Surface shear test apparatus
- Improvement in the sandpaper of the shear surface apparatus is suggested.
- Soil textural type as an influencing variable over the methodology selected should be taken into account.
- Methodology that would allow the measurement of surface shear strength without pre-treatment of the soil samples is needed. Improvement of the used device or use of alternative devices is advised.

Chain method
- The chain method is not the best methodology for this experimental research. Improvement of the method or the use of other methodologies is advised.

Influence of different rainfall intensities
- Different rainfall intensities applied influenced in a significant way water runoff amount and suspended sediment amount in runoff water.
- Slope played an important role. Significant differences in runoff water and suspended sediment amount were observed between both slopes applied.
- Time also is an influencing variable on runoff water and suspended sediment amount in runoff water.

Ca cohesive component, moisture content and aggregate stability
- Significant differences were observed between the before and after values of moisture content, Ca cohesive component and aggregate stability. But no relevant differences were observed between the different rainfall intensities applied.
- Moisture content and Ca cohesive component increased after the rainfall experiment.
- Aggregate stability decreased for the slope of 10-12º and increased for the slope 2,5. Slope threshold value it is suggested, from which the linear relationship of aggregate stability and Ca cohesive component changes.
- When applying slope 10-12º aggregate stability and moisture content seem to be the most important variables on crusting and water runoff processes. When applying slope

2.5º, moisture content seems to be the most important variable crusting and water runoff processes due to ponding processes.

- Moisture content may be linearly related to Ca cohesive component.
- Correlation between: aggregate stability and Ca cohesive component may be function of slope degree. Suggestion of non-linear correlation between them.
- Slope might have a major role on crusting processes and moisture content, Ca cohesive component and aggregate stability values after rainfall simulation.

Other influencing variables
- Soil textural type is suggested as an influencing variable that could partly explain the relationship that might exist between the variables studied.

Soil Surface roughness coefficient
- Qualitative data analysis of roughness is not reflecting real surface changes. Statistically roughness coefficient seems to be related to rainfall intensities applied.

Further research and recommendations

Further research is needed in order to know the influence of different rainfall intensities over the soil surface in terms of moisture content, shear strength and aggregate stability.

More research on the influence of <u>slope</u> in the studied variables (moisture content, Ca cohesive component and aggregate stability) is advised, as well as on the relationships between them.

The influence of <u>textural soil type</u> is suggested as an influencing variable on the response of the three parameters mentioned above after different rainfall intensities. Thus, should be taken into account in futures studies.

<u>Bulk density</u> measurements should be done in order to have better understanding of the shear strength forces and moisture content relationships.

Regarding the methodology followed in this research, further research is needed in order to find the most suitable devices for rainfall simulation experiments. Especially in terms of soil textural type (loamy soil) and moisture content at the end of the experiment:

- Improvement of the shear surface test apparatus is advised.
- Use of different method from chain is suggested: Alternative methods or improvement of the already used method.

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ANNEX

Annex 1 Rainfall experiments

Slope 2.5º
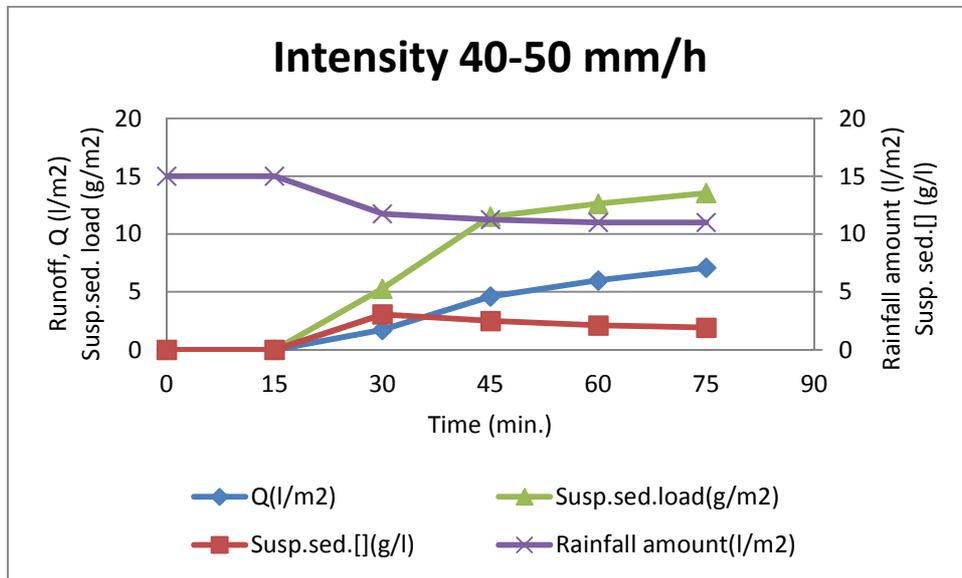
Figure 1.1 Rainfall experiment with intensity 40-50mm/h, run 1.
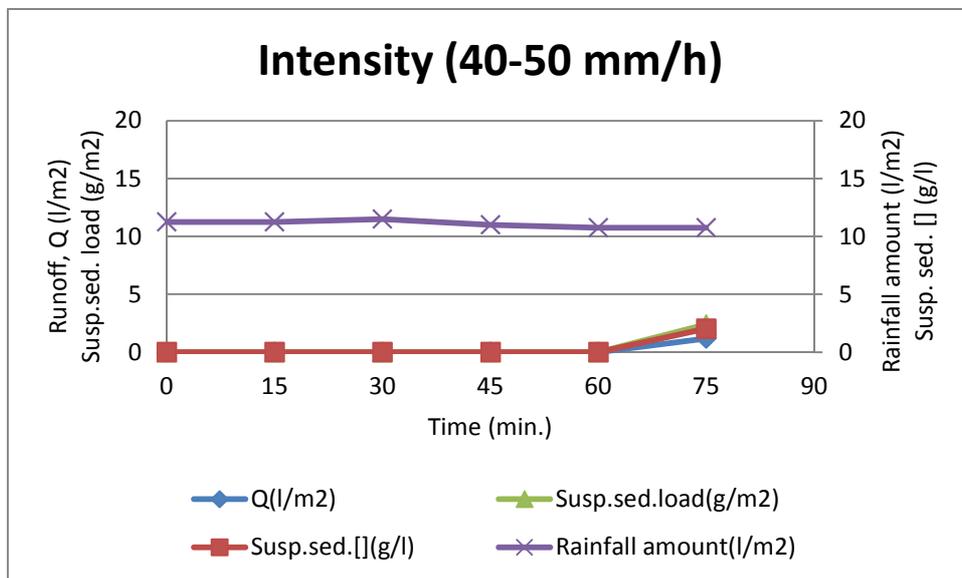
Figure 1.2 Rainfall experiment with intensity 40-50mm/h, run 3.
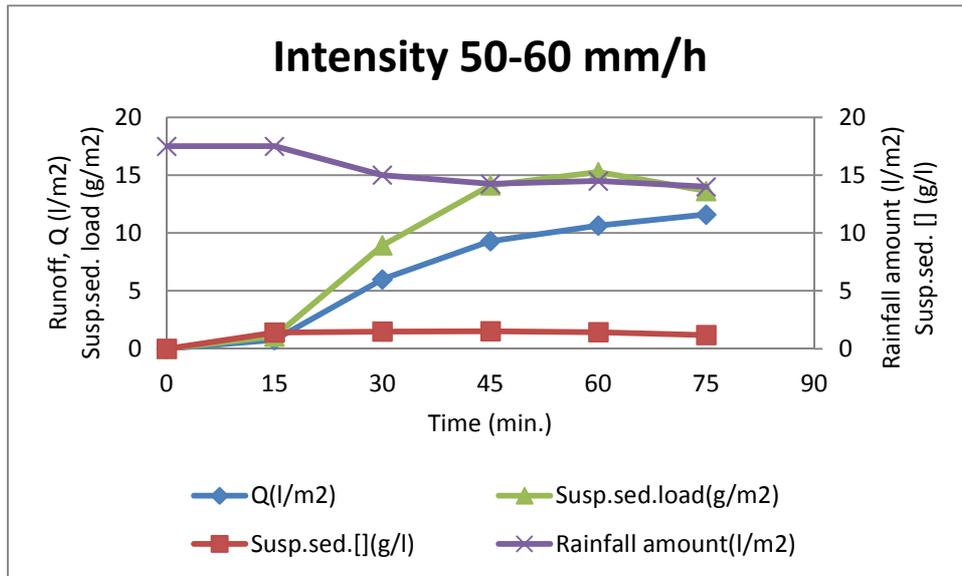
Figure 1.3 Rainfall experiment with intensity 50-60mm/h, run 1.
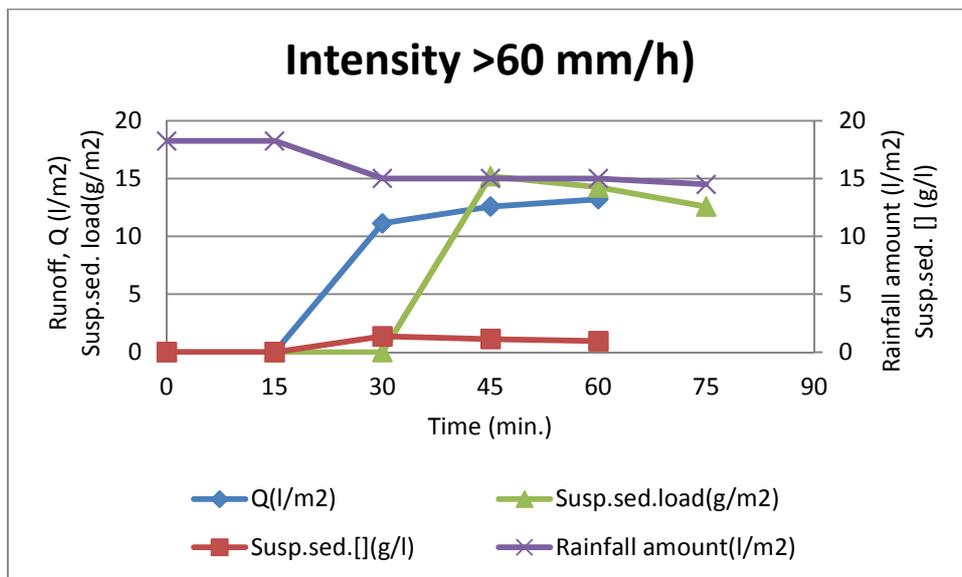
Figure 1.4 Rainfall experiment with intensity >60mm/h, run 1.
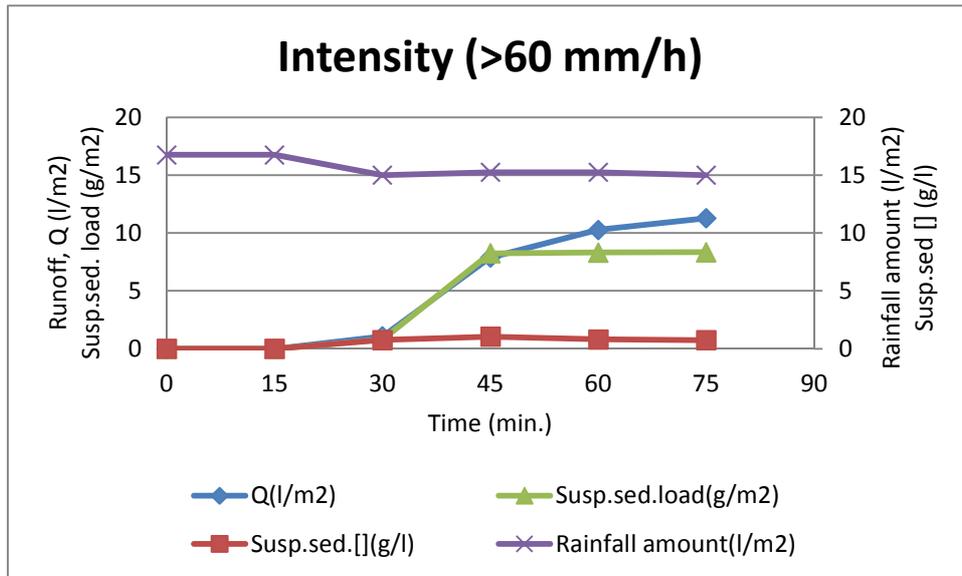
Figure 1.5 Rainfall experiment with intensity >60mm/h, run 2.
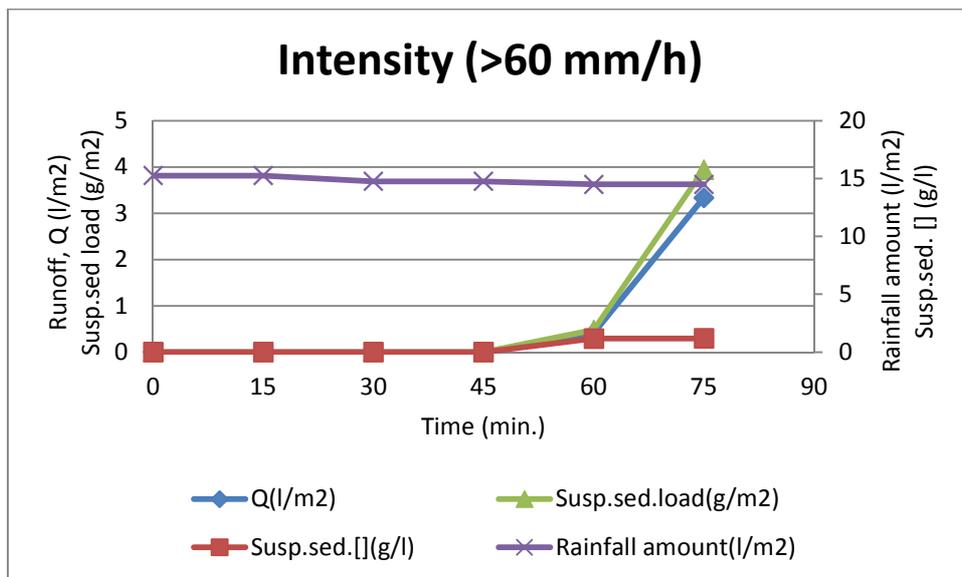
Figure 1.6 Rainfall experiment with intensity >60mm/h, run 4.

Slope 10-12º
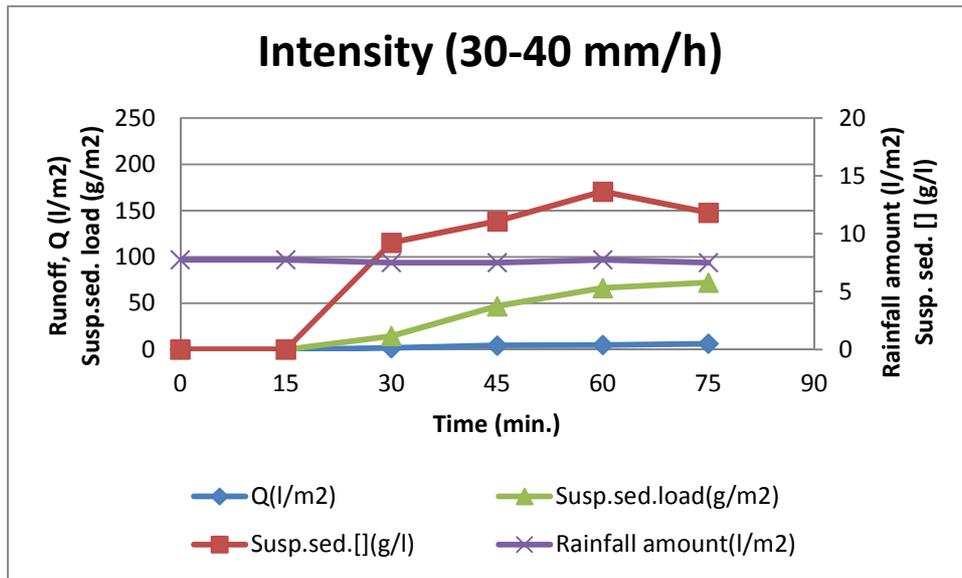
Figure 1.7 Rainfall experiment with intensity 30-40mm/h, run 1.
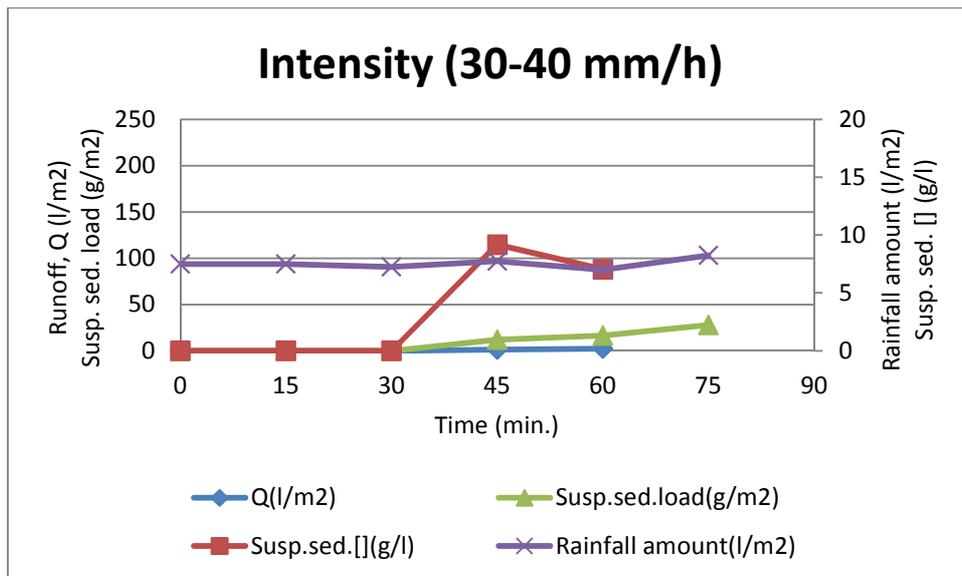
Figure 1.8 Rainfall experiment with intensity 30-40mm/h, run 2.
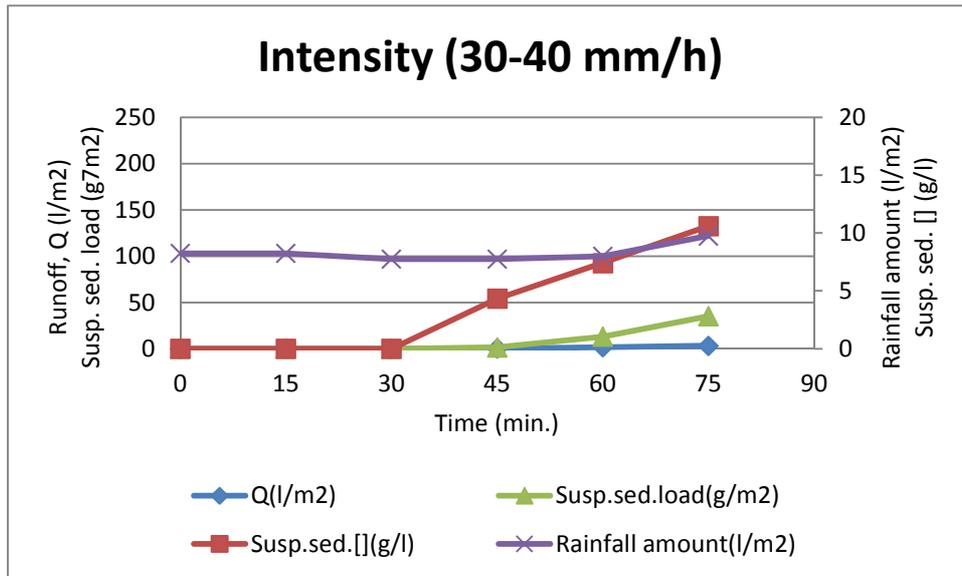
Figure 1.9 Rainfall experiment with intensity 30-40mm/h, run 4.
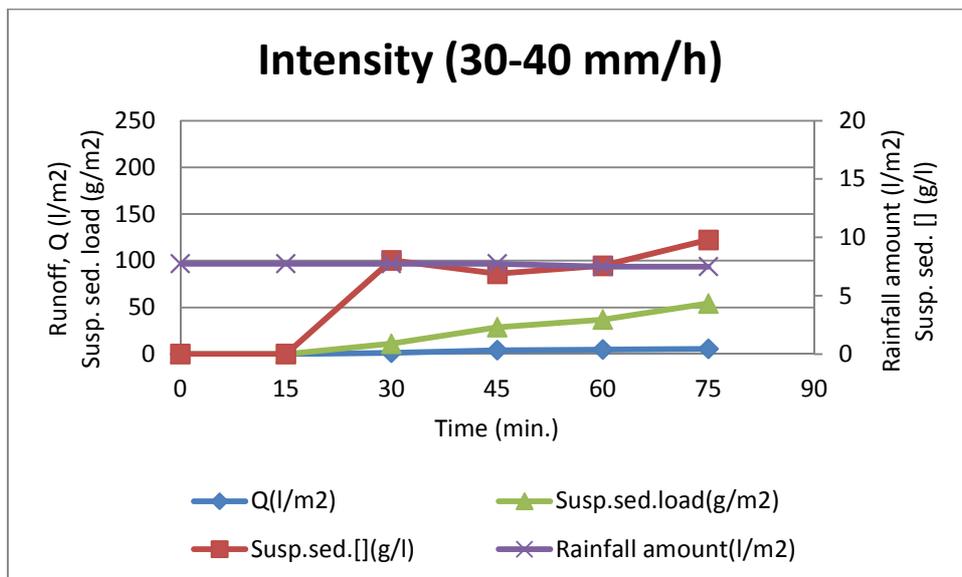
Figure 1.10 Rainfall experiment with intensity 30-40mm/h, run 5.

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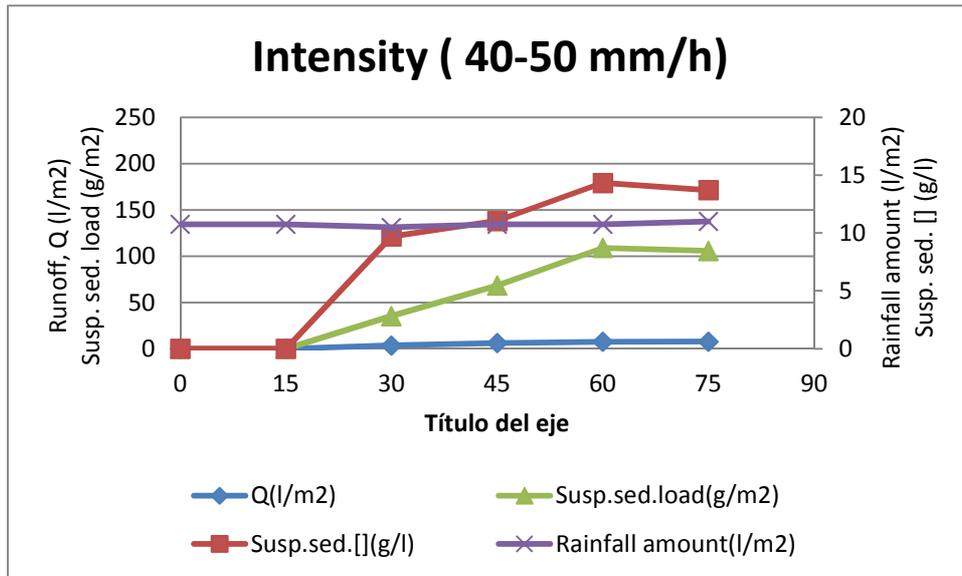
Figure 1.11 Rainfall experiment with intensity 40-50 mm/h, run 1.
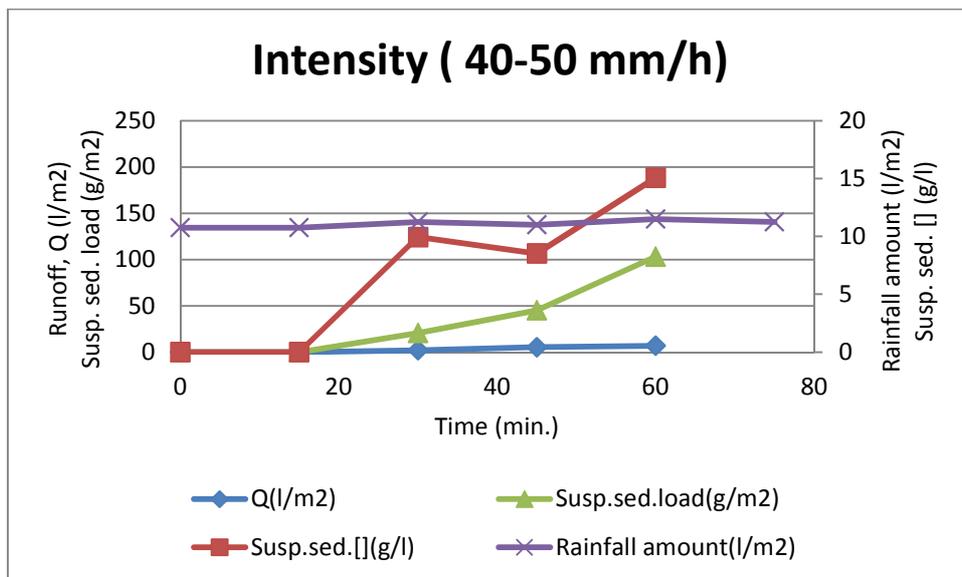
Figure 1.12 Rainfall experiment with intensity 40-50 mm/h, run 2.
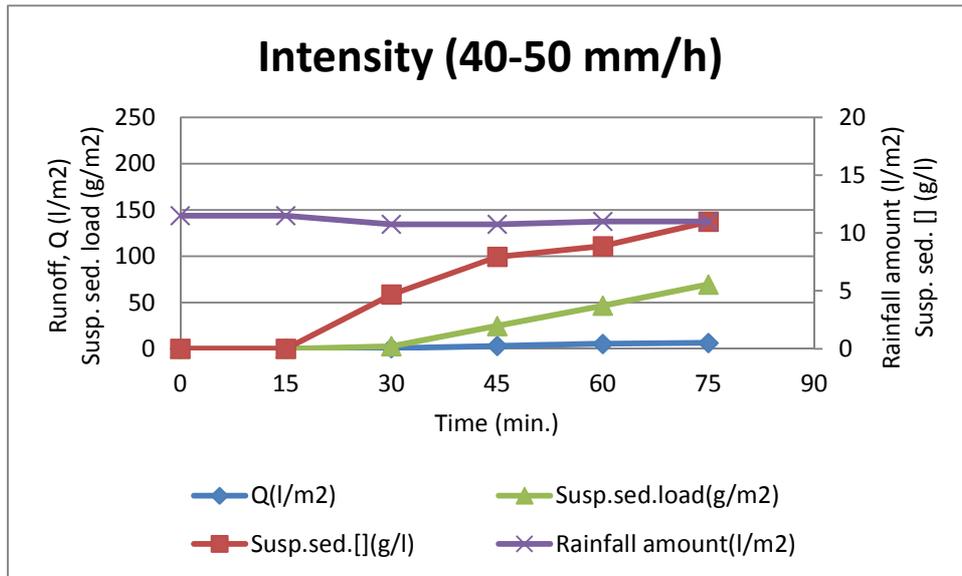
Figure 1.13 Rainfall experiment with intensity 40-50 mm/h, run 4.
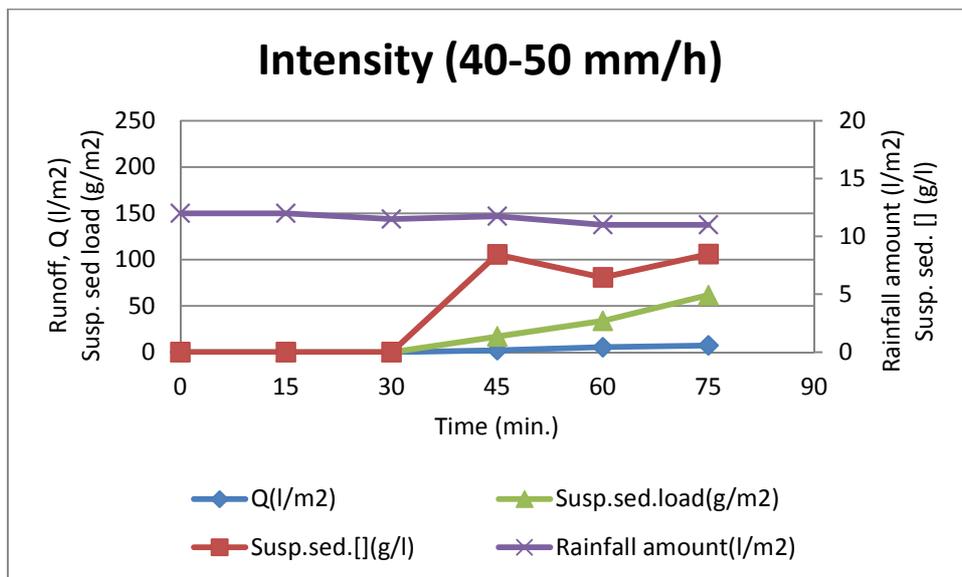
Figure 1.14 Rainfall experiment with intensity 40-50 mm/h, run 5.
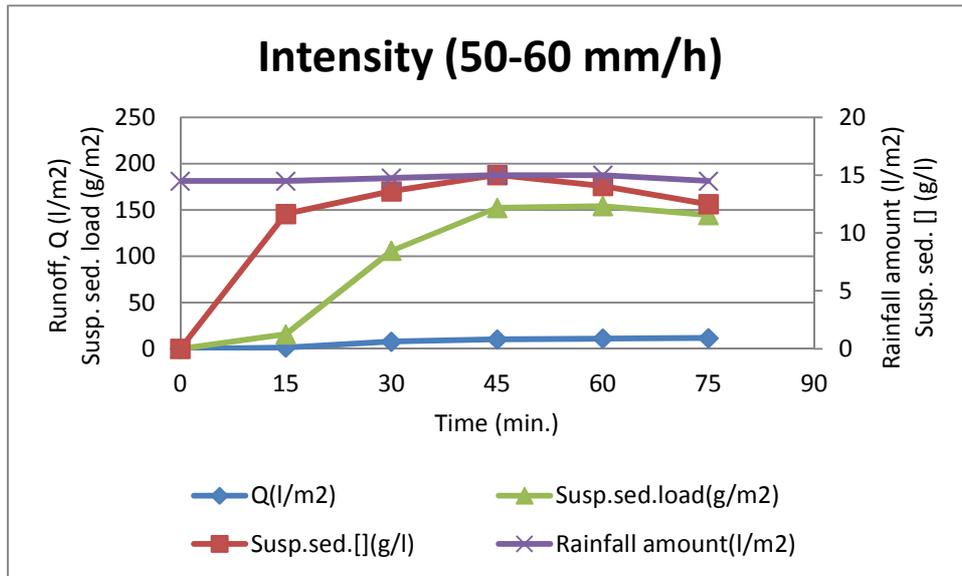
Figure 1.15 Rainfall experiment with intensity 50-60 mm/h, run 1.
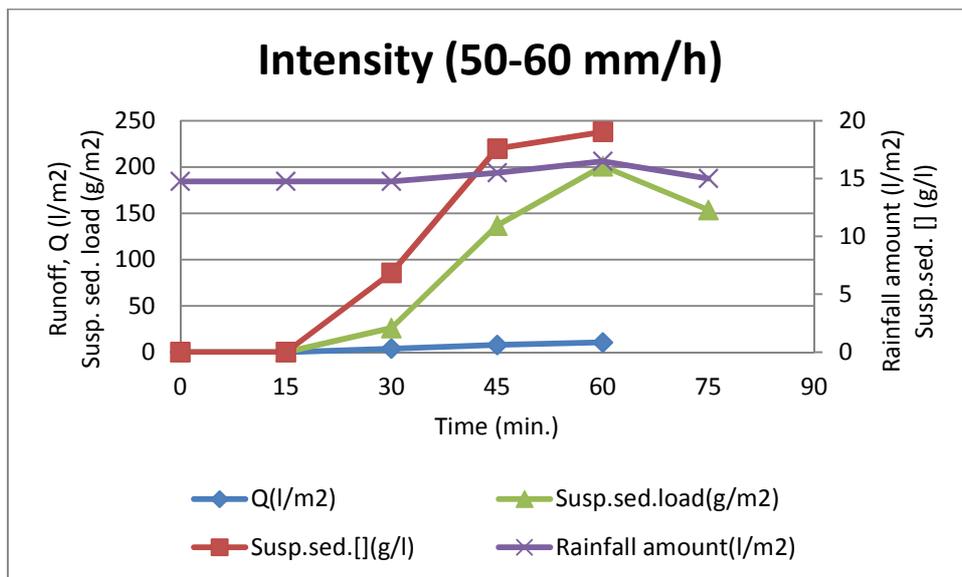
Figure 1.16 Rainfall experiment with intensity 50-60 mm/h, run 2.
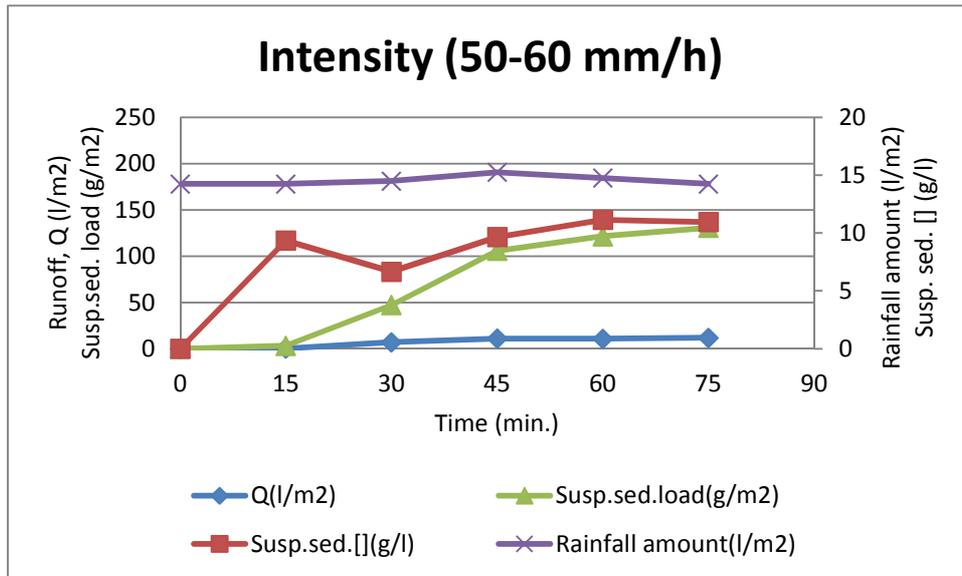
Figure 1.17 Rainfall experiment with intensity 50-60 mm/h, run 5.
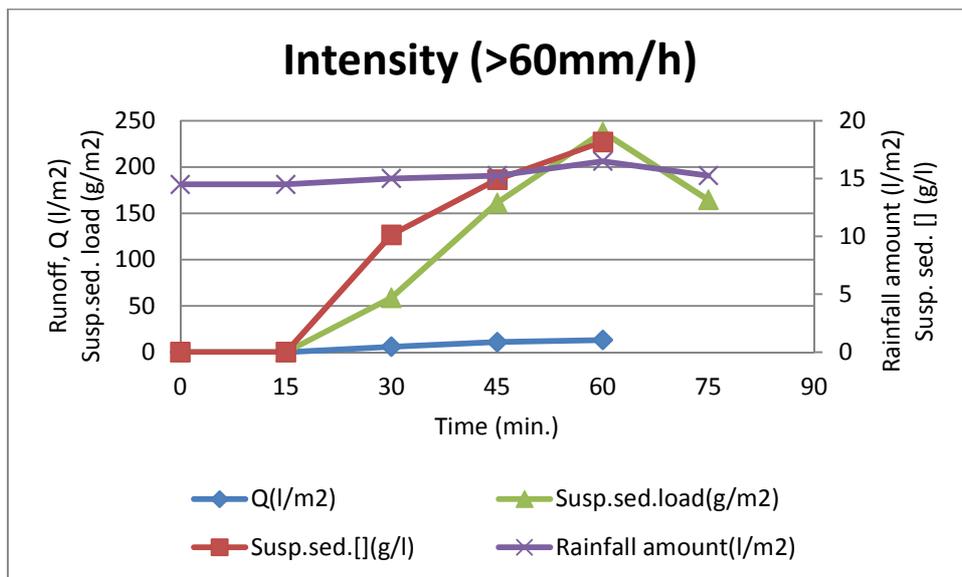
Figure 1.18 Rainfall experiment with intensity >60 mm/h, run 2.

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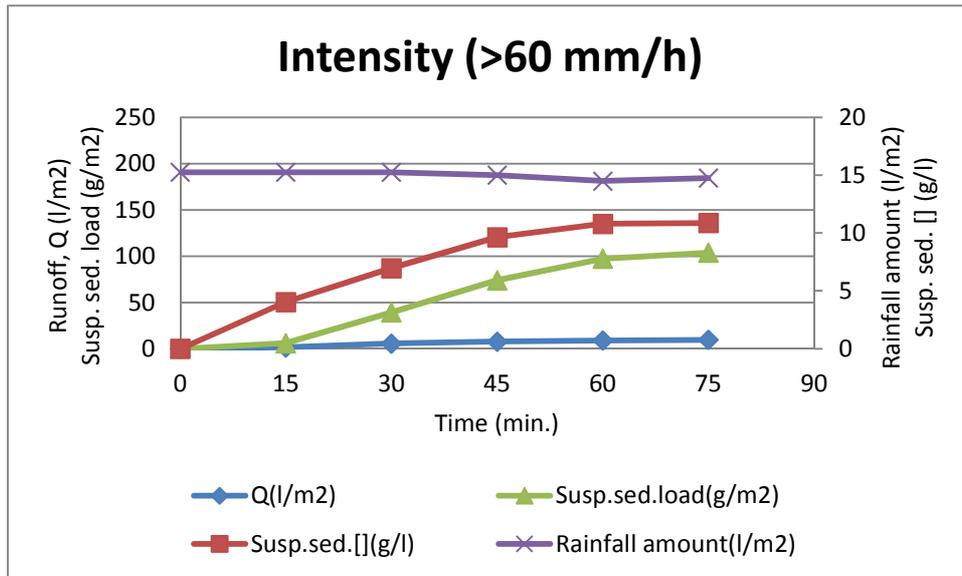
Figure 1.19 Rainfall experiment with intensity >60 mm/h, run 3.
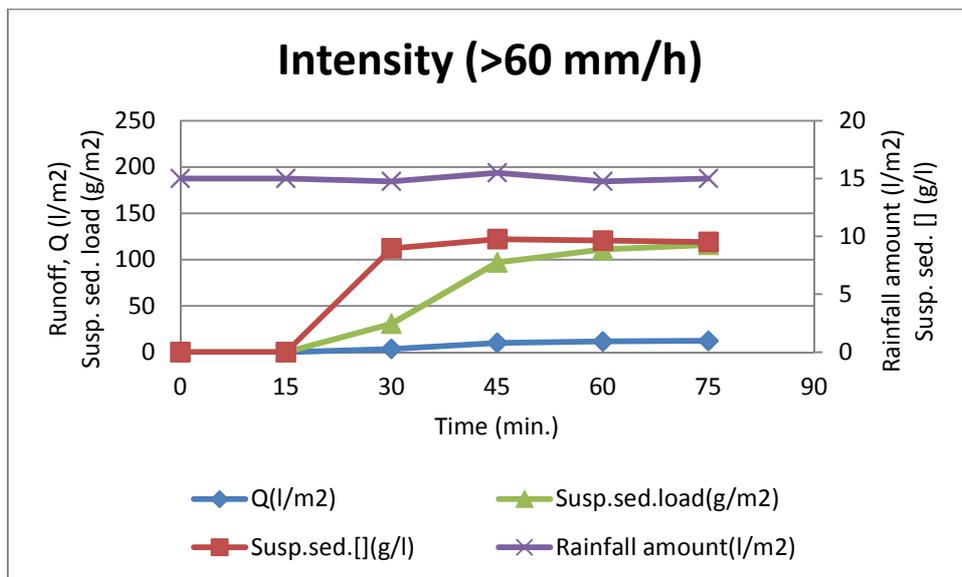
Figure 1.20 Rainfall experiment with intensity >60 mm/h, run 5.

Annex 2 Roughness coefficient

Slope 2.5º
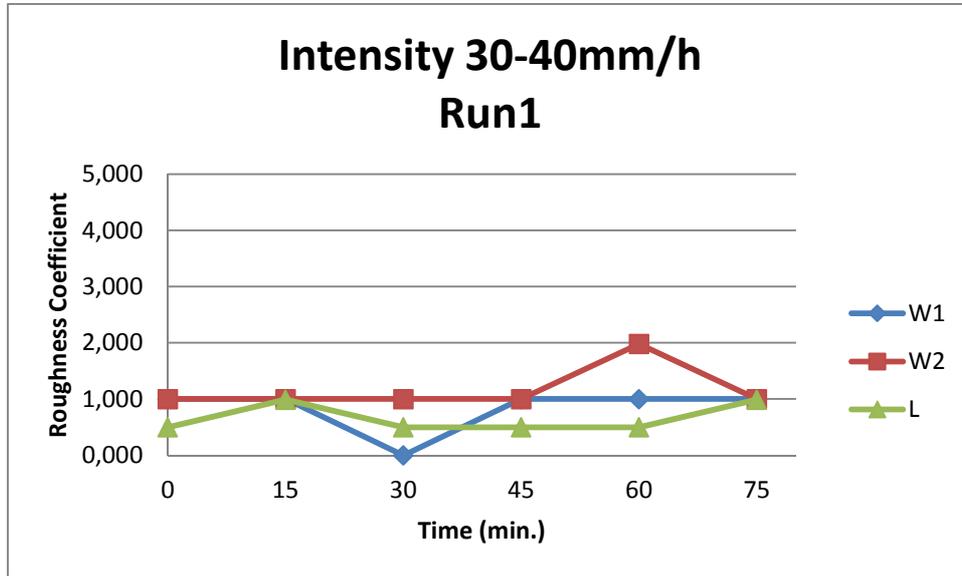
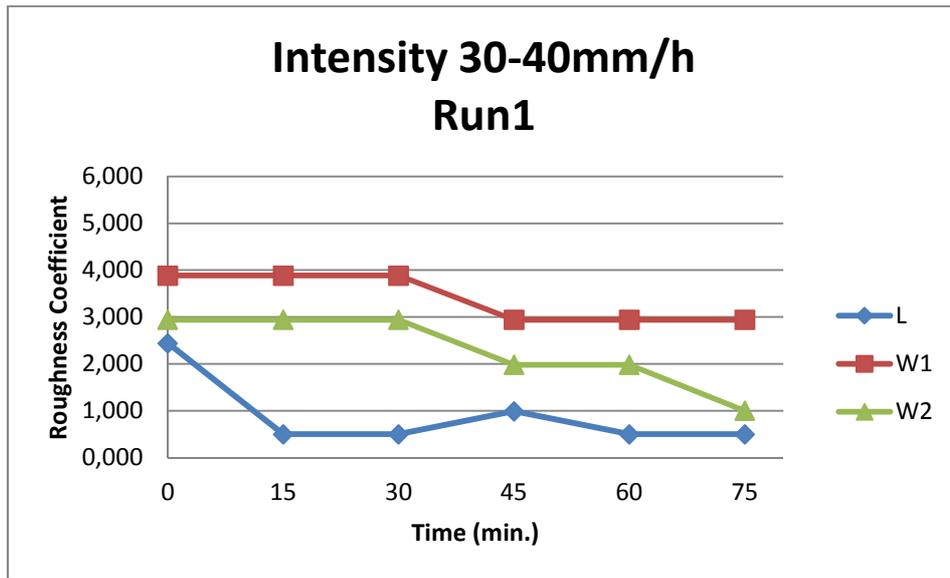**Figure 2.1** Roughness coefficients for Rainfall experiment with 30-40mm/h intensity.
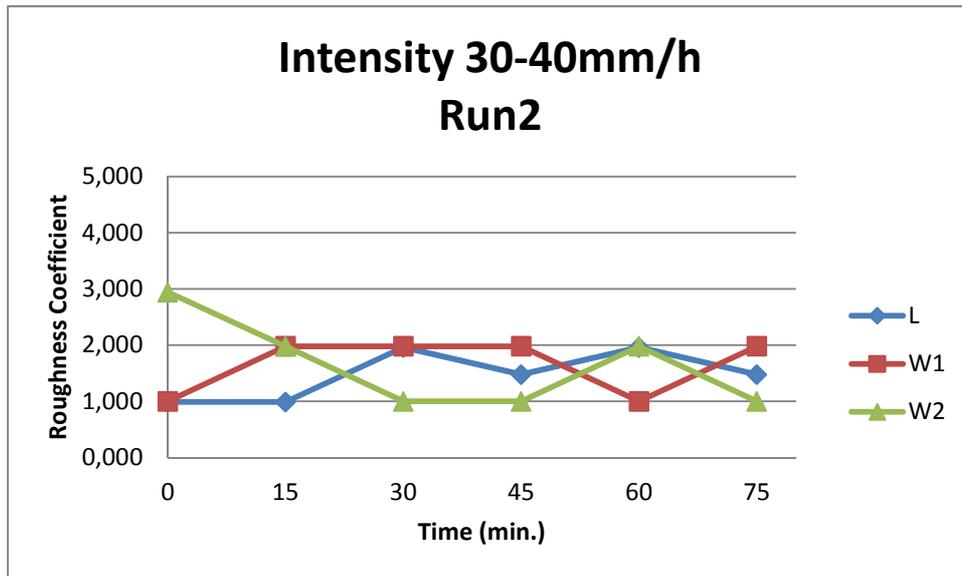
Figure 2.2 Roughness coefficients for Rainfall experiment with 30-40mm/h intensity.
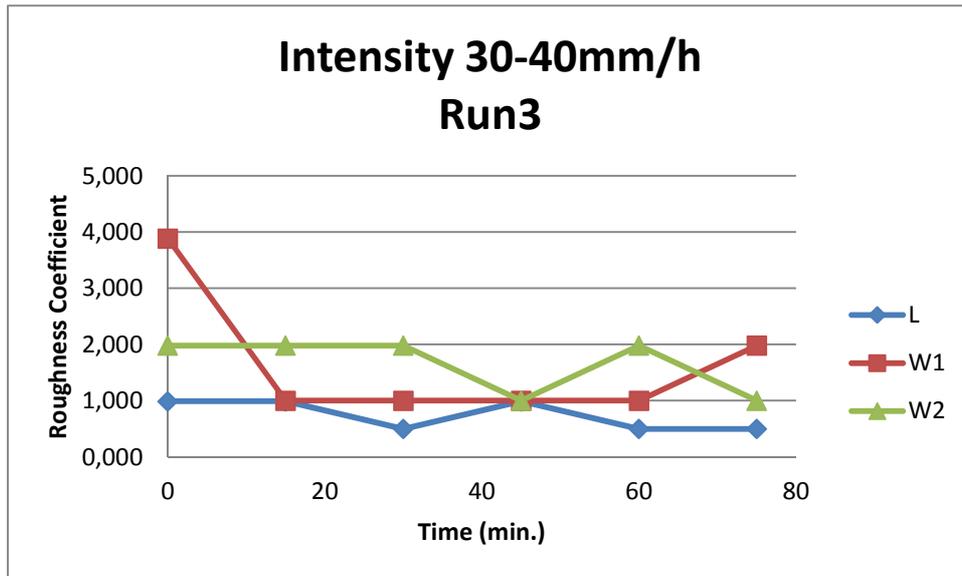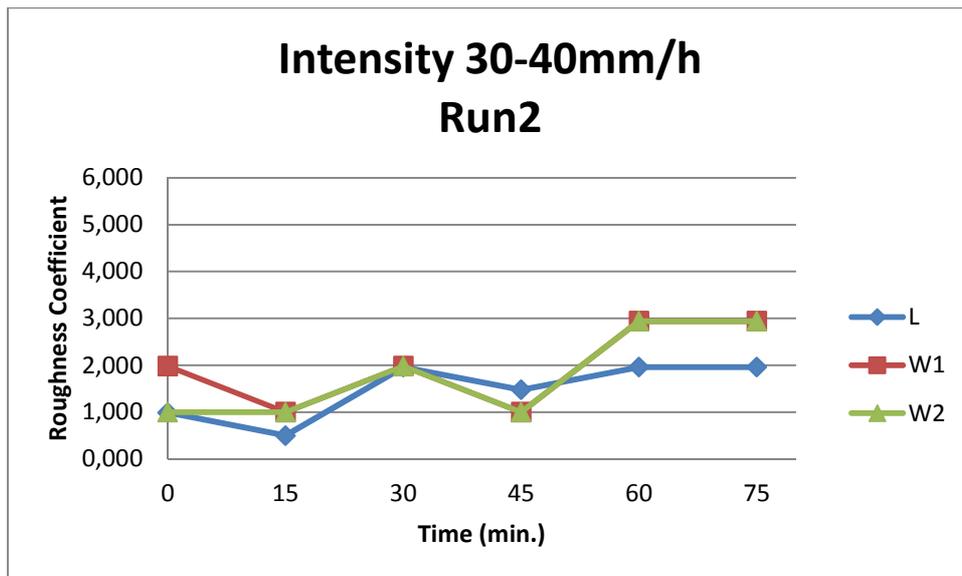
Figure 2.3 Roughness coefficients for Rainfall experiment with 30-40mm/h intensity.
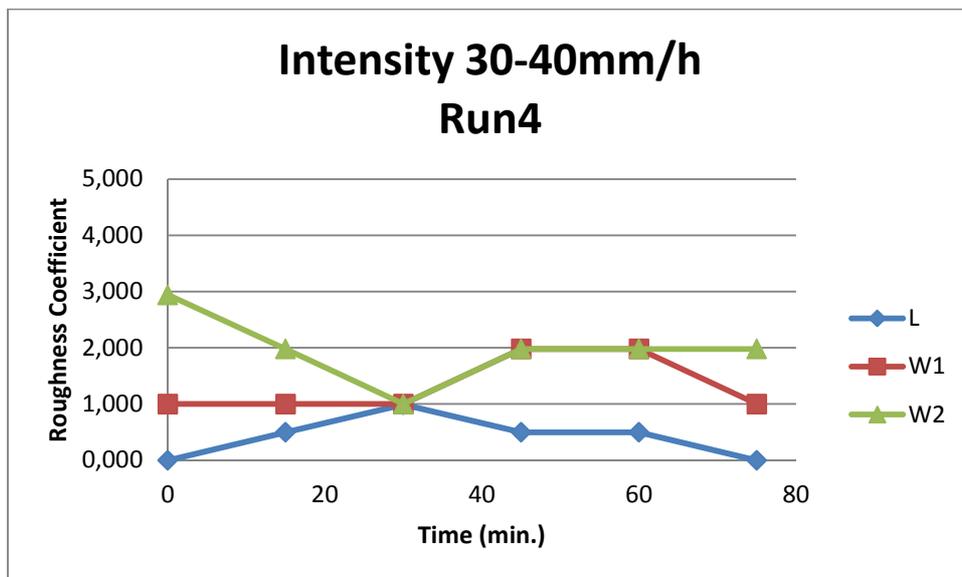
Figure 2.4 Roughness coefficients for Rainfall experiment with 30-40mm/h intensity.
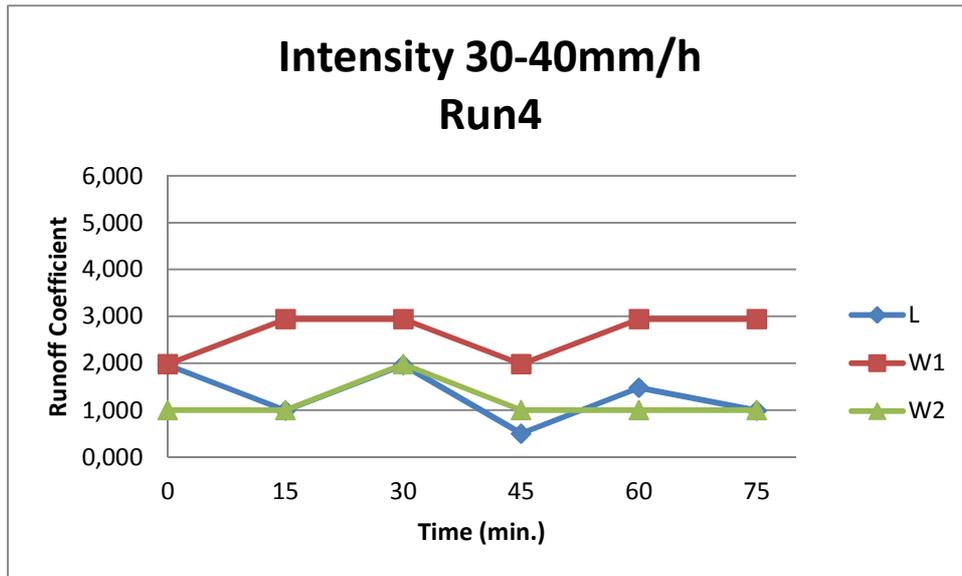
Figure 2.5 Roughness coefficients for Rainfall experiment with 30-40mm/h intensity.
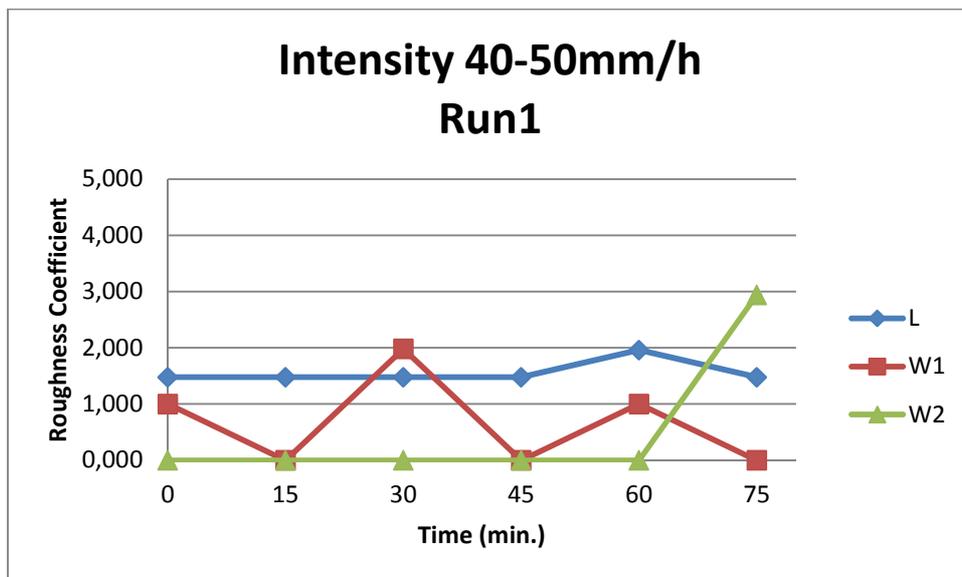
Figure 2.6 Roughness coefficients for Rainfall experiment with 40-50mm/h intensity.
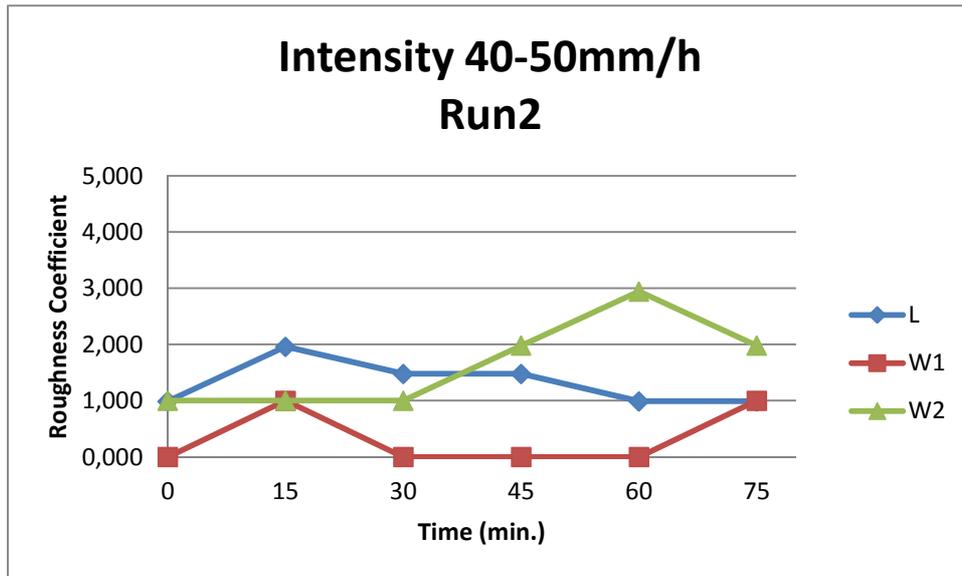
Figure 2.7 Roughness coefficients for Rainfall experiment with 40-50mm/h intensity.
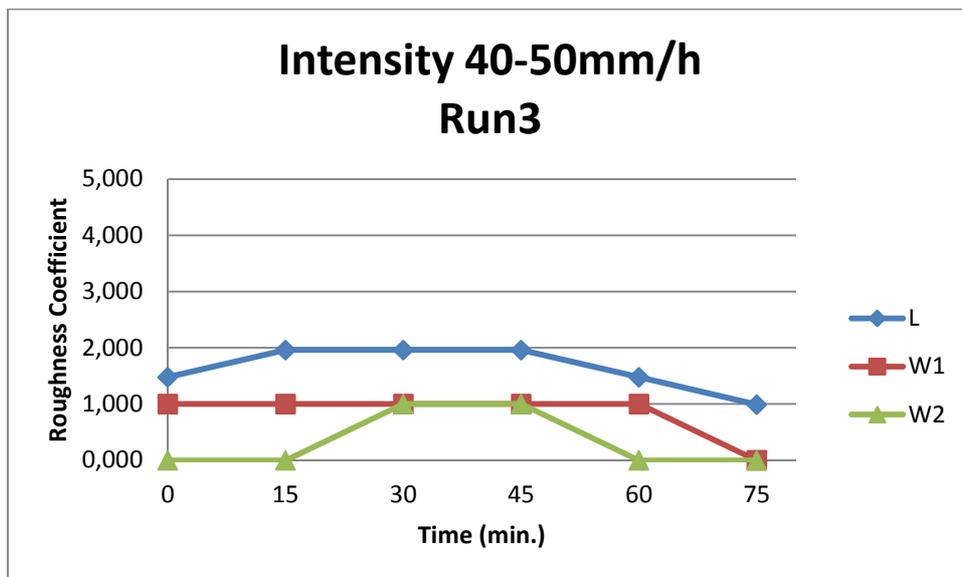
Figure 2.8 Roughness coefficients for Rainfall experiment with 40-50mm/h intensity.
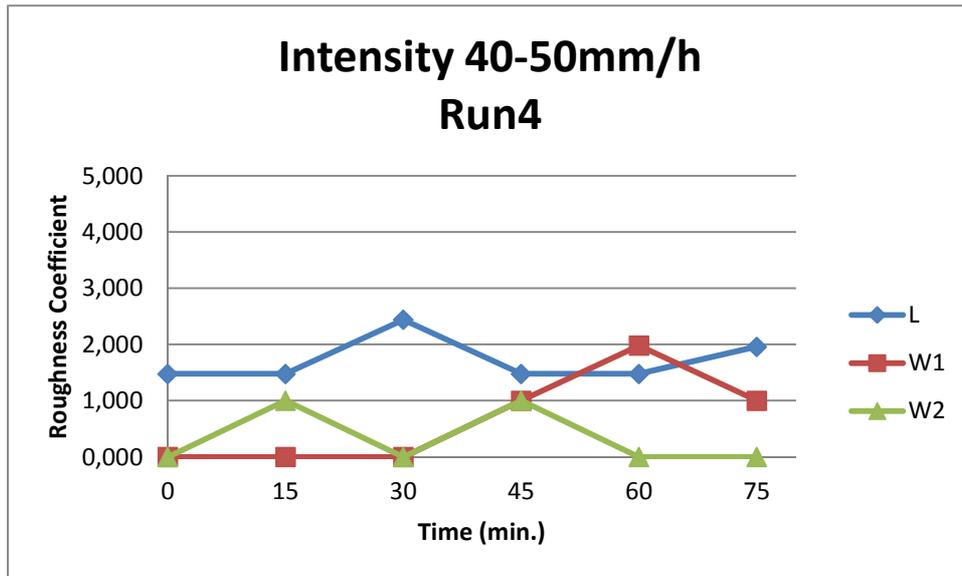
Figure 2.9 Roughness coefficients for Rainfall experiment with 40-50mm/h intensity.
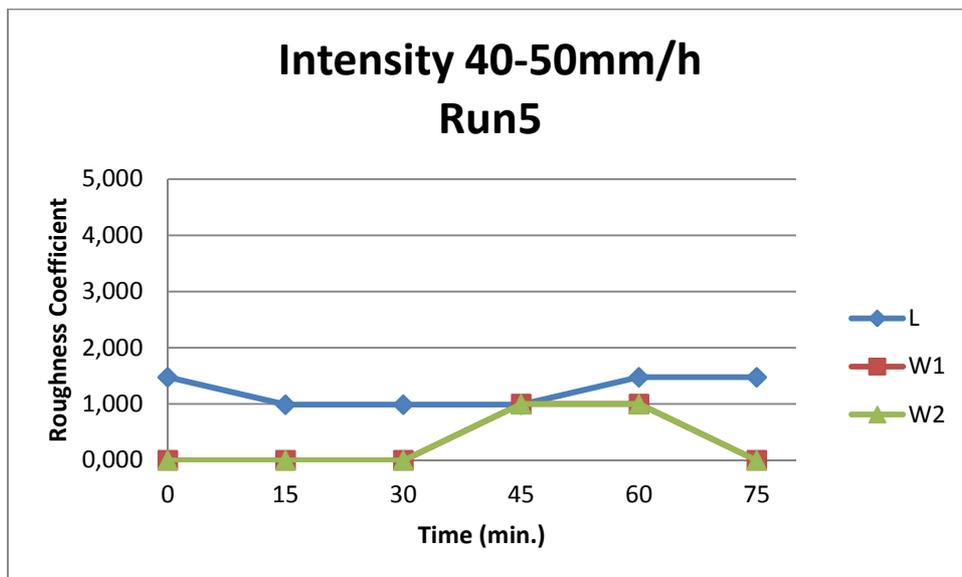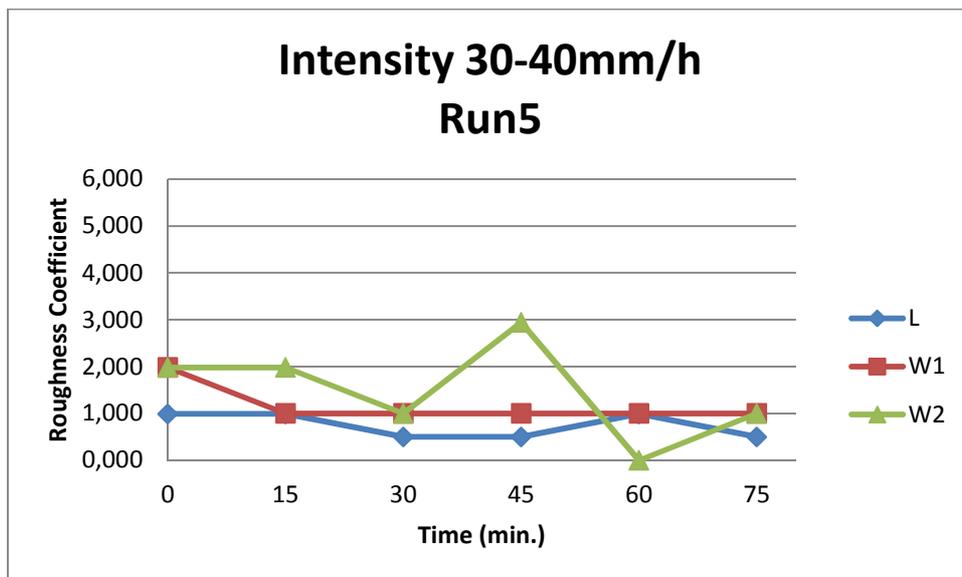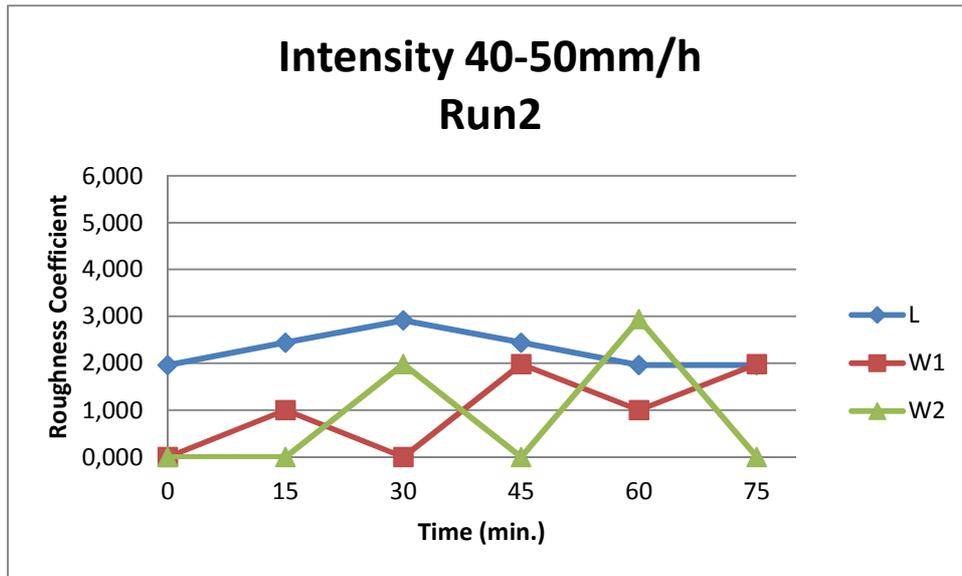

Figure 2.10 Roughness coefficients for Rainfall experiment with 40-50mm/h intensity.
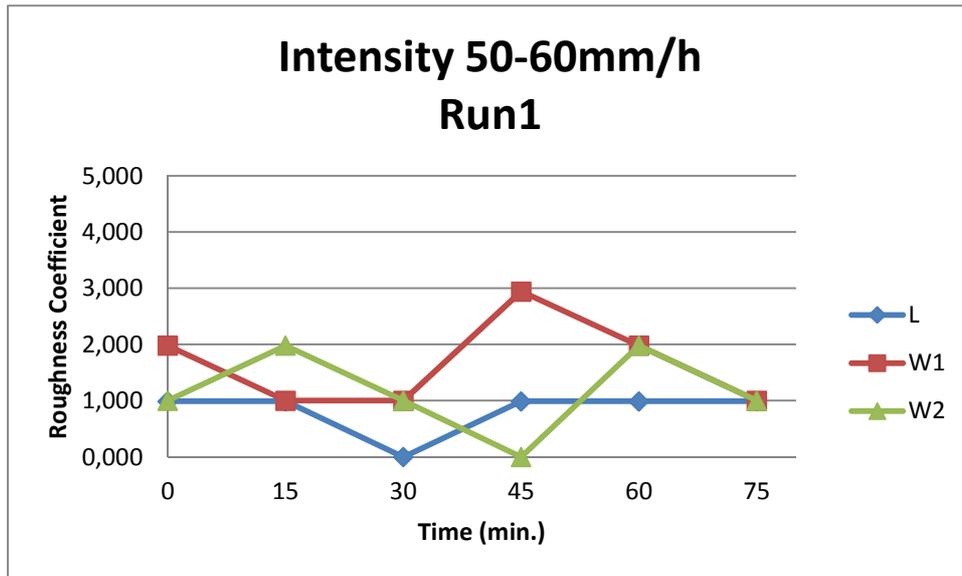
Figure 2.11 Roughness coefficients for Rainfall experiment with 50-60mm/h intensity.
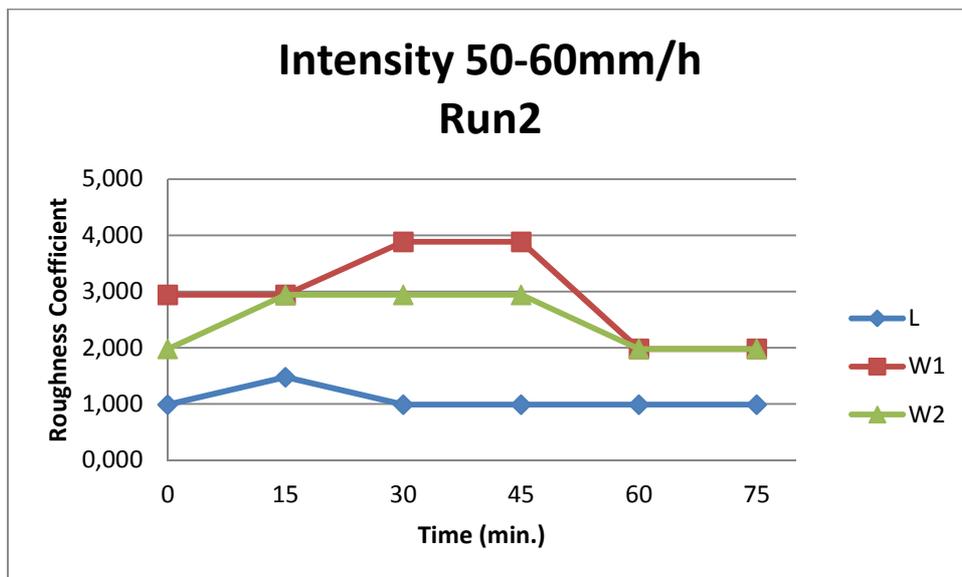
Figure 2.12 Roughness coefficients for Rainfall experiment with 50-60mm/h intensity.
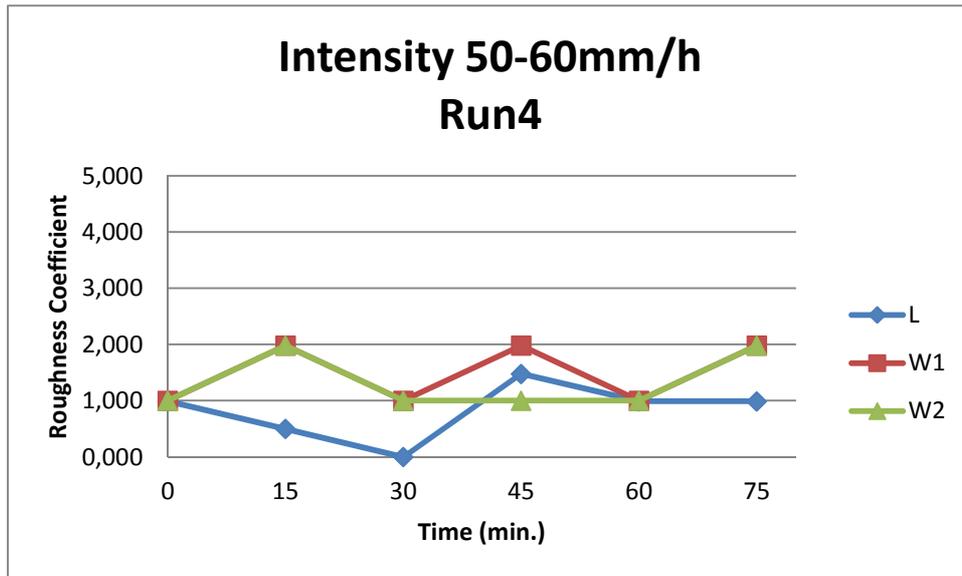
Figure 2.13 Roughness coefficients for Rainfall experiment with 50-60mm/h intensity.
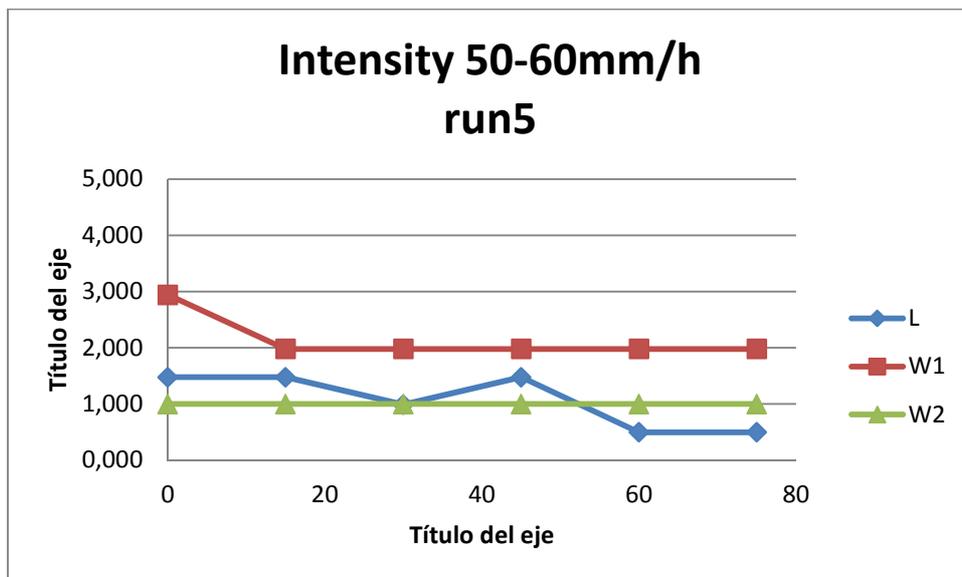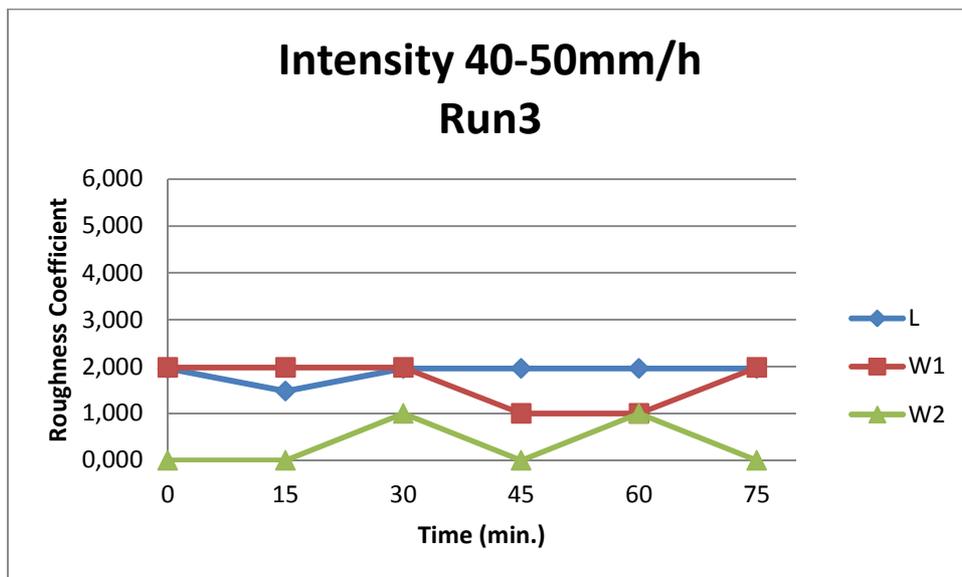

Figure 2.14 Roughness coefficients for Rainfall experiment with 50-60mm/h intensity.
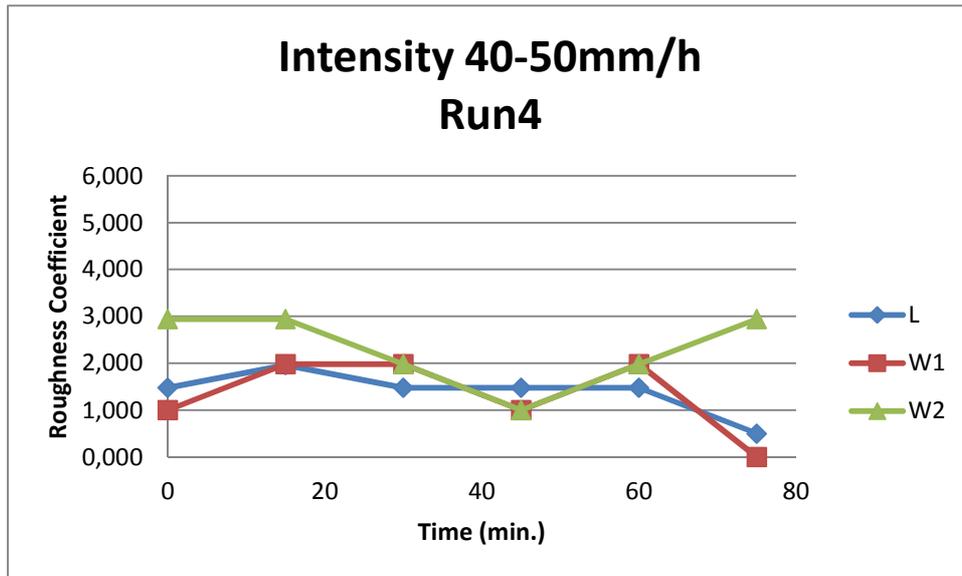
Figure 2.15 Roughness coefficients for Rainfall experiment with >60mm/h intensity.
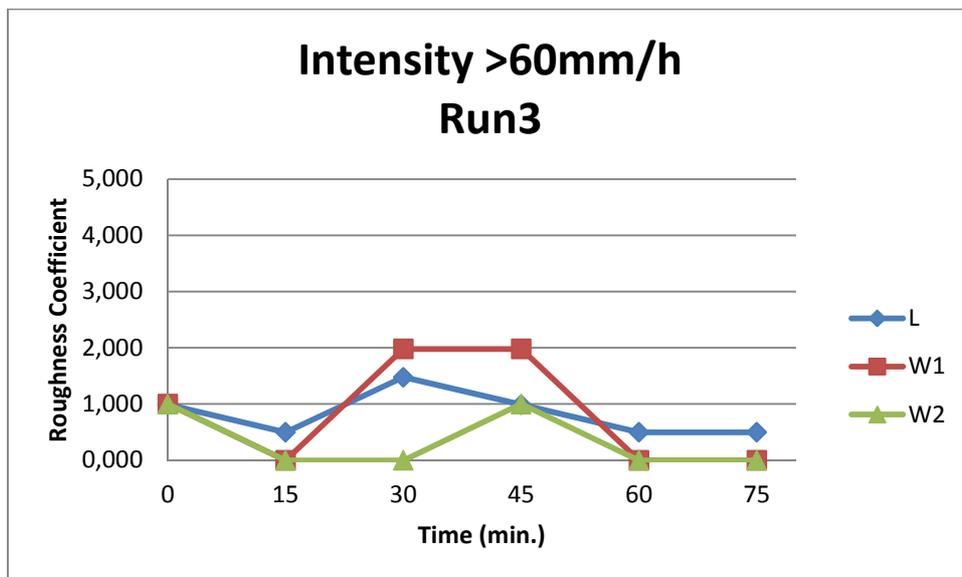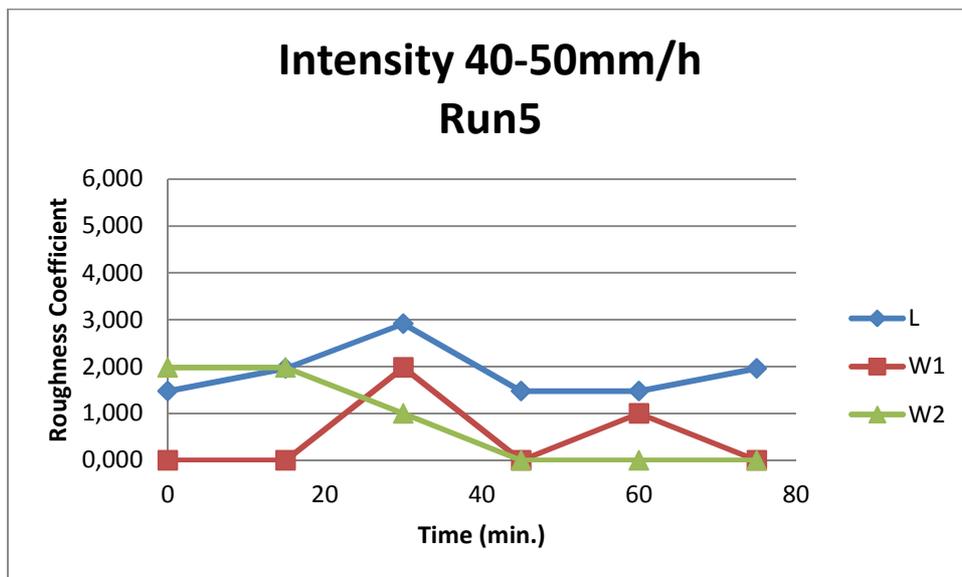

Figure 2.16 Roughness coefficients for Rainfall experiment with >60mm/h intensity.
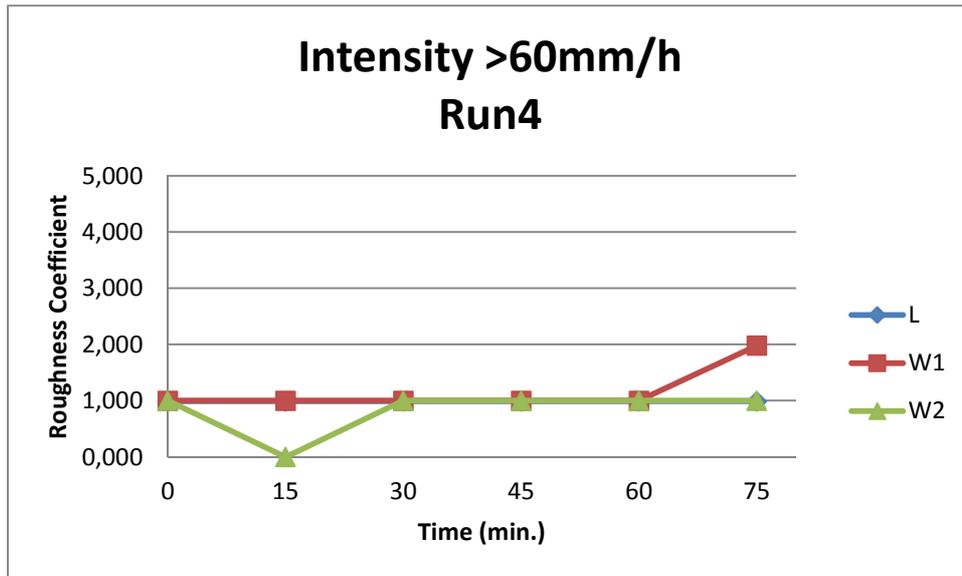
Figure 2.17 Roughness coefficients for Rainfall experiment with >60mm/h intensity.
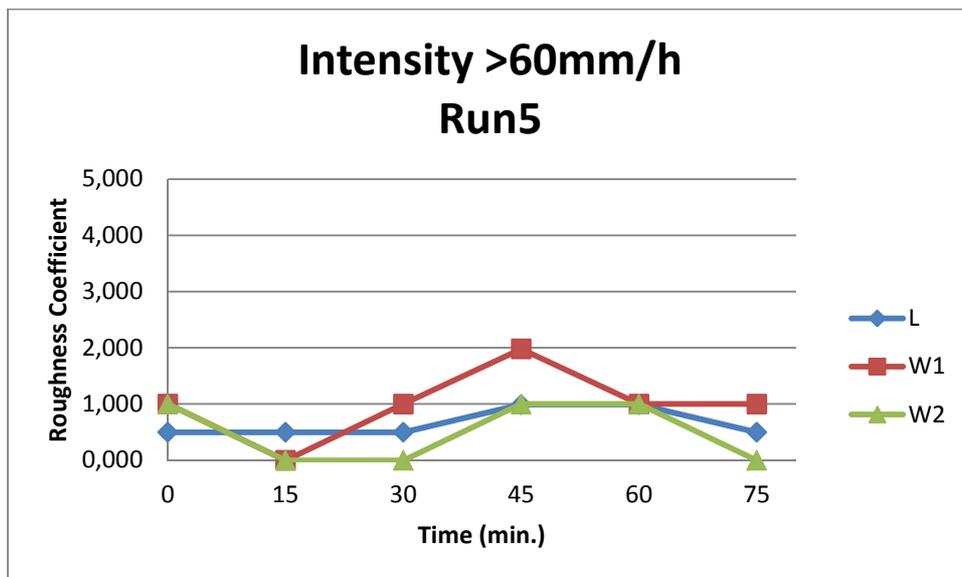
Figure 2.18 Roughness coefficients for Rainfall experiment with >60mm/h intensity.

Slope 10-12º

Figure 2.19 Roughness coefficients for Rainfall experiment with 30-40mm/h intensity.

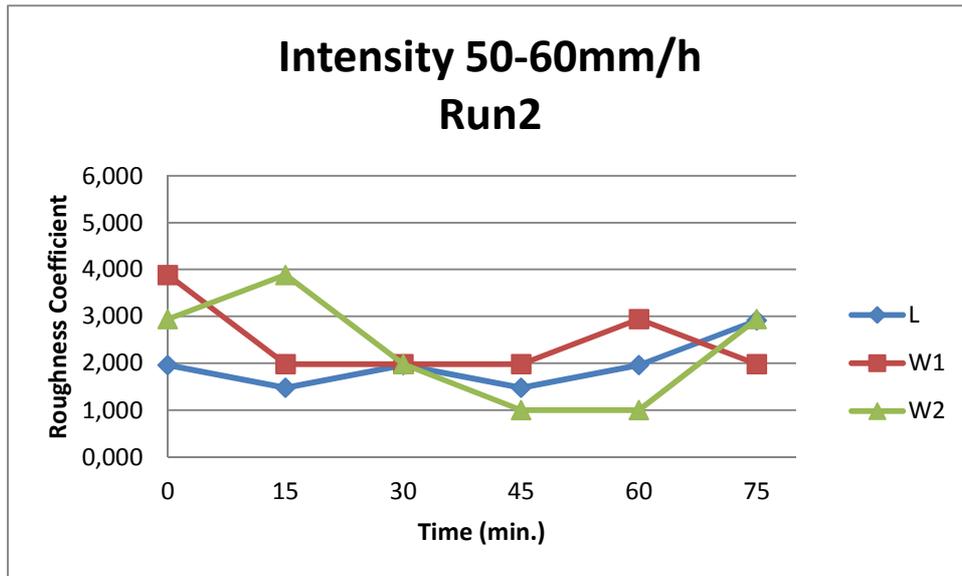**Figure 2.20** Roughness coefficients for Rainfall experiment with 30-40mm/h intensity.

Figure 2.21 Roughness coefficients for Rainfall experiment with 30-40mm/h intensity.

Figure 2.22 Roughness coefficients for Rainfall experiment with 30-40mm/h intensity.

Figure 2.23 Roughness coefficients for Rainfall experiment with 40-50mm/h intensity.

Figure 2.24 Roughness coefficients for Rainfall experiment with 40-50mm/h intensity.
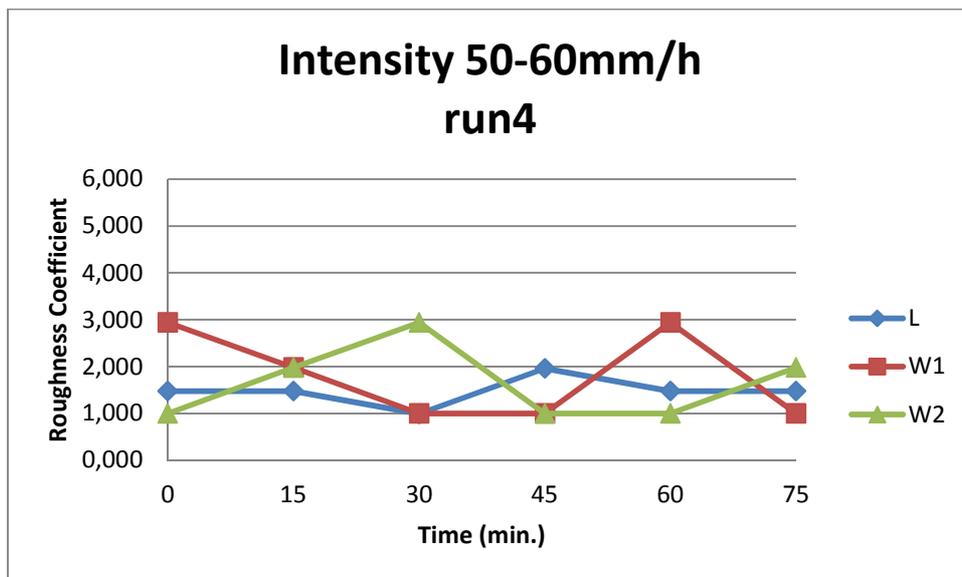
Figure 2.25 Roughness coefficients for Rainfall experiment with 40-50mm/h intensity.

Figure 2.26 Roughness coefficients for Rainfall experiment with 40-50mm/h intensity.

Figure 2.27 Roughness coefficients for Rainfall experiment with 50-60mm/h intensity.

Figure 2.28 Roughness coefficients for Rainfall experiment with 50-60mm/h intensity.
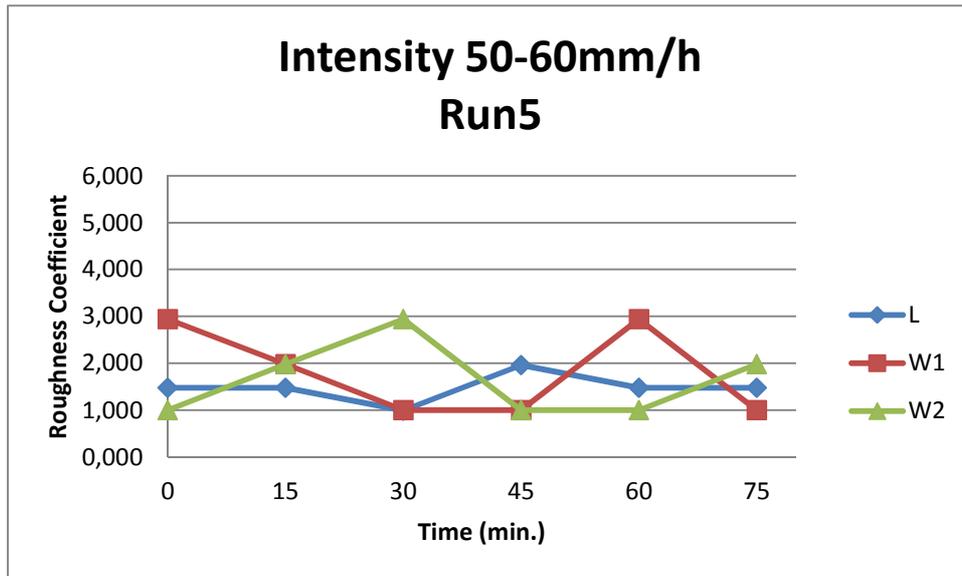
Figure 2.29 Roughness coefficients for Rainfall experiment with 50-60mm/h intensity.
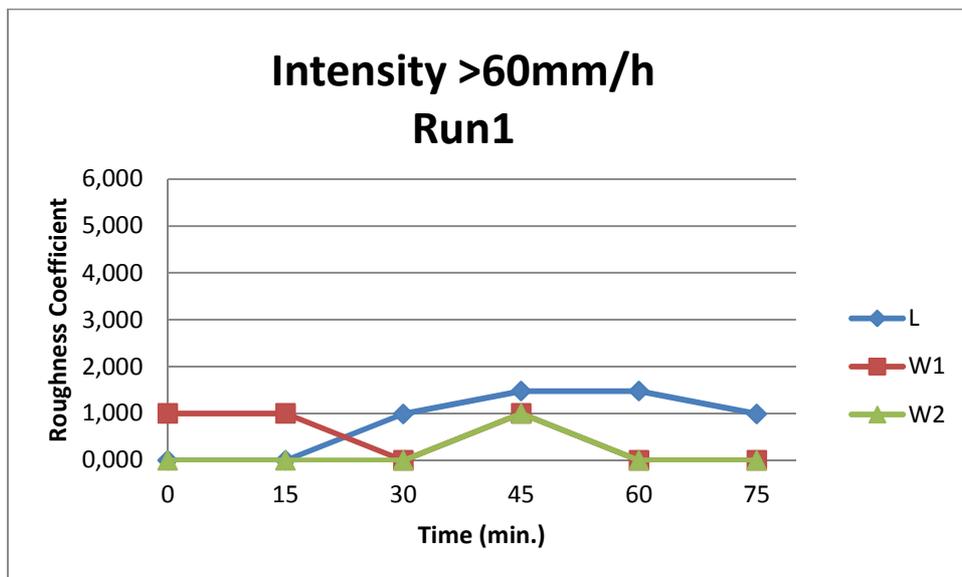

Figure 2.30 Roughness coefficients for Rainfall experiment with >60mm/h intensity.
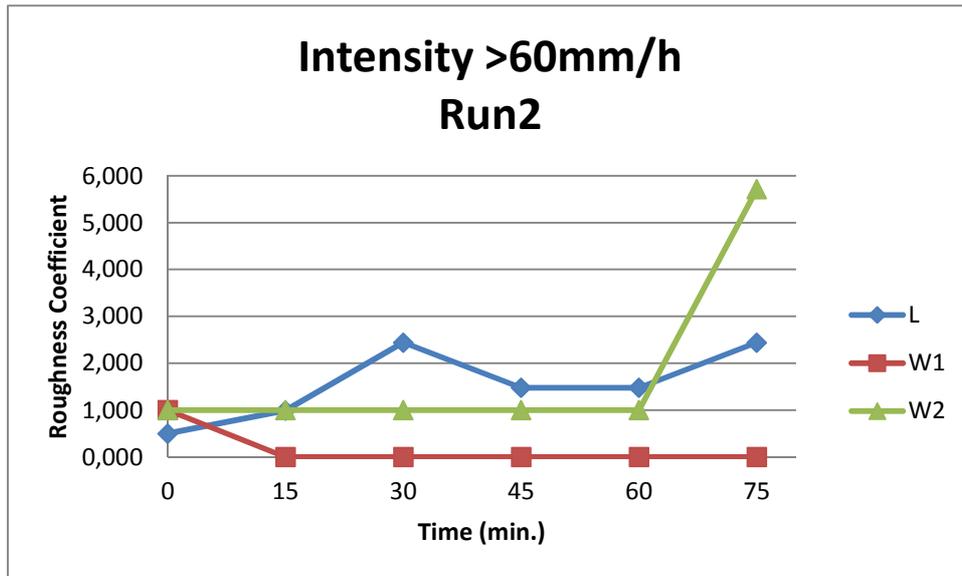
Figure 2.31 Roughness coefficients for Rainfall experiment with >60mm/h intensity.

Figure 2.32 Roughness coefficients for Rainfall experiment with >60mm/h intensity.

Figure 2.33 Roughness coefficients for Rainfall experiment with >60mm/h intensity.
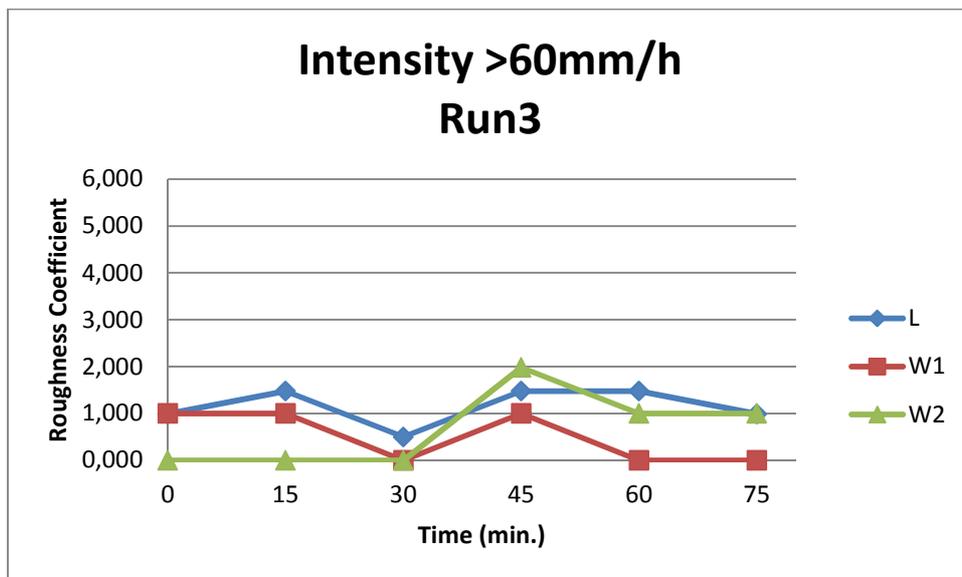

Figure 2.34 Roughness coefficients for Rainfall experiment with >60mm/h intensity.
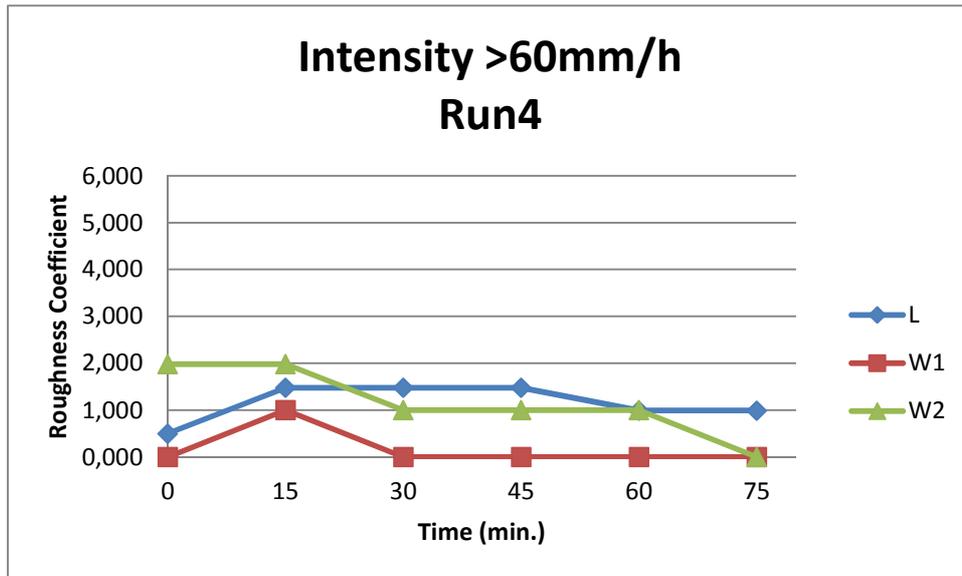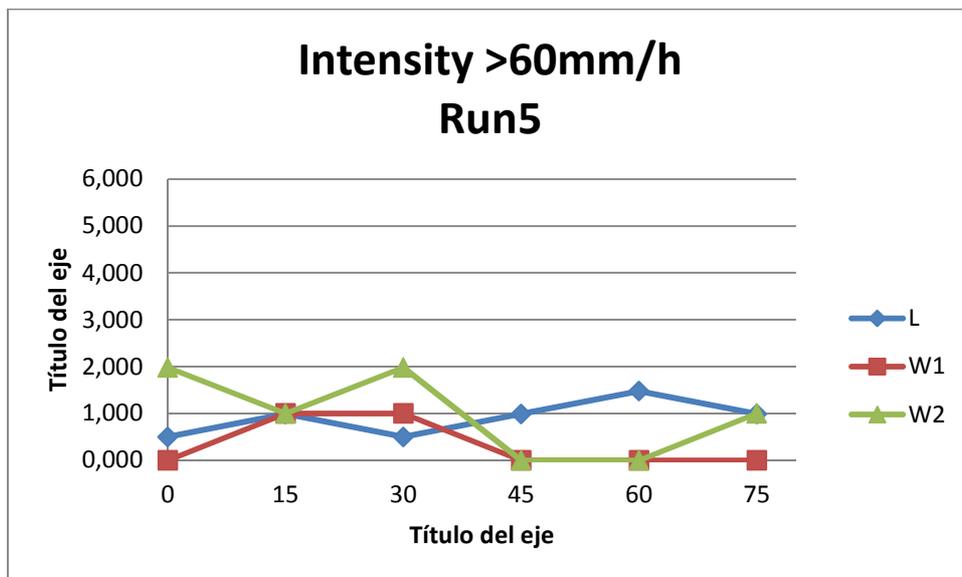
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Annex 3 Ca cohesive component, aggregate stability and moisture content

Figure 3.1 Moisture content, Ca cohesive component and Aggregate stability at the before and after the rainfall experiment.

Figure 3.2 Moisture content, Ca cohesive component and Aggregate stability at the before and after the rainfall experiment.
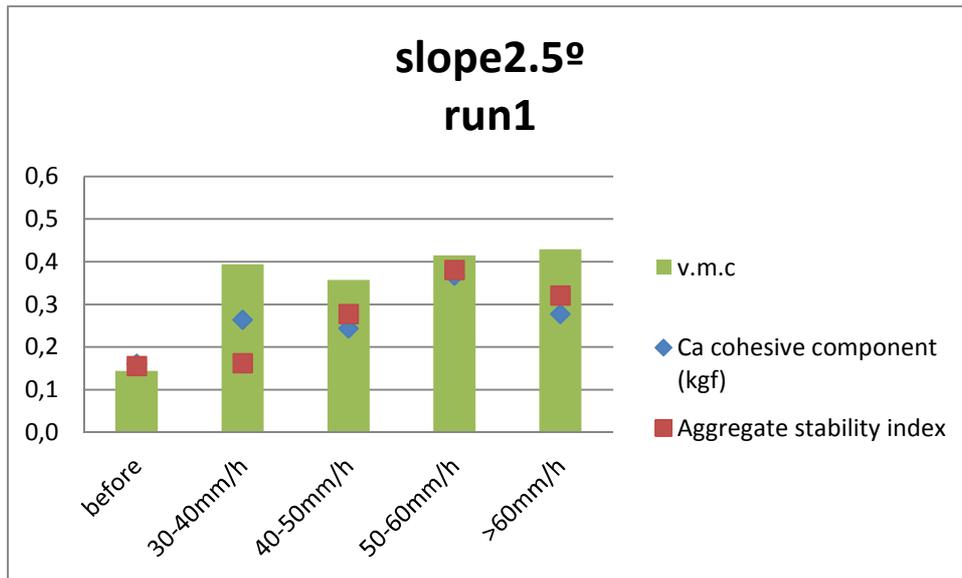
Figure 3.3 Moisture content, Ca cohesive component and Aggregate stability at the before and after the rainfall experiment.
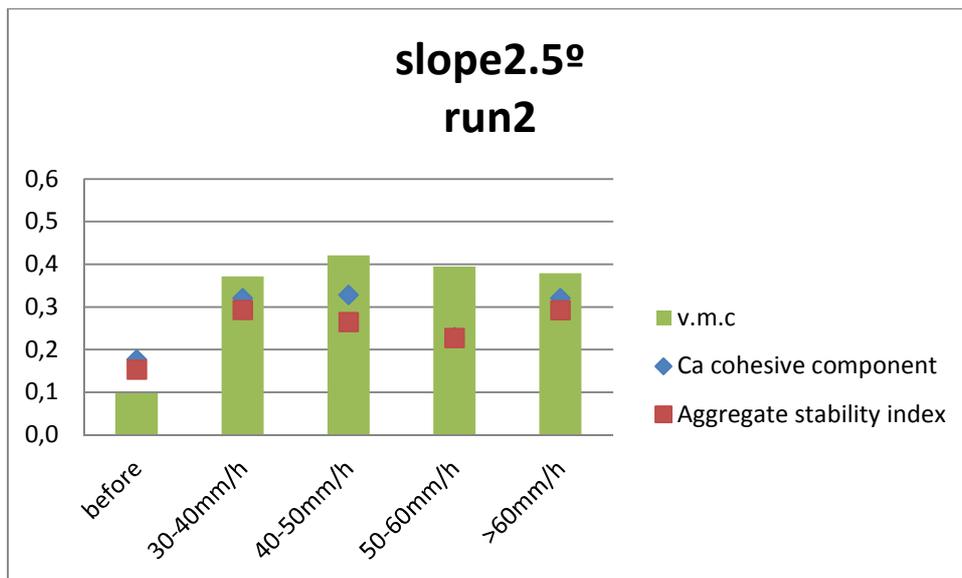

Figure 3.4 Moisture content, Ca cohesive component and Aggregate stability at the before and after the rainfall experiment.
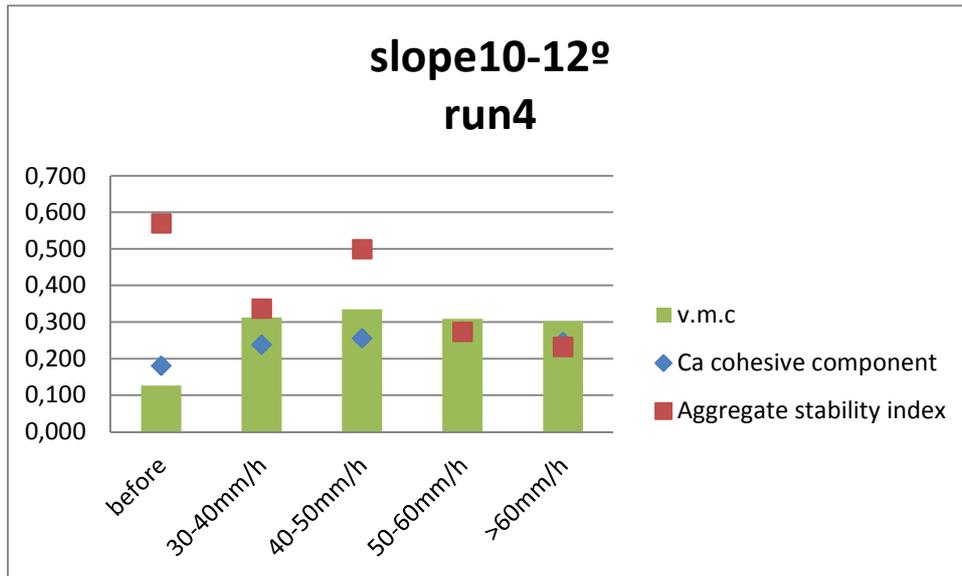
Figure 3.5 Moisture content, Ca cohesive component and Aggregate stability at the before and after the rainfall experiment.
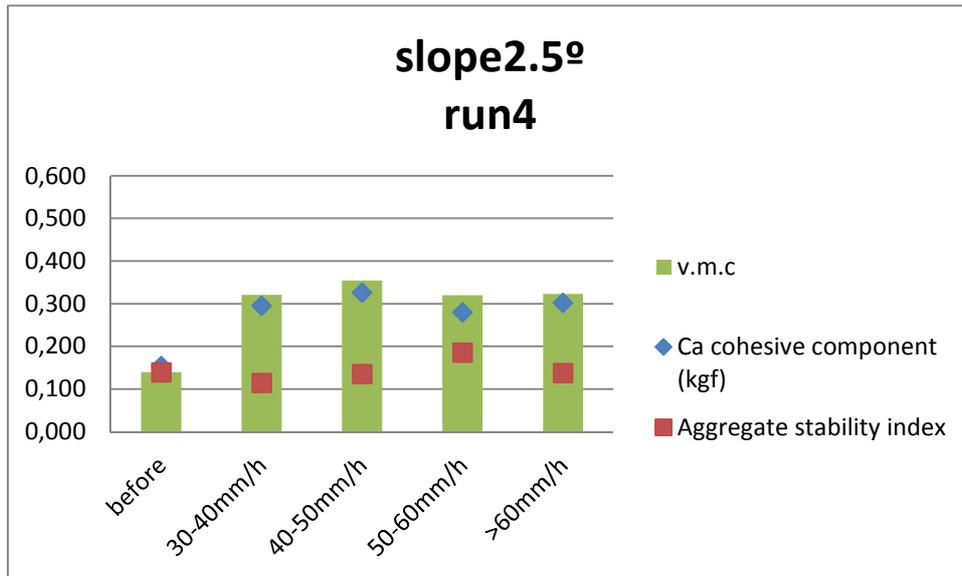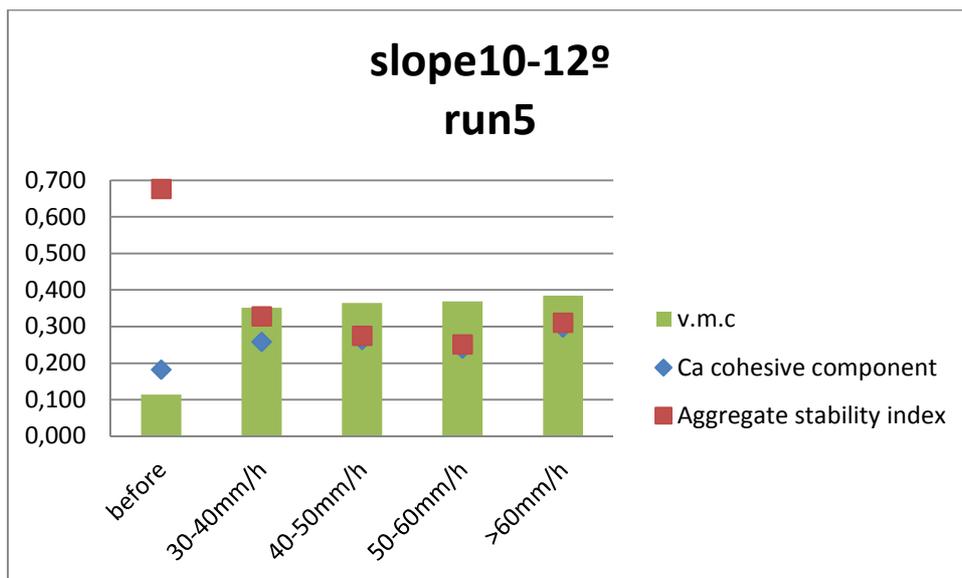

Figure 3.6 Moisture content, Ca cohesive component and Aggregate stability at the before and after the rainfall experiment.

Differences with the "before" conditions of the three variables: Ca, v.m.c and aggregate stability

Figure 3.7 Change in moisture content, Ca cohesive component and Aggregate stability**.**

Figure 3.8 Change in moisture content, Ca cohesive component and Aggregate stability**.**

Figure 3.9 Change in moisture content, Ca cohesive component and Aggregate stability**.**

Figure 3.10 Change in moisture content, Ca cohesive component and Aggregate stability**.**

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Figure 3.11 Change in moisture content, Ca cohesive component and Aggregate stability**.**

Figure 3.12 Change in moisture content, Ca cohesive component and Aggregate stability**.**

Figure 3.13 Change in moisture content, Ca cohesive component and Aggregate stability
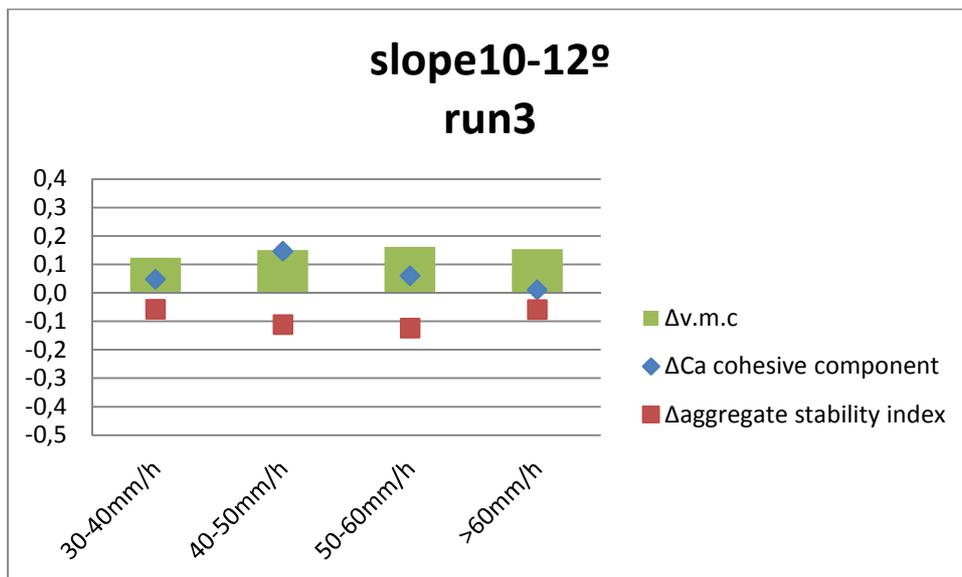
Figure 3.14 Change in moisture content, Ca cohesive component and Aggregate stability

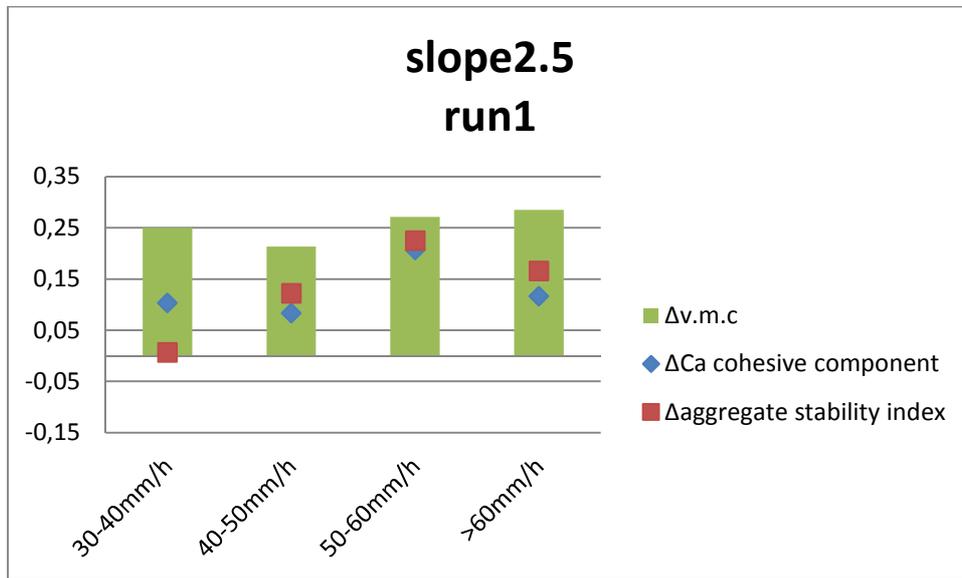**Figure 3.15** Change in moisture content, Ca cohesive component and Aggregate stability

Figure 3.16 Change in moisture content, Ca cohesive component and Aggregate stability
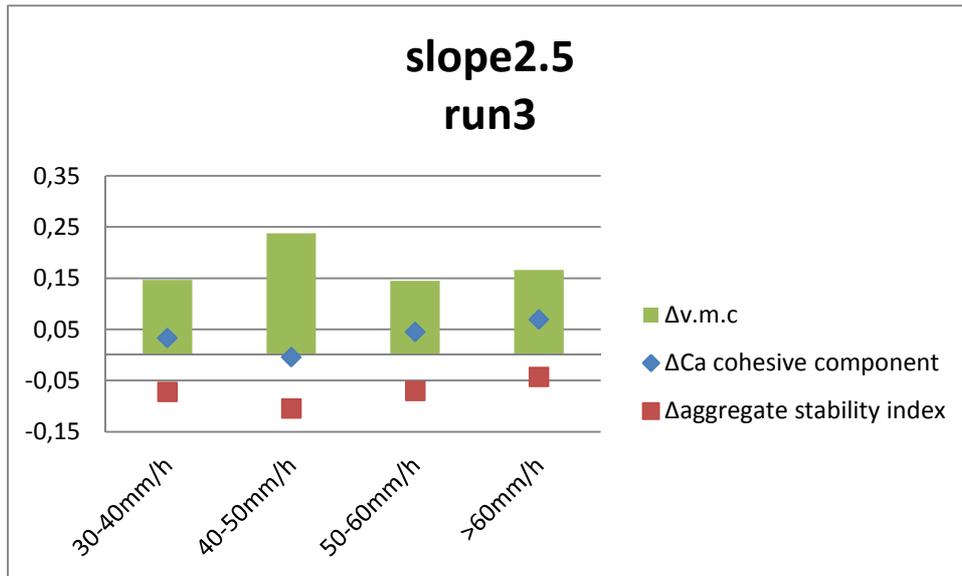
Run/ Repetition comparison for the three variables: Ca, v.m.c and aggregate stability

Figure 3.17 Run comparison for: moisture content, Ca cohesive component and aggregate stability.

Figure 3.18 Run comparison for: moisture content, Ca cohesive component and aggregate stability.

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Figure 3.19 Run comparison for: moisture content, Ca cohesive component and aggregate stability.

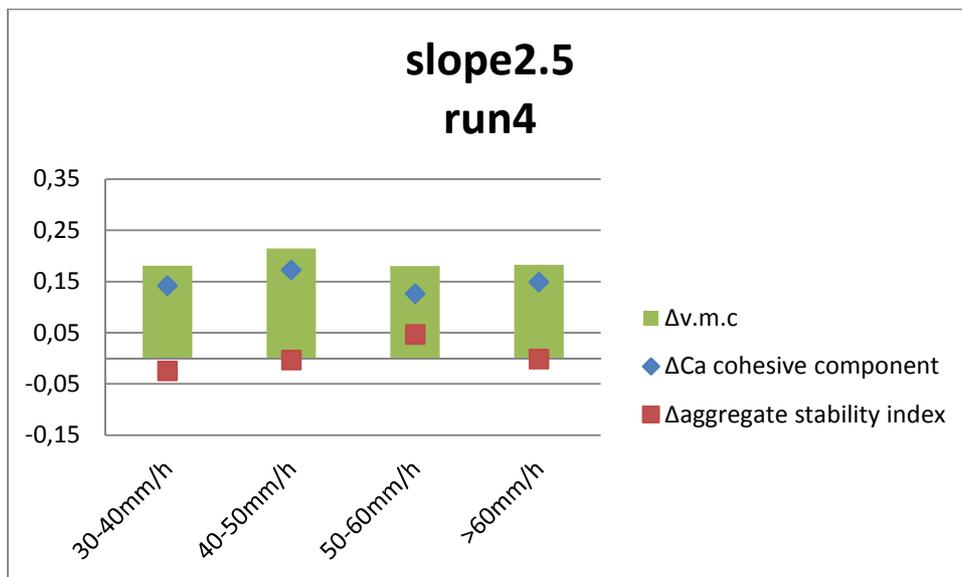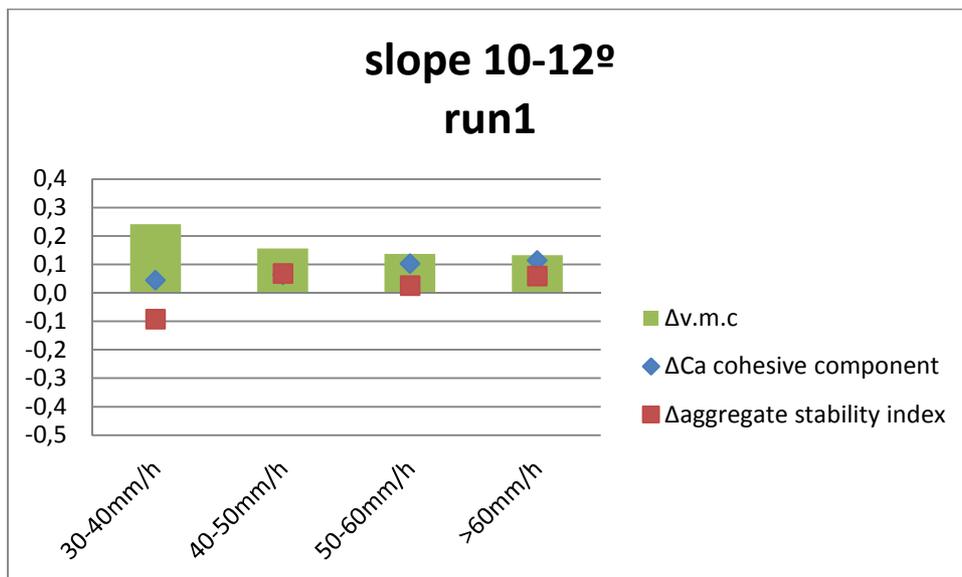**Figure 3.20** Run comparison for: moisture content, Ca cohesive component and aggregate stability.

Relationship between rainfall intensities, aggregate stability and shear resistance as parameters to evaluate soil erosion by water: an experimental study

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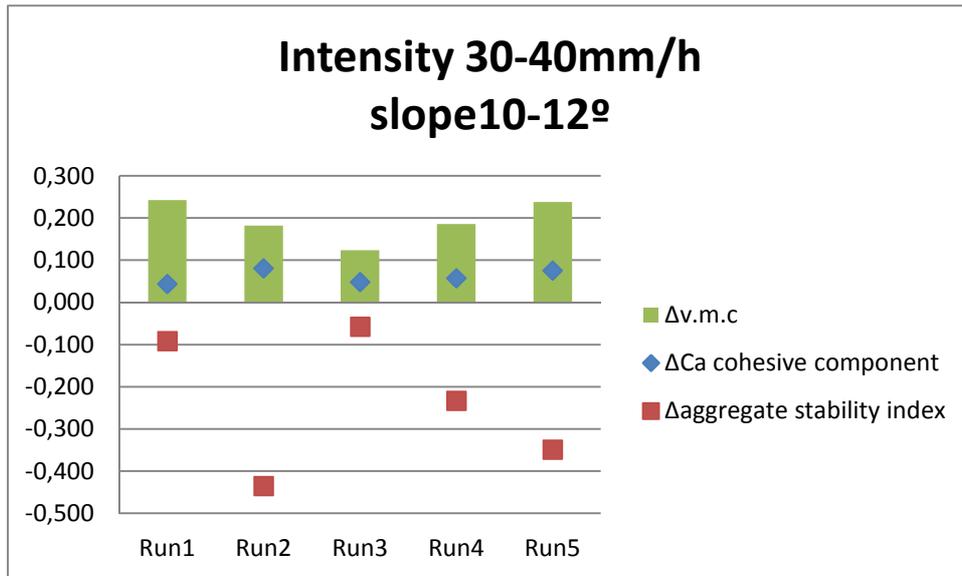
Figure 3.21 Run comparison for: moisture content, Ca cohesive component and aggregate stability.
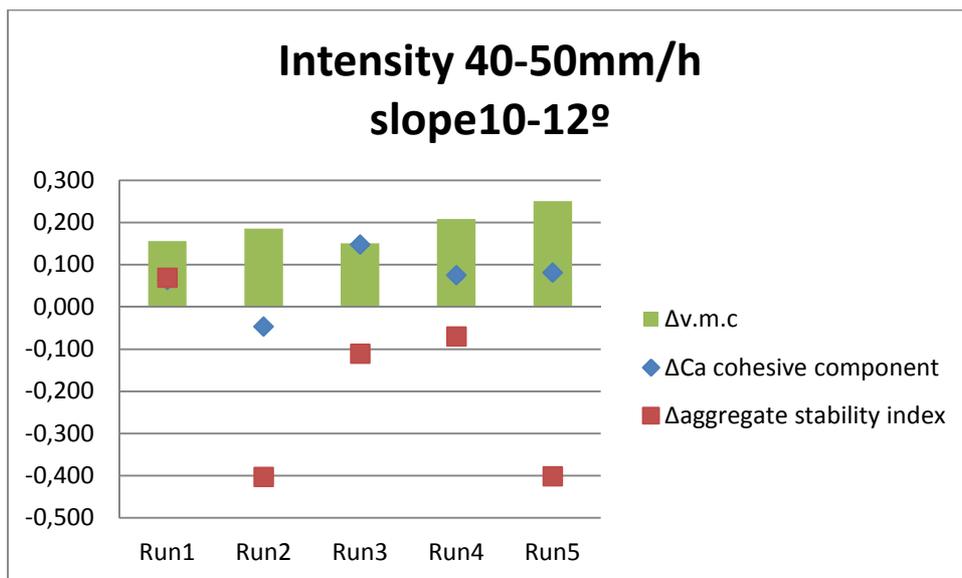
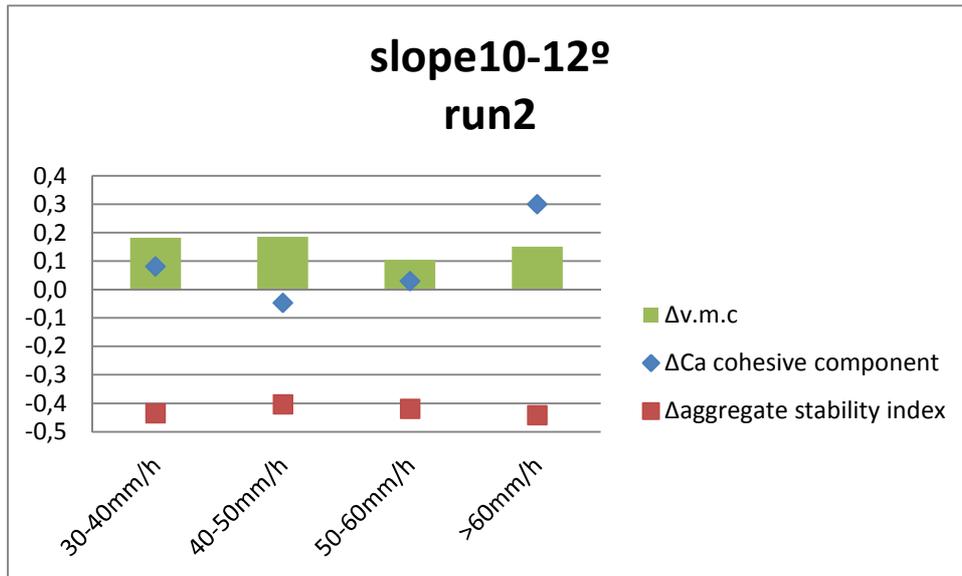**Figure 3.22** Run comparison for: moisture content, Ca cohesive component and aggregate stability.

Figure 3.23 Run comparison for: moisture content, Ca cohesive component and aggregate stability.


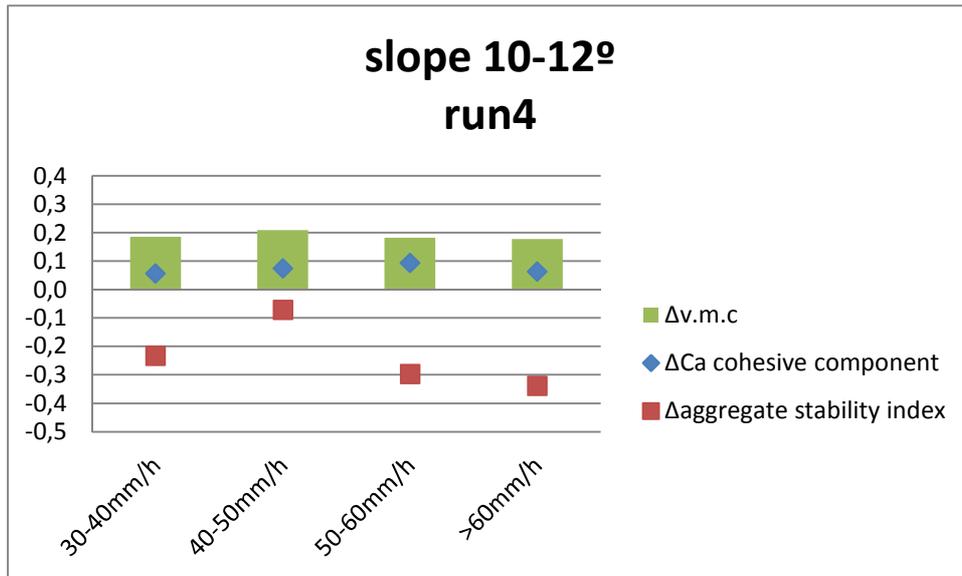**Figure 3.24** Run comparison for: moisture content, Ca cohesive component and aggregate stability.
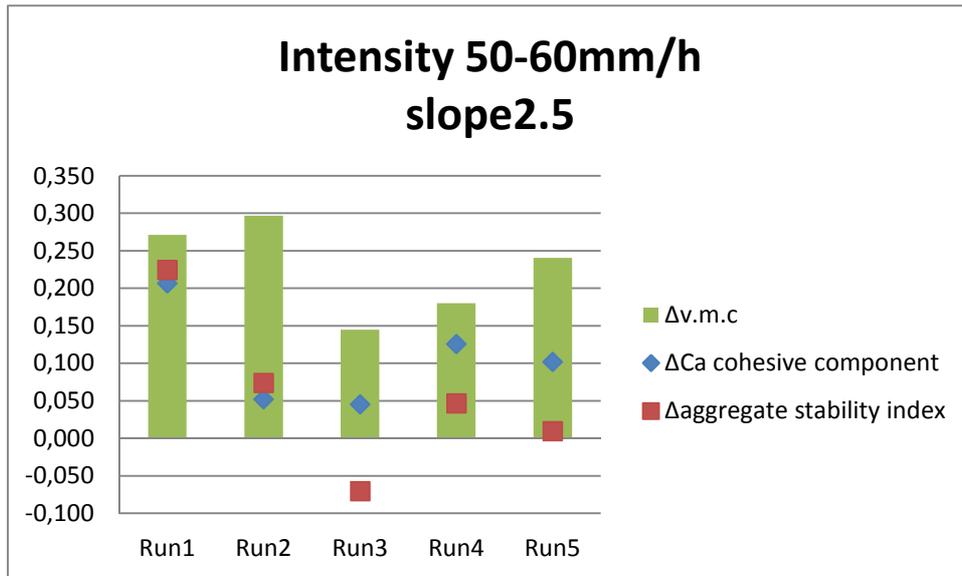
Annex 4 Statistical analysis

Significant differences: At the before and after conditions: Wilcoxon test

Ca cohesive component

Table 4.1 Sig. differences for intensity 30-40mm/h

Test Statistics[a,b]

	ShearStress0 - ShearStress
Z	-2,803[c]
Asymp. Sig. (2-tailed)	,005

a. IntensityBOX = 30-40mm/h

b. Wilcoxon Signed Ranks Test

c. Based on positive ranks.

Table 4.2 Sig. differences for intensity 40-50mm/h.

Test Statistics[a,b]

	ShearStress0 - ShearStress
Z	-2,497[c]
Asymp. Sig. (2-tailed)	,013

a. IntensityBOX = 40-50mm/h

b. Wilcoxon Signed Ranks Test

c. Based on positive ranks.

Table 4.3 Sig. differences for intensity 50-60mm/h.

Test Statistics[a,b]

	ShearStress0 - ShearStress
Z	-2,805[c]
Asymp. Sig. (2-tailed)	,005

a. IntensityBOX = 50-60mm/h

b. Wilcoxon Signed Ranks Test

c. Based on positive ranks.

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Table 4.4 Sig. differences for intensity >60mm/h.

Test Statistics[a,b]

	ShearStress0 - ShearStress
Z	-2,803[c]
Asymp. Sig. (2-tailed)	,005

a. IntensityBOX = >60mm/h

b. Wilcoxon Signed Ranks Test

c. Based on positive ranks.

Aggregate stability

Table 4.5 Sig. differences for intensity 30-40mm/h.

Test Statistics[a,b]

	AggregateStab - AggregateStability0
Z	-1,988[c]
Asymp. Sig. (2-tailed)	,047

a. IntensityBOX = 30-40mm/h

b. Wilcoxon Signed Ranks Test

c. Based on positive ranks.

Table 4.6 Sig. differences for intensity 40-50mm/h.

Test Statistics[a,b]

	AggregateStab - AggregateStability0
Z	-1,020[c]
Asymp. Sig. (2-tailed)	,308

a. IntensityBOX = 40-50mm/h

b. Wilcoxon Signed Ranks Test

c. Based on positive ranks.

Table 4.7 Sig. differences for intensity 50-60mm/h.

Test Statistics[a,b]

	AggregateStab - AggregateStability0
Z	-,968[c]
Asymp. Sig. (2-tailed)	,333

a. IntensityBOX = 50-60mm/h

b. Wilcoxon Signed Ranks Test

c. Based on positive ranks.

Table 4.8 Sig. differences for intensity >60mm/h.

Test Statistics[a,b]

	AggregateStab - AggregateStability0
Z	-1,070[c]
Asymp. Sig. (2-tailed)	,285

a. IntensityBOX = >60mm/h

b. Wilcoxon Signed Ranks Test

c. Based on positive ranks.

Moisture content

Table 4.9 Sig. differences for intensity 30-40mm/h.

Test Statistics[a,b]

	MoistContent0 - MoistContent
Z	-2,805[c]
Asymp. Sig. (2-tailed)	,005

a. IntensityBOX = 30-40mm/h

b. Wilcoxon Signed Ranks Test

c. Based on positive ranks.

Table 4.10 Sig. differences for intensity 40-50mm/h.

Test Statistics[a,b]

	MoistContent0 - MoistContent
Z	-2,803[c]
Asymp. Sig. (2-tailed)	,005

a. IntensityBOX = 40-50mm/h

b. Wilcoxon Signed Ranks Test

c. Based on positive ranks.

Table 4.11 Sig. differences for intensity 50-60mm/h.

Test Statistics[a,b]

	MoistContent0 - MoistContent
Z	-2,803[c]
Asymp. Sig. (2-tailed)	,005

a. IntensityBOX = 50-60mm/h

b. Wilcoxon Signed Ranks Test

c. Based on positive ranks.

Table 4.12 Sig. differences for intensity >60mm/h.

Test Statistics[a,b]

	MoistContent0 - MoistContent
Z	-2,803[c]
Asymp. Sig. (2-tailed)	,005

a. IntensityBOX = >60mm/h

b. Wilcoxon Signed Ranks Test

c. Based on positive ranks.

Significant differences: Roughness coefficient time threshold

Slope 2.5º

Table 4.13 Sig. differences for roughness coefficient, intensity 30-40mm/h.

Test Statistics[a,b]

	RoughnessI4L	RoughnessI4W 1	RoughnessI4W 2
Chi-Square	1,582	2,230	7,095
df	5	5	5
Asymp. Sig.	,903	,816	,214

a. Kruskal Wallis Test

b. Grouping Variable: event4

Table 4.14 Sig. differences for roughness coefficient, intensity 40-50mm/h.

Test Statistics[a,b]

	RoughnessI1L	RoughnessI1W 1	RoughnessI1W 2
Chi-Square	1,816	3,155	3,695
df	5	5	5
Asymp. Sig.	,874	,676	,594

a. Kruskal Wallis Test

b. Grouping Variable: event1

Table 4.15 Sig. differences for roughness coefficient, intensity 50-60mm/h.

Test Statistics[a,b]

	RoughnessI3L	RoughnessI3W 1	RoughnessI3W 2
Chi-Square	9,131	3,360	2,923
df	5	5	5
Asymp. Sig.	,104	,645	,712

a. Kruskal Wallis Test

b. Grouping Variable: event3

Table 4.16 Sig. differences for roughness coefficient, intensity >60mm/h.

Test Statistics[a,b]

	RoughnessI2L	RoughnessI2W1	RoughnessI2W2
Chi-Square	2,414	5,641	7,038
df	5	5	5
Asymp. Sig.	,789	,343	,218

a. Kruskal Wallis Test

b. Grouping Variable: event2

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Table 4.17 Sig. differences for roughness coefficient, intensity 30-40mm/h.

Test Statistics[a,b]

	RoughnessI4L	RoughnessI4W1	RoughnessI4W2
Chi-Square	5,738	1,251	1,325
df	5	5	5
Asymp. Sig.	,333	,940	,932

a. Kruskal Wallis Test

b. Grouping Variable: event4

Table 4.18 Sig. differences for roughness coefficient, intensity 40-50mm/h.

Test Statistics[a,b]

	RoughnessI1L	RoughnessI1W1	RoughnessI1W2
Chi-Square	3,954	2,748	4,649
df	5	5	5
Asymp. Sig.	,556	,739	,460

a. Kruskal Wallis Test

b. Grouping Variable: event1

Table 4.19 Sig. differences for roughness coefficient, intensity 50-60mm/h.

Test Statistics[a,b]

	RoughnessI3L	RoughnessI3W 1	RoughnessI3W 2
Chi-Square	2,993	4,173	1,401
df	5	5	5
Asymp. Sig.	,701	,525	,924

a. Kruskal Wallis Test

b. Grouping Variable: event3

Table 4.20 Sig. differences for roughness coefficient, intensity >60mm/h.

Test Statistics[a,b]

	RoughnessI2L	RoughnessI2W 1	RoughnessI2W 2
Chi-Square	10,912	11,600	,827
df	5	5	5
Asymp. Sig.	,053	,041	,975

a. Kruskal Wallis Test

b. Grouping Variable: event2

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Correlation analysis

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Table 4.21 Correlation analysis of all the variables studied.

Spearman's rho	Runoff SUM	Runoff MAX	Q mean	Q max	SuspSed ConcMEAN	SuspSed ConcMAX	SuspSed LoadMEAN	RainfallAmount MEAN	StartRunoff Sec	Runoff Coeff	RainfallAmount SUM	CaCohesive Conponent
Runoff SUM		,000		,000	,000	,000	,000	,003	,000	,000	,003	,546
Runoff MAX	,000		,000		,000	,000	,000	,001	,002	,000	,001	,551
Qmean		,000		,000	,000	,000	,000	,003	,000	,000	,003	,546
Qmax	,000		,000		,000	,000	,000	,001	,002	,000	,001	,551
SuspSed ConcMEAN	,000	,000	,000	,000		,000	,000	,053	,008	,060	,053	,379
SuspSed ConcMAX	,000	,000	,000	,000	,000		,000	,248	,855	,701	,248	,261
SuspSed LoadMEAN	,000	,000	,000	,000	,000	,000		,012	,000	,000	,012	,517

RainfallAmountMEAN	,003	,001	,003	,001	,053	,248	,012		,084	,024		,789
StartRunoffSec	,000	,002	,000	,002	,008	,855	,000	,084		,000	,084	,467
RunoffCoeff	,000	,000	,000	,000	,060	,701	,000	,024	,000		,024	,425
RainfallAmountSUM	,003	,001	,003	,001	,053	,248	,012		,084	,024		,789
CaCohesiveConponent	,546	,551	,546	,551	,379	,261	,517	,789	,467	,425	,789	
AggregateStab	,105	,097	,105	,097	,251	,254	,137	,136	,511	,293	,136	,122
MoistContent	,008	,011	,008	,011	,014	,007	,014	,269	,777	,751	,269	,705
RoughnessL	,218	,256	,218	,256	,150	,226	,183	,521	,400	,505	,521	,554
RoughnessW1	,065	,066	,065	,066	,049	,036	,043	,407	,469	,469	,407	,961
RoughnessW2	,714	,807	,714	,807	,630	,645	,720	,564	,943	,915	,564	,374
RoughnessL0	,695	,684	,695	,684	,752	,862	,766	,617	,789	,773	,617	,823
Roughness	,935	,994	,935	,994	,733	,408	,898	,878	,653	,433	,878	,187

W10												
Roughness W20	,681	,719	,681	,719	,327	,155	,445	,900	,940	,595	,900	,719
CaCohesive Conponent0	,967	,989	,967	,989	,650	,967	,773	,949	,139	,391	,949	,228
AggregateStability0	,816	,816	,816	,816	,794	,989	,859	,738	,585	,549	,738	,323
MoistContent0	,023	,031	,023	,031	,024	,006	,021	,603	,840	,853	,603	,120

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Table 4.22 Correlation analysis of all the variables studied.

Spearman's rho	Aggregate Stab	Moist Content	Roughness L	Roughness W1	Roughness W2	Roughness L0	Roughness W10	Roughness W20	CaCohesive Conponent0	Aggregate Stability0	Moist Content0
RunoffSUM	,105	,008	,218	,065	,714	,695	,935	,681	,967	,816	,023
RunoffMAX	,097	,011	,256	,066	,807	,684	,994	,719	,989	,816	,031
Qmean	,105	,008	,218	,065	,714	,695	,935	,681	,967	,816	,023
Qmax	,097	,011	,256	,066	,807	,684	,994	,719	,989	,816	,031
SuspSedConc MEAN	,251	,014	,150	,049	,630	,752	,733	,327	,650	,794	,024
SuspSed ConcMAX	,254	,007	,226	,036	,645	,862	,408	,155	,967	,989	,006
SuspSedLoad MEAN	,137	,014	,183	,043	,720	,766	,898	,445	,773	,859	,021
RainfallAmou ntMEAN	,136	,269	,521	,407	,564	,617	,878	,900	,949	,738	,603
StartRunoffSe c	,511	,777	,400	,469	,943	,789	,653	,940	,139	,585	,840

RunoffCoeff	,293	,751	,505	,469	,915	,773	,433	,595	,391	,549	,853
RainfallAmountSUM	,136	,269	,521	,407	,564	,617	,878	,900	,949	,738	,603
CaCohesiveConponent	,122	,705	,554	,961	,374	,823	,187	,719	,228	,323	,120
AggregateStab		,787	,942	,173	,321	,739	,303	,517	,000	,006	,079
MoistContent	,787		,188	,493	,819	,975	,622	,539	,939	,662	,476
RoughnessL	,942	,188		,372	,692	,100	,088	,112	,382	,066	,390
RoughnessW1	,173	,493	,372		,104	,609	,015	,035	,722	,183	,246
RoughnessW2	,321	,819	,692	,104		,656	,330	,203	,291	,071	,232
RoughnessL0	,739	,975	,100	,609	,656		,836	,004	,689	,311	,652
RoughnessW10	,303	,622	,088	,015	,330	,836		,014	,096	,223	,718
RoughnessW20	,517	,539	,112	,035	,203	,004	,014		,224	,598	,623
CaCohesiveConponent0	,000	,939	,382	,722	,291	,689	,096	,224		,001	,405

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AggregateSta bility0	,006	,662	,066	,183	,071	,311	,223	,598	,001		,295
MoistContent 0	,079	,476	,390	,246	,232	,652	,718	,623	,405	,295	

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Annex 5: Roughness changes in time: Qualitative observations

a)   b)   c)

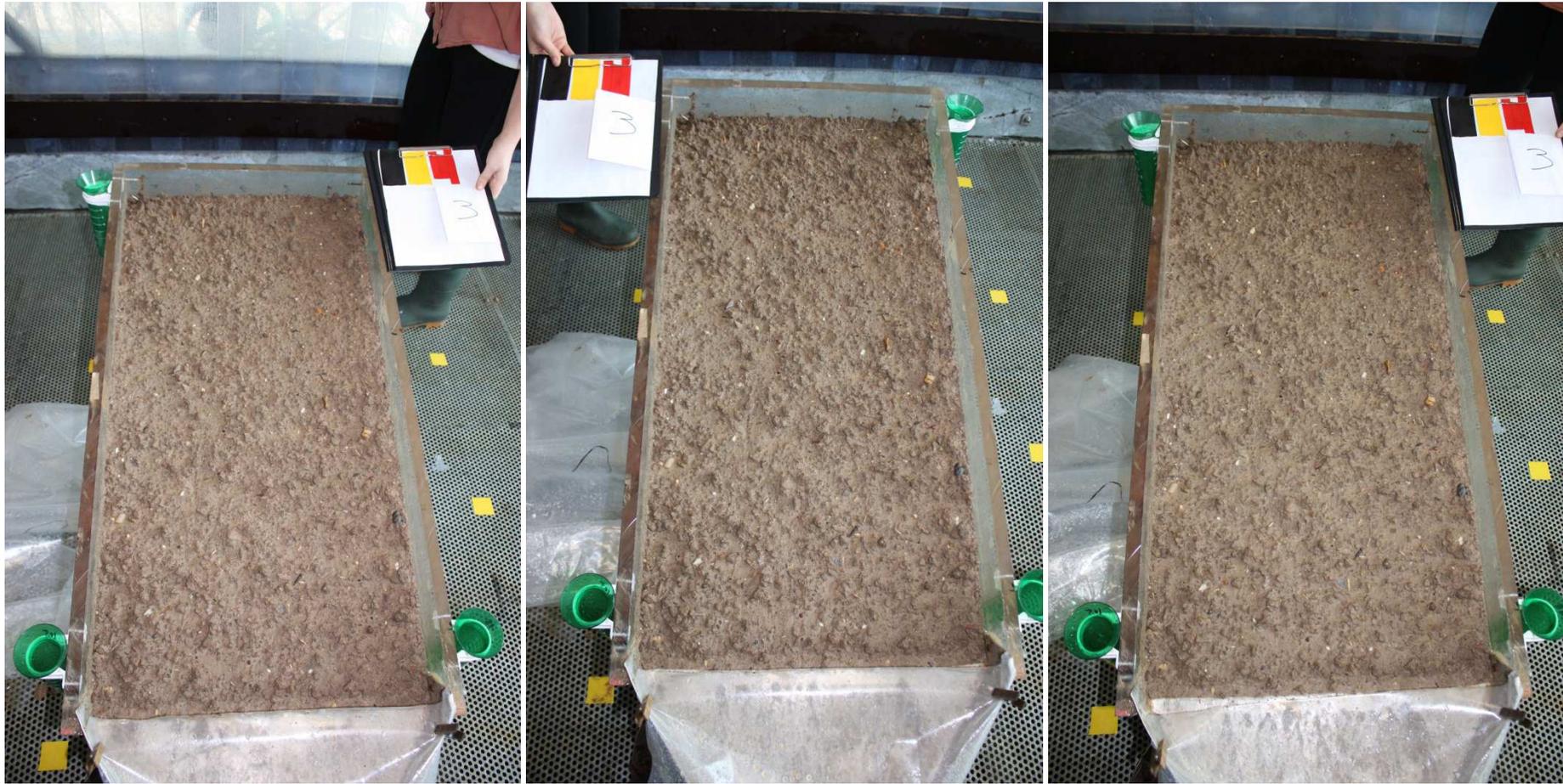**Figures 5-a, 5-b and 5-c** : Surface roughness changes in time for the box number 3= 50-60 mm/h (E0, E1 and E2).

d)   e)   f)

Figures 5-d, 5-e, and 5-f: Surface roughness changes for the box number 3= 50-60mm/h (E3, E4 and E5).