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Estimating water and sediment transport through the soil at field and laboratory

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Abstract

Soil erosion has been widely studied by many methods as a measure of loss of soil quality due to the importance of the conservation of the soil properties. However, these methods produce different results that are difficult to compare. In this thesis, rain simulations with a drip infiltrometer and a revised pinhole test were used to study the soil response and to quantify sediment transport. Simulated rain events in the field generated infiltration through the upper soil profile that was directly related to the rain intensity. A tension infiltrometer was used to estimate hydraulic conductivity in the soil before and after the simulated rain events in the field to study the effect on the soil surface. Turbidity was measured in the water samples from drainage water in the rain events and was used as a surrogate parameter for suspended soil sediment concentration. Turbidity displayed similar pattern regarding the rain intensity applied. The pinhole test methodology was developed for undisturbed soil samples and was amended by modifying the water content in the soil samples, in order to study the response at saturation and under drainage at 40 and 100 cm tension. The erosion process was studied by considering turbidity values together with outflow rate. Sediment discharge calculations were more accurate when both these parameters included. Soil samples in the pinhole test showed similar patterns for turbidity, outflow rate and sediment discharge. However, sediment transport was lower in saturated samples than in drained samples and was highest for the samples drained at 100 cm tension. Furthermore, topsoil proved to be more reactive with cavities sometimes developing in the soil specimen. Our recommendation is to express the results as concentration of transported sediment (mg/mL), as these numerical values are easier to understand and compare between different experiments. Regarding to the pinhole test, the recommendation is to use samples from the soil depth of interest and drained at 100 cm tension.

Key words: soil, erosion, drip infiltrometer, tension infiltrometer, Pinhole test, turbidity.

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1 Introduction

Soil conservation is a major concern worldwide. When a soil loses its inherent properties, its structure changes and so its functions, i.e. its production capacity. Soil aggregate stability is considered a major indicator of soil quality, since the overall stability of the soil structure depends on this parameter. There are many methods to calculate aggregate stability, which differ in terms of the methods used for artificial destabilisation, the scale of the stability and the way in which the results are expressed. Thus it is difficult to compare the results obtained using different methods.

Soil erosion by water is considered to be one of the major causes of soil degradation. Rain drops change the surface soil structure, breaking aggregates and compacting the soil. Furthermore, infiltration of rain water may cause internal soil erosion that changes the original composition and may thus be another pathway for soil losses. The changes in the soil layers are very interesting, so many devices have been developed for their study. Amézqueta (1999) proposed that for a complete description of soil structural stability, it is necessary to study micro-aggregates and macro-aggregates. For this reason, both scales are considered in this thesis.

When studying aggregate stability, field measurements give the most reliable results, but they are costly and time-consuming. Rain simulators have been used in some studies, largely for field measurements of the effect of rain on the soil (Boers et al., 1992). Tension infiltrometers have been used all around the world in order to measure the soil hydraulic properties (Angulo-Jaramillo, 2000). Soil hydraulic conductivity is the rate at which water moves through the soil, so it is a good parameter to reflect soil changes.

Laboratory tests are easier to carry out and to replicate, but the information obtained refers to a small scale. The pinhole laboratory test is one such example. In this test, the flow of water under hydraulic head through a hole in the soil accurately reproduces well soil conditions and water chemistry piping erosion potential (Mitchell, 2005). The test was designed by Sherard et al. (1976) to classify dispersive clays. It is carried out using a compacted soil specimen in a cylinder, to which different hydraulic heads are applied. The soil is classified according to the outflow rate of water and sediment for the different hydraulic head values applied and the final hole size. This test has been widely used and over the years some modifications have been made to the initial design to improve the results. For example, Nadal-Romero et al. (2011) studied its suitability for assessing the susceptibility of loss soils to piping erosion. Many studies have used it mainly to classify the soil for engineering purposes at different water contents, using distilled water and different hydraulic heads. The pinhole test has also been used in laboratory experiments to study soil erodibility (Botschek et al., 2002; Fauzilah et al., 2008). However, few studies have examined the quantitative parameters used in the test to estimate erosion processes.

The overall objective of this Master´s thesis was therefore to develop methodology to study internal soil erosion.

2 Objectives

Specific objectives of the study were to:

- Quantify soil infiltration rates using a rain simulator under different rain intensities,
- Estimate the effect of the rain splash on soil hydraulic conductivity using the tension infiltrometer,
- Develop the pinhole laboratory test methodology for undisturbed soil samples.

3 Materials and methods

This work comprised a field study and laboratory analyses. The field study included measurements of flow from rain simulations and measurements of hydraulic conductivity using a tension infiltrometer. The laboratory analyses included refinement of the pinhole test methodology and turbidity measurements.

The field study was carried at Vipängen, which is located near the city of Uppsala in central Sweden. The field belongs to the Swedish University of Agricultural Sciences (SLU) and the soil at the site is a medium clay, around 38% clay in the 0-30 cm layer increasing to 55% at 30-40 cm depth.

The different measurements of soil hydraulic properties and macro-aggregate stability were carried out from 15 October to 4 November, 2010. The rain simulator was used to study soil behaviour at different rain intensities and the drainage water was collected for subsequent analysis. The tension infiltrometer was used before and after the rain simulation test in order to evaluate differences in the soil hydraulic conductivity near saturation.

The laboratory analyses were carried out in the period February May 2011. Turbidity was measured in the drainage water samples collected from the rain simulator tests. The samples were then dried and the residue weighed to calculate soil particle concentration. In addition, the pinhole test methodology was developed and tested in undisturbed soil samples from three different depths in the soil profile, which were adjusted to three different water contents.

3.1 Rain simulator

The rain simulator used to measure surface runoff and infiltration rate was a drip infiltrometer (Figure 1) developed by Joel (Joel and Messing, 2001) later modified and used in several studies. The factors considered in the choice of equipment were that the instrument should provide accurate and uniform distribution of simulated rain events, be able to apply different rain intensities, and be able to simulate the splash effect of rainfall.

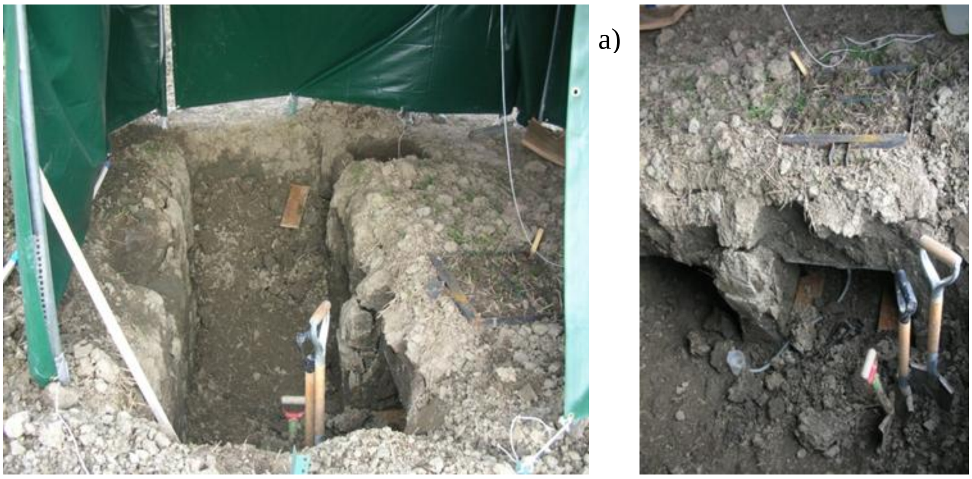
The main components and functions of the drip infiltrometer were: (1) a peristaltic pump to regulate water flow between the water supply tank, via a plastic tube, to (2) a drip plate that gave application rates equivalent to intensities of 15.5-140 mm/hour. This drip plate measured 0.5 m by 0.5 m and had 481 drippers (plastic tubes with 0.64 mm inner diameter) attached; (3) a stainless steel support for the drip plate; and (4) an runoff collector to prevent lateral water losses from the test surface (Figure 1). The support and the runoff collector were carefully hammered into the soil.

The simulated rain-water passed through the 45 cm upper soil layer and the water outflow was measured. The volume of outflow water was recorded regularly, and when a steady water outflow was obtained the rain intensity was changed. The rain intensity was modified in steps following two procedures. In the first procedure, here referred to as high-intensity run or "High", the rain intensity was altered from high to low intensity. In the second procedure, here referred as low-intensity run or "Low", the rain intensity was modified from low to high intensity. In both procedures, the rain intensity was varied between 15.5 mm/hour and 140 mm/hour, with 15.5 mm/hour being the lowest intensity the pump could supply.

3.1.1 Pit preparation

A pit of 1 m width, 3 m length and 1 m depth was excavated in the soil profile. At 45 cm depth, a cavity measuring 40 cm high, 65 cm wide and 85 cm depth was dug into one of the pit walls. Water and sediment that leached through the upper soil profile were collected from the roof of this cavity. A 1-2 cm trench was cut around the measurement area in order to limit the horizontal infiltration area and to ensure that the water would only move vertically. The trenches were filled with bentonite which was wetted to seal the cut (Figure 2).

Figure 1. Rain simulator positioned on the support in the soil and with the run-off collector visible.



a) b)

Figure 2. a) Initial pit. b) Side cavity and runoff collector.

3.1.2 Measurements

The volume of outflow water collected was measured at 5 to10 minute intervals due to different discharge rates. Water samples (100 mL approximately) were taken in bottles and transported to the laboratory for measurements of turbidity and determination of sediment concentration.

3.1.3 Analysis of drain water

Water turbidity was measured with the Hach Model 2100N Laboratory Turbidimeter which uses Nephelometric Turbidity Units (NTU). The measurements were made with the following configuration: automatic range, signal average on (i.e. the instrument microprocessor compiled a number of readings and averaged the results), and ratio on.

The procedure specified in the manufacturer's instruction manual for the Hach Laboratory Turbidimeter Model 2100N (HACH Company, 1996) was followed. First, the bottles containing the water samples from the rain simulation event were shaken to give homogeneous samples. Then, 30 mL were taken with a pipette from each bottle and transferred to the measuring cell of the turbidimeter. During preparation, care was taken to ensure that the sample never touched the walls of the cell. The top of the cell was then closed, it was spun and turned upside down twice and immediately placed in the instrument. The reading appeared within a few seconds but was rather unstable, with a variation of ±5 NTU. The procedure adopted was to record the highest value observed, because decrease in value was due to the sedimentation of the particles.

A small modification to the method for cleaning the cell was made compared with the instructions in the manual. Since the cell was used repeatedly for measurements during the day, the cleaning step was reduced from cleaning after each measurement (as specified in the manual) to cleaning only at the beginning of the working day. In order to check that the cell was clean, deionised water was used to measure turbidity at the start of the working day. With turbidity reading between 0.00 and 0.02 NTU over a period of 10-20 seconds the cell was considered clean. When higher readings were obtained, the cleaning operation was performed.

The same cell was used for all measurements in order to reduce variability caused by cell properties. It proved to be advisable to wait at least 10-20 seconds to see how the readings changed when performing the turbidity measurements on samples and, as in the cleaning process, the highest value was chosen. After each turbidity measurement, each water sample was transferred to a metal crucible. The crucibles were weighed, oven-dried for more than 12 hours at 105°C and weighed again once they had cooled in order to determine the weight of soil particles in the water samples. The real water volume was calculated by subtracting the weight of the dried crucible from the weight of the filled crucible:

Soil particle mass = Mass of dried crucible –Crucible mass

Water mass = Mass of filled crucible – Mass of dried crucible

The soil particle concentration (mg/mL) was then plotted against the turbidity (NTU) of each water sample to determine the relationship between turbidity and sediment concentration.

3.2 Tension infiltrometer

The tension infiltrometer (Soil Measurement Systems, 200 mm diameter disc) (Figure 3) was used to characterise the hydraulic conductivity (k) of the soil on the measurement plots before rain simulation (here called Reference) and after rain simulation (called High and Low, according to the rain simulation treatment) in three series. The hydraulic conductivity was measured using four different tensions: -5 cm, -3 cm, -1 cm and 0 cm.

The tension infiltrometer consisted of: (1) A bubble tower; (2) a water reservoir; (3) the disc; (4) a tube connecting the disc and the water tower; (5) an air entry tube and (6) the bubbling tube with a clamp. The bubble tower and the air entry tube controlled the tension applied at the soil surface, while the water reservoir provides the water for the experiment. The disc was used to establish the hydraulic continuity with the soil.

Figure 3. Tension infiltrometer in use in the field.

3.2.1 Preparation

The infiltrometer was filled with water before being placed in the measurement area. To prevent air entering the water reservoir, the procedure followed was to fill the water reservoir to 5 cm from the top from the disc under water, making the water flow in the opposite direction to that under normal operation. By applying suction to the pipe at the top of the water reservoir, bubbles in the water circuit were removed. This procedure was only carried out when first working with the instrument in each plot.

When the water reservoir had insufficient water to perform the next measurement and was already in place on the measurement area, a different procedure was used: The valve between the disc and the water reservoir was closed and then the top of the water reservoir was removed and it was filled with water to a level of 5 cm from the top.

The next step was to fill the bubble tower, while the valve still had to be kept closed. The top was removed, water was introduced to 7 cm from the top and the top was closed again. The air entry tube was used to control the water tension in the soil. The lower end of this tube had to be 4 cm + X cm from the water level, where X is the tension to be applied for the measurement (-5 cm, -3 cm, -1 cm or 0 cm). Between measurements, the position of the air entry tube had to be adjusted to set the tension.

The disc was placed on a flat surface with a thin layer of wet sand to improve the contact with the soil. The sand was wetted to an optimum water content and spread over a surface of the same size as the disc. The disc was placed on top and some weight was applied in order to improve the contact with the soil.

3.2.2 Measurements

The water volume in the water reservoir was recorded every 15 seconds at the beginning (between 10-30 minutes) and later every 30 seconds, until steady flow for each tension was reached. The duration of measurements at -5 cm tension was around 40 minutes, for -3 cm 30 minutes, for -1 cm 20 minutes and for 0 cm 15 minutes. The last values with a constant increase were then used to calculate the infiltration rate in the soil. The hydraulic conductivity was then calculated with the model described by Messing and Jarvis (1993), based on theories of Wooding (1968) for infiltration from a circular source and the Gardner (1958) exponential function for k. This model calculates k values for intermediate tensions to better describe the equation, in this case for -4 and -2 cm tension.

3.3 Pinhole test

The pinhole laboratory test was initially designed to identify dispersive clays (Sherard et al., 1976). It involves passing distilled water under a controlled hydraulic head through a 1 mm diameter hole made in a recompacted clay. The soil is classified according to the turbidity of the water outflow from the soil specimen, the hydraulic head applied, the state of flow and the final diameter of the hole (American Society for Testing Materials, D4647-93). The test is run during five minutes and then if the water and the flow have the established requirements (turbid water) the test is finished. Otherwise the hydraulic head is increased and the test continues. There are four standard hydraulic heads at which to run the test: 5, 18, 38 and 102 cm. Furthermore, the soil specimen can be disturbed or undisturbed.

In this thesis, the methodology was refined for undisturbed soil samples, which required some changes from the initial test. Only the 18, 38 and 102 hydraulic heads were used, all the water was collected and its turbidity was measured and some water samples were dried to determine the relationship between turbidity and soil particle concentration in the water. The aim of these modifications was to allow the soil erosion susceptibility to be determined on undisturbed soil samples.

The elements of the pinhole apparatus are (Figure 4): (1) A plastic cylinder (34 mm inner diameter) containing the soil specimen, through which runs a 1 mm diameter hole made with a needle; (2) a cone (4 mm min. diameter, 10 mm max. diameter and 13 mm high) to insert in the top of the specimen; (3) three wire mesh discs, one to place on top of the specimen and the other two at the bottom; (4) pea shingle (2-6 mm) to fill the rest of the cylinder; (5) a ring of moulding clay to seal the walls; (6) two end plates for the cylinder, one with inlet and standpipe connections and the other with outlet connection; (7) and a standpipe to read the hydraulic head (1190 mm long and 3 mm inner diameter).

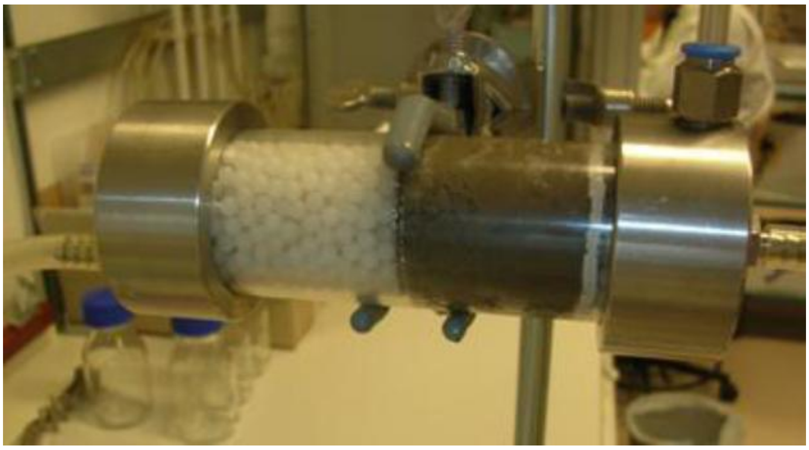


Figure 4. Pinhole cylinder with pea shingle, wire mesh discs, soil specimen, and moulding clay, enclosed by the end plates.

3.3.1 Specimen preparation test

There is no specified method for inserting undisturbed soil into the pinhole cylinder, so two ways for preparing the soil specimen were tested. The first of these was to press the cylinder into the soil, cut it to the appropriate length (around 38 mm) and then press the core to the appropriate place (50 mm from the bottom of the pinhole cylinder). Next, the cone and the needle had to be introduced in the specimen to make a 1 mm hole through it. One wire mesh disc was attached to the upper part and two to the lower part to separate the soil from the pea shingle (4-6 mm diameter) filling the remaining space above and below. The last step was to put on the caps, place the cylinder horizontally, install the standpipe for measuring hydraulic head and connect the top cap to the water supply to start the test.

For the first experiment on soil specimens, the samples were prepared as described above and then the test was run for 5 minutes with 31, 50 and 110 cm hydraulic head. The hydraulic head in the test was the height between the central axis of the cylinder and the water level in the tank supplying the water. The head was controlled by changing the position of the cylinder and the water level in the water tank.

The second way to prepare the soil specimen for the test involved following the instructions for compacted specimens (American Society for Testing Materials, D4647-93). First of all, the lower cap was filled with 5 cm pea shingle, two discs were placed on top and the soil was introduced. To keep the samples undisturbed in this step, a second cylinder was used to hold the specimen intact and it was then pressed through to the test cylinder. Once the specimen was in position in the test cylinder, cone and needle were inserted and one disc, pea shingle and the upper cap were placed on top. The test was run with the same hydraulic heads (31, 50, 110 cm) and the outflow water collected.

There was no difference in the turbidity of the outflow water between these two methods for sample preparation. Therefore since the first method was easier and the soil sample was not compacted, it was chosen for the experiment.

The next variable tested in the method development was the use of moulding clay to seal and prevent flow between the soil and the walls of the cylinder. While no consistent results were obtained in tests with or without moulding clay, it was decided to use moulding clay in the experiments to avoid possible flow between the cylinder and the specimen. The chosen material was a kind of moulding clay that was easier to work because it did not stick and did not colour the water.

The last variable was the pea shingle. The material available were small stones (4-6 mm diameter) and white plastic beads (4 mm diameter). These gave similar effects and neither coloured the water, but plastic beads were chosen because it was easier to check whether they were clean. However, they had the disadvantage of being so small that a single bead could block the outlet hole. The solution was to put a fourth wire mesh between the beads and the lower cap.

During the tests some important details were observed. For instance, when perforating the specimen with the needle, it was important to clean the needle before extracting it by it turning slowly. Sometimes there was no flow because the hole was blocked, and the top cap had to be removed and the hole had to be made again. It was also observed that the use of a turning valve to avoid bubbles in the stand pipe made it easier to read the actual hydraulic head.

3.3.2 Soil sample preparation

Undisturbed soil samples were taken from the field with cylinders of 72 mm diameter and 50 mm height. The samples were taken from three different depths: the topsoil (10-15 cm), the plough pan (22-27 cm) and the subsoil (35-40 cm).

The soil samples were stored at 4ºC until testing. Before the test commenced, all the samples were saturated for 2 weeks. Then some samples were drained in sandboxes to alter the water content. The sandbox, an airtight chamber, allowed the water tension in the sand to be controlled, and thereby the water content of the sample in contact with the sand inside the box. The tensions used in the boxes were 40 cm and 100 cm, in order to study the effect of different water contents (Nadal-Romero et al., 2011). Those authors reported that different antecedent moisture content in samples before the pinhole test influenced sediment discharge. Furthermore, Watts (1996) concluded that different soils have different stability depending on the water content, e.g. clay has a different response to mechanical disruption according to the water content, becoming sensitive above the plastic limit.

3.3.3 Implementation of the pinhole methodology

The test was run on four soil samples from each of the three depths at three different initial water contents (Table 1). For each soil sample the pinhole test was run at three hydraulic heads: 18 cm, 38 cm and 102 cm, in that order, with 6 minutes at each hydraulic. All the outflow water was collected in glass bottles to measure the volume and the turbidity of the water. In the 18 cm run, 6 bottles were used, with the water collected every minute, because the flow was low and 30 mL of sample were required for turbidity measurements. The bottles were numbered 1 to 6. For the 38 and 102 cm runs the water flow was higher than for 18 cm, so the water was collected every 30 seconds, using 12 bottles for each hydraulic head (bottles 1 to 12).

Table 1. Soil depth, water content and soil sample number.

Soil depth	Soil sample number		
	Saturated	40 cm	100 cm
Topsoil	1383, 1384, 1385, 1386	161, 163, 164	167, 170, 175
Plough pan	1390, 1391, 1392, 1393	165, 168, 169	172, 173, 178
Subsoil	1394, 1395, 1396, 1397	179, 180, 181	188, 192, 196

3.3.4 Analysis of water samples

The turbidity of all the water samples from the pinhole test was measured with the Hach Model 2100N Laboratory Turbidimeter used previously for the water from the rain simulation test. The same procedure for measurements was followed.

The next step was to dry the water samples after measuring the turbidity. It was not possible to dry all the samples because it was time-consuming. Therefore, bottles number 1, 3 and 6 from the 18 cm test and bottles 1, 5, 8 and 12 from the 38 cm and 102 cm tests were selected for drying. Dying was carried out in the same metal crucibles as were used for the water from the rain simulator and following the same procedure to calculate the soil sediment concentration in the water.

The data obtained were used to calculate a linear equation to estimate sediment concentration from turbidity. This equation was applied to estimate the concentration in samples that were not dried. The sediment concentration was then multiplied by the outflow volume to calculate the sediment discharge for every pinhole test. Turbidity can be a good indicator of soil particles in the water and is easy and fast to read. However, it does not take into account the water volume that has passed through the sample. For this reason, total sediment discharge is a better indicator of the total erosion produced in the sample.

4 Results and discussion

The results from the field measurements with the rain simulator and the tension infiltrometer and the laboratory analyses using the pinhole test are presented below.

4.1 Rain simulator

The rain simulation runs in the field were carried out in three plots and the series were designated L1, L2, H1, H2 and H3, where H and L are high and low intensity, as described earlier.

The first set of measurements with the rain simulator, low-intensity run 1 (L1), started with a rain intensity of 41 mm/hour and took about 40 minutes from the start of the simulation until outflow began. After few minutes, the rain intensity was decreased to 31 mm/hour and it took 30 minutes to get a steady outflow, after which the intensity was decreased to 15.5 mm/hour. Next, the intensity was increased to 140 mm/hour and a rapid increase in water flow was observed. Within 10 minutes the outflow increased to 100 mm/hour and was about 71% of input.

The second set of measurements, low-intensity run 2 (L2), started with intensity of 140 mm/hour for 23 minutes to wet the soil. When the outflow was initiated, the rain intensity was reduced to 31 mm/hour. The flow response was fast, with it taking 13 minutes to get a steady outflow of 21 mm/hour. The rain intensity applied was then decreased to 15 mm/hour for 10 minutes and the outflow decreased considerably, to an average value of 4.2 mm/hour. After that, an intensity of 31 mm/hour was applied again and an outflow rate of 20 mm/hour was reached in 20 minutes. The last intensity tested was 140 mm/hour, the response was fast and reached steady outflow of 75 mm/hour. The results of outflow and turbidity measurements for L2 are presented in Figure 5.

The turbidity curve showed initial values that then decreased and reached steady values over time, stabilising at around 50 NTU with 31 mm/hour of rain intensity. When high intensity was applied at the end of the run, turbidity values increased too, and when the pump was shut down the turbidity decreased. Nevertheless, the last turbidity values were higher (>80 NTU) compared to those obtained in run L1 for 31 mm/hour (50 NTU). This may be due to the high rain intensity applied disturbed the soil and particles susceptible to erosion remained in place for later erosion. Furthermore, the outflow rate was lower than applying 31 mm/hour and thus the total sediment discharge was lower.

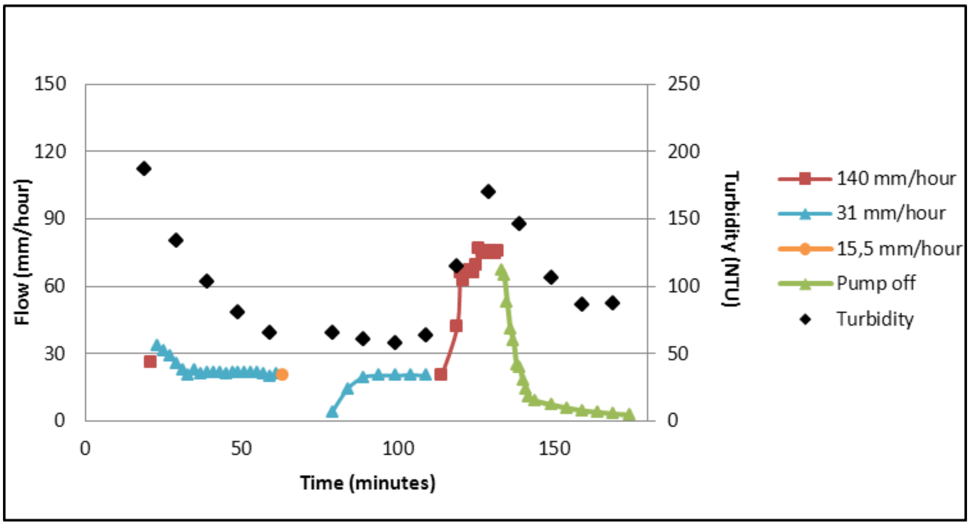


Figure 5. Rain intensity, drain outflow and water turbidity for rain simulation series L2.

In the third set of measurements, here called high-intensity run 1 (H1), the starting intensity was 140 mm/hour. Drain outflow was observed after 11 minutes and reached a maximum outflow rate of 120 mm/hour at 8 minutes after the flow started. The pump was stopped 23 minutes after the start and the outflow decreased considerably. Then after 10 minutes, the pump re-started at its highest intensity again. Later, the intensity was decreased and fast responses in drain flow were observed. At a rain intensity of 70 mm/hour it took 12 minutes to reach a steady flow (48 mm/hour), while with an intensity of 41 mm/hour took 13 minutes (33.6 mm/hour) and with a rain intensity of 31 mm/hour it took 20 minutes to reach steady flow (18.24 mm/hour). At the end, the pump was turned off and drain flow decreased slowly. All results are presented in Figure 6.

The turbidity values for some samples of the outflow are also shown in Figure 6. The turbidity proved be directly related to the rain intensity, with decreasing input rate decreasing both the outflow and the turbidity. With a rain intensity of 31 mm/hour, the turbidity values were over 50 NTU.

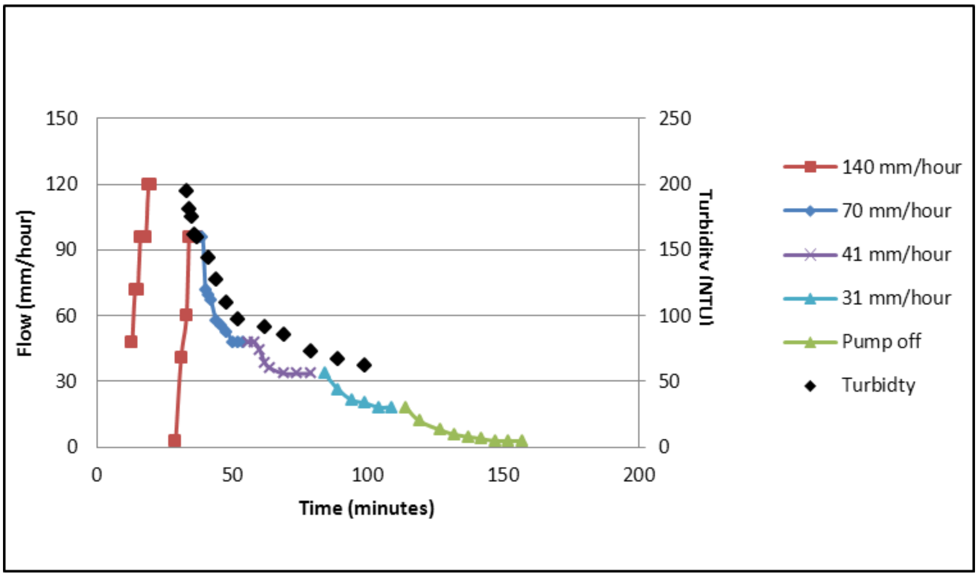


Figure 6. Rain intensity, drain outflow and water turbidity for rain simulation series H1.

The results of the fourth series of measurements, high-intensity run 2 (H2), are shown in Figure 7. An intensity of 140 mm/hour was applied for 15 minutes to wet the soil and then changed to 31 mm/hour for few minutes and back to the highest intensity again. The second time the highest rain intensity was applied it took 28 minutes to reach a steady flow, of approximately 67 mm/hour. Each of the next set of decreasing rain intensities (70, 41, 31 and 15.5 mm/hour) took 20 minutes to stabilise, but only in the last two intensities the outflow reached 50% of the input flow.

The turbidity values were similar to those observed in series H1, but at the end of the run they stabilised at around 80 NTU, instead of 50 NTU as in H1.

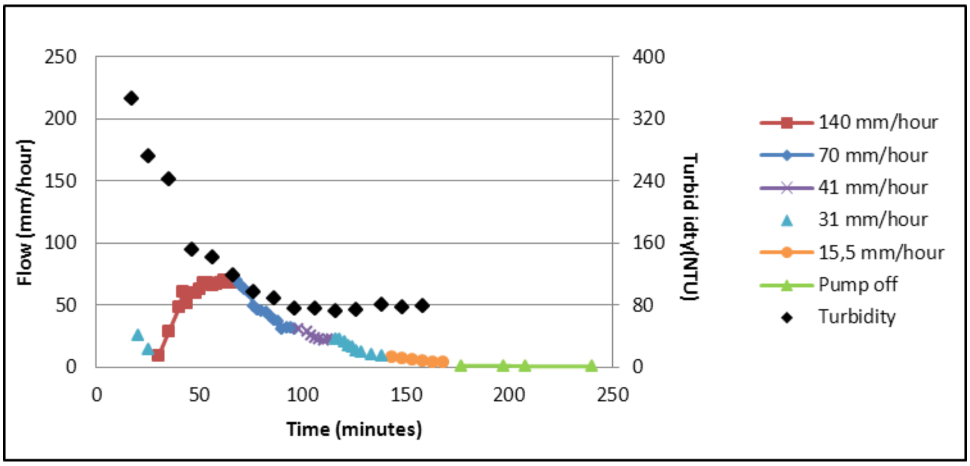


Figure 7. Rain intensity, drain outflow and water turbidity for rain simulation series H2.

The results of the final set of measurements, high-intensity run 3 (H3), are shown in Figure 8. In this series, the highest intensity (140 mm/hour) was run until a steady outflow (80 mm/hour) was reached. After that, the rain intensity was decreased step by step, first 70 mm/hour, then 41 mm/hour, 31 mm/hour and finally 15.5 mm/hour. The flow response until steady state was reached was not fast, but the output values at steady state were over 50% of the input flow.

Very high turbidity values were recorded at the beginning (1159 NTU), but these decreased with decreasing flow, as in the other series of measurements.

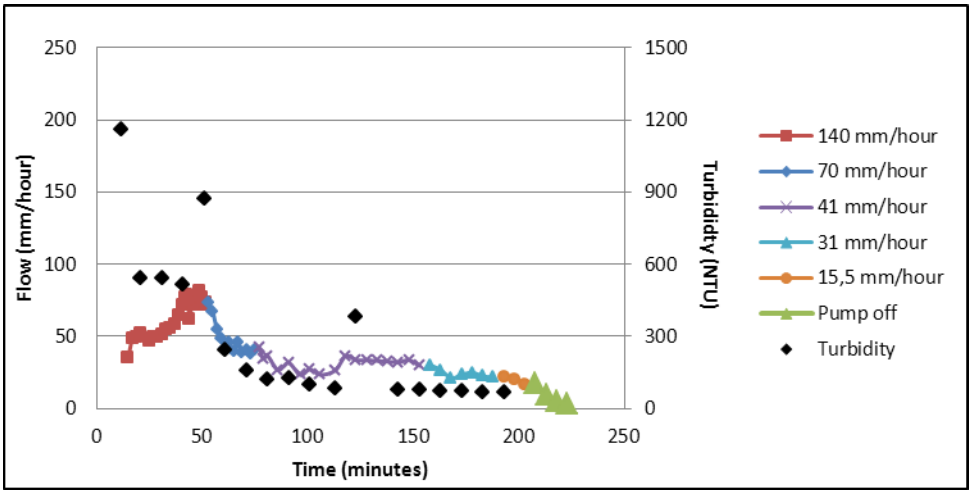


Figure 8. Rain intensity, drain outflow and water turbidity for rain simulation series H3.

The water samples collected from the water draining during the rain simulations showed a direct positive relationship with soil sediment concentration, as depicted in Figure 9.

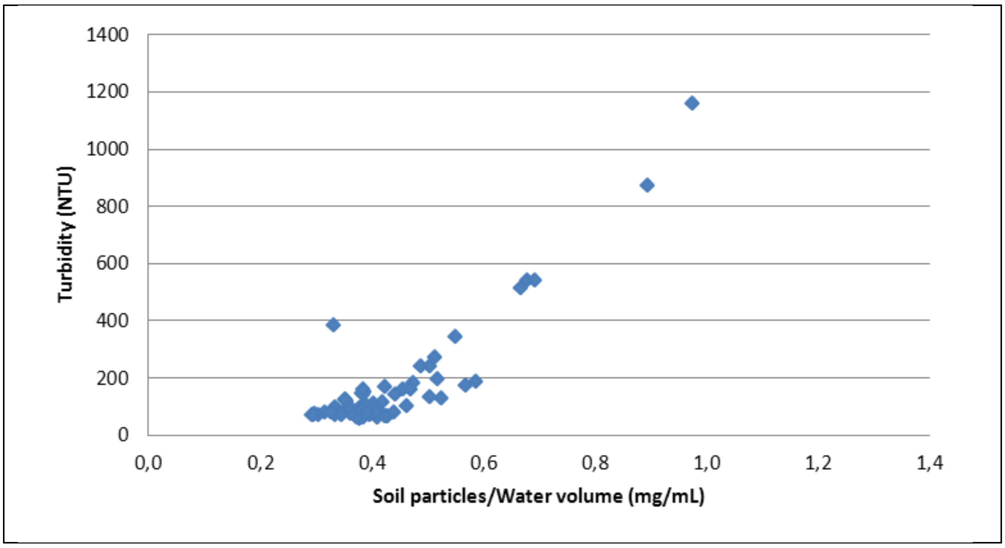


Figure 9. Sediment concentration (mg/mL) as a function of turbidity (NTU) in water outflow from the soil profile from the rain events.

A general conclusion from the rain simulation measurements was that outflow and turbidity had a direct positive relationship with the rain intensity applied. However, the values obtained varied widely between replicates. This could be due to the measurement procedure, since the state of the soil and its moisture content were different and thus the soil disturbance was also different. In addition, studying soil erosion from turbidity values alone does not give complete information. In order to get a measure of the total sediment transport, the outflow volume also has to be considered. For example, the turbidity values in rain simulation L2 were expected to be lower when the rain stopped than with rain. However, considering the outflow volume, which was very low, the total sediment transport was lower when the pump was turned off than before. According to this experience, complementary information may be helpful in understanding the real erosion process. A possible solution is to study total sediment discharge, as was done later using the modified pinhole test. Nevertheless, more repetitions are recommended when studying soil behaviour in rain simulations.

Concerning surface runoff, at all rain intensities there was no runoff from the soil surface. For this process to occur, a higher rain intensity would be required.

4.2 Tension infiltrometer

As expected from the principle of the method, at high negative tension values in the tension infiltrometer, the water moved slowly from the device into the soil and k values were low. When the tension was lowered (decreasing negative values), movement of the water was faster and k values increased (Figures 10, 11 and 12). The values of k obtained for the different tensions are similar to those reported by Messing and Jarvis (1993) for the same soil. However, there was no pattern between the simulated rain treatments and hydraulic conductivity in the soil. Furthermore, the presented results disagree with the conclusions by Messing and Jarvis (1993) about that the rain impact decreases k values, since the results for the undisturbed (Reference) soil where always lower values (except 0 cm tension for R3) than for the series after the rain events. This could be due to spatial variability in the soil and the sensitivity of the parameter (k). Furthermore, it was sometimes not possible to obtain measurements with the tension infiltrometer just after the simulated rain event and in some cases days had to elapse before measurement was possible. The rain area was covered, but the water content in the soil could still change, affecting the results. Apart from this, there were some difficulties in finding an appropriate area for the apparatus because the soil had an irregular surface, and a lot of sand was sometimes needed to keep the contact between the disc and the soil. These complications could also have had some impact on the results.

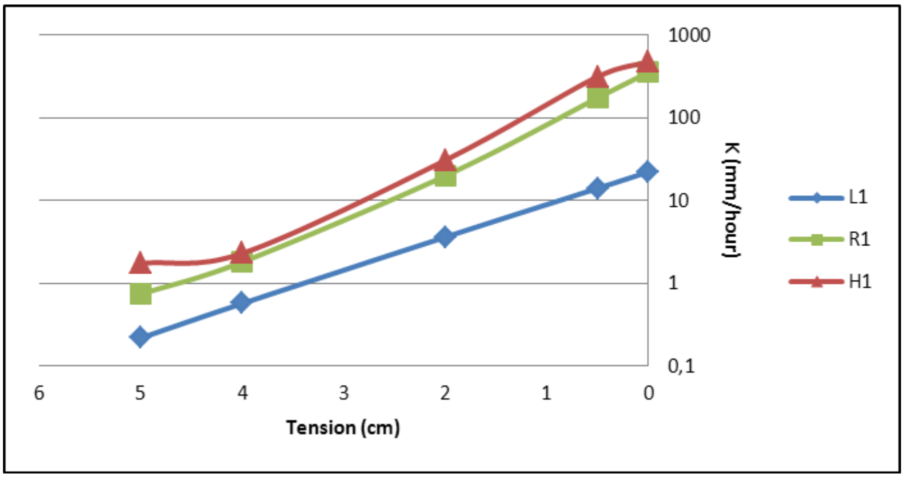


Figure 10. Hydraulic conductivity (k) for different water tensions applied to the soil (-5, -3, -1 and 0 cm) in tension infiltrometer measurement for different treatments (Low, Reference and High). Series 1.

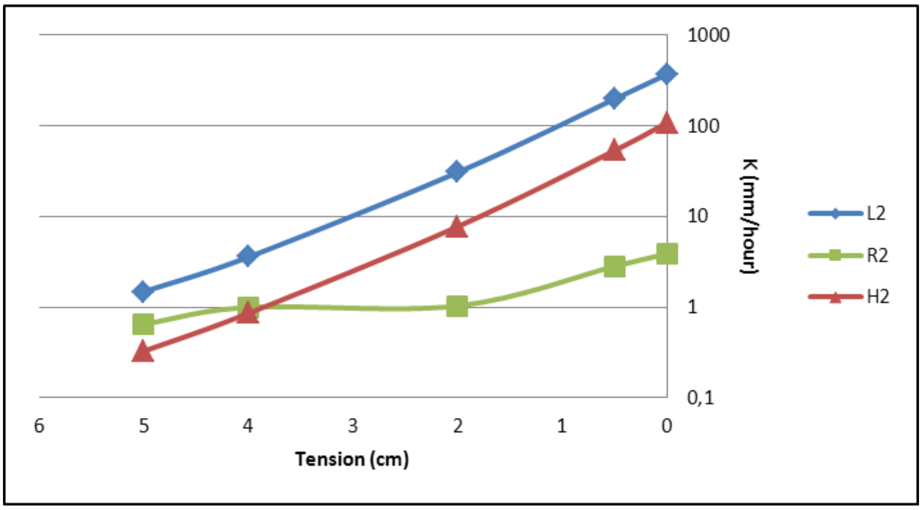


Figure 11. Hydraulic conductivity (k) for different water tensions applied to the soil (-5, -3, -1 and 0 cm) in tension infiltrometer measurements for different treatments (Low, Reference and High). Series 2.

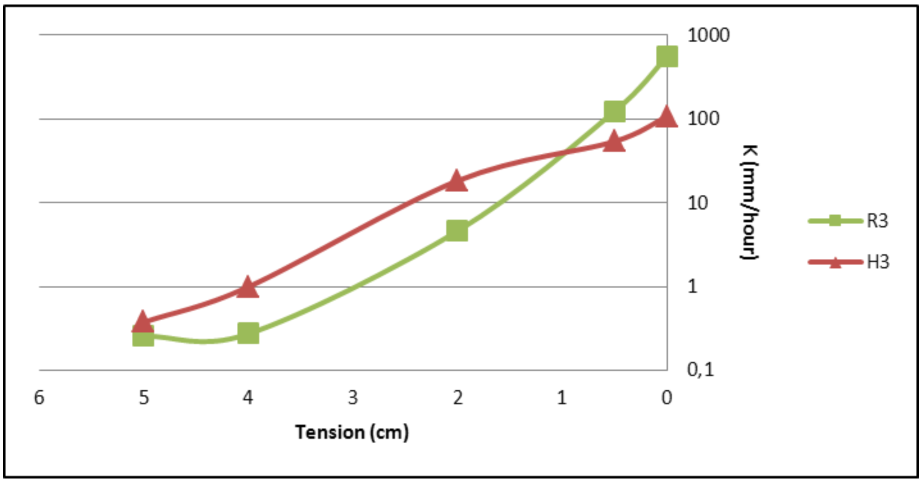


Figure 12. Hydraulic conductivity (k) for different water tensions applied to the soil (-5, -3, -1 and 0 cm) in tension infiltrometer measurements for different treatments (Reference and High). Series 3.

4.3 Pinhole test

The pinhole test was carried out on 30 soil samples, which were divided into three groups with different water content. Therefore all the results are grouped depending on these water contents, and subdivided depending on the depth at which the soil samples were taken.

The sediment concentrations in selected samples and turbidity outflow water are plotted in Figures 13, 14 and 15 to show the relationship between turbidity and soil losses in outflow. This relationship was used to estimate the sediment concentration of the outflow. In addition, graphs were drawn of water turbidity, outflow rate and sediment concentration (pinhole test) for all samples together to better determine the relationship between these parameters.

The relationship between turbidity values and sediment concentration was positive and was within a similar range to that observed in the drainage water from the simulated rain events in the field. The equations for these relationships are shown in Figures 13-15. They were linear and all except two were fitted (R^2>0.8) or well adjusted (R^2 >0.9). The exceptions were the equations for samples from 22-27 cm and 35-40 cm depth drained at 40 cm tension. As the diagrams show, the data points were very close and concentrated around a cloud, so the equation could not be completely adjusted. The low turbidity values in some samples may not have provided good information about concentration. Turbidity proved to be more sensitive to low sediment concentration values than to high vales. Williamson and Crawford (1978-1995) observed similar results for turbidity in streams and concluded that when turbidity is not too low, it is a good surrogate for total suspended solid concentration evaluations. They found that turbidity values < 6 NTU did not provide realistic information about suspended sediment concentration.

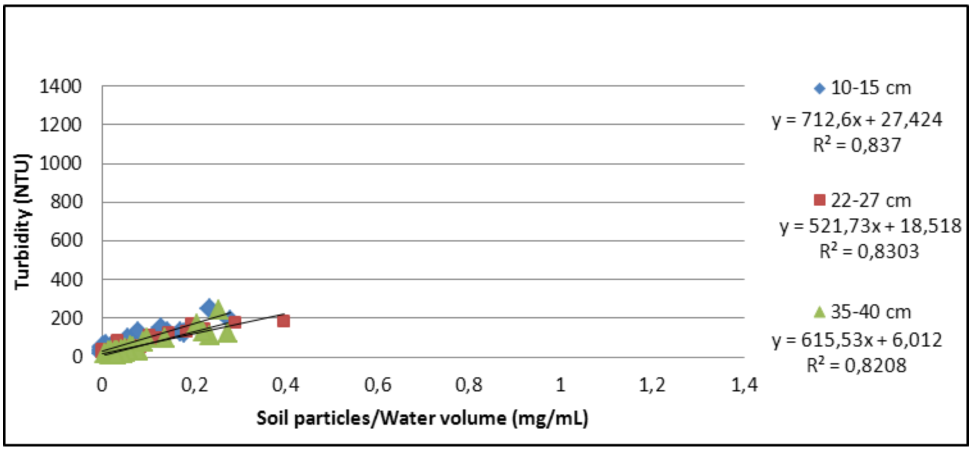


Figure 13. Sediment concentration (mg/mL) versus turbidity (NTU) in water outflow from soil samples from three different soil depths and water-saturated in the pinhole test.

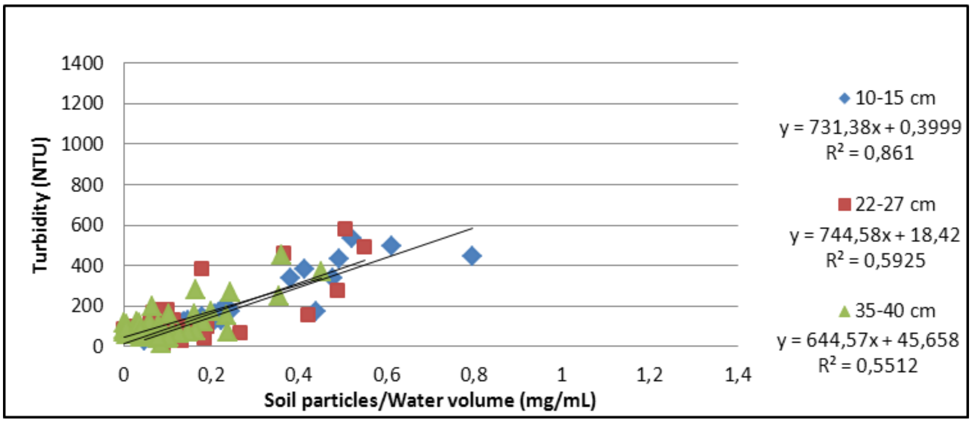


Figure 14. Sediment concentration (mg/mL) versus turbidity (NTU) in water outflow from soil samples from three different soil depths and drained to 40 cm tension in the pinhole test.

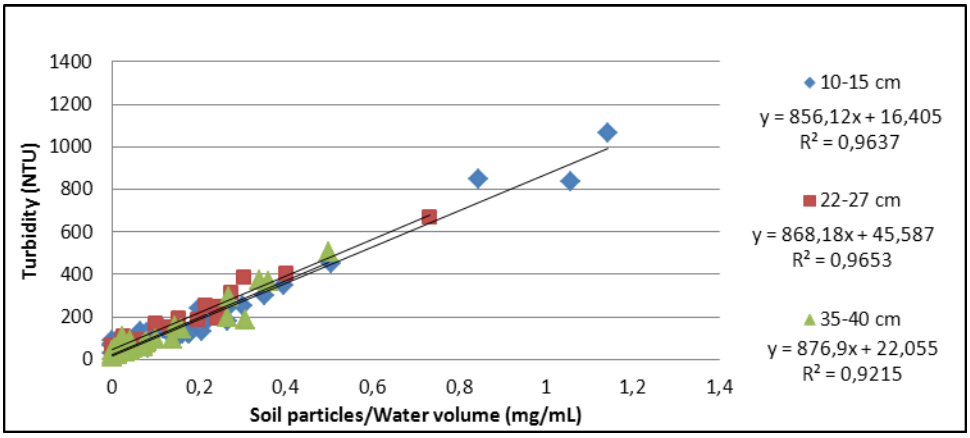


Figure 15. Sediment concentration (mg/mL) versus turbidity (NTU) in water outflow from soil samples from three different soil depths and drained to 100 cm tension in the pinhole test.

An example of the results for a pinhole test for an individual soil sample is shown in Figure 16, where turbidity, outflow rate and sediment discharge are depicted as a function of time. At 18 cm hydraulic head turbidity was low, while at 38 cm hydraulic head it had higher values at the beginning of the run but these then decreased, reaching steady lower values. For the last hydraulic head applied (102 cm), the response was similar to that for the 38 cm hydraulic head. However, for some soil samples the initial turbidity values for 102 cm hydraulic head were sometimes lower than for 38 cm. For calculated total sediment discharge, the curve had the same shape as the turbidity curve, but the initial values for 38 cm hydraulic head were always lower than those for 102 cm head showing better the soil erosion process.

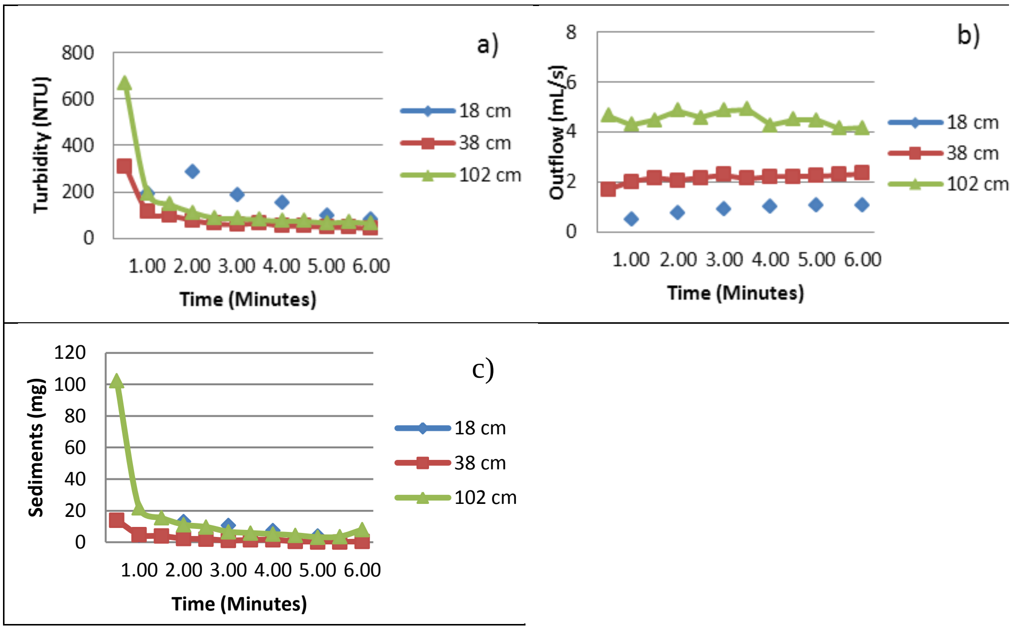


Figure 16. (a) Outflow water turbidity, (b) outflow rate and (c) sediment discharge as a function of time for soil sample 172 (drained at 100 cm and from 22-27 cm depth) under 18, 38 and 102 cm hydraulic head.

The results of all pinhole tests are presented in Figures 17-25. They are divided according to water content and soil depth, and subdivided into the three hydraulic heads used at the test. All tests showed the same pattern: Turbidity values had a wide range of values between replicates, but the shape of the curves was always the same for all tests.

In the outflow, more similar values were observed. At 18 cm hydraulic head the flow was around 0.5-1 mL/s, for 38 cm head 2-3 mL/s and for 102 cm head 4-5 mL/s. However, there were some exceptions where the soil specimen broke and the outflow reached very high values.

Calculation of sediment concentration had some difficulties. For saturated soil samples, the equation used to estimate sediment concentration was adjusted (R^2>0.8) but the regression gave unrealistic results, with many resulting in negatives values. In these cases the sediment discharge was not considered. These calculated sediment concentrations were lower than the values calculated from the dried samples, creating an unrealistic curve going up and down. However, this happened only for some samples. In general, sediment outflow curves had the same shape as the turbidity curves, with low, steady values for 18 cm hydraulic head and a high initial value and then steady values for 38 and 102 cm hydraulic head.

There were small differences between samples with different water contents. Saturated samples had lower sediment outflow than partially drained samples for both the high initial values at the beginning of the test and the steady final values. The samples drained in the sandbox (40 and 100 cm tension) showed higher values of sediment outflow. This agrees with Nadal-Romero et al. (2011), who found that higher soil water content gave less sediment discharge.

There were exceptions to this finding for the hydraulic head applied, especially in some soil samples from the surface layer (10-15 cm depth). During the pinhole test, some small cavities were created in some samples (161, 164, 167 and 175) due to the roughness of the surface and thus soil density appeared lower (less compacted). Due to this, the turbidity and the water flow were higher in these samples than in other corresponding samples, as shown in Figures 20 and 23.

In spite of these difficulties, the modified pinhole test was simple and easy to reproduce. The recommendations for this test are to drain clayey soil samples at 100 cm and to calculate soil sediment discharge in the outflow in order to study the soil response to the different hydraulic heads. For a complete view of the soil specimen response during the pinhole test, cumulative sediment discharge may better reflect the response to the three hydraulic heads applied.

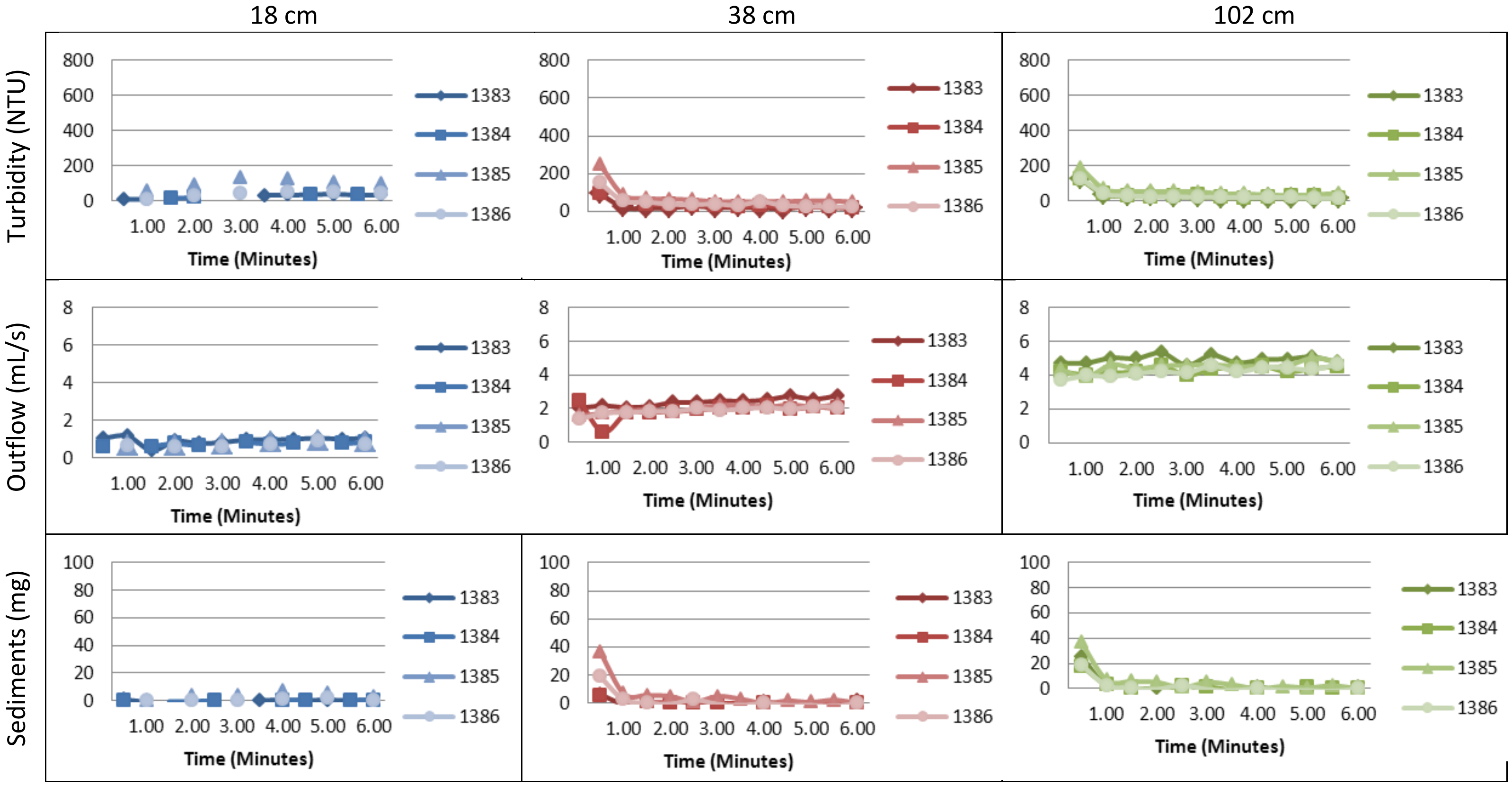


Figure 17. Outflow water turbidity, outflow rate and sediment discharge from saturated soil samples (1383, 1384, 1385 and 1386) from 10-15 cm depth subjected to 18, 38 and 102 cm hydraulic head for the pinhole test.

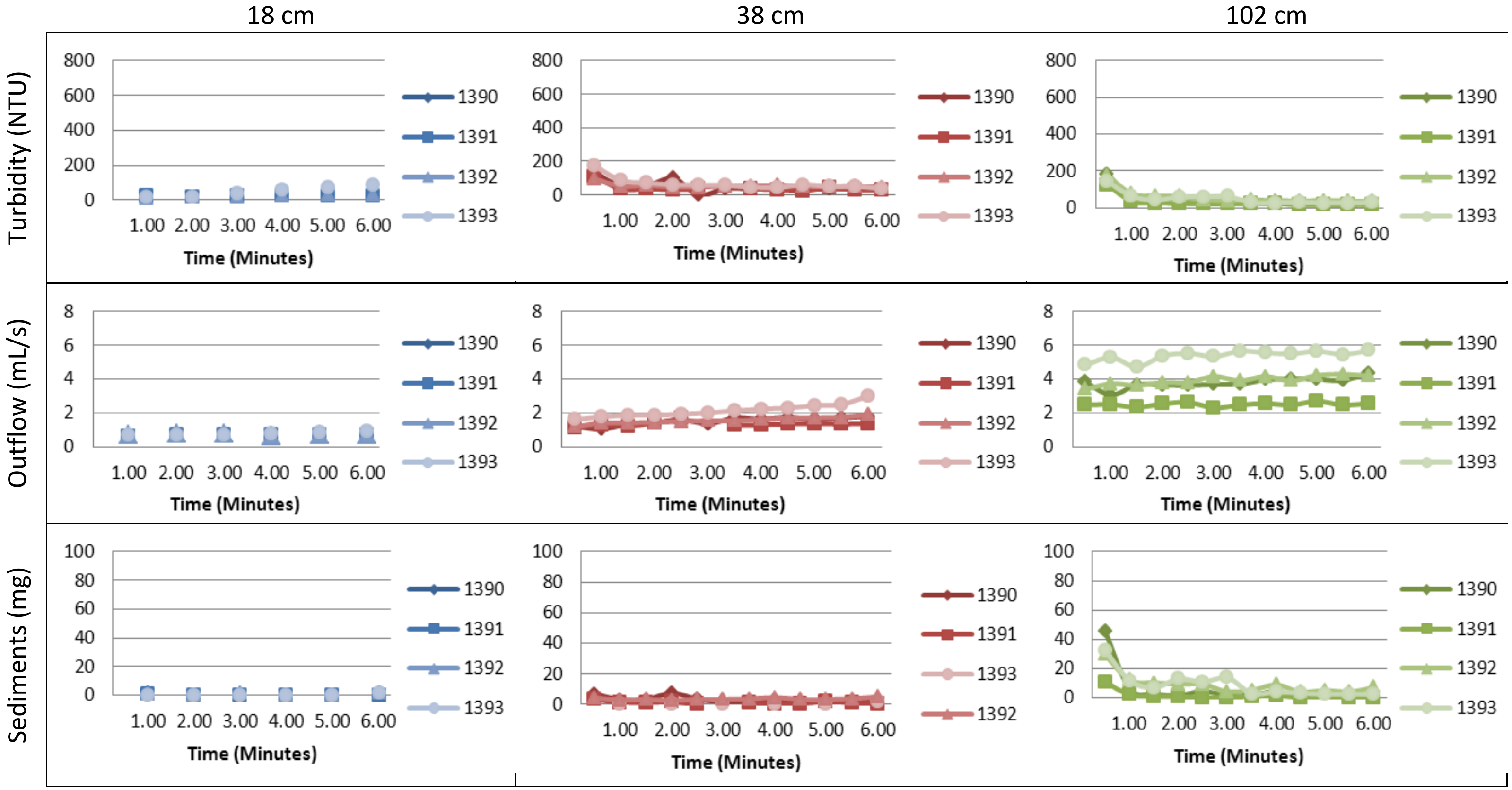


Figure 18. Outflow water turbidity, outflow rate and sediment discharge from saturated soil samples (1390, 1391, 1392 and 1393) from 22-27 cm depth subjected to 18, 38 and 102 cm hydraulic head in the pinhole test.

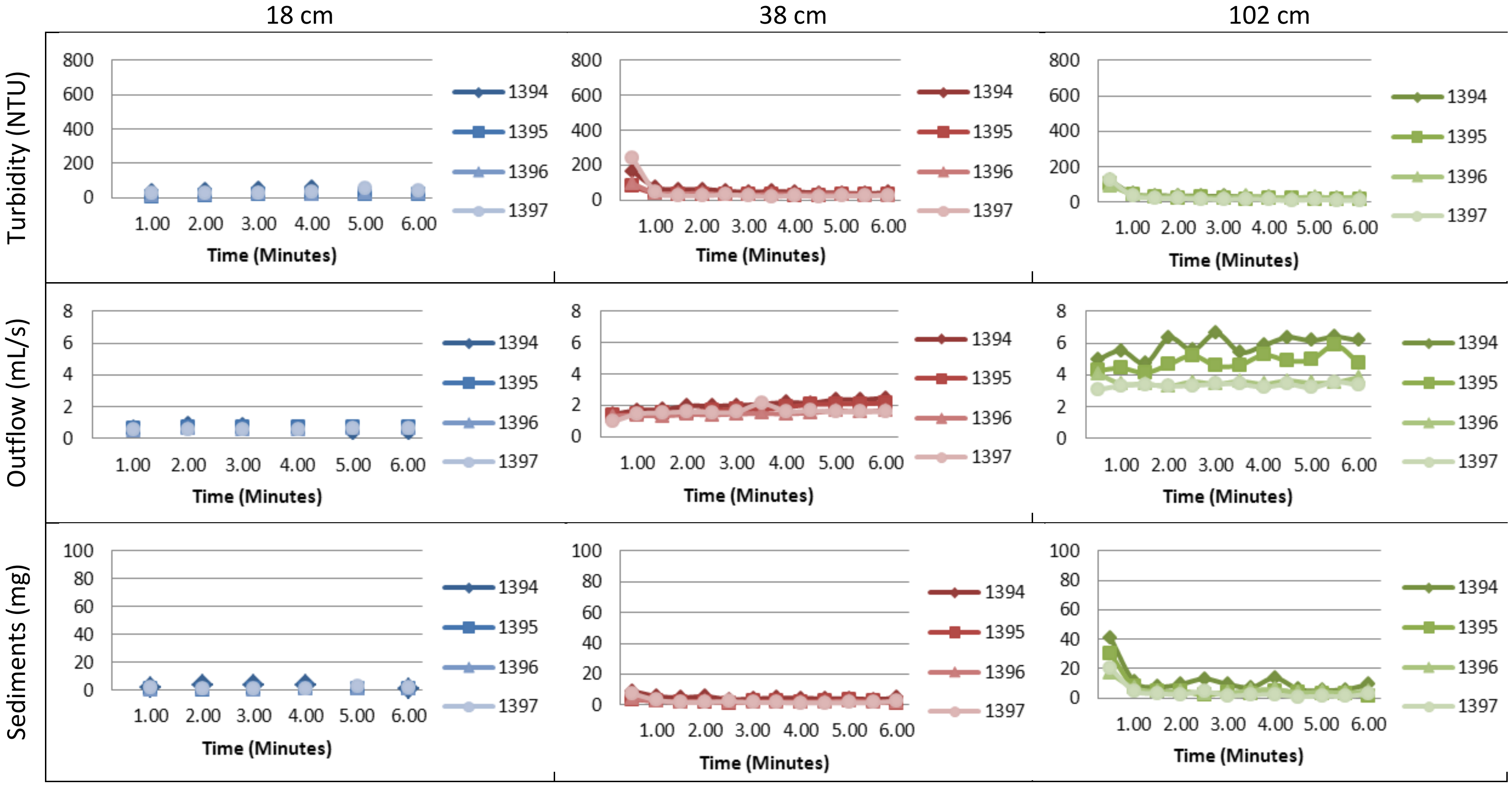


Figure 19. Outflow water turbidity, outflow rate and sediment discharge from saturated soil samples (1394, 1395, 1396 and 1397) from 34-40 cm depth subjected to 18, 38 and 102 cm hydraulic head in the pinhole test.

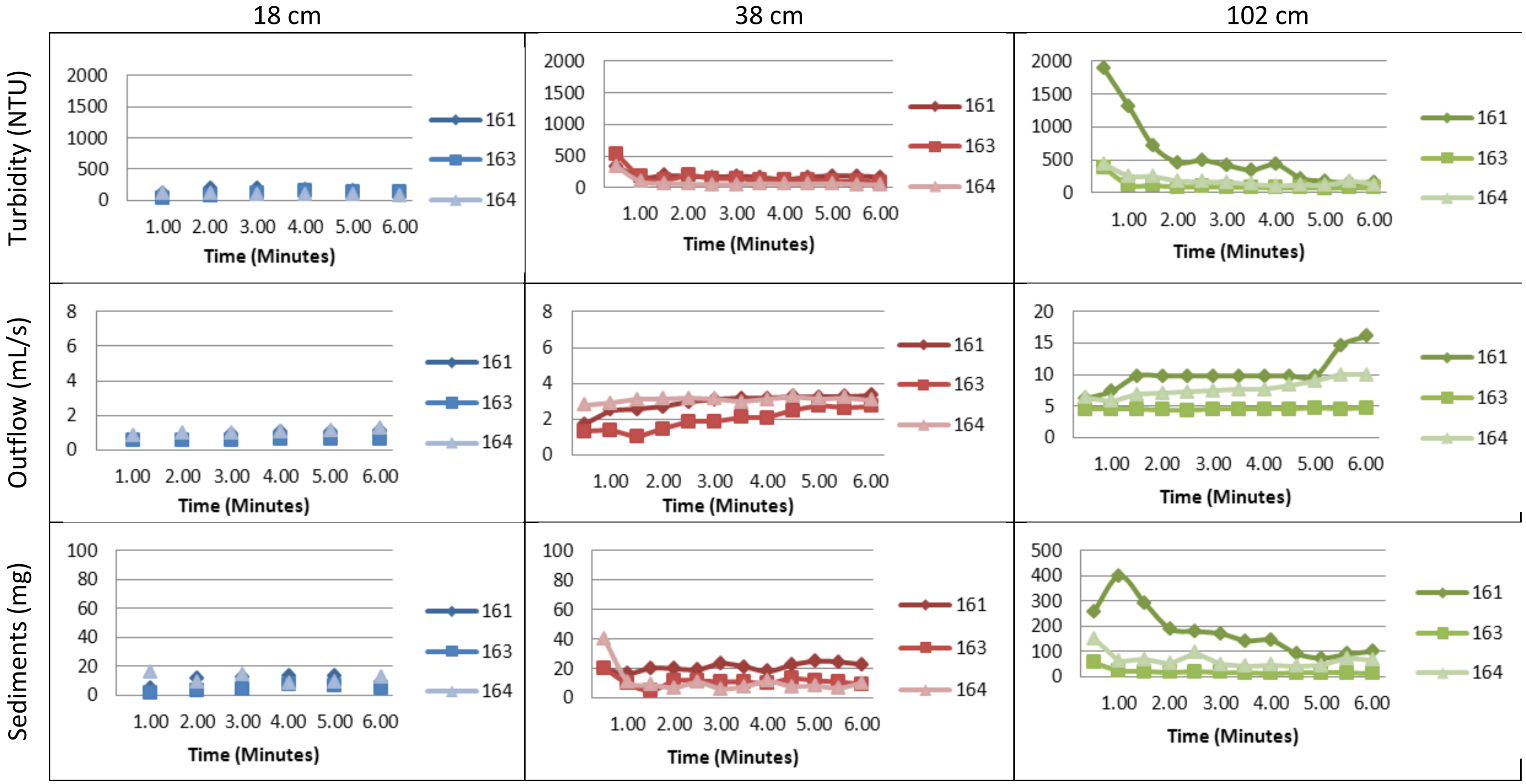


Figure 20. Outflow water turbidity, outflow rate and sediment discharge from soil samples (161, 163 and 164) from 10-15 cm depth drained at 40 cm tension and subjected to 18, 38 and 102 cm hydraulic head in the pinhole test.

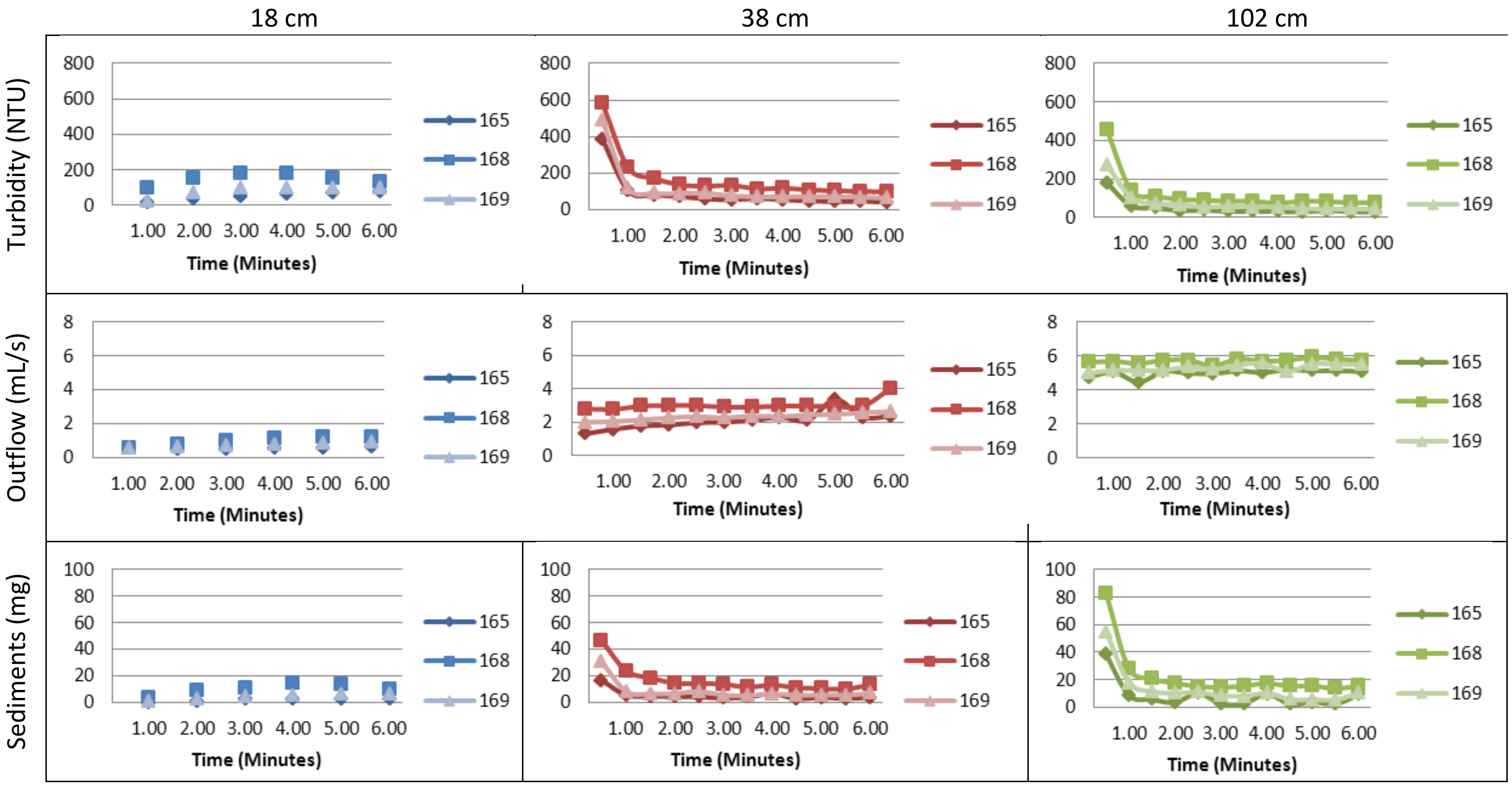


Figure 21. Outflow water turbidity, outflow rate and sediment discharge from soil samples (165, 168, 169) from 22-27 cm depth drained at 40 cm tension and subjected to 18, 38 and 102 cm hydraulic head in the pinhole test.

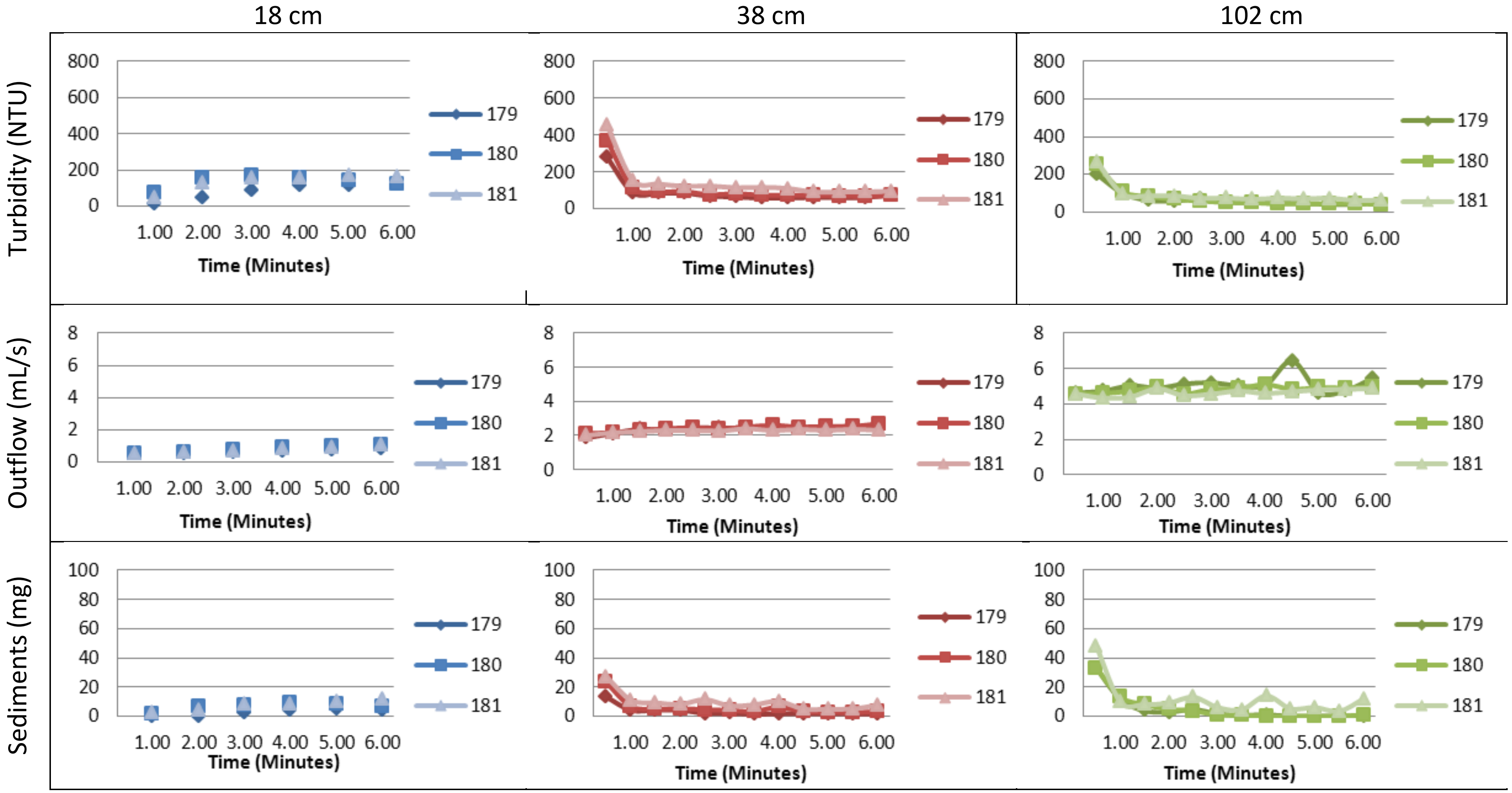


Figure 22. Outflow water turbidity, outflow rate and sediment discharge from soil samples (179, 180 and 181), from 35-40 cm depth drained at 40 cm and subjected to 18, 38 and 102 cm hydraulic head in the pinhole test.

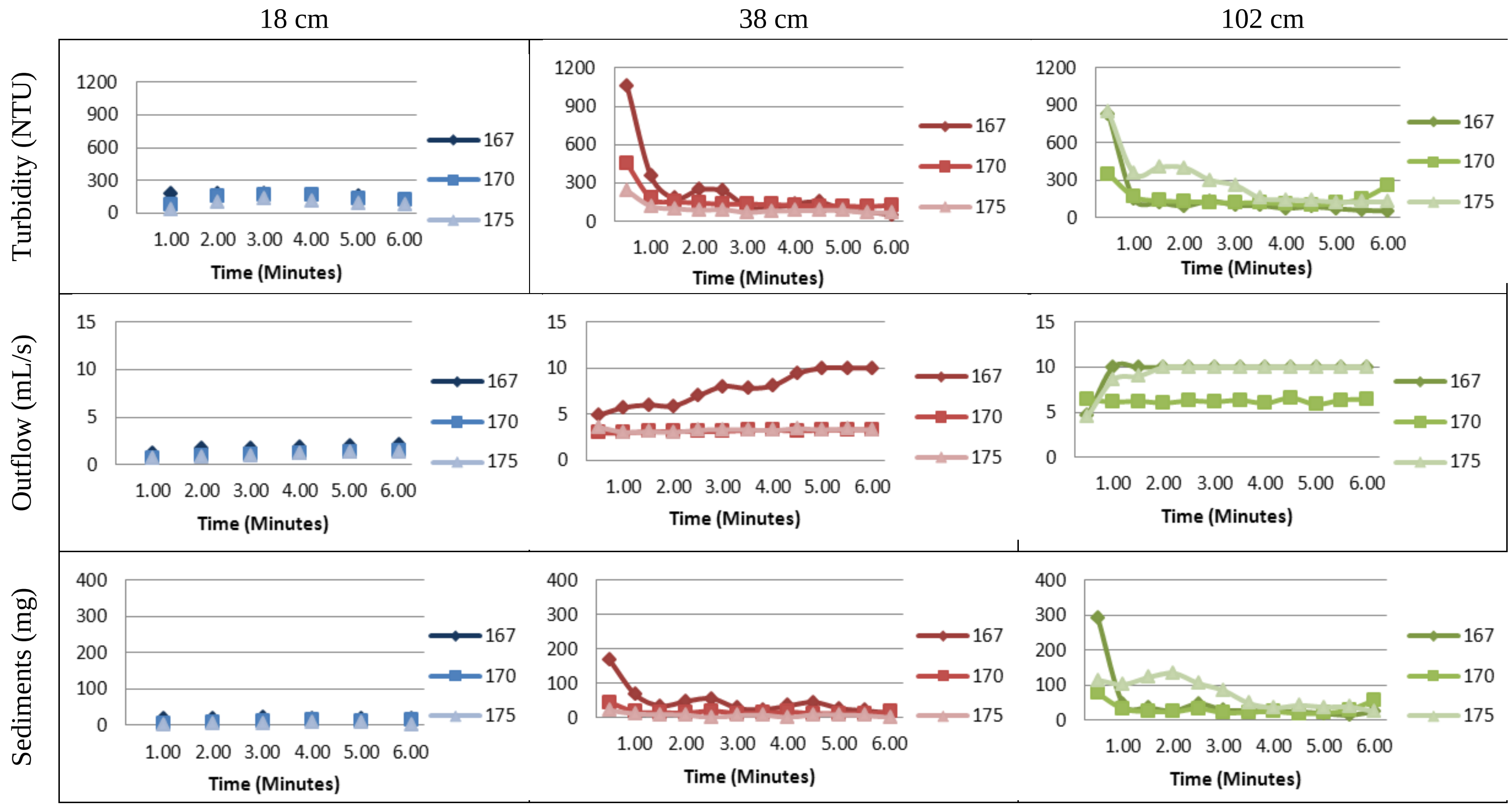


Figure 23. Outflow water turbidity, outflow rate and sediment discharge from soil samples (167, 170 and 175) from 10-15 cm depth drained at 100 cm and subjected to 18, 38 and 102 cm hydraulic head in the pinhole test.

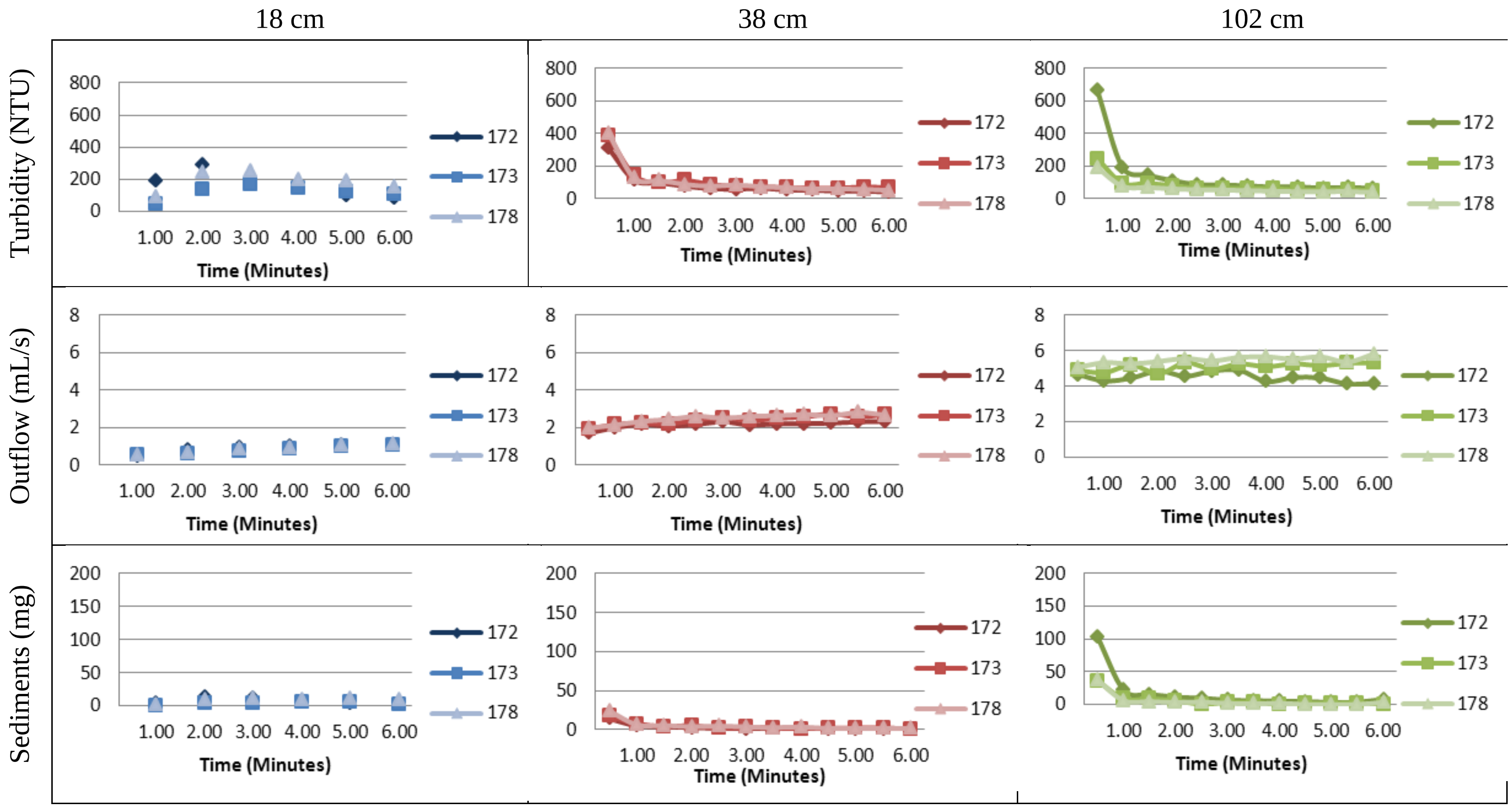


Figure 24. Outflow water turbidity, outflow rate and sediment discharge from soil samples (172, 173 and 178) from 22-27 cm depth drained at 100 cm and subjected to 18, 38 and 102 cm hydraulic head in the pinhole test.

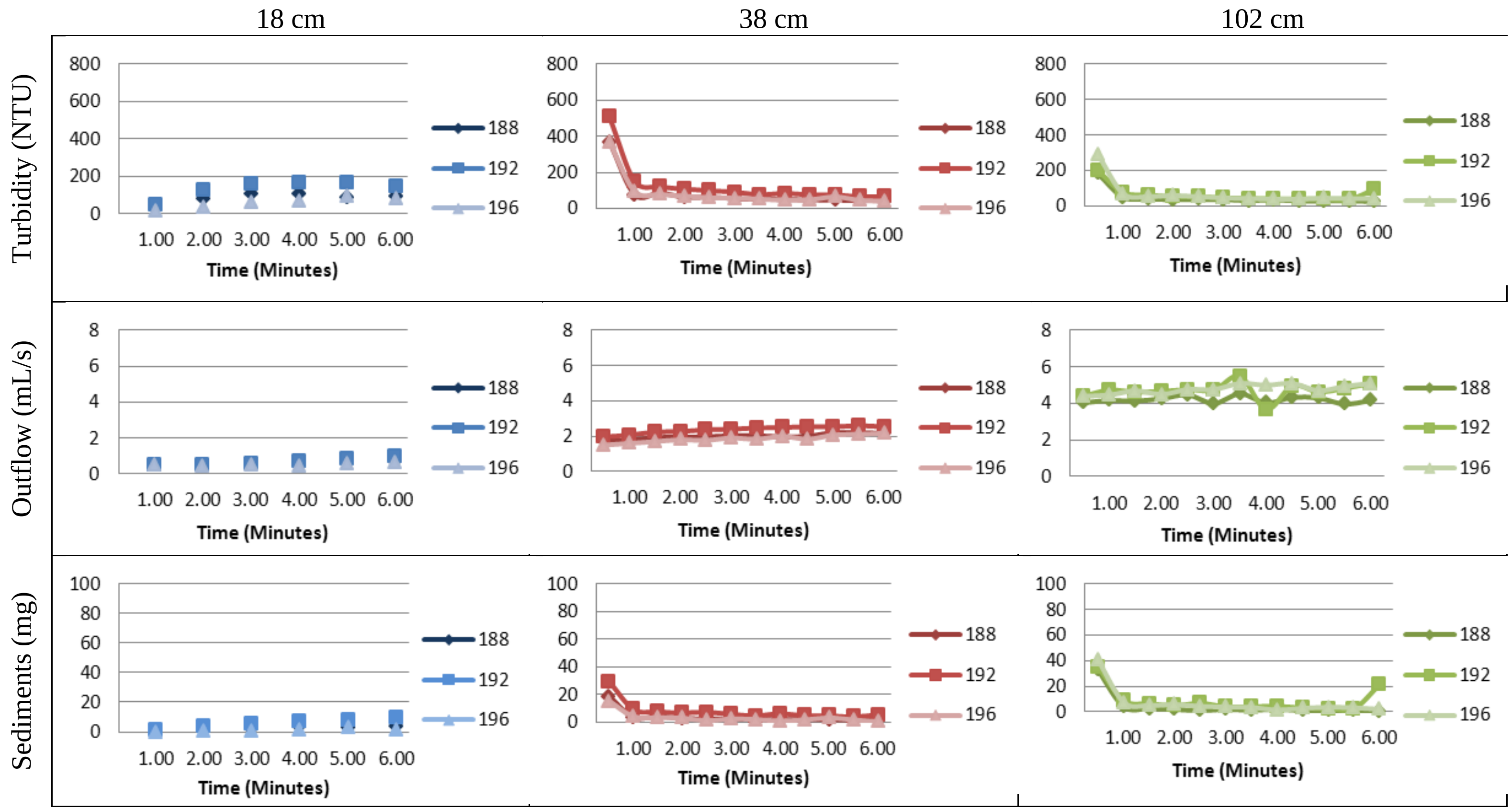


Figure 25. Outflow water turbidity, outflow rate and sediment discharge from soil samples (188, 192 and 193) from 35-40 cm depth drained at 100 cm and subjected to 18, 38 and 102 cm hydraulic head in the pinhole test.

5 Conclusions

Applying different rain intensities to soil using the rain simulator produced directly related flow rates, i.e. with increasing rain intensity giving increasing outflow volume. The actual outflow rates were determined by rain intensity and soil conditions, i.e. soil water content. However, when a high rain intensity was applied first the outflow reached more than 50% of the input flow, while when low intensity rain was applied at the beginning, the outflow was less than 50% of the input flow.

The tension infiltrometer did not show the expected differences between treatments because there was great variation between replicates. This may have been due to the spatial variability in the soil or to difficulties in measurements. Use of a greater number of replicates is recommended to overcome the problem of variability in the soil.

Different variables were tested in method development for the pinhole test. The hydraulic head showed a positive relationship with outflow rate and turbidity values of the water collected during the test. Specimen preparation proved to be easier and the sample was not so compacted when pressing the pinhole cylinder into the soil. A moulding clay that was easy to work and did not stick or colour the water was used to seal and prevent flow between the soil specimen and the walls of the cylinder. Instead of pea shingle, white plastic beads (4 mm diameter) used because was easy to check for cleanness. In addition to this, it was found to be important to extract the needle by turning it slowly when perforating the soil specimen in order to avoid blocking the hole, while use of a turning valve to avoid bubbles in the stand pipe made it easier to read the actual hydraulic head.

Analysis of water collected from soil samples during the pinhole tests proved that turbidity is a good surrogate parameter for soil sediment discharge. A linear relationship was found between the two in the pinhole tests, but this relationship must be verified since the low turbidity values found here may not be representative. Furthermore, for erodibility analysis turbidity values must be considered together with outflow rates. Our recommendation is to express the results as transported sediment (mg) or cumulative sediment discharge, as these numerical values are easier to understand and compare between different experiments. In the soil samples tested here, topsoil proved to be more reactive than lower layers, and samples drained at 100 cm had higher sediment transport. Therefore, our recommendation is to use samples from the soil depth of interest and drained at 100 cm.

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