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Master Thesis

Water repellency and critical water content in hydrophobic soils in New Zealand

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by

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Abstract

Soil water repellency poses an important problem for pasture farming in New Zealand. It causes low infiltration rates and increased surface runoff resulting in less soil water storage as a supply to plant growth. Water repellency is thought to appear on dry soils, when the water content falls below a critical level. The main objective of this study was thus the determination of this critical water content for five soil types (pallic, recent, brown, organic and gley) from ten different sites under pastural land use on the north island of New Zealand. The second aim of the study was to find out when and how often during the year water repellency is likely to occur. This was done with the help of a water balance model and the previously determined critical water contents.

Occurrence and gravity of soil water repellency was measured in the laboratory on both undisturbed and disturbed soil samples with the Water Droplet Penetration Time Test (WDPT) and the Molarity of Ethanol Droplet Test (MED). Measurements were started on nearly saturated samples and then repeated every day, while the samples were air- drying. When the samples reached a reasonably dry state, they were rewetted and another test cycle was started. Measurements were carried out during three to four drying cycles. All samples were found to be water repellent at least temporarily. Repellency tests confirm that water repellency does not exist on soils with water contents higher than 0.50m³/ m³. The critical water contents were rather constant during the 2nd, 3rd and 4th test cycles and showed- depending on the different soil orders- values between 0.32m³/ m³ and 0.50m³/ m³.

In the modelling part, the water content in the top soil layer was simulated by the help of a water balance model every day for the time between April 2008 and April 2012. The modelled water contents fell below critical water contents during two to three thirds of a year of average annual precipitation. This happened more frequently in summer than in winter. Repellency- induced surface runoff was found to be a considerable issue in regions where high rainfall intensities are combined with high critical water contents.

Zusammenfassung

Hydrophobe Böden stellen ein signifikantes Problem für die neuseeländische Weidewirtschaft dar. Sie verringern die Infiltrationskapazität, erhöhen den Oberflächenabfluss und führen auf diese Weise zu einem geringeren Bodenwasserspeichervolumen. Üblicherweise tritt Hydrophobie auf trockenen Böden auf, wenn der Wassergehalt ein kritisches Maß unterschreitet. Das primäre Ziel dieser Arbeit war daher die Bestimmung dieses kritischen Wassergehalts für fünf verschiedene Bodenarten (Bleicherde, „recent soil" (vgl. Tschernitza), Braunerde, organischer Boden und Gley) an zehn verschiedenen Standorten. Alle diese Standorte werden als Weiden genutzt und befinden sich auf der Nordinsel Neuseelands. Im zweiten Teil der Arbeit wurden mithilfe eines Bodenwasserhaushaltsmodells sowie der im ersten Teil ermittelten Bodenparameter die Häufigkeit und der Zeitpunkt des Auftretens von Hydrophobie im Jahresverlauf ermittelt.

Der Ausprägungsgrad der Bodenhydrophobie wurde mithilfe zweier Testmethoden an ungestörten und gestörten Bodenproben im Labor bestimmt: dem „Water Droplet Penetration Time Test" (WDPT) sowie dem „Molarity of Ethanol Droplet Test" (MED). Diese Tests wurden zuerst auf den fast gesättigten Bodenproben durchgeführt und danach jeden Tag auf den an der Luft trocknenden Proben wiederholt. Sobald die Bodenproben einen einigermaßen trockenen Zustand erreicht hatten und sich ihr Gewicht nur mehr geringfügig veränderte, wurden sie wiederbefeuchtet und eine neue Messreihe wurde gestartet. Auf diese Weise wurden pro Bodenprobe jeweils drei bis vier Messreihen durchgeführt. Zumindest zeitweilig konnte Hydrophobie auf allen Bodenproben festgestellt werden. Die Testversuche bestätigen, dass Böden mit Wassergehalten höher als $0.50 m^3/m^3$ nicht hydrophob sind. Die kritischen Wassergehalte waren während der Messreihen zwei, drei und vier ziemlich konstant und erreichten- abhängig von den verschiedenen Bodenarten- Werte zwischen $0.32 m^3/m^3$ und $0.50 m^3/m^3$.

Im zweiten Teil der Studie wurde der Bodenwassergehalt in der obersten Bodenschicht mithilfe eines Wasserhaushaltsmodells für den Zeitraum zwischen April 2008 und April 2012 in Tagesschritten modelliert. Die berechneten Wassergehalte unterschreiten während zwei bis drei Drittel aller Tage eines Jahres mit durchschnittlicher Niederschlagsmenge den kritischen Wassergehalt. Dies passiert besonders häufig während der Sommermonate von Oktober bis April. Zusätzlich stellte sich heraus, dass durch Hydrophobie verursachter Oberflächenabfluss vor allem an jenen Standorten ein Problem ist, welche sowohl durch hohe Niederschlagsintensitäten, als auch durch hohe kritische Wassergehalte charakterisiert sind.

Preface

This master thesis was carried out as a part of my master education in water management under the supervision of Andreas Klik from the Institute of Hydraulics and Rural Land Management of Boku Wien, and Ranvir Singh from the Soil and Earth Sciences Group at the Massey University, New Zealand.

I want to thank all the people at Massey University who constantly provided help and support, especially Ranvir Singh who was always there when I had questions and who guided me through this work. I also want to express special thanks to Mike Bretherton who patiently helped me with all my problems, and provided and explained me his water balance model. Further I want to thank Andreas Klik for the opportunity to conduct this master's thesis in New Zealand and for his incredibly nice supervision.

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1. Introduction

Soils are the basis of life for plants, animals and humans and provide an enormous range of services for our environment. They are the foundation of agriculture and food production, they hold natural resources and comprise our cultural history. Beyond that soils assure the regulation of the water balance: Water which is stored in soils serves as a steady supply for plants. Water which is filtrated in soils assures the continuous availability of high quality fresh water. The foundation of the soil's regulative impact on the water balance is the infiltration of the water in the soil. Certain soils, however, do not wet up spontaneously when water is applied to their surface. This phenomenon is called soil water repellency (SWR) and disturbs the hydrologic balance. It inhibits the rapid infiltration of rain water, causes the augmentation of overland flow and reduces the plant available water up to killing pasture plants. Soil water repellency has been observed under different climate conditions in more than 50 countries. It can occur under many kinds of different land uses such as pasture land, dune sands or forest and shrub land (Dekker et al., 2005), (Mueller & Deurer, 2011), (Deurer et al., 2010). In New Zealand, it is an emerging problem for the local pastural industry especially on the north island (Deurer et al., 2010), (Deurer & Mueller, 2010).

The cause of soil water repellency is not yet thoroughly understood. Soil water repellency is a transient property and is related to the soil water content. It increases during dry periods and decreases or totally disappears during prolonged wet periods (Ritsema et al., 1994). Still, it does not predominantly occur in dry climates, but has been observed in a variety of different climate zones from the tropics to the subarctic. Furthermore, it can occur under many kinds of different land uses such as pasture land, dune sands or forest and shrub land (Mueller & Deurer, 2011), (Deurer et al., 2010). Soil water repellency also depends on the soil texture and on physical and chemical soil properties such as the carbon and nitrogen contents, the pH and the bulk density (Deurer et al., 2011), (DeBano, 1981).

Observations have shown that soils behave in a hydrophobic manner only when the water content falls below a certain critical value. Deurer et al. (2011) roughly determined this critical limit at a volumetric water content of 45% which they stated to be a generic for the north island of New Zealand. It would be of use to define this critical water content more precisely as to allow on the one hand a more effective irrigation of affected soils by keeping soil water contents above the critical threshold and on the other hand a more accurate forecasting of situations in which water repellency will possibly occur (Dekker et al. 2001), (Dekker et al., 1998), (Cisar, 2000). Furthermore, the relationship between soil water repellency and soil water content is nonlinear. It would also be of great use to identify the relationship as to determine the times when soil water repellency is potentially most severe.

1.1 Research objectives

This thesis aims to analyze the relationship between water repllency and soil water content in hydrophobic soils in New Zealand. It determines the critical water content for soil water repellency at ten selected sites in the north island of New Zealand. It also aims to estimate the frequency and time periods at which critical soil water content levels are reached indicating the potential occurrence of soil water repellency at the study sites.

As an indicator for the occurrence of soil water repellency, a critical water content below which this phenomenon arises is evaluated by the means of two experimental test methods: (i) the water drop penetration time (WDPT) test and (ii) the molarity of ethanol droplet (MED) test. The obtained critical water content is then implemented in a daily soil water balance model to simulate the seasonal occurrence and duration of soil water repellency over a period of four years. The study can be divided mainly into two parts: an experimental part where the soil water repellency at different soil moisture contents as well as the physical soil properties are determined in the laboratory environment and a simulation part where these obtained soil parameters are implemented in a daily water balance model.

The specific objectives of this study are to:

- Identify the relationship between potential and actual soil water repellency
- Identify a relationship between the degree and severity of soil water repllency
- Identify the non- linear relationship between soil water repellency and volumetric water content
- Compare the measurement results from disturbed and undisturbed soil samples
- Observe the re- establishment of soil hydrophobicity during different wetting and drying cycles in the laboratory environment
- Analyse the SWR and soil moisture measurements to determine the critical water content levels for the selected soil types at different sites
- Model the daily soil water balance to simulate soil moisture content in the top 50 mm soil layers at the selected sites
- Estimate the frequency and duration for which critical water levels are reached as an indicator of potential occurrence of SWR at the selected sites
- Compare model results for different seasons and years of different amounts of rainfall
- Estimate frequency of occurrence of moderately persistent soil water repellency

Chapter 2 reviews the existing literature and presents the state of knowledge on soil hydrophobicity. In chapter 3 the research procedure is explained. There is given detailed information about the geographic location of the sampling sites as well as about the test methods. Furthermore, the water balance model and its practical application are presented and the statistical data analysis method is introduced. In chapter 4 all observed and measured results are presented and discussed. In addition, the problems which have arisen during the research process are pointed out and possible solutions are given. Chapter 5 sums up the results of the study and gives an outlook on future research objectives.

2. Literature Review

2.1. Effects and consequences of water repellent soils in New Zealand

Soil water repellency is primarily an issue for non- irrigated locations since it only occurs when the soil is relatively dry. The cultivation of pasture is thus likely to be influenced by this problem. In New Zealand, pastural agriculture is conducted on approximately 6 million ha of the total land area and presents an extremely important factor in the country's economy (Deurer & Mueller, 2010). SWR occurs in all regions on the New Zealand North Island, independent of climate and soil order (Mueller et al. 2010; Deurer et al, 2011). The appearance of SWR is also thought to be connected with the 'dry patch syndrome' (DPS) (Deurer et al., 2007). Deurer & Mueller (2010) quantified the losses in pasture growth due to soil water repellency with 35% for the Maraetotara Region in Hawke's Bay, New Zealand. As documented in literature, the water infiltration rate on hydrophobic soils compared to hydrophilic ones is reduced by a factor ranging between 6 (Wallis & Horne, 1992) and 25 (De Bano, 1971). SWR also has an impact on the storage of soil water and in the following on the efficient use of fertilisers. Furthermore, it is a cause for increased preferential flow and marks a risk for aquifer contamination (Ritsema & Dekker, 1994). SWR also increases overland flow and the risk of soil erosion (Shakesby et al., 2000). Burch, et al. (1989) observed an increase of surface runoff between 5 and 15% compared to hydrophilic soil. It influences the stability of soil aggregates (Mataix-Solera & Doerr, 2004) and has an impact on the carbon storage in the soil (Piccolo & Mbagwu, 1999). In addition, it reduces germination and plant growth (Blackwell, 2000). The severity of the problem for New Zealand's pastural land use depends on the temporal appearance and its duration. It is therefore of great practical use to investigate when and how long SWR potentially occurs in the course of a year (Doerr et al., 2007).

2.2. Physics of soil water repellency

2.2.1. Surface tension, contact angle and water potential

The phenomenon of soil water repellency relies on the interaction of cohesion and adhesion. While cohesion describes the mutual attraction of the water molecules, adhesion refers to the attraction forces between the liquid and the solid phase (water molecules and soil particles). Water has a strongly dipolar molecule structure and thus possesses an exceptionally high surface tension of 72mN/m. For water to spread on a solid surface, this surface tension must be overcome by adhesive forces. If the adhesive forces are too small, water will assume a spherical droplet shape without wetting the organic surface when interacting (Doerr, 2006). A contact angle is formed between the liquid and the solid phase as portrayed in figure 1. The mechanical equilibrium of this contact angle is given by Young's equation:

$$\gamma_l \cos\theta = (\gamma_s - \gamma_{sl}) \quad \textbf{(2.1)}$$

Where
γl... liquid- air surface tension
θ... contact angle
γs... solid- air surface tension
γsl... solid- liquid interfacial tension

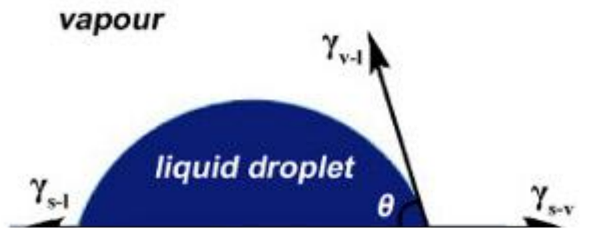


Figure 1: The state of a liquid droplet on a solid surface (Qu et al., 2010)

If the contact angle is less than 90°, the soil is classified as wettable; if it exceeds 90°, the soil is water repellent.

While all dominant soil components have higher surface free tension than water and are thus hydrophilic, organic materials such as waxes or polymers can have surface tensions below 72mN/m and thus repel water (Tschapek, 1984, Zisman, 1964).

The matrix potential Ψ_m in a pore with radius r depends on the surface tension σ, the contact angle θ, the gravity g and the water density ρ_w:

$$\psi_m = \frac{\sigma \cos\theta}{\rho_w\, r\, g} \quad \textbf{(2.2)}$$

Because of the influence of the contact angle, hydrophobicity also has an impact on the matrix potential. If the contact angle declines below 90°, the matrix potential is negative and water infiltrates under a negative pressure. Small pores fill up first, followed by the bigger ones. If the contact angle exceeds 90°, the matrix potential turns positive. Then the big pores will fill up first, followed by the smaller ones (Bauters et al., 1999). In reality, however, the organic material which leads to water repellency does not cover the soil surface uniformly, but is unevenly spread in form of small particles accounting for the hydrophobic effect (Bisdom et al., 1993).

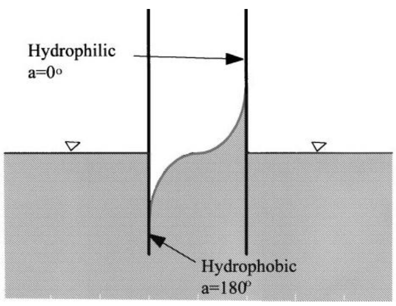


Figure 2: Shape of meniscus between two plates, one is hydrophobic, the other hyrdophilic (Bauters et al., 1999)

Figure 2 shows the effect of pores having different contact angles on the basis of the meniscus between two plates, one being hydrophobic (CA= 180°), the other being hydrophilic (CA=0°). The phase transition zones in real soils, however, are very complex. For this reason an average contact angle is taken, which in this case would be 90° (Bauters et al., 1999).

The relation between water potential and water content depends on the soil texture as well as on the pore volume and can be displayed in pf- curves. For study sites where the soil characteristics (soil structure, bulk density, soil texture) differ a lot, Kajiura & Tange (2010) thus state that the water potential is a more robust indicator for water repellency than the water content. However, in this study, water repellency is referred to the water content and not to the water potential.

2.2.2. Characterisation of mechanisms and substances leading to soil water repellency

There are a number of causes and mechanisms leading to soil water repellency which are not yet totally understood. Studies on the processes and mechanisms influencing hydrophobicity present different and sometimes even contradictory results (Doerr et al., 2000). However, it is generally acknowledged that hydrophobic organic coatings are one of the main causes for water repellency (Doer et al., 2000). Wilkinson & Miller (1978) and Rankin & Ross (1982) examined single sand grains in high magnification and found organic coatings in water repellent sands which were not present in non-repellent ones. The microscopic examination of those coatings doesn't allow consistent conclusions, but general ideas about their character have been developed. The hydrophobic compounds are thought of being absorbed in small particles which cover the mineral grains. The amphiphilic molecules then tend to produce hydrophobic coatings by binding their polar ends to the soil surface as presented in Figure 3 (II) by means of complex formation, hydrogen bonding or adsorption by Van-der Waal's forces. Ma'shum & Farmer (1985) could prove that the orientation of the organic matter determines the repellency: When shaking water repellent soil, the organic coatings detach from the sand grains and reduced SWR can be measured in the following. It is not evident how much repellent substance is needed to induce severe soil water repellency to a soil. However, studies by Bauters et al. (1999), Ma'shum et al. (1988) and Doerr et al. (2000) have shown that only small quantities of hydrophobic substances are needed to render a soil water repellent. Another cause of hydrophobicity is the presence of water repellent interstitial matter in the soil matrix. This phenomenon is, however, less important than the hydrophobic coating (Doerr et al., 2000). The real situation is very complex due to the presence of many polar and non- polar compounds which make up the strong interfacial films.

The break- up or hydration process which is necessary to change from a hydrophobic to a hydrophilic state usually goes along with an increase of water content. Doerr et al. (2000) give two possible explanations for this phenomenon. In soils where hydrophobicity is due to amphiphilic coatings, water is assumed to weaken the bond between these coatings and the soil particle leading to a detachment. The result is the breakup of the organic cover which renders the soil hydrophilic. A second idea is based on the impact of surface effective substances such as humic and fulvic acids which migrate from the soil into the water reducing its surface tension until infiltration is possible. This concept, however, only works for moderately hydrophobic soils and is no explanation for severely repellent ones.

There have been made many attempts to characterise and identify the chemical compounds which make up the organic coatings. Generally speaking it is thought that there are two main groups of organic compounds which lead to soil water repellency. The first group consists of the aliphatic hydrocarbons which are non-polar and can therefore hardly build up adhesive forces with water. The second group is polar, but consists of an amphiphilic structure, meaning that its functional group is hydrophobic on one end and hydrophilic on the other as shown in Figure 3 (I). The amphiphilic molecules tend to produce hydrophobic coatings by binding their polar ends to the soil surface as presented in figure 3 (Doerr et al., 2000).

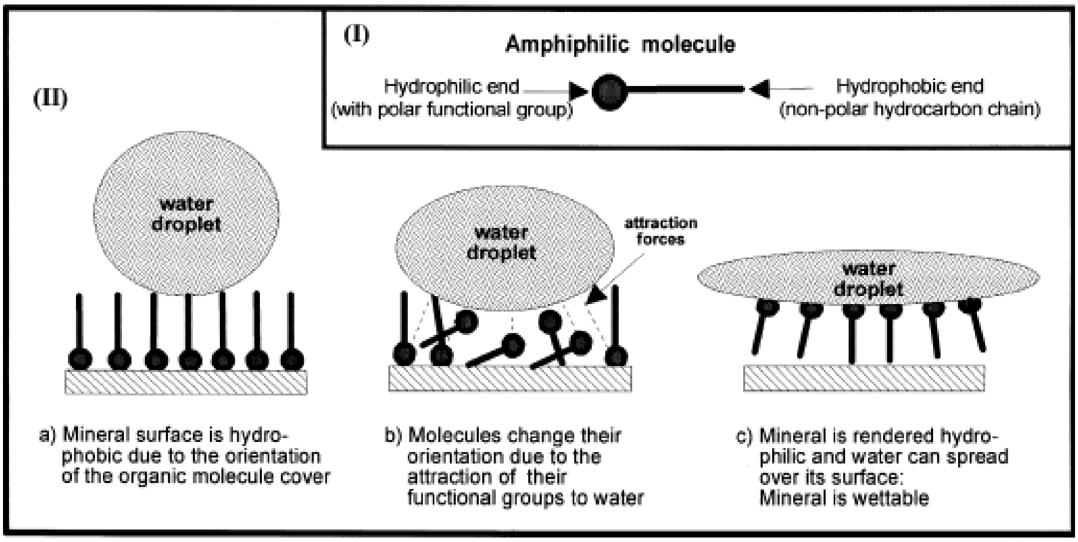


Figure 3: Schematic representation of an amphiphilic molecule (I) and demonstration of the mechanism leading to water repellency (II) (Doerr et al., 2000)

Many studies investigated the nature of the organic compounds by means of extractants. The results, however, are not consistent. This may indicate the presence of different extraction conditions, but also the occurrence of differences in the organic coatings' structure (Wallis, 1991). Ma'shum et al. (1988) observed an amphiphilic mixture of iso- propanol and ammonia to be responsible for repellency on a study site in Australia. Savage et al. (1972) found amines to induce repellency on non-repellent sand. While Miller & Wilkinson (1977) observed a resemblance between the organic coatings and fulvic acids, Roberts & Carbon (1971) stated that not the fulvic, but the humic acid fraction of the organic coating is responsible for the repellent behaviour. A number of studies also observed the influence of fatty acids on soil water repellency and found positive relations.

2.3. Biological and physical factors leading to soil water repellency

2.3.1. Biological factors

Doerr et al. (2000) associate the occurrence of water repellency with selective microbial plant decomposition: parts of plants that contain hydrophobic compounds such as waxes, aromatic oils or resins are generally more resistant to microbial decomposition than hydrophilic parts. On a study site in Southern California, Holzhey (1969) observed that grasses developed a thin root zone with high organic matter content in which seasonal water repellency was most persistent. DeBano (1999) states that certain crops, grass species and legumes seem to intensify soil water repellency. This could be due to specific associations between plants and microorganisms. Gordon et al. (1985) mention that the allelopathic function of certain plants can promote hydrophobicity: In order to suppress the germination of competing vegetation, these plant species release hydrophobic organic acids as root exudates which accumulate in the soil and induce hydrophobicity. Doerr et al. (2006) indicate a relationship between soil water repellency and land cultivation methods such as ploughing. There may also be a connection between soil water repellency and the existence of mealy bugs as described by Mueller & Deurer (2011).

2.3.2. Physical factors

The physical factors leading to soil water repellency include the impact of the soil texture, bulk density and atmospheric conditions such as the influence of relative humidity and high temperatures (Mueller & Deurer, 2011).

Soil water repellency typically appears in coarse textured sandy soils. Fine soils such as clay have a much higher specific surface area and are thus less exposed to organic coatings. In addition, the tendency of sandy soils to be more acidic than clayey ones also promotes soil water repellency (Woche et al., 2005; Doerr et al., 2000). However, Doerr (2006) could not find an obvious relationship between the clay content and the soil water repellency and claim that 'finer-textured soils should not necessarily be expected to be less repellent'. De Jonge et al. (1999) divided the soil in 6 different sized fractions and observed that the finest fractions reveal the highest degree of water repellency. They discovered that high particle sizes go along with low degrees of SWR and low critical water contents at which the soil becomes wettable. Goebel et al. (2004) found the following explanation for this phenomenon: while the dispersion (=non- polar) components of the small aggregate fractions are of similar size to those of the big aggregate fraction, the polar components are significantly smaller; a phenomenon which then leads to reduced wettability.

Deurer et al. (2011) observed a close negative relationship between bulk density and the degree of SWR with a coefficient of determination of 0.7. This relationship can be explained by the fact that an accumulation of hydrophobic organic material in the topsoil reduces the bulk density of the more dense mineral soil. A decrease in bulk density therefore goes along with an increase in soil water repellency (Deurer et al., 2011).

Various studies observed the influence of relative humidity (RH) on SWR and found that high RH leads to increased soil water repellency. Jex et al. (1985) observed that long- term exposure (>10 days) to high RHs (90 -100%) caused a sharp increase in repellency of originally already repellent sands. They also found a relationship between water repellency and ambient temperature and concluded that the increase of SWR is the result of a biological process. Doerr et al. (2002) explored the effects of short- term exposure (<1 day) to 4 different RHs (32– 98%) on the water repellency of air dried soil samples under laboratory conditions. They found water repellency to increase by 1- 2 repellency classes (see Table 2 and

Table 3 in sections 3.2.4 and 3.2.5) for samples which were exposed to high RH prior to analysis. Due to the fact that such short- term exposure to high RH has a great influence on SWR, Doerr et al. (2002) concluded that physicochemical rather than microbiological processes (as stated by Jex et al. (1985)) are responsible for changes in soil behaviour. Doerr et al. (2002) further assume that previous studies may have incorrectly classified actually repellent soils as wettable by executing SWR- tests under ambient lab conditions with low RH. In order to get SWR results which best reflect the most critical field conditions, they thus suggest that SWR tests should be carried out after exposing the samples to high RH. In this study, however, the effect of relative humidity is not taken into account and experiments are carried out under ambient laboratory conditions.

Fire, causing high temperatures, can also induce hydrophobicity. During burning, the hydrophobic substances become volatilised and condense in a concentrated form (Doerr et al., 2000). However, water repellency can also be influenced by temperatures much lower than those reached by a fire. Soil samples should therefore rather be air- dried than oven- dried before they are tested on water repellency (Doerr et al., 2000).

2.4. Persistence and severity of water repellency

Contact angles, which are formed between the solid and the liquid phase as described in section 2.2.1, are generally not static, but decrease gradually as time elapses. They are the result of interaction between the three phases: soil, liquid and gas. However, the adjustment of the equilibrium contact angle may take very long. Therefore, a distinction is made between the persistence and the severity of soil water repellency.

The persistence describes the time needed for the water drop to infiltrate the soil and is a kinetic measurement. Douglas et al. (2007) state that a convergence in the following equation is needed for a soil to wet after a time delay of a few seconds to a few hours:

$$\gamma SL_w - \gamma SV_w = \gamma LV_w \quad \textbf{(2.3)}$$

Where
γSL_w...solid- liquid interfacial tension
γSV_w...solid- vapor interfacial tension
γLV_w...liquid- vapor interfacial tension

They give two main reasons for this to happen. First, the high water vapour pressure next to the droplet causes adsorption of water at the soil organic interface and hence an increase in γSL_w -γSV_w. The second possibility is a change in the arrangement of organic molecules due to the proximity of water and water vapor pressure which also causes an increase in γSL_w -γSV_w.

Severity refers to the degree of water repellency during a limited period of time which is expressed by the ‘initial advancing contact angle’, the angle that is formed at the first appearance of droplet entry into soil. It is a thermodynamic measurement (Roy & MacGill, 2002). By means of Young’s equation it can also be expressed by the ‘critical surface tension’ at which instantaneous wetting occurs (Douglas et al., 2007).

While the degree of water repellency is measured with the MED- test, the persistence is the result of the WDP- tests (see sections 3.2.4 and 3.2.5). Douglas et al. (2007) describe the contact angle to be determined by the cohesive energy of the organic film which is adsorbed on the soil and the WDPT to be determined by the difference in cohesive energies between this adsorbed film and the water. A large difference between these forces will lead to a large droplet penetration time. They state that the alterations of WDPT and MED between the diverse soil types are due to variable organic films of different cohesive energies.

It depends on the spatial circumstances which of the two parameters is more significant for the description of hydrophobicity on a certain location. If SWR is a problem all year round, water may not have enough time to reach the equilibrium contact angle. It will quickly run off and the more adequate description is therefore the severity of water repellency. In flat, low-lying spots, however, prolonged soil/ liquid contact time will lead to a build- up of hydrostatic pressure which can in the following overcome SWR. It is then adequate to describe the hydrophobicity by means of persistence (Roy & MacGill, 2002).

However, numerous studies show that severity and persistence of water repellency are connected. Leelamanie & Karube (2009) observed that the persistence responds to the initial contact angles. Crockford et al. (1991) found a good correlation between persistence and severity for most of their samples taken on a site in Australia, but not for all. Harper & Gilkes (1994) implemented a conversion formula to describe the close relationship between persistence and severity of SWR which they found for clayey soils in Australia. Douglas et al. (2007) found a coefficient of determination of 0.8. Doerr (1998) reported moderately good correlation values for a study site in Portugal and found a coefficient of determination of 0.73. The correlation was better for highly water repellent soils and lesser for moderately repellent ones. Dekker & Ritsema (1994) could only observe a poor relationship between persistence and severity for an extensive study on dune sand in the Netherlands.

Different authors found different correlation equations for the relationships between the persistence (expressed by the WDPT- test) and the severity (expressed by the MED- test) of water repellency as demonstrated in Figure 4, where King (1981) examined sandy soil in Australia, Harper & Gilkes (1994) did their study on clayey soils in Australia and Deurer et al. (2011) analyzed different soil types in New Zealand. The soil samples examined in this study are chosen ones from the same sites which have been investigated by Deurer et al. (2011). Their equation will therefore be the reference correlation for this study.

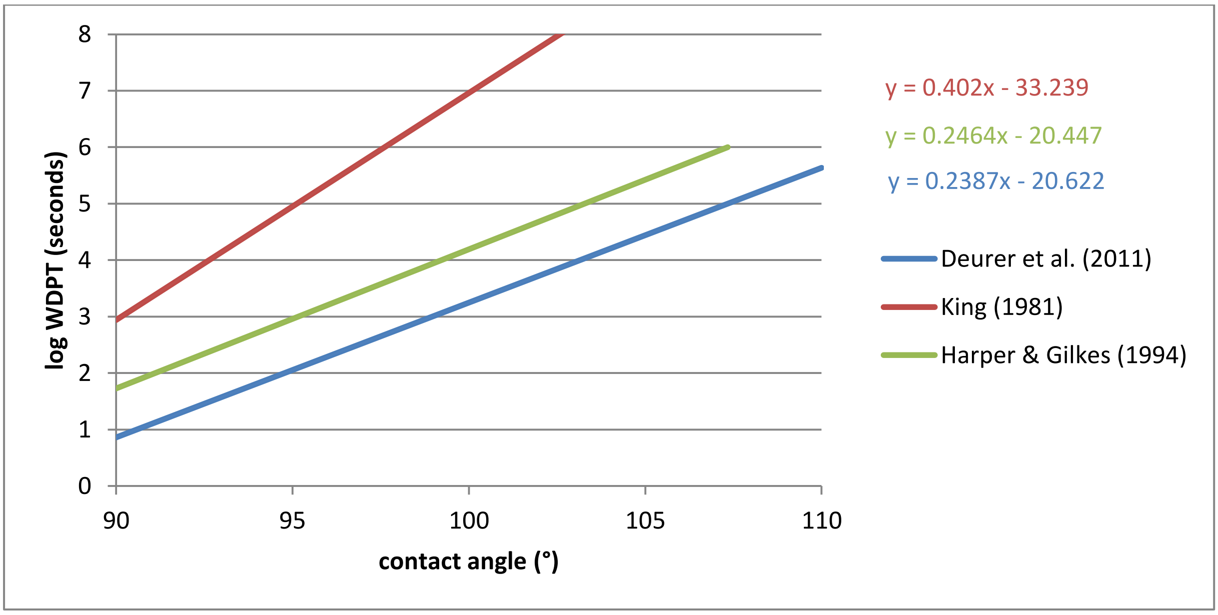


Figure 4: Relationship between the persistence and the degree of SWR

2.5. The concept of the critical water content

Water repellency is a transient property; its variations are considered to depend strongly on the soil moisture content. Water repellency generally occurs in dry soils and disappears when the soil water content exceeds a certain critical limit. However, studies have shown that this simple concept of the critical threshold cannot sufficiently explain the complex relationship between water repellency and soil water content (Doerr et al., 2000).

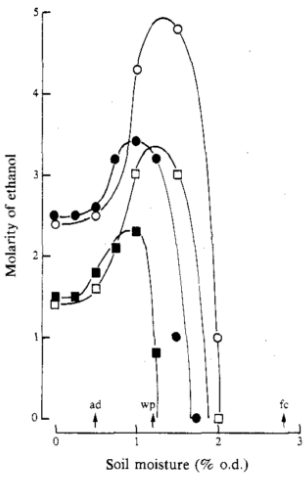
Dekker et al. (2001) have proposed to rather determine a transition zone than a sharp threshold. In this transition zone the soil can act either hydrophobic or hydrophilic depending on the wetting history. They examined the actual water repellency on more than 200 field samples on dune sand in the Netherlands and found the transition zone between 0.18 and 0.23 m^3/ m^3 volumetric moisture content. Doerr & Thomas (2000) measured a critical gravimetric water content of 28 (g/g) in the field on their study site in Portugal. However, they used different hydrophobicity thresholds and qualified soils with WDPT < 60 seconds as hydrophilic. Taeumer et al. (2005) set the transition zone between gravimetric water content values of 0.03 and 0.18 g/g for medium- sized sand under grassland in eastern Germany. Berglund & Persson (1996) found critical thresholds of up to $0.50m^3/ m^3$ moisture content for organic soils in Sweden.

However, all those values must be taken with care, as the comparability between the critical water contents which have been found in various climates on diverse soil types is not assured. The only really comparable results with the ones found in this study are those by Doerr et al. (2000) and Deurer et al. (2011). Doerr et al. (2000) found critical volumetric moisture contents between 3 and $0.24m^3/ m^3$ for sandy soils on a study site in the UK. For this same site they also specified water content values for organic soils ($0.27- 0.56m^3/ m^3$), for loamy soils ($0.16- 0.38\ m^3/ m^3$) and for clayey soils ($0.26- 0.40m^3/ m^3$). Deurer et al. (2011) found an approximate and average critical water level of $0.45m^3/ m^3$ on their study sites in the New Zealand North Island.

Doerr et al. (2000) mention that an upper threshold of the transition zone which indicates the absence of SWR is useful, the lower limit, however, cannot be specified well and may be an unreliable predictor. The variability of the critical water content may be caused by the wetting history of the soil which has an influence on the severity of SWR. Another cause could be the heterogeneous distribution of the water in and around the micro aggregates of the soil (Dekker et al., 2001). Furthermore, it is thought to depend on the soil texture because of the huge differences in available surface area (Doerr & Thomas, 2000).

2.6. The relation between soil moisture content and water repellency

SWR varies non- linearly with the water content. King (1981) observed SWR values increasing rapidly with increasing moisture content between air- dry and wilting point, reaching a peak near the wilting point and then decreasing rapidly to zero as the moisture contents approached field capacity. De Jonge et al. (1999) found two possible shapes for the curve relating SWR and moisture content on hydrophobic soils. Some soils show 'one- peak- behaviour', meaning that SWR is very little at low water contents. It increases with the augmentation of the water content, reaches its peak just before the wilting point and then decreases until the soil becomes wettable when moisture approaches field capacity. This theory coincides well with the statements made by King (1981) and Regalado & Ritter (2005). The second possible shape observed by De Jonge et al. (1999) is a ‘double- peak- curve’ which they found for oven- dried samples. The first peak of SWR occurs at very low water contents which are close to zero. With the increase of the moisture content the repellency firstly decreases, but then increases again at low to intermediate soil water contents up to a second peak. In the following it decreases until the soil becomes wettable again above the critical water content. Figures 5 And 6 show the relationships between water content and water repellency as found by King (1981) and DeJonge (1999). Figure 6a shows curves with ‘one- peak- behaviour’, Figures 6b to 6d show examples for ‘double- peak- curves’.



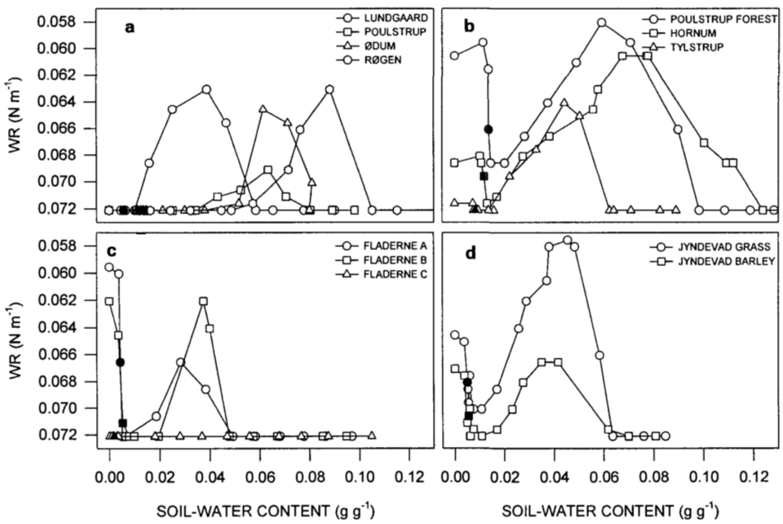


Figure 5: Water repellency as a function of soil water content for sandy soils in South Asutralia (King, 1981)

Figure 6 (a-d): Water repellency as a function of soil water content for different Danish soils (DeJonge, 1999)

The first peak may be caused by the temperature treatment due to oven- drying (De Jonge et al., 1999). A possible explanation is the reorientation of the hydrophobic molecules when facing water loss (De Jonge et al., 1999; Doerr et al., 2000). However, in field conditions these effects are not relevant, because such low water contents will never be reached (Regalado & Ritter, 2005). Different studies diverge on the influence of oven- drying on soil water repellency. While Dekker et al. (1998) stated that already low oven temperatures such as 43°C can increase SWR significantly, King (1981) found SWR to be basically unchanged when oven- dried. Crockford et al. (1991) and Berglund & Persson (1996), in contrast, found SWR to be almost zero for soil in an oven- dry state and then to increase to a peak which they found at a volumetric water content between 0.2 and 0.3 m^3/m^3.

As stated above, there has also been observed an increase of SWR with an increase of soil moisture at low soil water contents (King, 1981; De Jonge et al., 1999; Goebelet al., 2004). One possible explication is given by Jex et al. (1985) who assume that an increase in soil moisture which goes along with a rise in relative humidity causes enhanced activity of microorganisms producing hydrophobic substances. However, this assumption does not accord with observations by Goebel et al. (2004) who analysed samples where contact angles decreased at a maximum relative humidity of 99.9%. Another explanation is given by Doerr et al. (2002) who observed an increase of SWR with exposure of the soil samples to high relative humidity (98%): the high relative humidity causes vapour condensation and hence an energy release. This energy is the trigger for hydrophobic organic parts of previously disrupted hydrophobic materials to reorient as illustrated in Figure 3 (II). However, this theory stands in contrast to the observations who found SWR to decrease again after having reached the peak value near the wilting point.

Regalado & Ritter (2005) found a very close relationship (R^2=0.997 for Φ_{min}) between the soil water contents at minimum and maximum soil water repellency and the integrated area below the repellency curve which they could therefore determine easily. They combined the two parameters area and min/max soil water contents to a single one which characterizes the average soil water dependent repellency.

Taeumer et al. (2005) achieved reasonably good results with a simple linear approach presenting SWR as a function of water content and soil organic matter and neglecting all other possible influences.

In conclusion it must be said that the timing of and the processes influencing the variations of SWR with changes in the soil moisture content are still hardly understood and should be objective of further studies (Doerr & Thomas, 2000; Doerr et al., 2000).

2.7. Actual and potential water repellency

The non- linear relationship between water content and SWR induced the distinction between the 'actual water repellency', which is measured at field moist soil and the 'potential water repellency', which is measured in an oven- dry or air- dry state and is assumed to be the maximum SWR which can be reached. Standardized tests measure the potential water repellency as to be able to compare the results. However, the potential water repellency cannot give any information about the critical water content, below which SWR starts to occur and may also not be the highest possible SWR which can be reached by a soil. De Jonge et al. (1999) even observed water repellent soils to be wettable after conducting the standard method of pre-treatment prior to SWR measurements where the samples are oven- dried at 65°C for 48h and equilibrated for 24 hours. Dekker et al. (2001) therefore recommend measuring the actual water repellency and finding out the level of the critical water content which is of more practical use than the potential water repellency. This is also the approach followed in this study.

There is, however, a difference in the correlation of persistence and severity between actual and potential water repellency. Goebel et al. (2004) and Dekker et al. (1998) found WDPT values to remain unchanged while the contact angles showed smaller values for the intact soils than for those homogenized by heat treatment.

2.8. Temporal variations of water repellency

De Jonge et al. (1999) observed the seasonal occurrence of soil water repellency in the field on study sites in Denmark. They found very good correlation between the soil water content and SWR and state that the problem of SWR can possibly be avoided by keeping soil water content above the critical threshold. Soil water repellency only occurred in the summer season between May and mid-

August. As the soil in the field did not become extremely dry, they could only observe the first peak of SWR and not the second one.

On a study site in Portugal, Keizer et al. (2005) observed that the soil water content is one important determinant for the severity of soil water repellency, but is by itself not sufficient to account for the temporal variations in SWR which also appear to depend on factors other than soil moisture. They found no clear seasonal pattern for the Mediterranean- type climate region and observed the temporal variations to be very large within short periods of time.

Doerr & Thomas (2000) examined the re- establishment of SWR after thorough wetting. While SWR can be expected to remain absent above certain soil water content, it is not sure that it re-establishes when the soil water content falls below this threshold value. They concluded that the prediction of the temporal behaviour of hydrophobicity is thus very complex. Especially for climates where the occurrence of dry periods is rather unpredictable, the relationship between soil moisture and hydrophobicity may not be of great use. This can also be the explication for the different results cited above by De Jonge et al. (1999) and Keizer et al. (2005) who examined study areas in very different climate regions.

2.9. Re- establishment of SWR when drying

The influence of the wetting history on the re- establishment of soil hydrophobicity is a central question for the evaluation of SWR in the course of one year. Generally, SWR is expected to be re-established when the soil is drying out again after a wetting period (Valat, et al., 1991; Walsh et al., 1995). This process is expected to be caused by the re- establishment of amphiphilic coatings. When soil moisture decreases the polar ends reorient and interact through hydrogen bonds while the non-polar, hydrophobic ends, point outwards causing soil water repellency (Doerr et al., 2000). Another explication is given by heat, which can reactivate soil water repellency to some extent, similar to the heat treatment in the outdoor fabric industry which is used to reinstate the lost impermeability of Goretex clothes (DeBano, 1981).

However, studies have shown contrasting results. Crockford et al. (1991), Imeson et al. (1992) and Ritsema & Dekker (1994) observed the re-establishment of hydrophobicity during extended dry periods. Burch et al. (1989) observed the paradox phenomenon that some usually water repellent soils were dry and hydrophilic at the same time. Doerr & Thomas (2000) described laboratory experiments where SWR didn't re-establish when drying and a completely new input of hydrophobic substances was required to render the soil hydrophobic. Quyum (2000) analyzed the impact of cyclic wetting and drying on hydrophobic soils. He observed that the MED values as well as the WDPT values decreased progressively with the number of cycles. The trend observed was similar for air-dried and oven- dried soils. Quyum (2000) did not make an attempt to analyse the reason for this decrease in hydrophobicity.

The re- establishment of SWR is hence a very complex process, depending on various factors and can- similarly to the loss of soil water repellency with the increase of the soil moisture content- not be explained sufficiently. It may rather depend on biological processes than alone on soil- moisture driven ones (Doerr & Thomas, 2000). However, the concept of the critical water content is still very useful from a land- management point of view and hydrophobicity is thought of being absent as long as the soil moisture remains above the critical level.

In this study soil water repellency tests are carried out on re-wetted samples in order to observe the re- establishment of hydrophobicity in laboratory conditions as well as possible changes in the critical moisture level.

2.10. Effect of sample disturbance on the determination of SWR

Graber et al. (2006) carried out WDPT measurements on more than 300 undisturbed and disturbed soil samples on a study site in Israel to prove the representativeness of laboratory results for soil water repellency in the field. However, they could not observe a close relationship between the results obtained from the measurements on undisturbed and disturbed samples. They also investigated possible influences on these discrepancies and could not find any correlations between the repellency changes and soil moisture content or organic matter content. They specified the probable major reasons for the variations to result from differences in surface roughness, pore size distribution, pore connectivity and soil bulk density. The distribution and orientation of the materials which are responsible for soil water repellency are also thought to cause the differences in results.

The present study is based on the work of Deurer et al. (2011) who examined SWR on disturbed soil samples. The goal of this study, however, is to determine the temporal appearance and the duration of soil water repellency in the field which thus requests reliable results for the critical water content under field conditions. Soil water repellency measurements are therefore executed on both disturbed and undisturbed samples to (I) compare the obtained results with those of the vast study by Deurer et al. (2011) and other studies and (II) to obtain reliable results which can be used in a water balance model.

2.11. Remediation strategies for the management of hydrophobic soils

One frequent technique to fight SWR is the application of surfactants in order to increase the soil water infiltration. Surfactants are amphiphilic molecules, containing both a hydrophilic and a hydrophobic functional group. While the hydrophobic group will orientate in direction of the soil particles, the hydrophilic group attracts the polar water molecules as presented in Figure 7. The benefits of surfactants, however, are controversial. Their performance depends greatly on the field conditions such as location, weather, application rate and dilution rate used for the application (Cisar et al., 2000; Kostka et al., 2007; Henle et al., 2007). Furthermore, surfactants only have an influence on the upper soil layer and have no impact on SWR occurring in greater depths. Another issue is the economic efficiency. The application of the expensive surfactants must be repeated regularly throughout the dry seasons. After the application of wetting agents, heavy irrigation is necessary to limit their toxicity. Still, Crabtree & Gilkes (1999) and Wallis & McAuliffe (1990) found significantly positive effects of surfactants in their studies carried out on pasture. There could not be found any studies concentrating on the potential ecological problems arising by the application of surfactants (Mueller & Deurer, 2011).

Figure 7: Adsorption of water on hydrophobic material with the help of surfactants (Henle et al., 2007)

Another common method is claying. As stated above clay minerals have an extremely high specific surface area and are thus a lot less exposed to organic coatings than sandy soils. Furthermore, most clay minerals are hydrophilic (Tschapek, 1984). Clay covers the hydrophobic surfaces of sand and by this means counteracts the hydrophobic coatings. The efficacy of claying depends on the clay's surface area and dispersion, that is to say on its physical and chemical properties (e.g. cristal structure, pH, electrical conductivity, cation exchange capacity). Claying is widely used in Australia where it achieves good results (Cann, 2000). Harper & Gilkes (1994) and McKissock et al. (2000) found that an addition of only 1-2 % of clay changes soil from a hydrophobic to a hydrophilic state. The benefits of the application of clay can be stated as follows: increased infiltration, increased microbial activity, reduced preferential flow and reduced erosion by crust formation (Quyum, 2000). Because of economic reasons and the high amount of clay which is required for the treatment, the use of this method is limited to sites where clay is readily available (Cann, 2000; Mueller & Deurer, 2011; Deurer et al., 2011). Claying is an appropriate method for sandy soils. SWR, however, also occurs in heavier soils. It is not sure if claying can be recommended for these soils as there may be increased compaction and a decrease in permeability.

A very simple remediation strategy is the selection of plant species which are able to cope with reduced soil water availability. Especially for regions which are prone to drought, this can be an appropriate option. However, it must be accepted that stocking rates and pasture productivity may be reduced (Mueller & Deurer, 2011).

Horne & McIntosh (2000) applied various extraction methods on Himatangi Sand to extract the organic compounds which are a main cause for SWR. However, this method cannot be used in field at large scale.

Another remediation strategy is cultivation. As stated in several studies (e.g. Rodriguez- Alleres et al., 2007; Doerr, 2006) cultivated land was much less affected by SWR than non-cultivated land. Holzhey (1969) diluted hydrophobicity by mixing hydrophobic topsoil with hydrophilic soil on a study- site in California. A disadvantage of this method is the decrease of the soil organic matter content with the concomitant reduction in water- and nutrient- holding capacity. Tillage can also affect soil which suffers from SWR in a positive way. However, cultivation can lead to increased soil erosion (Mueller & Deurer, 2011).

Soil aeration which is based on the breakdown of the water repellent surface layer is a technique frequently used on golf courts (Mueller & Deurer, 2011; De Bano, 1981). In agriculture, this method allows the preferential flow to be conducted from the repellent surface into the furrows to the seeds (Mueller & Deurer, 2011).

The addition of lime can improve the wettability of hydrophobic soil. The mechanism is based on the increase of the pH resulting from the application of lime. Humic acids which are available in the soil dissolve in water when the pH increases. They decrease the surface tension of water which then leads to an increase of infiltration (Schnitzer & Khan, 1978). Another mechanism is the increase of biological processes and productivity when the pH of acid soils increases (Lupwayi et al., 2009).

A new approach for removing hydrophobicity in a biological way is the inoculation of soil with wax-degrading bacteria. Roper (2006) investigated this remediation method under field conditions and stated that the increase of soil wettability by an increased activity of wax- degrading bacteria has good potential.

2.12. Impact of extreme climatic events on SWR

As models show, the on-going climate change is related with an increase in extreme climatic events such as droughts and floods. This results in more pronounced drying and wetting cycles of the soil as well as in a change of soil organic matter and thus has an impact on the issue of soil water repellency. A higher frequency of droughts and heat waves presumably increases the severity of SWR as well as the period of time in which it occurs (Goebel et al., 2011).

In this study the extent and the period of occurrence of soil water repellency is modelled for four years for selected sites on the New Zealand North Island. It would be interesting to investigate temporal trends in the occurrence of soil water repellency. The minimum time in climatology to give any reliable statements, however, is 30 years (Becker, 2012).

3. Material and Methods

3.1. Location and Characteristics of Sampling Sites

3.1.1. Selection of sampling sites

The present study is built on the work by Deurer et al. (2011) who investigated the extent of soil water repellency on 50 sites under pastural land use on the New Zealand North Island. In order to use the existing results and to compare common observations, we chose to select our eight sampling sites from this pool of 50 different locations. The selection was carried out by using the three indicators Soil Order, Annual Water Deficit (AWD) and Profile Readily Available Water (PRAW). AWD is the sum of the differences between monthly estimates of mean rainfall and potential evaporation calculated using the method of (Priestley & Taylor, 1972). PRAW describes the volume of water per area between field capacity and the permanent wilting point and is therefore an indicator of plant-available water. It was calculated from weighted averages over the profile section to the potential rooting depth and is expressed in (mm) (Deurer et al., 2011; LRIS New Zealand, 2012).

The indicator 'soil order' is represented by the following classes which are the most common found in New Zealand: Allophanic (L), Brown (B), Gley (G), Granular (N), Organic (O), Pallic (P), Podzol (Z), Pumice (M), Recent (R) and Ultic (U). In accordance with Deurer et al. (2011), both AWD and PRAW were grouped into three classes (AWD: 0= 0mm (nil), 1= 1-50mm (low), 2= 51-394mm (high) and PRAW: b= 0-49mm, c= 50-74mm, d= 75-100mm). The aim was then to identify the five most representative combinations of these three factors for the area of New Zealand. For that purpose we used three different data layers for soil order, AWD and PRAW provided by the New Zealand Land Resource Inventory as shown in Figures 8 to 10. These data layers were intersected by the aid of ArcGIS. As a result we obtained a large number of polygons which were integrated to 90 (=10*3*3) possible combinations.

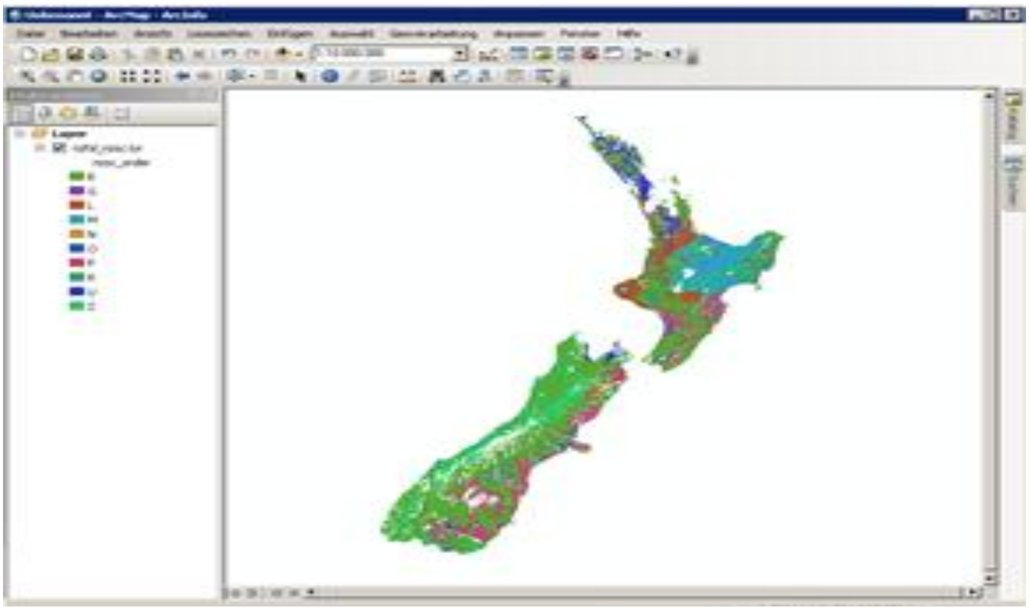


figure 8: GIS layer, soil type

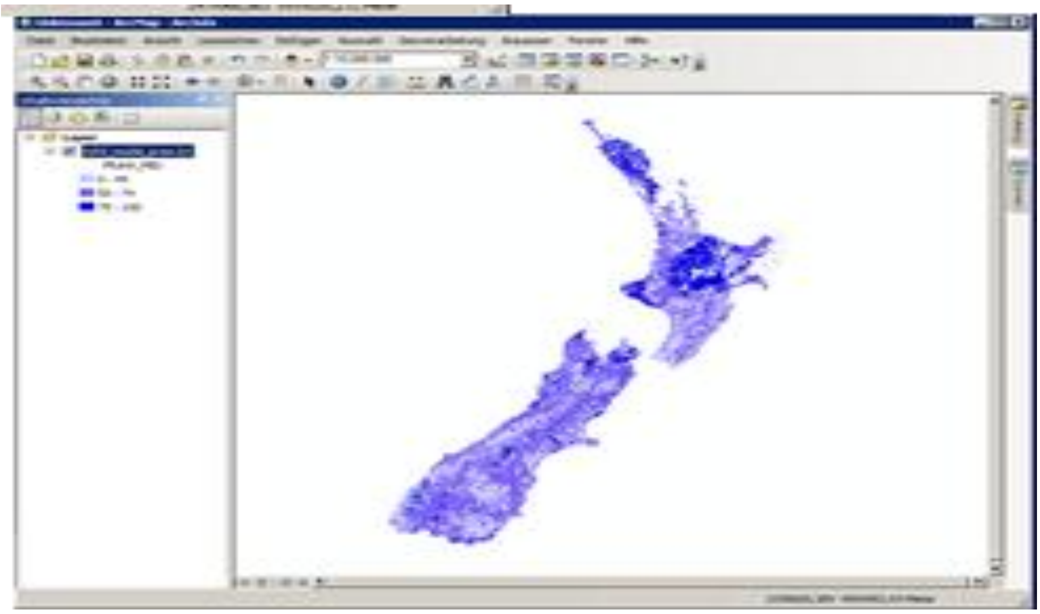


Figure 9: GIS layer, profile readily available water

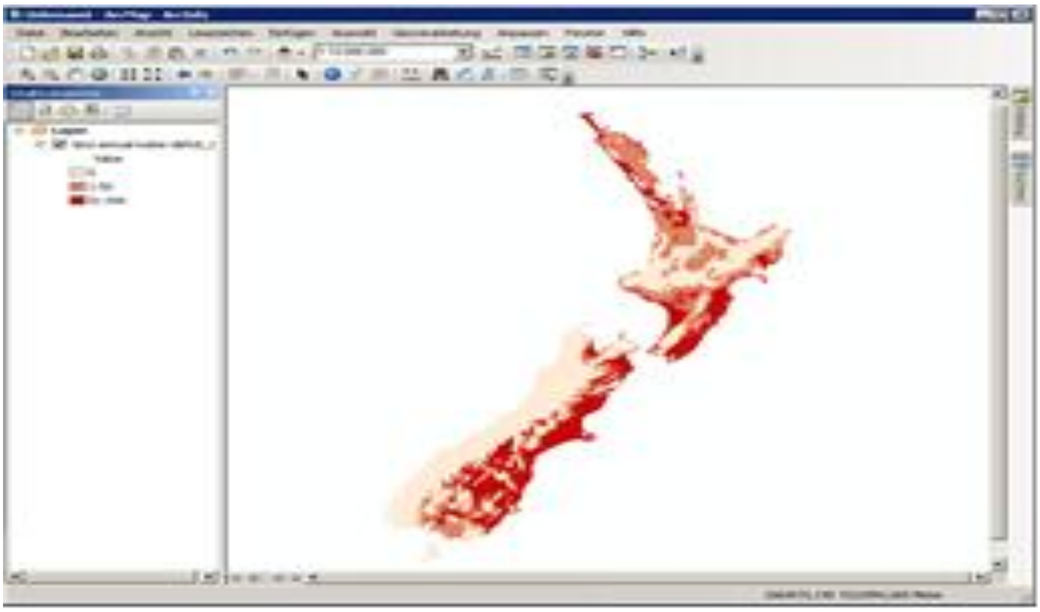


Figure 10: GIS layer, annual water deficit

For each combination the representativeness which is expressed by the covered land area was calculated. The combinations were then sorted by the size of the area, starting with the combination which comprised the largest extent. We also calculated the covered area in % for each combination. Cumulating these results got us Figure 11, which demonstrates the best case scenario where five soil samples can be used to obtain knowledge for 36.3 % of New Zealand's total surface area.

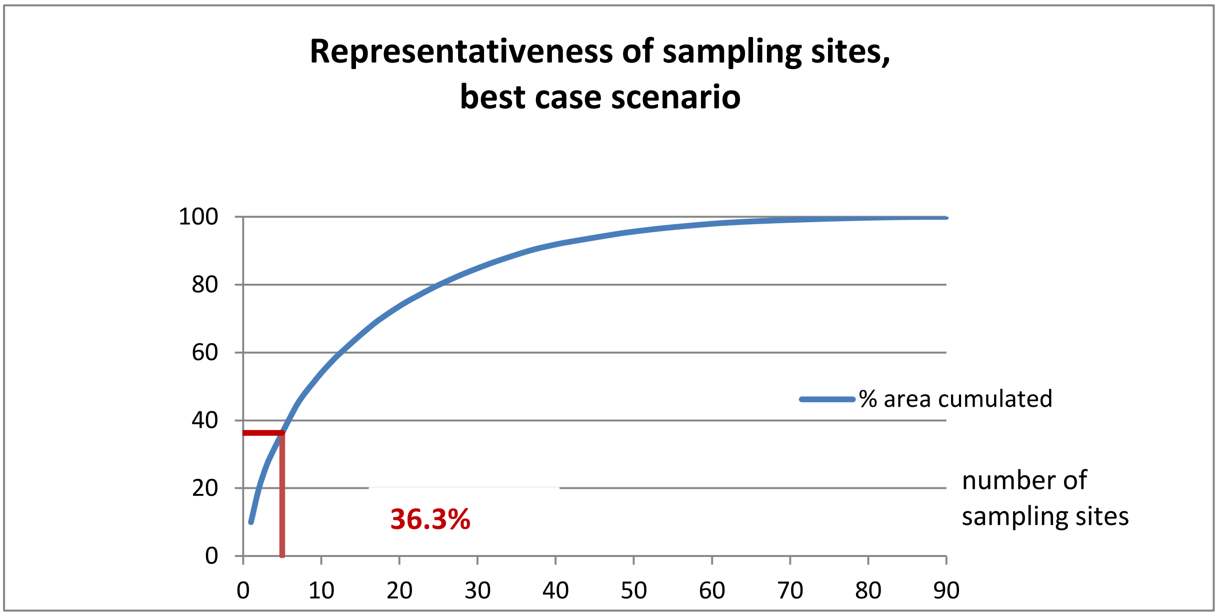


Figure 11: Representativeness of sampling sites, best case scenario: 5 sites represent 36.3% of the whole New Zealand land area

3.1.2. Geographic locations

The five combinations were then selected from the sites sampled by Deurer et al. (2011). However, these sites were wide spread all over the North Island and the sampling would have taken too much time and effort. We therefore tried to identify sampling sites which are on the one hand geographically close together and reasonably close to Palmerston North and on the other hand still very representative. This got us eight sites: five sites in the Hawke's Bay region and three sites in the Taranaki region. They are indicated in Figure 12 and are representative for 20.3% of New Zealand's total area.

In addition, there have been sampled two places on a site near Alfredton in the Tararua District where extensive research on soil properties has been done (indicated with a yellow mark in figure 12). Furthermore, the water balance model (Bretherton et al., 2010) which is used in this study has also been developed with the parameters of this location. The results of this site may therefore be used as a reference to precedent studies. Figures 13 to 15 show the exact location of the sampling sites.

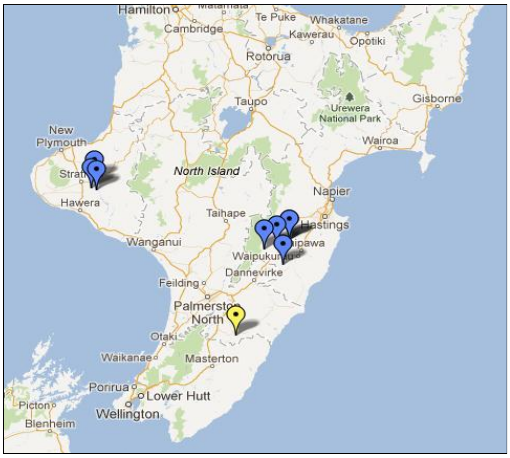


Figure 12: Geographic location of chosen sampling sites

Figure 13: Detailed geographic location of chosen sampling sites in Hawke's Bay

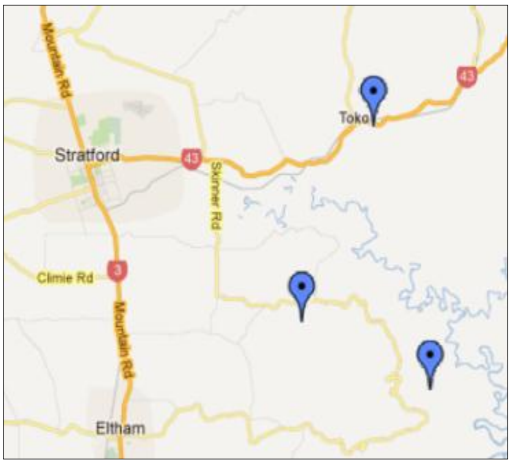


Figure 14: Detailed geographic location of chosen sampling sites in Taranaki

Figure 15: Location of reference sites near Alfredton in the Tararua district

3.1.3. Geology and Climate conditions

3.1.3.1. Taranaki- Stratford

The climate in the Taranaki region is mild, sunny and windy. It is characterised by moderate temperatures ranging between means of 7.5°C in the coldest month (July) and 16.5°C in the warmest month (February). The long- term average annual rainfall in Stratford amounts to 1600 mm. The long- term total annual Priestly-Taylor potential evapotranspiration adds up to 800mm. The annual water deficit as the difference between the annual rainfall and the annual evapotranspiration is thus very low in the Taranaki region which results in AWD- classes of 0 as described in section 3.1.1.

Geologically, Taranaki is a very young region. It is composed of Miocene to Pleistocene sandstones and mudstones and is influenced by the volcanic activity of mount Taranaki whose last major eruption dates back 360 years. The region is characterised as laharic colluviums originating in the late Quaternary (Pleistocene) (Lambert, 2010). The most common soil types in the Taranaki region are allophanic, brown, gley, recent and pallic soil. One of the taken soil samples from the Taranaki is of organic soil type; this soil order is, however, of rather minor importance in the region (Waikato Regional Council, 2011).

Taranaki region is agriculturally highly developed and dairy farming is the basis of Taranaki's economy. The most common land use is thus high producing grass land (Ministry for the Environment, 2009).

3.1.3.2. Hawke's Bay- Central Hawke's Bay district

The climate in the Hawke's Bay is dry and warm due to its sheltered position in the east of the Northland's main mountain ranges. It is characterised by mild temperatures ranging between means of 12°C in the coldest month (July) and 24°C in the warmest month (February). It is generally very sunny. The central Hawke's Bay district is the driest part of the region with a long- term average annual rainfall of only 800 mm. The long- term total annual Priestly-Taylor potential evapotranspiration amounts to 720 mm. Due to the rather minor difference between annual rainfall and annual evapotranspiration, the annual water deficit can be rather important in some places, depending on their specific location in Hawke's Bay region.

Geologically, Central Hawke's Bay is a very heterogeneous region made up of mudstone, limestone, sandstone and argillite. Its hills are prone to erosion. The plains to the south are composed by alluvial deposits. The Geological Atlas specifies sandstone and siltstone, dating in the Late Cretaceous (145-65 Mio. years ago), further bentonic mudstone, greensand, siliceous claystone and limestone from the Eocene (56- 34 Mio. years ago), aggradations and gravel from the late Quaternary, and marine sandstone, siltstone, pumiceous tuff, coquina limestone and conglomerate from the Pliocene (Lambert, 2010). The most common soil types in Hawke's Bay are allophanic, brown, recent, pallic, ultic, podzol and melanic soil (Waikato Regional Council, 2011).

The Hawke's Bay region is divided into plains and hilly parts. While the plains are renowned for their vineyards and orchards, in the hilly parts sheep and beef farming on low and high producing grass land predominates (Ministry for the Environment, 2009).

3.1.3.3. Tararua District- Alfredton

The climate in the Tararua District is warm and dry due to its sheltered position created by the Tararua Range. It is characterised by mild summers and cool winters with mean annual temperatures ranging between 12°C in the coldest month (July) and 24°C in the warmest month (January). The region receives a lot of sunshine and the long- term annual rainfall amounts to 1200 mm. The long- term total annual Priestly-Taylor potential evapotranspiration amounts to 750 mm. The annual water deficit is thus of medium importance.

The landscape is geologically very young and made up of greywacke and argillite rock. The low- lands are composed of alluvial gravel which carried by the rivers from the Tararua Range. The whole zone is very prone to earthquakes due to its closeness to the collision zone of the Pacific tectonic plate and the Australian plate (Schrader, 2010). The most common soil types in the Tararua District are allophanic, brown, gley, recent and pallic soil (Waikato Regional Council, 2011).

Agriculture is the basis of the Tararua Districts' economy. However, due to its rugged terrain and hilly topography, agriculture is less intensive than in other parts of New Zealand and mainly consists of low producing grass land. Furthermore silviculture has some importance in this region (Ministry for the Environment, 2009).

3.1.4. Characteristics of sampling sites

The 10 sampling sites are characterised by 5 different soil orders: Recent, Pallic, Organic, Gley and Brown soil. In addition, each site is allocated to a class of annual water deficit and profile readily available water. The sites can thus be categorized by a 'sampling code' (e.g. B0c): a letter for the 'soil order', a number for the 'annual water deficit' and a letter for the 'profile readily available water'. The profile available water and the annual water deficit are only determined for the Hawke's Bay and Taranaki Region samples and not for those from the Alfredton site. The annual water deficit is zero for the sites in the water-rich Taranaki region and rather high (≥ 50 mm) for the dry Hawke's Bay sites with one exception. In all Taranaki samples and in two out of five Hawke's Bay samples the profile available water is of average quantity (50-74 mm). Two more Hawke's Bay samples are characterised by very little (0-49 mm) and one site by much available water (75-100 mm). Furthermore the coordinates of each sampling site are shown. Table 1 presents the characteristics of the different sampling sites.

Table 1: Characteristics of sampling sites: coordinates, site code, soil order, PRAW and AWD

Sample nr:	Region	coordinates	Site code	soil order	PRAW (mm)	AWD (mm)
1	Hawke's Bay	-39.92314, 176.20354	R0c	Recent soil	50-74	0
2	Hawke's Bay	-39.85205, 176.46329	R2b	Recent soil	0-49	51-394
3	Hawke's Bay	-39.90349, 176.33560	P1c	Pallic soil	50-74	0-50
4	Hawke's Bay	-40.06630, 176.39600	P2d	Pallic soil	75-100	51-394
5	Hawke's Bay	-40.14088, 176.52434	P2b	Pallic soil	0-49	51-394

6	Taranaki	-39.39691, 174.37831	O0c	Organic soil	50-74	0
7	Taranaki	-39.32376, 174.41890	G0c	Gley soil	50-74	0
8	Taranaki	-39.41775, 174.44301	B0c	Brown soil	50-74	0
9	Tararua	-40.64385, 175.89790	Pn	Pallic Soil	n.s.	n.s.
10	Tararua	-40.64385, 175.89790	Ps	Pallic Soil	n.s.	n.s.

In the following sub- sections the sampled soil orders and the specific sampling sites are described in detail.

3.1.4.1. Recent Soils

Recent soils are very young soils, occurring on alluvial floodplains, unstable steep slopes, and slopes mantled by young volcanic ash. They are generally fertile, profound soils with high plant- available water capacity which occur in regions without significant erosion and sediment build- up. They show a high variability in soil texture. While the topsoils are well developed, the subsoils only present poor development. Their quality becomes lower with the occurrence of rocks and dense clay (Waikato Regional Council, 2011).

Recent soils were sampled on two of the sampling sites: both sites in the Hawkes Bay region (Figures 16-17) where one 'R0c' located in 0 mm AWD and 50-74 mm PRAW zone, and the other 'R2b' located in 51- 394 mm AWD and 0- 49 mm PRAW zone.

Figure 16: Site R0c in Hawke's Bay

Figure 17: Site R2b in Hawke's Bay

3.1.4.2. Pallic Soils

Pallic soils are seasonally dry soils which occur in summer-dry, winter-wet regions with an annual rainfall between 500 and 1000 mm. New Zealand's pallic soils are probably unique in the world. They are formed by loess derived from schist or greywacke. Pallic soils show low permeability and high bulk density. Their agricultural use of is limited because of the great density of the subsoil and the limited rooting depth (Waikato Regional Council, 2011).

Pallic soils were sampled on five of the sampling sites: three sites in Hawke's Bay (Figures 18-20) and the two sites in the Tararua Region (Figure 21). Hawke's Bay's pallic samples show quite different values of AWD and PRAW: sample 'P1c' is located in 0-50mm AWD and 50-74mm PRAW zone, sample 'P2d' in 51-394mm AWD and 75- 100mm PRAW zone and sample 'P2b' in 51-394mm AWD and 0- 49mm PRAW zone. For the pallic soil samples in Tararua region neither the annual water deficit nor the profile readily available water is known.

Figure 18: Site P1c in Hawke's Bay

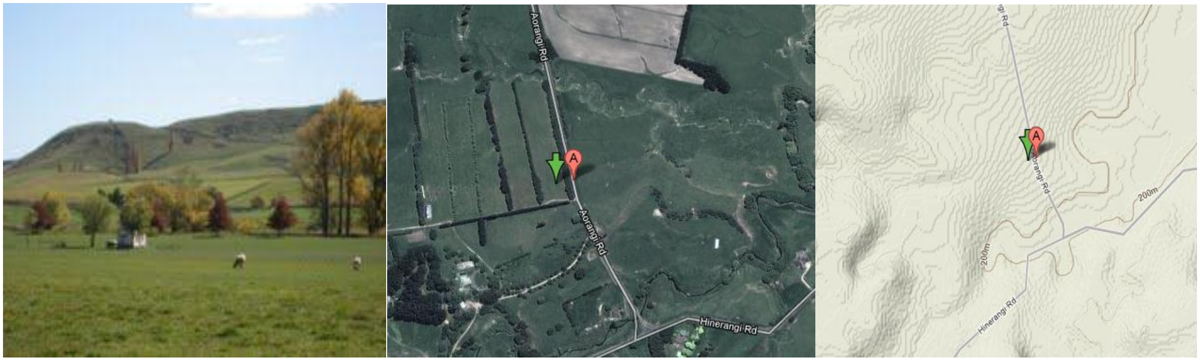


Figure 19: Site P2d in Hawke's Bay

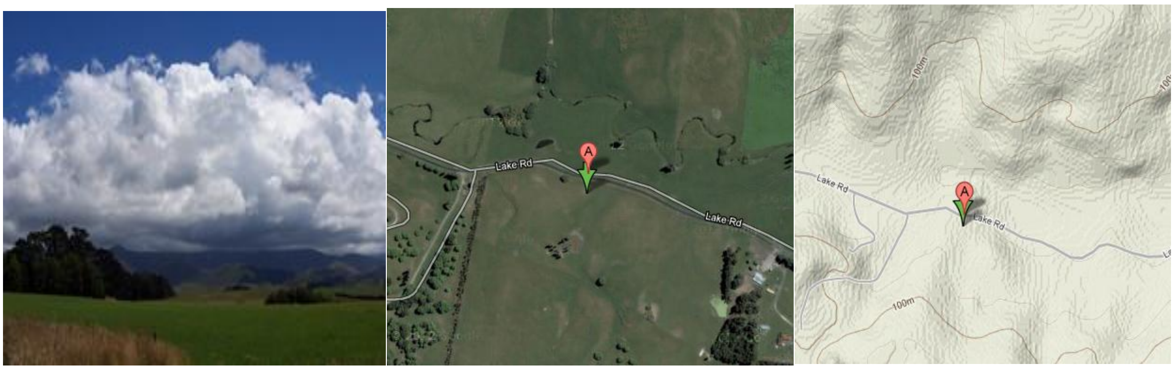


Figure 20: Site P2b in Hawke's Bay

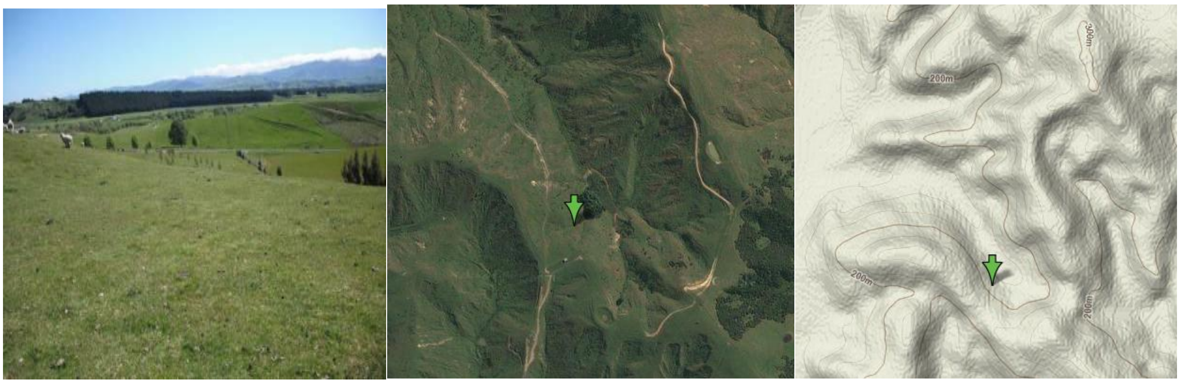


Figure 21: Site PS and PN in the Tararua region

3.1.4.3. Organic soils

Organic soils are permanent wet soils formed by peat or forest litter. Organic matter dominates the soil build-up, as mineralization processes only take place very slowly. They are rather unsuitable for agriculture, as they need drainage and fertilisation. They show high acidity, low bulk density, low nutrient availability and a high shrinkage potential when dried. They occur on flat to gently undulating land of peat swamps (Waikato Regional Council, 2011).

Organic soil was sampled on one site in the Taranaki Region (Figure 22); it is, however, not a typical soil type for this region. The sample ‘O0c’ is located in 0mm AWD and 50-74mm PRAW zone.

Figure 22: Site O0c in the Taranaki region

3.1.4.4. Gley Soils

Gley soils are waterlogged, occurring in areas with high ground- water levels or within the range of seepages. Their use in agriculture is very limited and drainage measures are obligatory. They show a shallow potential rooting- depth and relatively high bulk- density. The organic soil content is generally high (Waikato Regional Council, 2011).

Gley soil was sampled on one site in the Taranaki Region (Figure 23). Sample 'G0c' is located in 0mm AWD and 50-74mm PRAW zone.

Figure 23: Site G0c in the Taranaki region

3.1.4.5. Brown Soils

Brown soils are the most common soils all over New Zealand. They occur in relatively wet climates with an annual rainfall above 800- 1000mm where summer droughts are uncommon and soils are moist throughout the year. They possess relatively stable topsoils, and a low to moderate base saturation. As a consequence of leaching processes, their fertility is limited and they are usually acid. When fertilized, however, they provide good land for dairy farming (Hewitt, 2009).

Brown soil was sampled on one site in the Taranaki Region (Figure 24). Sample 'B0c' is located in 0mm AWD and 50-74mm PRAW zone.

Figure 24: Site B0c in the Taranaki region

3.2. Soil Sampling and Tests

3.2.1. Soil Sampling

At the 5 sites in Hawke's Bay we collected 5 samples of undisturbed soil cores per site; at the 3 sites in Taranaki and 2 sites in the Tararua district we collected 6 samples of undisturbed soil cores per site (75 × 50 mm inner diameter). Altogether, we thus took 55 undisturbed samples. All samples were placed in sealed plastic bags and brought to the lab for further analysis.

The samples were taken on the 8th of April, 2012 at the sites in Hawke's Bay, on the 12th of June, 2012 on the sites in the Tararua district and on the 13th of June, 2012 at the sites in Taranaki region. The samples were collected in humid periods when the soil was moderately to strongly wet. All samples except for the organic soil from the Taranaki region were wettable in their field moist state.

3.2.2. Preparation of samples prior to analysis

Wettability tests were executed 1.) on three undisturbed samples per site and 2.) on two respectively three disturbed samples per site. It is thought that the measurements on the undisturbed samples are closest to the actual water repellency in the field and thus the most realistic ones. However, the standardized method for the measurement of water repellency proposes its determination on disturbed samples (Roy & MacGill, 2002). Previous studies by Deurer et al. (2011) and Holzinger (2012) followed this standardized method for the measurement of soil hydrophobicity at the selected sites. It was thus necessary to also carry out measurements on disturbed samples to compare the results of the present study with those of earlier studies.

The preparation of the samples included the following steps:

The undisturbed soil samples were cleaned; grass and plant material was removed from their surface and they were ready to be tested.

The preparation of the disturbed samples followed the standard method by Roy & MacGill (2002). This standard method, however, does not allow comparing the results obtained on disturbed and undisturbed samples because of the influence of different bulk densities. In order to eliminate this problem we tried to set the bulk densities of the disturbed equal to the undisturbed samples. We divided the disturbed samples of bulk topsoil in their field moist state into portions having the same mass as the undisturbed soil samples. Those portions were then sieved (5mm), dried at 65°C for 48h and left for 24 hours at room temperature to re- equilibrate. Following the standard method, the soil would then be placed into petri-dishes with a depth of about 1cm. In this study, however, they were put into cylinders equal to those of the undisturbed soil samples.

Graber et al. (2006) mention the following three reasons as main causes that repellency of disturbed samples differs from that of undisturbed samples: (i) changes in soil structure, (ii) a different distribution and orientation of the material responsible for repellency and (iii) small-scale (mm and cm) differences in repellency becoming averaged in mixed samples. By keeping the bulk density constant, it is possible to eliminate the first source of deviation. The reasons (ii) and (iii), however, still remain.

3.2.3. Measurement of the physical soil properties

For each study site, the average bulk density, the field capacity as well as the water content at permanent wilting point were determined.

3.2.3.1. Determination of the bulk density

The bulk density of disturbed and undisturbed soil samples was determined by means of the following formula:

$$\rho_{bulk} = \frac{m_{dry}}{V_{core}} \quad \textbf{(3.1)}$$

While V_{core} as the volume of the sampling cylinder is a known parameter for both disturbed and undisturbed samples, m_{dry} had to be determined additionally. For the disturbed soil samples, m_{dry} was specified by weighing the samples right after the drying process, which was performed within the standard preparation procedure as described in section 3.2.2. For the undisturbed samples, the determination of m_{dry} was more complicating because oven- dried samples are not undisturbed anymore. This is why they were oven- dried and weighed after having completed all SWR- tests.

The bulk density was determined for each disturbed and undisturbed sample. The bulk densities of the three respectively two replicates per site were then averaged as to get one reliable result for each site.

3.2.3.2. Determination of the field capacity by means of the vacuum- method

The field capacity is defined as the soil water content at a matrix- potential of 0.6 bar. To determine the field capacity of a soil sample, the previously saturated sample is drained by applying a vacuum to the water phase. The leakage of the water must be enabled by a semi-permeable porous medium (permeable for water, impermeable for air). When the leaking water flow stops, the sample is in hydrostatic equilibrium. The average soil water content can then be linked to the applied matrix potential (Durner & Iden, 2011).

The field capacity is influenced by the number of coarse pores. The use of undisturbed samples is thus indispensable to preserve the structure of the soil. To reduce the time needed for the measurement, it is necessary to use relatively small sampling rings. The chosen sampling rings have a diameter of 5 cm and a height of 2 cm. The samples were saturated with the help of a ceramic plate where the water could enter the samples from below. The saturation was completed after one day and a suction head of 0.1 bar (corresponding to 1m water column or pf= 2) was applied to the ceramic plate. A bubble tower which works like a Mariotte's bottle is used to control the suction head (Figure 22). To prevent evaporation from the samples, they were put into plastic bags. Equilibrium was reached after three days and the samples were weighed. After drying them at 105°C for 48 hours they were weighed again. The soil water content at field capacity was then determined by means of the weight difference and the volume of the sampling ring.

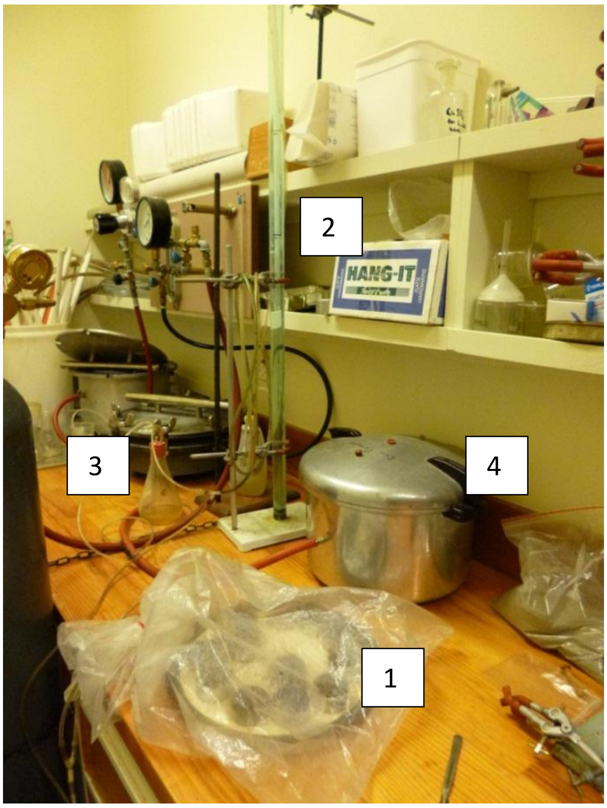


Figure 25: Field capacity- vacuum method: (1) samples on ceramic plate in plastic bag, (2) bubble tower, (3) bottle for leaking water, and (4) vacuum pot.

3.2.3.3. Determination of the water content at the wilting point by means of the pressure membrane apparatus

The soil water content at wilting point is defined as the water content at a matrix- potential of 15 bar. To determine the soil water content at the wilting point, a saturated soil sample is placed in a pressure membrane apparatus, where the gas phase is kept at over- pressure while the water phase can drain through a porous ceramic plate which is in contact with the atmospheric ambient pressure (Durner & Iden, 2011).

At the wilting point all coarse and medium sized pores are drained and water only remains in the fine pores. Thus, the soil water content at the wilting point is not influenced by the soil structure, but only by the soil texture and disturbed samples can be used for this measurement. Due to the high matrix potential, the stabilisation process needs a lot of time and it is important to choose very small sampling rings. We took sampling rings with a diameter of 5.5 cm and a height of 1 cm. The samples were saturated as described in section 3.2.3.2 and placed in the pressure membrane apparatus (Figure 23). The lid was firmly sealed and the pressure of 15 bar (corresponding to 150 m water column or pf=4.2) was applied. When no more drainage water could be observed within 24 hours, equilibrium was regarded to be reached. This happened after seven days. The soil water content at the wilting point was then determined by means of the weight difference and the volume of the sampling ring.

Figure 26: Pressure plate apparatus (Robinson et al., 2003)

The available water holding capacity was calculated as the difference between the soil water contents at the field capacity and the permanent wilting point as presented in equation 3.2.

$$AWC = \theta_{fc} - \theta_{pwp} \qquad \textbf{(3.2)}$$

3.2.4. Determination of critical soil water content by the Water Droplet Penetration Time (WDPT) test

The Water Drop Penetration Time (WDPT) describes the persistence of water repellency. The test method records the time taken by a standard- sized water droplet to completely infiltrate a soil. A high WDPT value corresponds to a high persistence of water repellency (Moody & Schlossberg, 2010). Considering that water repellent soils possess contact angles ≥ 90°, it can also be said that the WDPT describes the time it takes a soil to fall below a CA of 90°.

Starting with the field- moist samples, the water drop penetration time was measured by pipetting 100µl - drops of distilled water onto the surface of the sample and recording the time needed for complete infiltration (Figure 24). For a more reliable result, there were always applied three drops on every sample and the time replicates were then averaged.

During the air- drying of the samples, measurements of the persistence of SWR were conducted every day until no significant changes in soil moisture content could be recorded. This happened after about 2 weeks. The samples were then rewetted from the top by the help of a spray- bottle and from the bottom by standing in water- filled petri- dishes. When they reached the hydrophilic state, another test- cycle started. The moisture levels in the dry state- right before rewetting- were different for the different soil types. Each soil type, however, always reached the same minimum moisture level during every test- cycle.

We adopted the approach by Roy & MacGill (2002) who classified a soil to be 'water repellent', if the droplet infiltration time exceeded 10 seconds. This chosen threshold, however, is not absolute.

Other studies e.g. (Deurer et al., 2011) used a limit of 5 seconds above which soils are thought to be hydrophobic.

The classification system for the persistence of SWR used in this study is based on (Deurer et al., 2011). However, the observed water droplet penetration times mainly showed values smaller than 10 minutes. The classification system was therefore adapted to these smaller time ranges by fitting intermediate classes between the original ones and adjusting them to the logarithmic WDPT time scale. The modified classification system is presented in Table 2.

Table 2: Classification of water droplet penetration times

Class 0 (<10s)	Class 1 (10-25s)	Class 2 (25-60s)	Class 3 (1-3min)	Class 4 (3-10min)	Class 5 (10-60min)	Class 6 (>1h)
wettable	Slightly persistent	Moderately persistent	Strongly persistent	Very strongly persistent	Severely persistent	Extremely persistent

In this manner, four respectively three test- cycles of wetting and drying phases were executed. The main interest lay on the time step when the persistence changed from class 0 to class 1, thus from hydrophilic to hydrophobic and where the volumetric soil water content coincided with the critical water content.

Figure 27: WDPT- test: water droplets testing on soil samples

3.2.5. Determination of the critical contact angle by the Molarity of Ethanol Droplet (MED) test

The Molarity of Ethanol Droplet describes the degree of water repellency of a soil by means of the contact angle. A series of aqueous ethanol solutions which induce different surface tensions is prepared for the measurement. The higher the ethanol concentration, the lower will be the surface tension and the faster will be the penetration of the ethanol droplet in the soil surface. The test method determines the degree of water repellency on the basis of the lowest ethanol concentration permitting droplet penetration within 10 seconds.

Especially on the undisturbed soil samples, the MED- test results showed large deviations which depended on the droplet placement on the samples. In order to straight out these variations, the degree of water repellency was also fitted into a classification system. We distinguished four categories as shown in

Table 3.

Table 3: Classification of contact angles

Class 0 (<90°)	Class 1 (90°-95°)	Class 2 (95°-100°)	Class 3 (100°-105°)	Class 4 (105°-110°)	Class 5 (110°-115°)
wettable	Slightly severe	Moderately severe	severe	strongly severe	extremely severe

The separation between wettability and water repellency (class 0 and class 1) coincides for the persistence and the degree of SWR.

Drops of ethanol solutions were pipetted onto the soil samples. Increasing ethanol concentrations were used until the drop penetrated within 10s. We used 24 ethanol solutions of different molarities ranging from 0.171 to 10.087. To achieve reliable outcomes, three drops of this target solution were applied. The resulting ethanol concentration was then converted to surface tensions using the relationship found by Roy & MacGill (2002) who experimentally determined the relationship between the molarity and the surface tension of an aqueous ethanol solution as displayed in Figure 28.

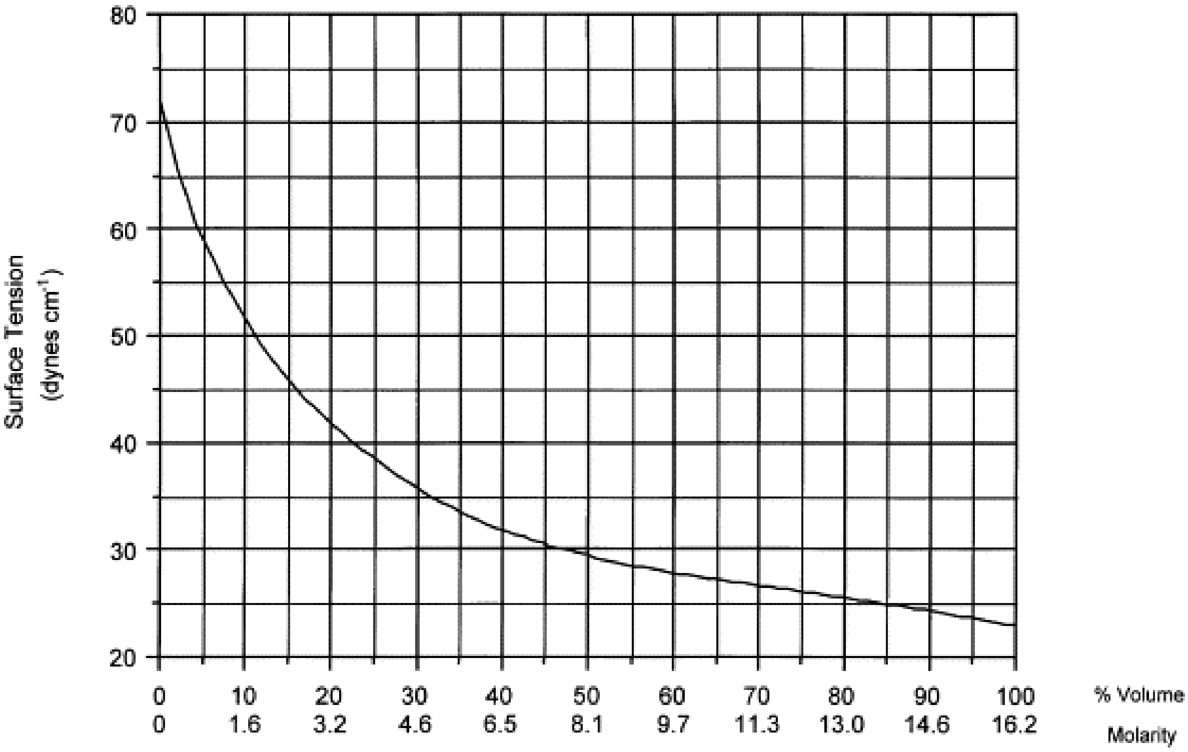


Figure 28: Relationships between liquid–air surface tension and the vol% of 95% ethanol in an ethanol–water solution respectively the molarity of an ethanol- water solution (Letey et al., 1999)

This relationship corresponds to the equation

$$y = 61.05 - 14.75 * \ln(x + 0.5) \qquad \textbf{(3.3)}$$

Where
x... Molarity of Ethanol Solution (M)

γ...liquid surface tension (mN/m)

The obtained liquid surface tension can be converted into contact angles (CA) on the basis of Young's equation (Young, 1805) as illustrated in Figure 29.

$$\gamma_l \cos\theta = (\gamma_s - \gamma_{sl}) \qquad \textbf{(3.4)}$$

Where
γl... liquid- air surface tension
θ... contact angle
γs... solid- air surface tension
γsl... solid- liquid interfacial tension

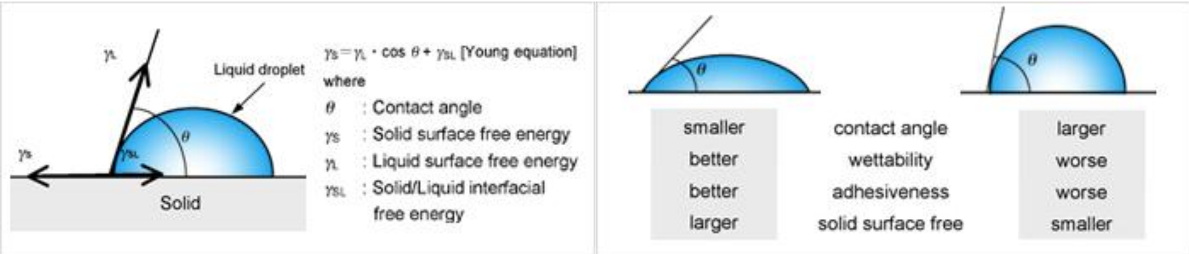


Figure 29: Relationship between surface tension and contact angle (Kyowa Interface Science Co., 2007)

This equation can further be combined with the assumptions made by (Girifalco & Good, 1960) for the relation of attractive constants between molecules

$$y_{sl} = y_s + y_l + 2\Phi\sqrt{y_s y_l} \qquad \textbf{(3.5)}$$

Where
Φ... ratio between the molar volumes (close to unity for a water–hydrocarbon system)

This leads to

$$\cos\theta = 2\sqrt{\gamma_s/\gamma_l} - 1 \qquad \textbf{(3.6)}$$

The MED- test provides the 90°-surface tension and γ_l is thus selected for cos θ = 0 which results to

$$\cos\theta = \sqrt{\gamma_{90°}/\gamma_l} - 1 \qquad \textbf{(3.7)}$$

Setting the water- air surface tension γl= 71.27 mN /m, we obtained the results presented in 8 and Annex A.

In accordance to the WDPT-test, the MED-test was also conducted every day until no changes in soil moisture content could be recorded. The samples were then rewetted from the top by the help of a spray- bottle and from the bottom by standing in water- filled petri- dishes. When they reached the hydrophilic state, another test- cycle started. This cycle was repeated three times.

3.2.6. Water distribution within the soil sample

The volumetric water content in the soil sample is determined by the following formula:

$$\theta = \frac{m_{humid} - m_{dry}}{V} \left(\frac{m^3}{m^3}\right) \quad \textbf{(3.8)}$$

Where

m_{humid} … mass of humid soil sample (g)

m_{dry} … mass of dry soil sample (g)

V… volume of sample (cm^3)

In order to match a level of soil water repellency with the correct water content it is thus necessary to have a homogeneous water content distribution within the sample. While the water will be evenly distributed in the saturated sample, the top part of the sample will dry out faster than the lower parts during the process of air drying. In order to quantify the extent of this irregularity, we looked at results obtained by Schindler & Müller (2006) who examined the water loss over time by evaporation in three different depths of a soil sample. Their soil samples have virtually the same dimensions as the ones used in this study; a comparison is thus judged to be valid. Figure 30 shows tension profiles in the sample of clayey silt. The tension is related non- linearly to the water content and serves in this graphical representation as an indicator for the water content. It can be seen that the tension profiles are practically vertical up to a tension of 400 hPa which corresponds to a pf-value of 2.6. As described in sections 3.2.3.2 and 3.2.3.3 the field capacity was defined at pf= 2 and the wilting point at pf=4.2. Hence, the irregularities in the distribution of the water content in the soil sample occur somewhere between field capacity and wilting point. As stated by De Jonge et al. (1999) and King (1981), soils become water repellent when the water content approaches field capacity. It can thus be assumed that the water distirbution within the soil sample at the point of critical water content is homogeneous. At low water contents, however, the measured SWR- levels are probably matched with over- estimated water contents.

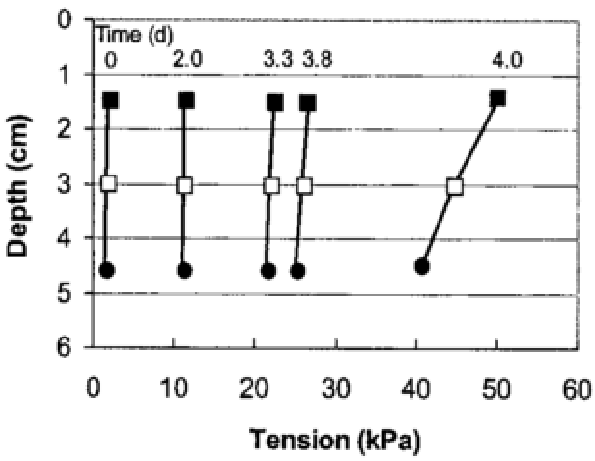


Figure 30: Tension profiles in the sample of clayey silt from China, evaporation rate 5.4 mm/ d (Schindler & Müller, 2006)

In order to match the correct water content with the corresponding level of SWR, it would be of use to merely determine the water content in the very top layer of the sample and not of the whole sample.

3.3. Statistical Data Analysis- ANOVA

An ANOVA- test was used to compare the soil water repellency results obtained in this study with the results found in previous studies. Furthermore, we also used it to compare the critical water contents for the different sampling sites and for the different soil orders.

The ANOVA- test shows if the mean difference between two groups of results is significant. We took a confidence interval of 95%. The obtained p- values must thus be greater than 0.05 in order to confirm our 0- hypothesis H0: $\gamma_1 = \gamma_2$ and state that there are no significant differences between the mean values of the groups.

3.4. Soil Water Balance Modeling

As a second aim of this study, we wanted to predict the occurrence of hydrophobicity within a year on a specific field site with the help of the obtained lab results. For this purpose a daily water balance model was used. The model joins the spatial and temporal characteristics of the field site by combining climatic and geographic data with the parameters obtained in the lab such as the critical water content, the available water holding capacity and the soil properties.

The used water balance model was developed by Bretherton et al. (2010). The model is a simplification of an earlier model by Bircham & Gillingham (1986) and is based on two daily soil water balances which are calculated in parallel: the first and main water balance is calculated for the root- zone from 0-300 mm, and the second one for the topsoil layer from 0-50 mm. The consideration of two separate soil water balances allows the inclusion of a 'soil rewetting function' into the model which limits infiltration when the soil surface is dry and which takes into account the possible influence of soil water repellency. Both soil water balances are based on the parameters soil 'water holding capacity' (Wa), 'drainage' (D), 'infiltration' (I) and 'evapotranspiration' (E). Evapotranspiration depends on the presence of available water, and ranges between the reference crop rate E_0 and 0.

The available water in the root zone at the start of the next day is modelled as follows:

$$\boldsymbol{W_{n+1} = W_n + I - D - E} \qquad \textbf{(3.8)}$$

Where

Wn+1...	Equivalent depth (mm) of available soil water at the start of the next day, n+1
Wn...	Equivalent depth (mm) of available soil water at the start of day n
I...	Water infiltrating the soil profile (mm) on day n
D...	Drainage leaving the soil profile (mm) on day n
E...	Evapotranspiration leaving the soil profile (mm) on day n

There are two main differences between the first and the second soil water balances: (I) the soil water holding capacity has experimentally been justified to be smaller for the top- soil layer than for the root-zone; (II) the evapotranspiration of the top soil layer (E_s) is a fraction of the evapotranspiration of the root zone ($E_{root\ zone}$). $E_{top\ soil}$ depends largely on the root density: when the whole root zone is at field capacity, a large fraction of the evapotranspiration will be from the top soil layer because of its higher root density. The top soil thus dries out faster and contributes less and less to the evapotranspiration. $E_{top\ soil}$ is then calculated as follows:

$$E_s = \frac{E_0 * W_s}{2W_{s,a}} \quad \textbf{(3.9)}$$

Where

E_s... Evapotranspiration from the top soil layer
E_0... Reference crop evapotranspiration
W_s... Soil water content in the top soil layer
$W_{s,a}$... Soil water storage capacity in the top soil layer

According to Eq. 3.9, at field capacity half of the total evapotranspiration comes from the top soil layer. When the top soil dries out and the amount of available water decreases, the water uptake from the root zone becomes more and more important. $E_{root\ zone}$ proceeds at the reference crop rate E_0 if water is available and decreases down to zero when the water is used up.

To calculate the reference crop evapotranspiration E_0, the model used the Penman- Monteith equation suggested by Allen et al. (1998). The effect of slope and aspect on the incoming solar radiation was determined with the equations by Revfeim (1982).

When the available water holding capacity of a soil is exceeded, the surplus water is lost either by drainage or by surface runoff, depending on the rainfall intensity and the infiltration capacity. Surface runoff can be produced by two different mechanisms:

(I) When the soil is saturated, water can no longer infiltrate and the excess water creates overland flow.

(II) When the rainfall intensity exceeds the infiltration rate, only a part of the rainfall can infiltrate. The remaining precipitation runs off as Hortonian overland flow.

The model, however, considers neither surface runoff due to saturation nor Hortonian overland flow occurring on wettable soils because these kinds of flows are spatially and temporally variable. They depend on a variety of factors such as the hydraulic properties of the soil and the morphology of the catchment. If it was to simulate such flow in an adequate way, there would be needed a multi-dimensional model of water movement for the area above the location of interest (O'Loughlin, 1990; Bretherton et al., 2010). In the model, all surface runoff is due to soil water repellency and occurs when the following two criteria are satisfied:

(I) The soil water content in the top soil layer must be below the critical water content.

(II) The rainfall intensity must be higher than the set maximum infiltration capacity for hydrophobic soils.

For the reference site in Alfredton, Bretherton et al., (2010) experimentally found a maximum value for the infiltration capacity on hydrophobic soils of 1 mm/ 10 min. This value was taken as a fixed parameter and not changed for the simulations on the study sites in Hawke’s Bay and Taranaki region because there was no available experimental data we could refer to.

Bretherton et al. (2010) compared measured and modelled values for the water content in the top 50 mm on their study site in Alfredton. They found them in quite close agreement, except for the south and east aspect, where the model underestimated the actual water content. Despite those variations, Bretherton et al. (2010) consider the model results accurate enough to give useful predictions when repellency is likely to limit infiltration.

Bretherton et al. (2010) also compared the measured and modelled values for the repellency-induced surface- runoff and observed both under and overestimated results. They believe this to be a result of the coarseness of the rainfall data and the simplicity of the infiltration restriction in the model. A better prediction would require more detailed rainfall intensity and runoff data as well as a more sophisticated description of the effect of soil water repellency on infiltration in the water balance model. Still, the model is a good indicator for when repellency- induced runoff is most likely to occur.

3.5. Practical application of the soil water balance model

It was decided to simulate the soil water balance for four years at each site, from April 2008 to April 2012. In order to obtain useful, stabilized results in April 2008, we started to run the model already some time before, in December 2007. The soil water balance model required input data concerning (I) climate parameters, (II) soil parameters and (III) location parameters.

3.5.1. Climate Data

The climate data was obtained from the National Institute of Water and Atmospheric Research (NIWA). NIWA holds a climate database which is an archive of climate data from New Zealand and the Pacific Islands. They store climate data which dates back up to 160 years. Data from about 260 climate stations is loaded daily and data from 170 climate stations is loaded hourly into this database. The study sites, however, are not exactly located next to those climate stations and we therefore used the ‘virtual climate network’ which is also provided by NIWA. It consists of an interpolated grid of 11 491 virtual climate stations covering the area of New Zealand. The grid separation is 0.05 deg latitude which represents approximately 5 km (NIWA, 2013).

For each study site, the nearest virtual station was identified and the following climate data was downloaded for the time between 01/12/2007 and 16/06/2012:

- The daily minimum/ maximum temperature (°C)
- The daily relative humidity (%)
- Flat surface short wave radiation ($\frac{MJ}{m^2 d}$)
- The daily wind speed ($\frac{m}{s}$)
- The total daily rainfall (mm)

However, the model also requires the 10- minute-rainfall as an input data. NIWA does not provide this parameter for its virtual climate stations. For each of the three study regions we therefore identified the geographically closest climate station measuring 10-minute rainfall data and got the following three locations:

- Waipawa EWS for the study sites in the Hawke's Bay region;
- Stratford EWS for the study sites in the Taranaki region; and
- Palmerston North for the study sites in the Tararua region.

These climatic stations are all located at distances between 9 and 40 km from our study sites as indicated in Table 4.

In order to prove the similarity of the rainfall regimes between the study sites and the climatic stations, we compared the daily rainfall totals of the climatic stations with those of the virtual climatic stations for the study sites as shown as an example in Figure 31.

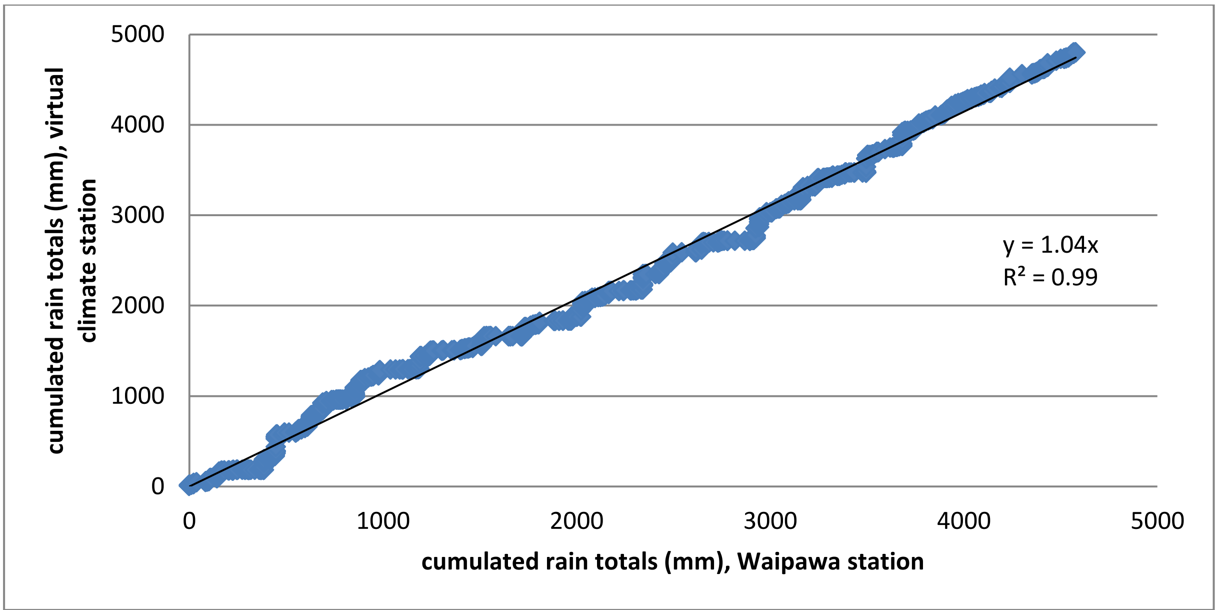


Figure 31: Relationship between the daily rainfall totals for the virtual climatic station 'R2b" in the Hawke's Bay region and the climate station 'Waipawa EWS"

Table 4 presents the coefficient 'A' for the relationship between the virtual-climatic and the climatic stations daily rainfall totals for different study sites:

$$\textbf{rain totals}_{\text{virtual climatic station}} = \textbf{A* rain totals}_{\text{climatic station}} \quad \textbf{(3.10)}$$

The correlation between virtual and actual cumulated rain totals is pretty close to one for all sites except for R0c (Table 4), suggesting that the 10-minute rainfall data measured at the closest climatic stations could be regarded as reliable for the study sites. The site R0c showed a coefficient of almost 2, which means that the cumulative daily rainfall of the virtual climatic station was almost double than the cumulative daily rainfall measured at the closest climatic station 'Waipawa Ews'. This was, however, accepted because it would have been a disproportionate effort to prepare an additional rainfall data set for site R0c. We decided to use the original 10-minute-rainfall-data from the closest climatic stations instead of adapting it for the different locations of the study sites. The use of modified data was relinquished in order to not provoke any further unnecessary estimation.

Table 4: Reliability of climatic station data for actual locations

Waipawa Ews:	**P1c**	**P2d**	**R2b**	**P2b**	**R0c**
Correlation Coeff. 'A':	1.206	1.198	1.036	1.050	1.944

Coefficient of determiantion R^2:	0.995	0.996	0.993	0.994	1.982
Distance from measuring station (km)	24.6	14	17.1	22.4	35.3

Stratford Ews:	**B0c**	**O0c**	**G0c**	**Palmerston Ews:**	**PS, PN:**
Correlation Coeff. 'A':	0.842	0.932	0.906		1.228
Coefficient of determiantion R^2:	1.000	1.000	1.000		0.999
Distance from measuring station (km)	15	9.1	9.9		37.9

3.5.2. Soil Data

The soil water balance model requires the following parameters as soil data input:

- Maximum available water content (mm) in the top soil layer (0-50 mm);
- Minimum water content (mm) in the top soil layer (0-50 mm);
- Maximum available water content (mm) in the root zone (0-300 mm);
- The critical water content for SWR (m^3/m^3)

The maximum available water content is defined as the difference between the soil water contents at field capacity and at the permanent wilting point (see sections 3.2.3.2 and 3.2.3.3). The minimum water content is the amount of water which remains in the soil after all the available water has been removed, i.e. the water content at the wilting point. The maximum available water content in the root zone has not been measured, but set to a constant value of 90 mm which was experimentally found by Bretherton (2010) on the reference site in Alfredton. It has no influence neither on the soil water content in the top- soil layer nor on the repellency- induced surface runoff and is thus of no importance for simulations in this study. The critical water content was measured as described in sections 3.2.4 and 3.2.5.

3.5.3. Location Parameters

The soil water balance model requires the altitude, aspect and slope as location input parameters for each site as presented in Table 5.

Table 5: Location parameters of each study site.

Study Site No.:	Region	Site code	Altitude (m)	Aspect	Slope (°)
1	Hawke's Bay	R0c	545	SE	20

2	Hawke's Bay	R2b	216	n.a.	flat
3	Hawke's Bay	P1c	293	N	3
4	Hawke's Bay	P2d	216	n.a.	flat
5	Hawke's Bay	P2b	65	NNE	12
6	Taranaki	O0c	241	n.a.	flat
7	Taranaki	G0c	191	n.a.	flat
8	Taranaki	B0c	162	W	14
9	Tararua	PN	205	N	20
10	Tararua	PS	205	S	20

4. Results

4.1. Soil Property Results

The bulk densities were measured for every undisturbed soil sample and then averaged for each study site (Table 6). The replicates showed very similar results with standard deviations between 0.02 and 0.07. The field capacities were measured on two replicates per site which were then also averaged (Table 6). The results for the two replicates were also very similar and the averages can thus be regarded as reliable. The wilting point was measured on one sample per site. The available water holding capacity was calculated as the difference between the average field capacity and wilting point at each study site (Table 6).

While pallic and recent soils are quite heavy soils with bulk densities around 1g/cm³, brown and especially organic and gley soils are of much lighter structure with bulk densities around 0.5 g/cm³. This goes in line with the available water holding capacity: while pallic and recent soils provide about 0.22m³/m³ of available water, brown and gley soils are limited to around 0,15m³/m³ and the organic soil offers no more than 0,11m³/m³ of available water. These results are in good agreement with the soil's descriptions from section 3.1.4.

Table 6: Physical soil properties of the different study sites

Soil Order	Region	Sample code	Bulk density ρ_{bulk} (g/cm^3)	Field capacity (m^3/m^3)	Wilting point (m^3/m^3)	Available water holding capacity (m^3/m^3)
Pallic Soil	Hawke's Bay	P1c	0.87	0.41	0.18	0.22
		P2d	0.93	0.42	0.18	0.24
		P2b	1.10	0.43	0.28	0.15
	Tararua Region	PS	0.78	0.48	0.26	0.22
		PN	0.98	0.48	0.26	0.22
Recent Soil	Hawke's Bay	R0c	0.80	0.38	0.18	0.21
		R2b	0.95	0.34	0.13	0.21
Brown Soil	Taranaki Region	B0c	0.65	0.39	0.24	0.15
Organic Soil	Taranaki Region	O0c	0.54	0.41	0.30	0.11
Gley Soil	Taranaki Region	G0c	0.55	0.49	0.32	0.16

The soil's texture for different soil types (Table 7) was roughly classified with the help of field capacity and wilting point as described by Rowell et al. (1997). It is in good agreement with the soil textures of New Zealand soils as they are described by Hewitt (2009).

Table 7: Approximation of soil texture for the different soil types

	Approximate Texture
Pallic soil	silt
Recent soil	silty loam
Brown Soil	clayey loam
Organic Soil	Organic peat
Gley Soil	Clay and sand

4.2. Soil Water Repllency Results

All direct results obtained from the SWR measurements (WDPT- & MED- tests) are presented in Annex B:. They are structured in results from disturbed and undisturbed samples and in results from different drying cycles. The samples are defined by their sampling code as described in section 3.1.5. In addition to 'soil order', 'AWD' and 'PRAW' there is given another number to distinguish between the different replicates. The results are structured such as they finally lead to answering the main question of this study which is to test the concept of the critical water content and its application in New Zealand environment.

Soil water repellency was present on all undisturbed samples and on all but one disturbed samples. The explanation for the 2 replicate disturbed samples of site P2d to not show any soil water repellency at all may be due to the preparation process of those samples. The sieving and re-installation of the soil into the cylinder after the oven- drying must have destroyed the effects of hydrophobicity.

All samples except for the organic soil were wettable in their field moist state so that it was possible to start the laboratory experiments on undisturbed samples which were in a hydrophilic state and observe their change to the hydrophobic state already in the first cycle.

The actual water repellency was measured on both the undisturbed and the disturbed samples; the potential water repellency was measured on the disturbed samples.

Table 8 shows how many replicates of undisturbed and disturbed samples were tested per study site as well as how many test cycles were executed on each replicate sample. Altogether, 47 undisturbed and disturbed soil samples were tested in a minimum of 2 and in a maximum of 4 repetitive test cycles on hydrophobicity.

Table 8: Number of replicates of undisturbed and disturbed samples which were tested per study site and number of test cycles which were repeated on each replicate sample.

Study site	No. of replicates of undisturbed samples	No. of test- cycles executed on each replicate	No. of replicates of disturbed samples	No. of test- cycles executed on disturbed samples
P1c	3	4	2	3
P2d	2	4	2	3
P2b	3	4	2	3
PS	3	3	-	-
PN	3	3	-	-
R0c	3	4	2	3
R2b	2	4	2	3

B0c	3	3	3	2
O0c	3	3	3	2
G0c	3	3	3	2

4.2.1 Potential soil water repellency and its temporal variance

Immediately after the oven- drying and preparation of the disturbed samples, the potential soil water repellency was measured. It is thought to be the maximum water repellency which can be reached. As can be seen in Annex A, this was true for the brown soil and the gley soil where both the water drop penetration times and the contact angles were at a maximum. For the organic soil, two out of three replicates showed maximum water drop penetration times in the oven- dry state; the contact angles, however, were not at their possible maximum. All pallic soil samples of the Hawke's Bay sites were wettable in the oven- dry state whereas the pallic soil samples from the Tararua site showed maximum WDPT- values and two out of six samples also maximum contact angles. Samples from one site of recent soil showed water repellency, but no maximum values, whereas those from the other recent soil site were wettable. In conclusion it can be said that the potential water repellency is not a good indicator for the maximum possible water repellency which can be reached. Generally, water drop penetration times are more frequently at maximum than contact angles when measured in the oven- dry state. The potential soil water repellency values (exclusion of the samples where no SWR could be measured) were averaged for the different soil orders and are presented in figure 32.

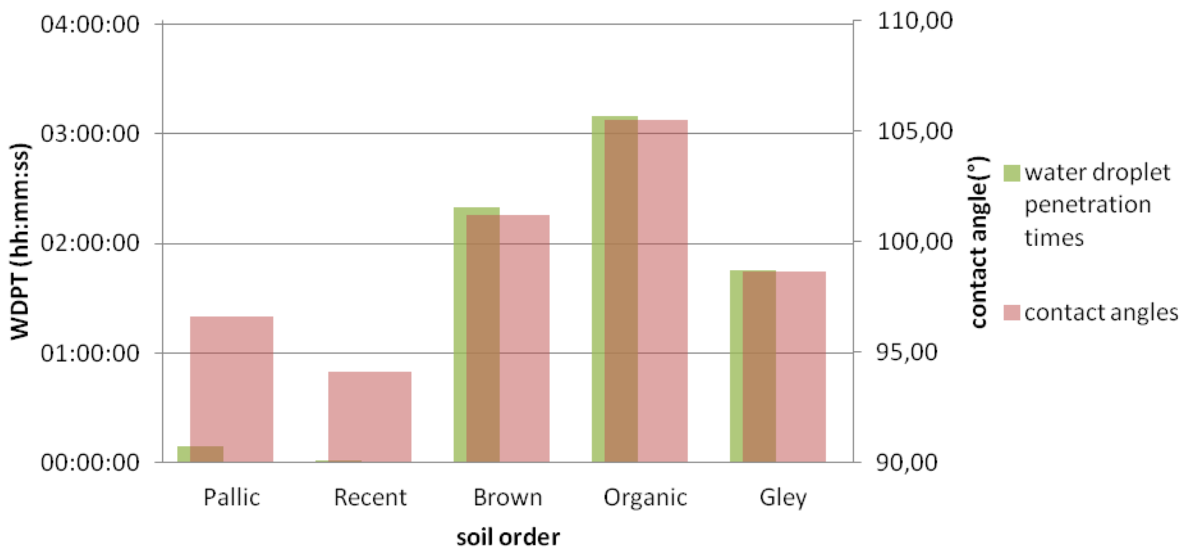


Figure 32: Degree and persistence of potential soil water repellency, averaged for the different soil orders

On the three sites in the Taranaki region (brown, organic and gley soil), the potential soil water repellency was measured by Deurer et al. (2011) and Holzinger (2012) at different times in the year 2011. We thus wanted to find out if the potential water repellency changed with the time. Figure 33 and Figure 34 present the degree and persistence of the potential water repellencies at the three sites in the Taranaki region which were measured at four different points in time. The measurements seem to be relatively consistent without having any significant changes in time. However, it can be observed that water repellencies measured in the present study are generally higher than those measured in the previous studies by Deurer et al. (2011) and Holzinger (2012). In order to statistically evaluate the different SWR- results, we performed an ANOVA test which compared both contact angles and water drop penetration times found in this study in June 2012 with those found by Deurer et al. (2011) in January 2010 and Holzinger (2012) in April 2011 and August 2011. The data inputs and results obtained with the ANOVA- test are presented in Annex G.

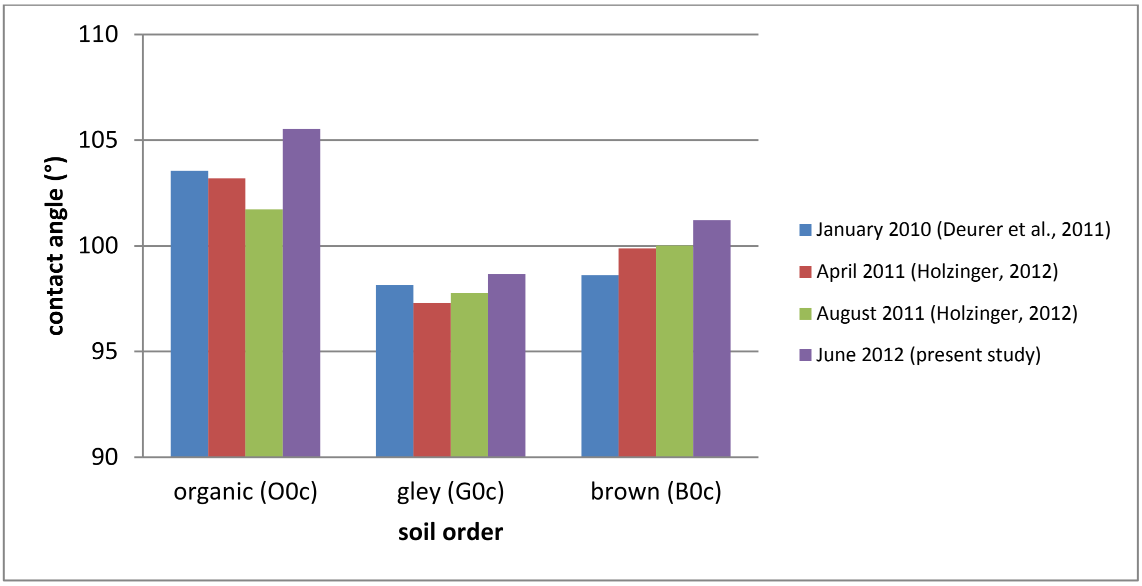


Figure 33: Comparison of potential SWR (expressed by contact angles) at the study sites O0c, G0c and B0c, measured during different seasons at different times of the year in the course of different studies (January 2011 by Deurer et al. (2011), April 2011 and August 2011 by Holzinger (2012), June 2012 in the present study)

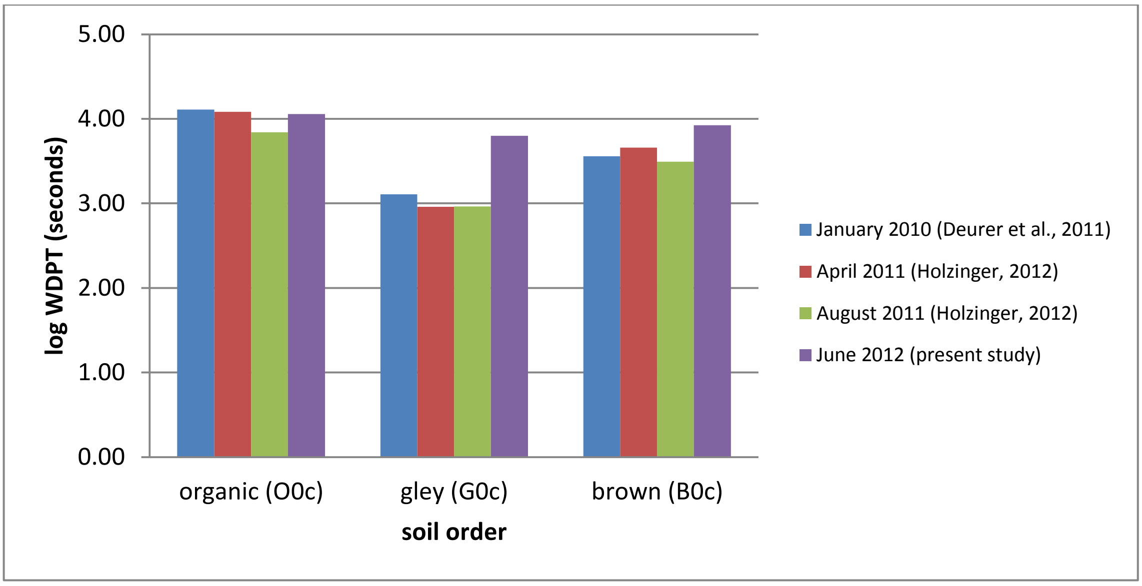


Figure 34: Comparison of potential SWR (expressed by log WDPT times) at the study sites O0c, G0c and B0c, measured during different seasons at different times of the year in the course of different studies (January 2011 by Deurer et al. (2011), April 2011 and August 2011 by Holzinger (2012), June 2012 in the present study)

The ANOVA- test shows no significant difference in the average degree of potential soil water repellency for the brown and gley soil and also not for the persistence of the brown and organic soils. The degree of SWR for the organic soil as well as the persistence of SWR for the gley soil is significantly higher in the present study than in those by Deurer et al. (2011) and Holzinger (2012). This difference, however, can be due to the differently built soil samples in this study.

Holzinger (2012) compared her own measurements with those of Deurer et al. (2011) and found some of the measured water repellencies to be significantly lower in winter than in summer. Most samples, however, did not show any significant differences at all.

In conclusion it can be said that the potential water repellency did not change from 2011 to 2012. It can thus be assumed that soil water repellency is always present, the actual degree and persistence, however, depend on the field conditions such as the soil water content.

The relationship between actual and potential water repellency is not evident. Actual water repellency cannot be derived from potential water repellency. This fact has also been stated by Graber et al. (2006).

4.2.2 Relationship between persistence and degree of SWR

The water droplet penetration time test is a very time- intensive test. It would thus be of help if there could be identified a close relationship between the degree and the severity of water repellency, so that the one can assume the severity by means of the degree of water repellency.

As presented in Figure 35, the relationship between the water drop penetration times and the contact angles for the potential water repellency is moderately close with a coefficient of determination of 0,76. It corresponds very well to the relationship found by Deurer et al. (2011).

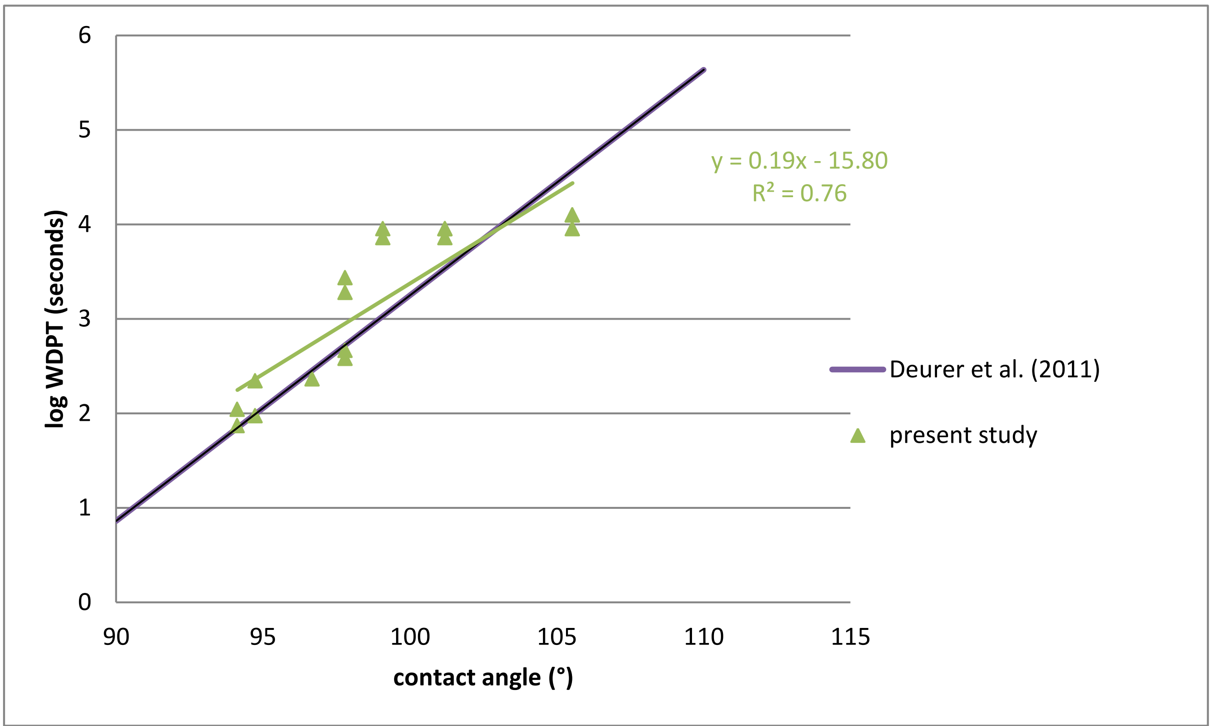


Figure 35: Relationship between CA and WDPT values for potential soil water repellency

As presented in Figure 36, the relationship between the water drop penetration times and the contact angles for the first drying cycle of the undisturbed samples is poorly to moderately close for the different soil orders with coefficients of determination ranging between 0,22 and 0,77. However, as presented in Figure 37, the relationship stabilizes for the 2nd and 3rd cycle and is approximately the same for all soil orders with coefficients of determination ranging between 0.18 and 0.68. This is fairly in line with the coefficient of determination of 0.48 found by Deurer et al. (2011).

An estimated correlation equation can be given with

$$\log WDPT = 0.06CA - 4.38 \quad 4.1$$

However, due to the relatively small coefficients of determination, it is not recommended to use the contact angle as a stand- alone indicator for the severity of soil water repellency.

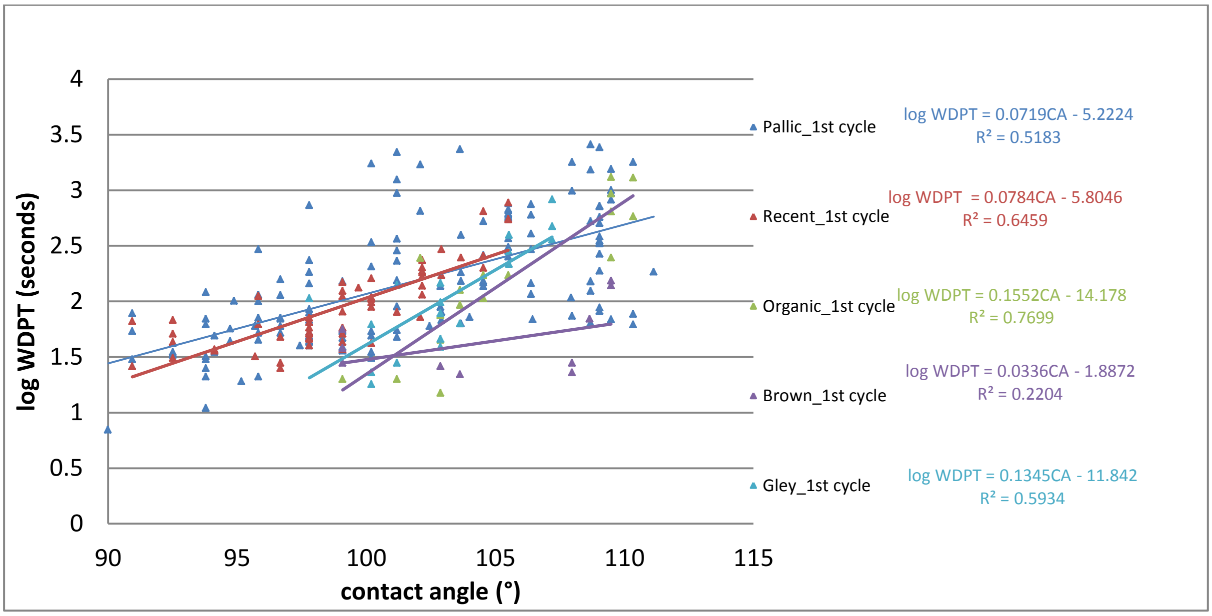


Figure 36: Relationship between CA and WDPT values for undisturbed samples, first drying cycle, presented for the different soil orders

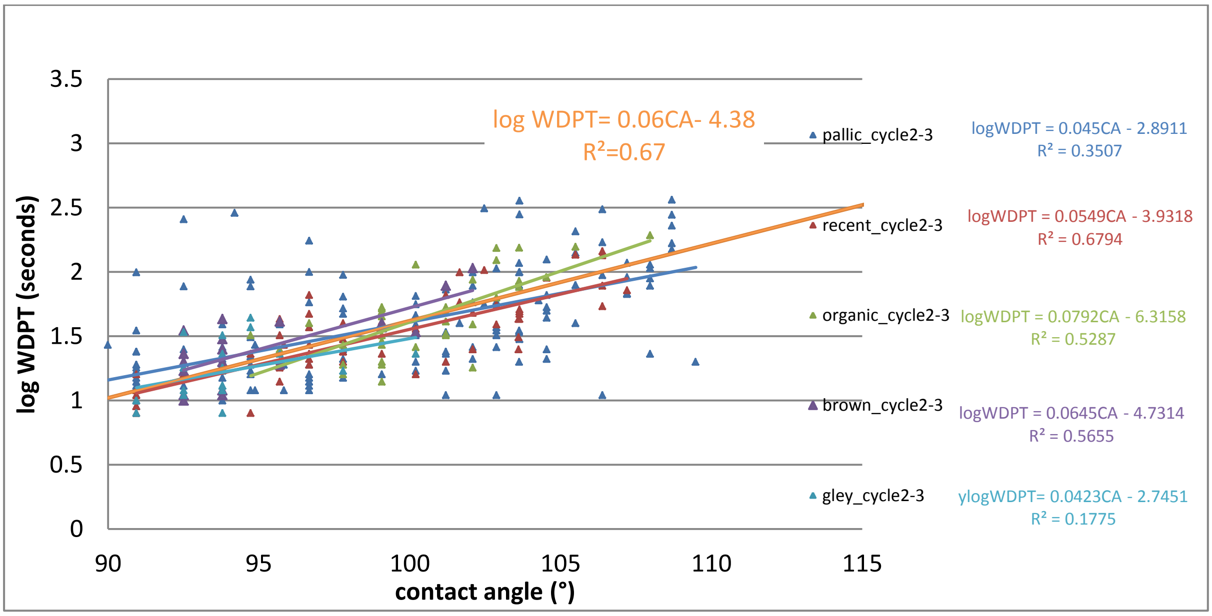


Figure 37: Relationship between CA and WDPT values for undisturbed samples, second and third drying cycle, presented for the different soil orders

As presented in Figure 38, the relationship between the water droplet penetration times and the contact angles for the disturbed samples is the same for all soil orders as well as for all drying cycles and was found to be moderately close with a coefficient of determination of 0.73. Figure 39 presents the experimentally found relationships between the water droplet penetration times and the contact angles for the undisturbed and disturbed samples. For the same water drop penetration times, the contact angles of the disturbed samples were a lot smaller than for the undisturbed samples. One possible reason for this difference could be the oven- drying of the disturbed samples.

Goebel et al. (2004) and Dekker et al. (1998) stated that heat treatment let WDPT values remain unchanged while the contact angles decrease.

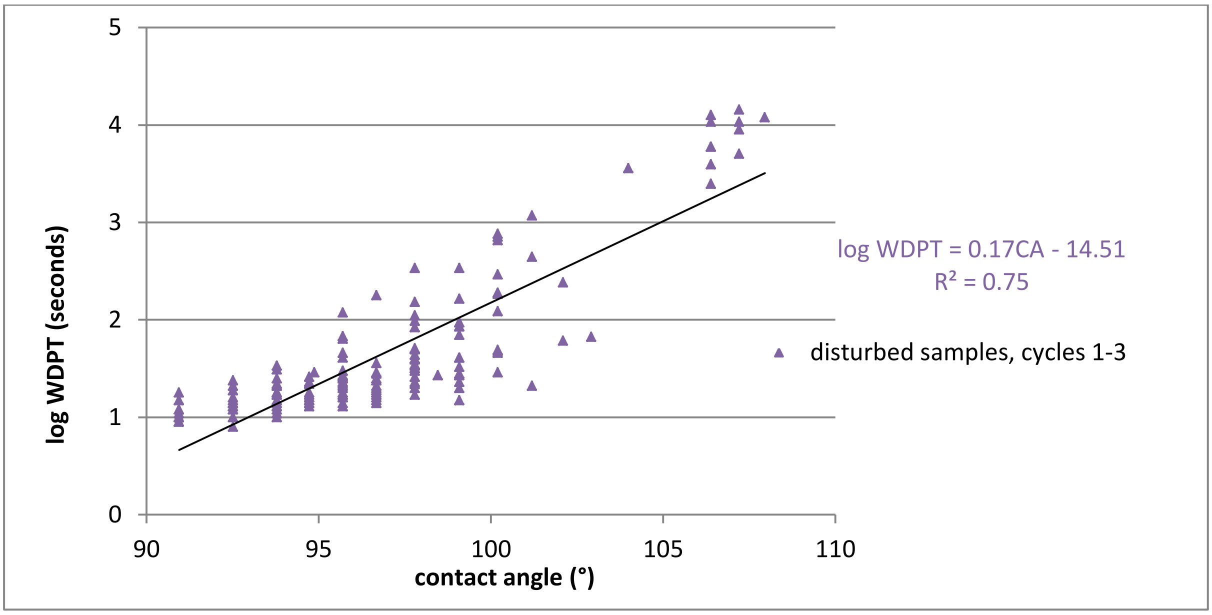


Figure 38: Relationship between CA and WDPT values for disturbed samples, for all drying cycles, for all soil orders

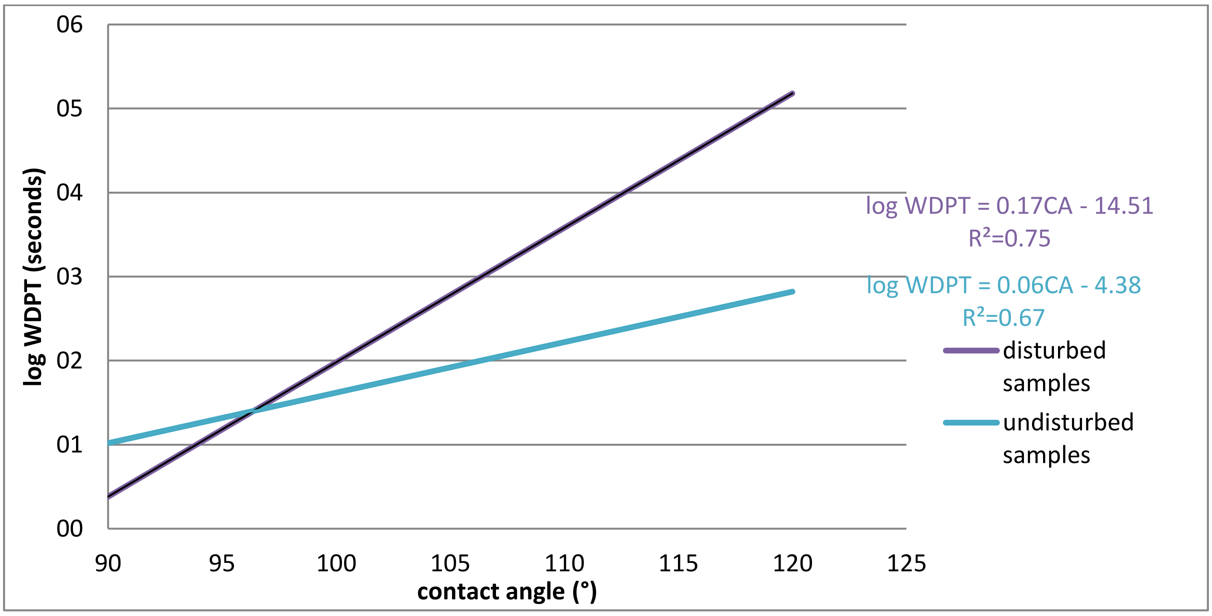


Figure 39: Differences between the relationships of WDPT and CA for disturbed and undisturbed samples, the coefficients of determination are with R^2=0.75 respectively R^2=0.67 not too bad.

4.2.3 Description of the water repellency curves for the undisturbed samples

Figures 40 to 43 present soil water repellency curves for different soil orders which were determined either with the WDPT or with the MED- tests. All soil water repellency curves observed on the undisturbed samples have the typical single- peak- shape which is described in literature (King, 1981; Regalado & Ritter, 2005). At very low soil water contents close to 0, soil water repellency increases with increasing moisture content, it then reaches a peak and finally decreases rapidly to 0 to regain the state of wettability. Two- peak- behaviour as described by De Jonge et al., (1999) was not observed. Soil water repellency was present at all moisture levels below the critical water content for all soil orders except for the brown soil, where two of the three replicate samples showed wettability at very low moisture contents. All soil water repellency curves have similar shapes, but different water contents at which they become hydrophobic and at which they reach their peak SWR value. These differences also occur within one soil order from different sites (e.g. figure 40: critical water contents have a range of about 0.15 m^3/m^3, the water contents of peak SWR differ in approximately 0.2 m^3/m^3). The organic soil was hydrophobic already during the first measurement and the repellency curve therefore starts at a WDPT- value >0. The differences between the results of WDPT- and MED- tests are not very pronounced, the curves obtained with the WDPT- test, however, seem to be more consistent and are thus presented below. The complete set of soil water repellency curves for all tested soil samples can be found in Annex C: C, D, E and F.

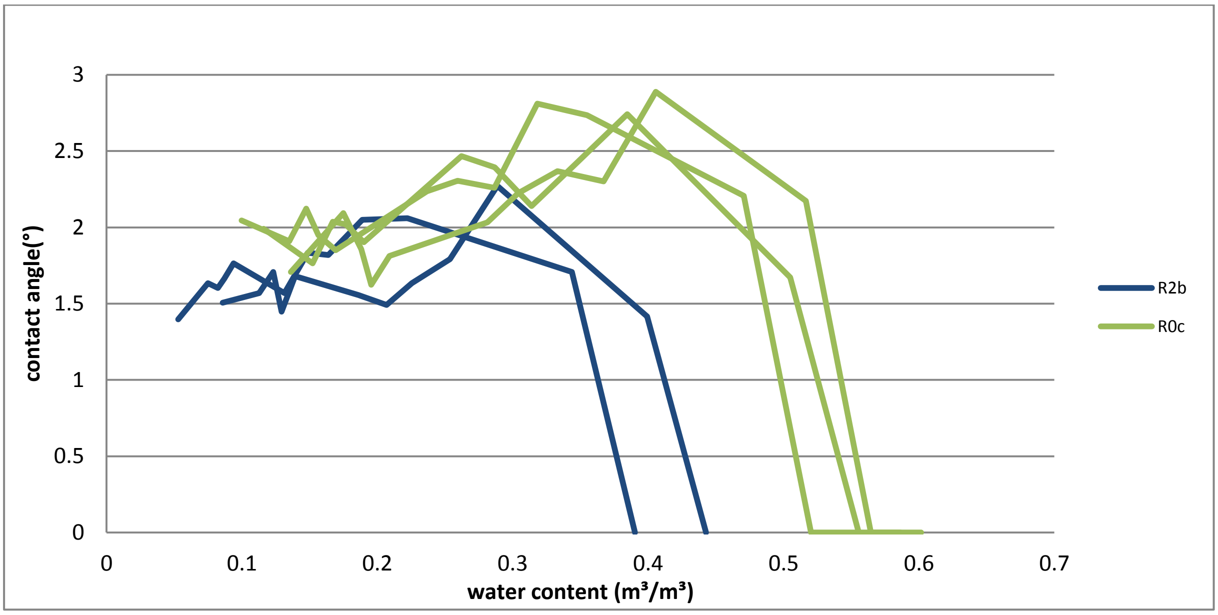


Figure 40: Soil water repellency curves; 1st drying cycle; Hawke's Bay's recent soils

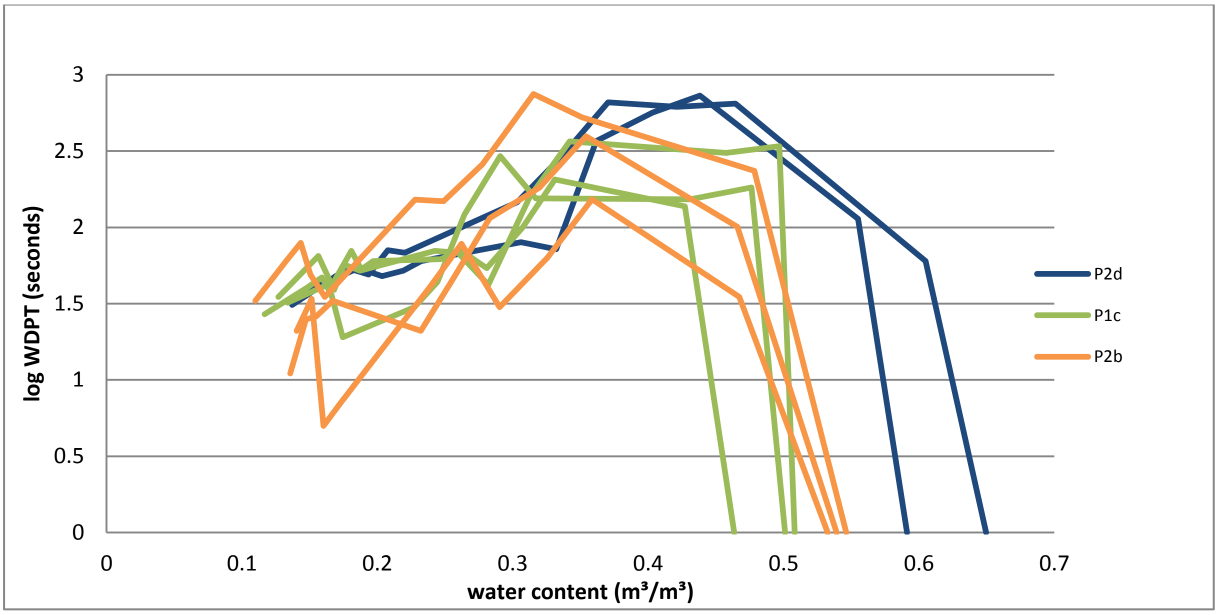


Figure 41: Soil water repellency curves; 1st drying cycle; Hawke's Bay's pallic soils

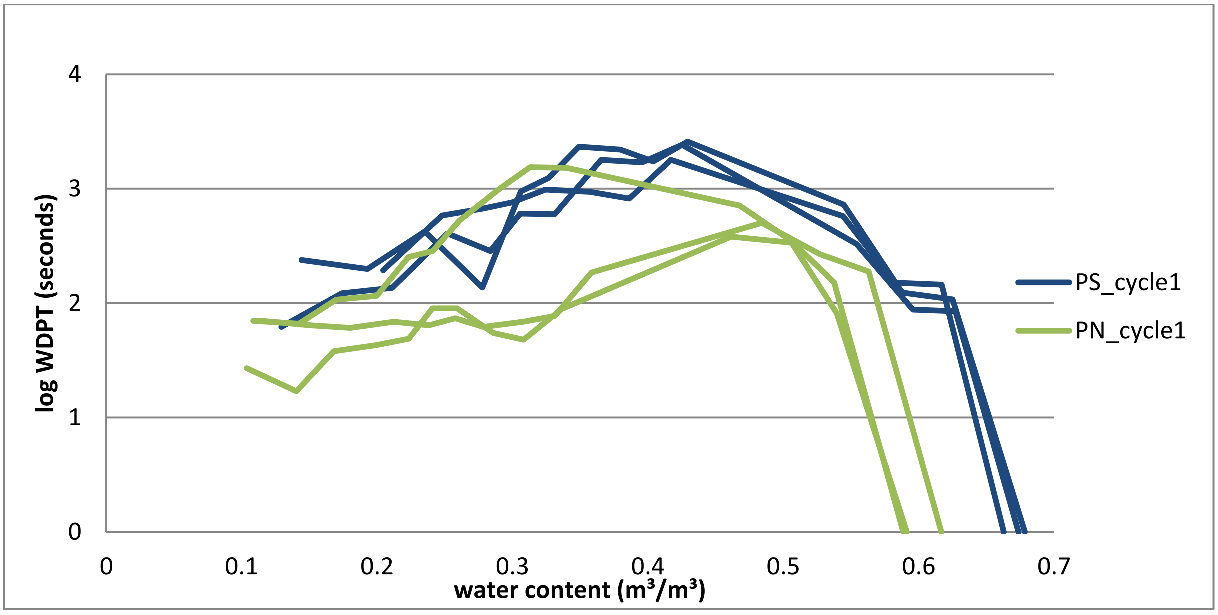


Figure 42: Soil water repellency curves, 1st drying cycle, Tararua's pallic soil

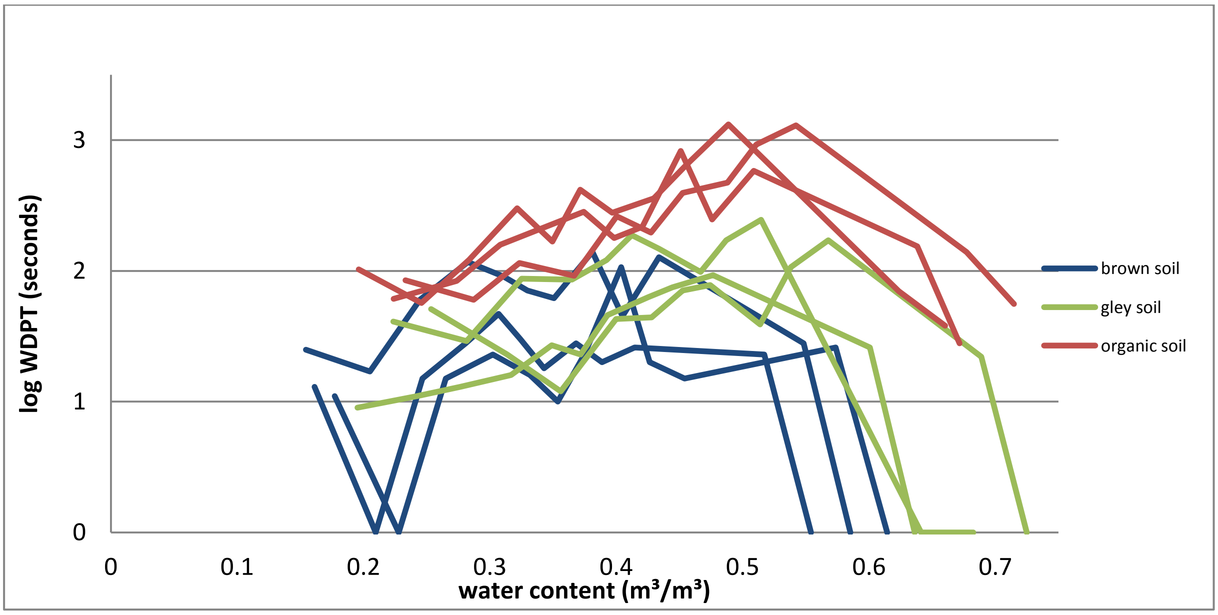


Figure 43: Soil water repellency curves, 1st drying cycle, Taranaki's brown, gley & organic soil

4.2.4 Re- establishment of soil water repellency- comparison of different drying cycles for the undisturbed samples

As described in section 2.3.4, soil water repellency tests were executed during four drying cycles on the undisturbed soil samples as to observe the possible re- establishment of soil water repellency. Between the cycles the samples were rewetted until they were wettable again. Both the WDPT- and MED- tests showed that soil water repellency re-established when the moisture content reached below the critical water content. However, this critical water content threshold decreased with every cycle, especially between the 1st and 2nd cycles (**Fehler! Verweisquelle konnte nicht gefunden werden.**-46). The magnitude of the contact angles stayed essentially the same over the course of the cycles, the WDPT values, however, were significantly lower for the 2nd, 3rd and 4th cycles than for the 1st cycle (Figures 44 to 49). The shape and magnitude of the SWR curves is more or less the same in all test cycles for water contents below 0.35 m³/ m³; above water contents of 0.35 m³/ m³, it is still the same in 2nd to 4th cycle, but differs in the 1st cycle. While in the first cycle all samples stayed water repellent at all water content values below the critical threshold value, in the following cycles some samples became wettable as they reached water contents close to zero (e.g. figure 46 and 47: sample P2d, cycle3). However, all samples were water repellent at some stage of every drying cycle, albeit to a lower extent. Replicate samples show very homogeneous results. The complete set of graphs for all tested soil samples can be found in Annex C, D, E and F.

The higher levels of hydrophobicity in the first cycle may be caused by the fact that the samples were still under the influence of the field conditions. A second reason for this discrepancy could be the impact of microorganisms which are still alive in the first cycle, but die in the following cycles due to the drying processes.

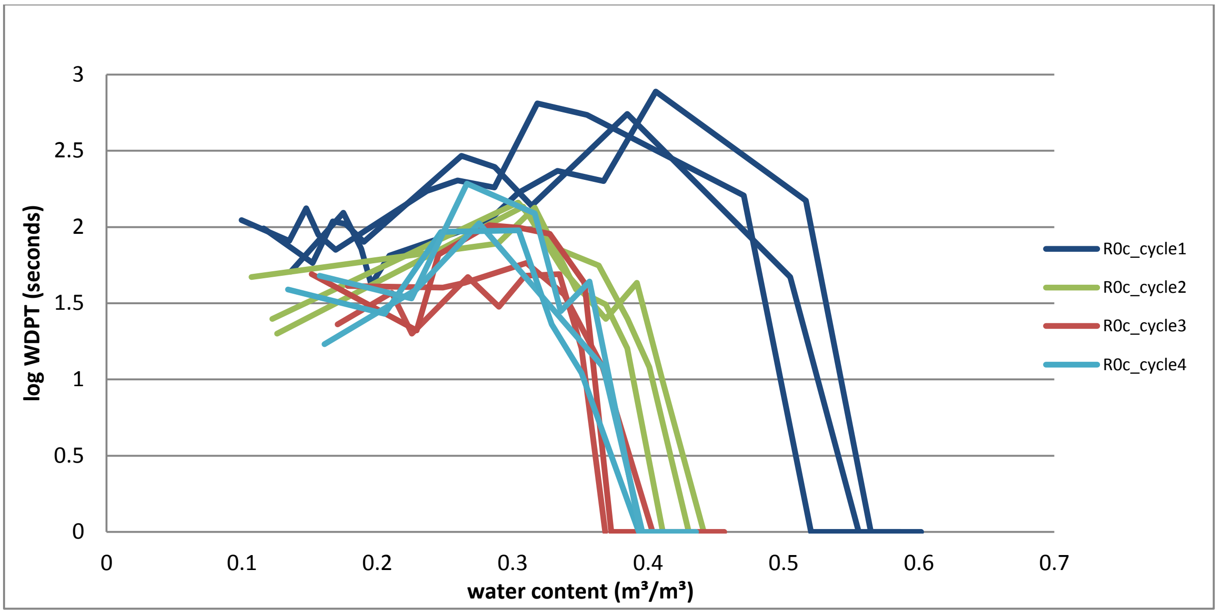


Figure 44: Soil water repellency curves, expressed by water droplet penetration times, undisturbed samples, different drying cycles, site R0c

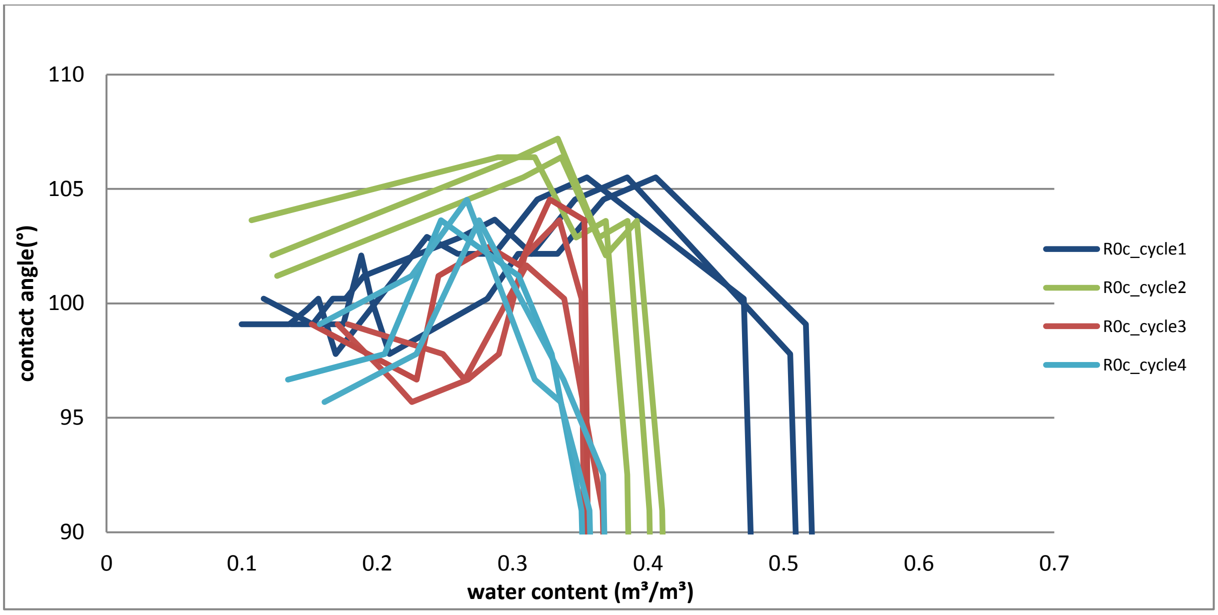


Figure 45: Soil water repellency curves, expressed by contact angles, undisturbed samples, different drying cycles, site R0c

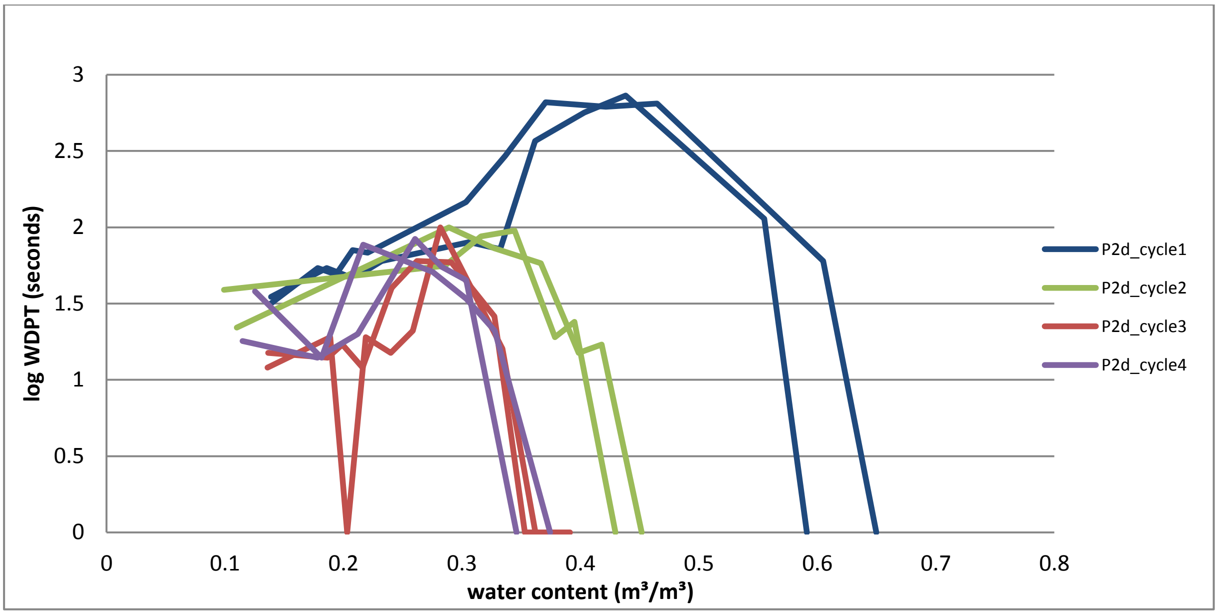


Figure 46: Soil water repellency curves, expressed by water droplet penetration times, undisturbed samples, different drying cycles, site P2d

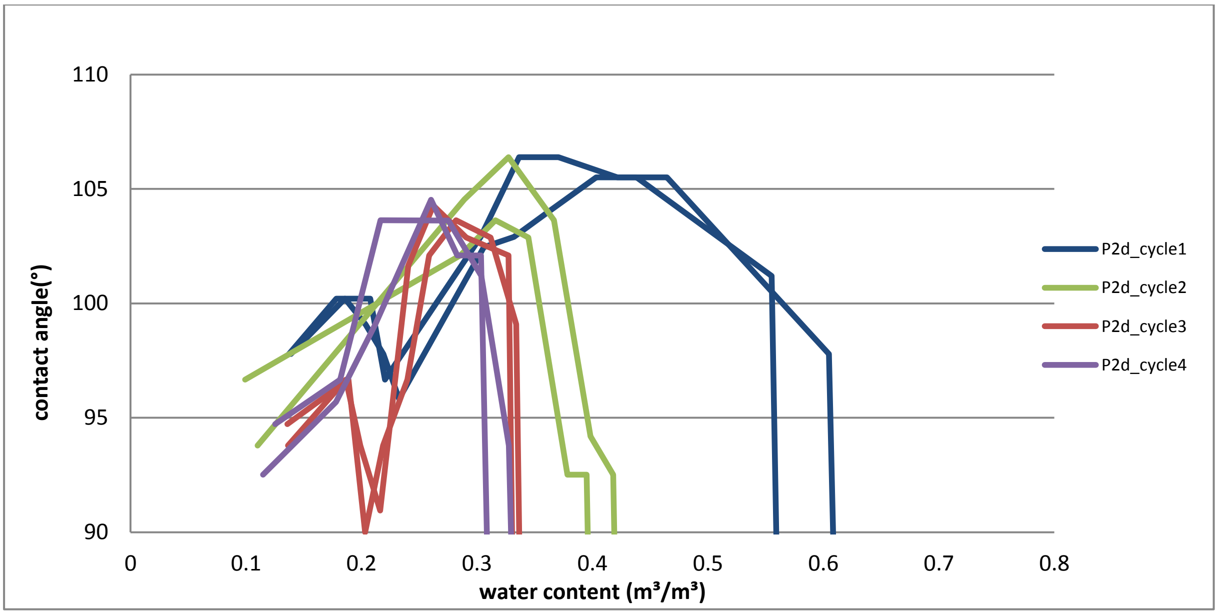


Figure 47: Soil water repellency curves, expressed by contact angles, undisturbed samples, different drying cycles, site P2d

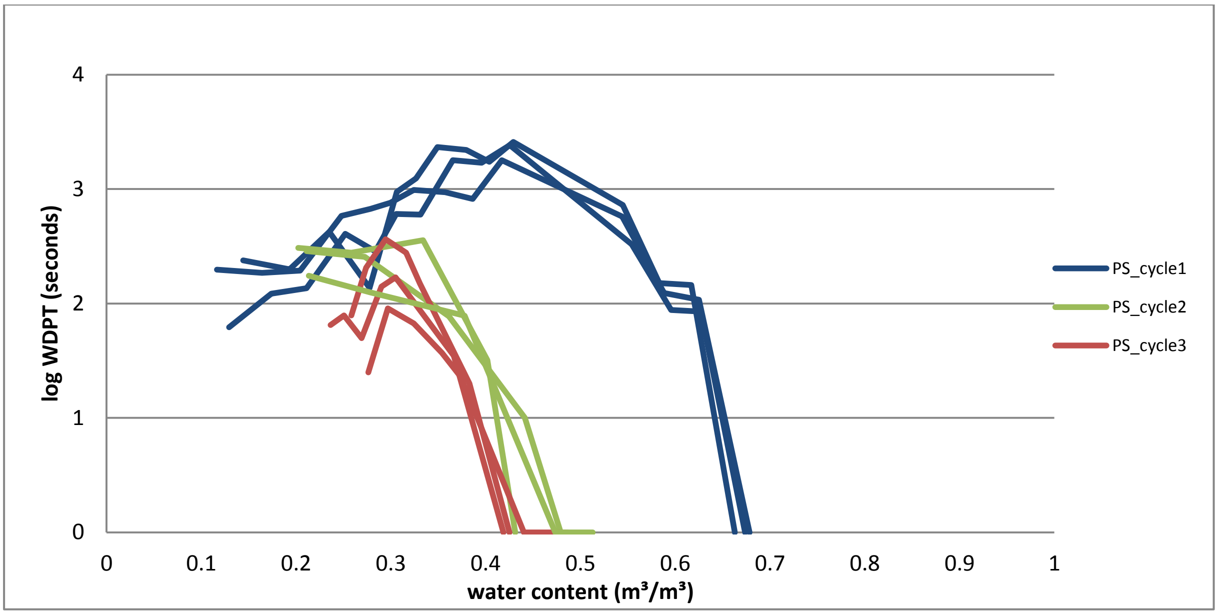


Figure 48: Soil water repellency curves, expressed by water droplet penetration times, undisturbed samples, different drying cycles, site PS

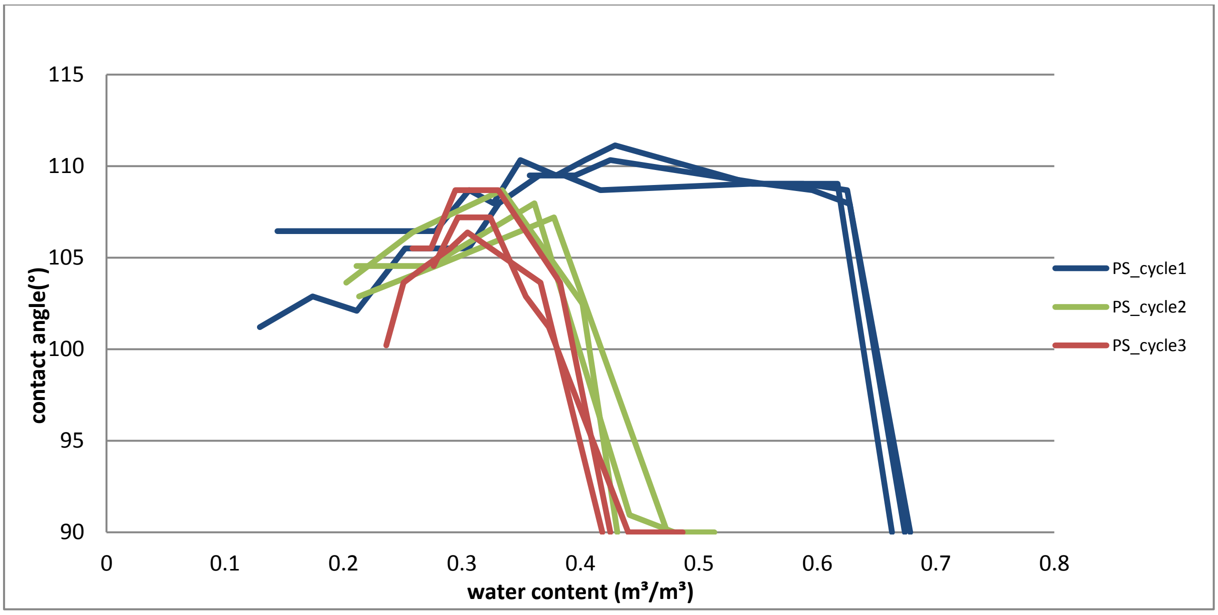


Figure 49: Soil water repellency curves, expressed by contact angles, undisturbed samples, different drying cycles, site PS

4.2.5 Description of the water repellency curves for the disturbed samples

The typical shape of a soil water repellency curve is less pronounced for the disturbed samples (Figures 50 to 55). At very low soil water contents, before the peak value of SWR is reached, some samples do not show any repellency at all while others remain water repellent at a relative constant level. Interestingly, this phenomenon does not only occur in between one soil order, but even in between two replicates of the same soil sample (e.g. soil sample R0c in figure 51). This suggests that the individual treatments of the soil samples (the sieving process and the solidification of the oven-dried soil in the cylinder) have an important influence on soil water repellency measurements. The disturbed samples from the site P2d did not showed any water repellency at all at whatever soil water content, while the undisturbed soil samples for this site showed water repllency during all wetting and drying cycles (Figure 46 and 47). This may be explained with the destruction of repellent soil compounds when the samples were created. Especially the mixing and homogenization process could have led to abrasion of hydrophobic coatings (Ma'shum et al., 1988).

SWR tests were not performed on the Tararua’s disturbed samples because of mould formation on the surface of the samples which would distort the results. The samples of organic and brown soil were solely water repellent at very low water contents < 0.10 m^3/m^3 as presented in figures 54 and 55. It is difficult to give a plausible explanation for this phenomenon; it is possible that the reason is a combination of different phenomena caused by the heat treatment as described in section 2.3.2.

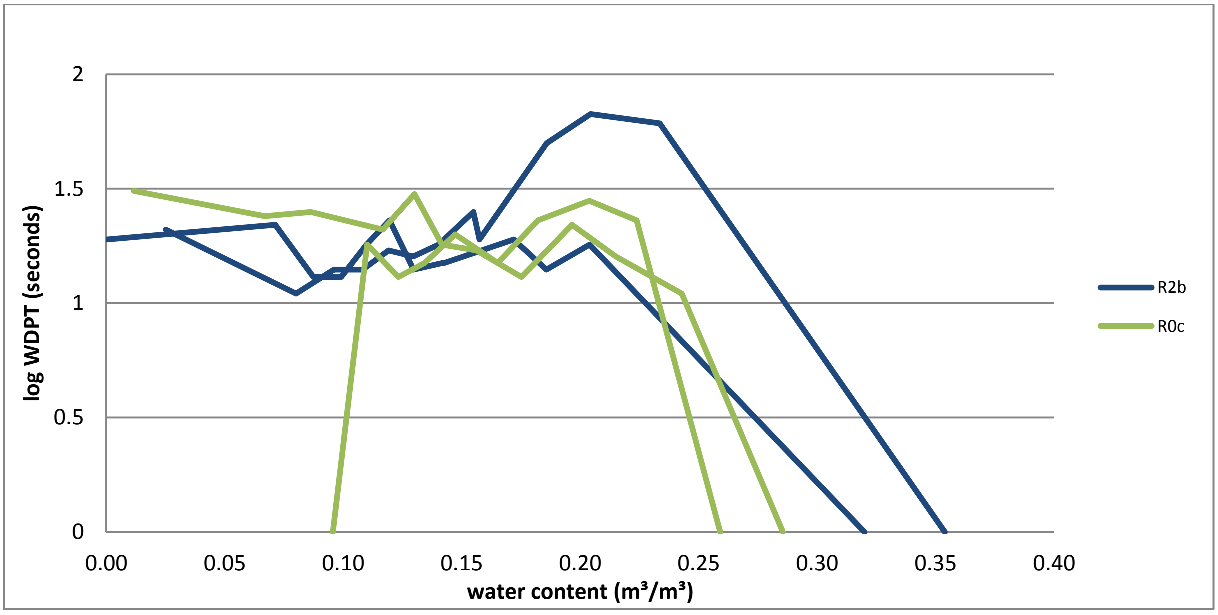


Figure 50: Soil water repellency curves, expressed by water droplet penetration times, 1st drying cycle, disturbed samples, recent soils

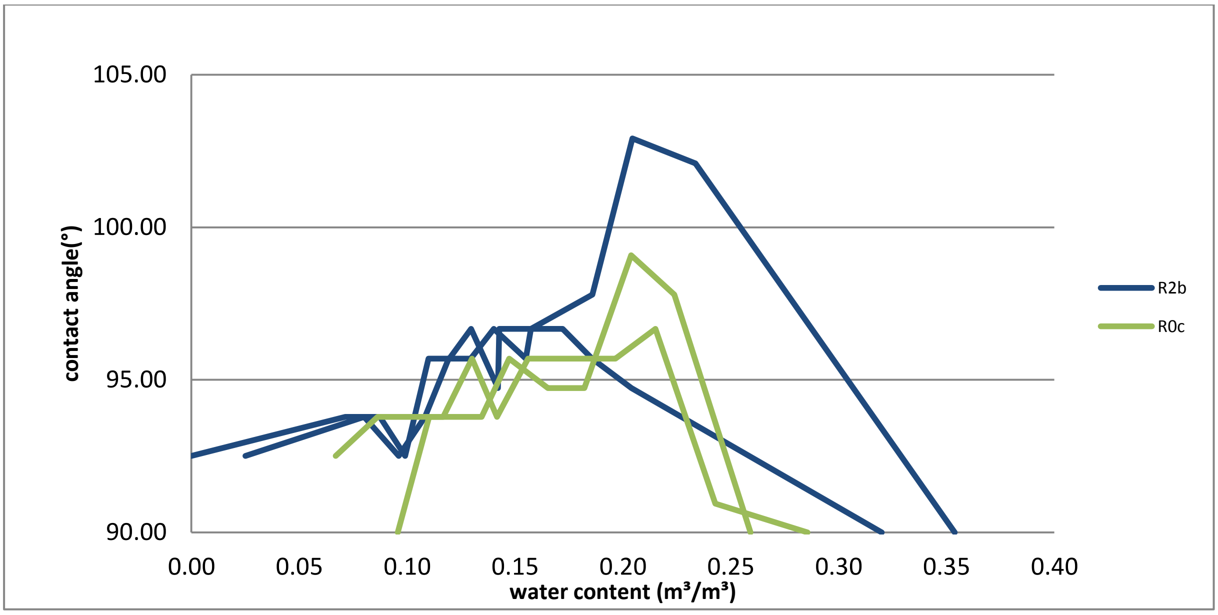


Figure 51: Soil water repellency curves, expressed by contact angles, 1st drying cycle, disturbed samples, recent soils

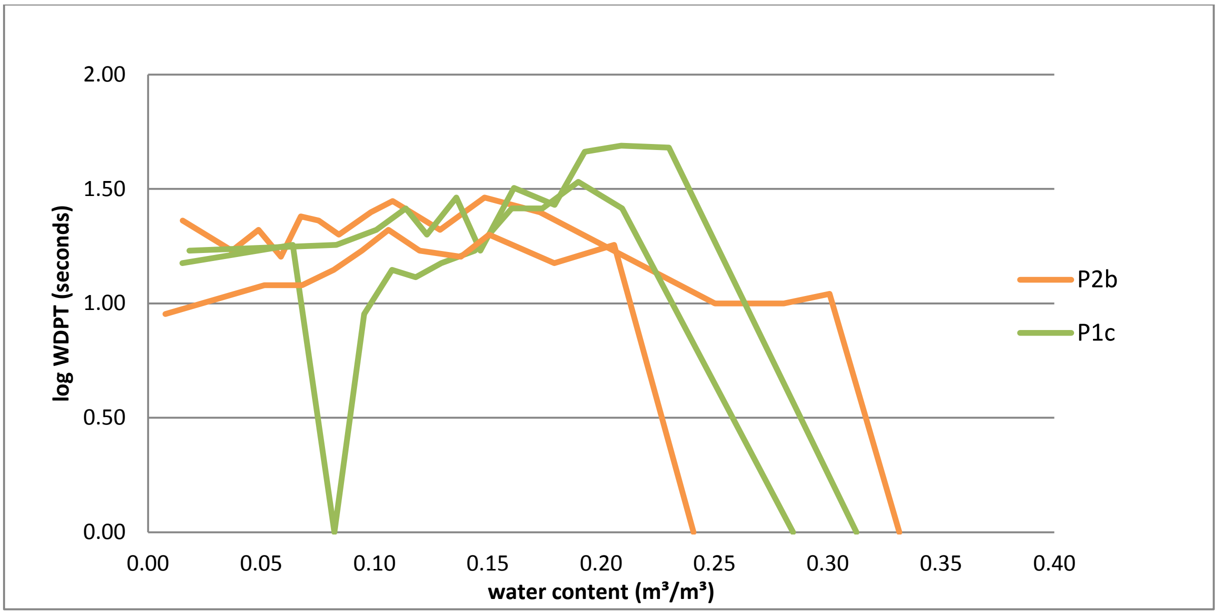


Figure 52: Soil water repellency curves, expressed by water droplet penetration times, 1st drying cycle, disturbed samples, Hawke's Bay's pallic soils

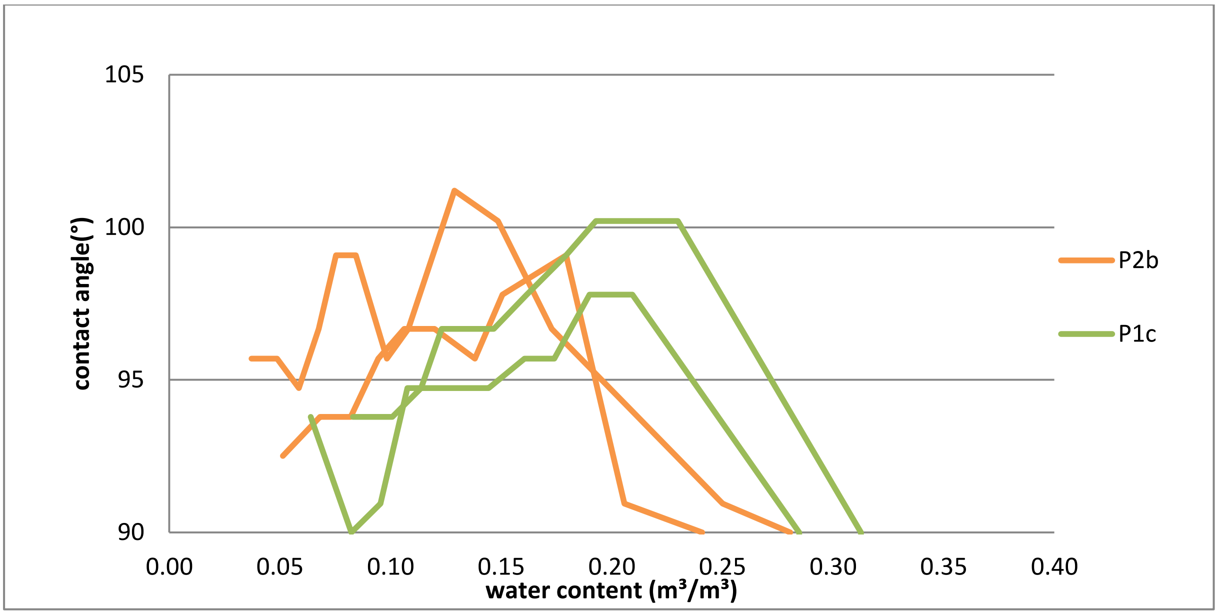


Figure 53: Soil water repellency curves, expressed by contact angles, 1st drying cycle, disturbed samples, Hawke's Bay's pallic soils

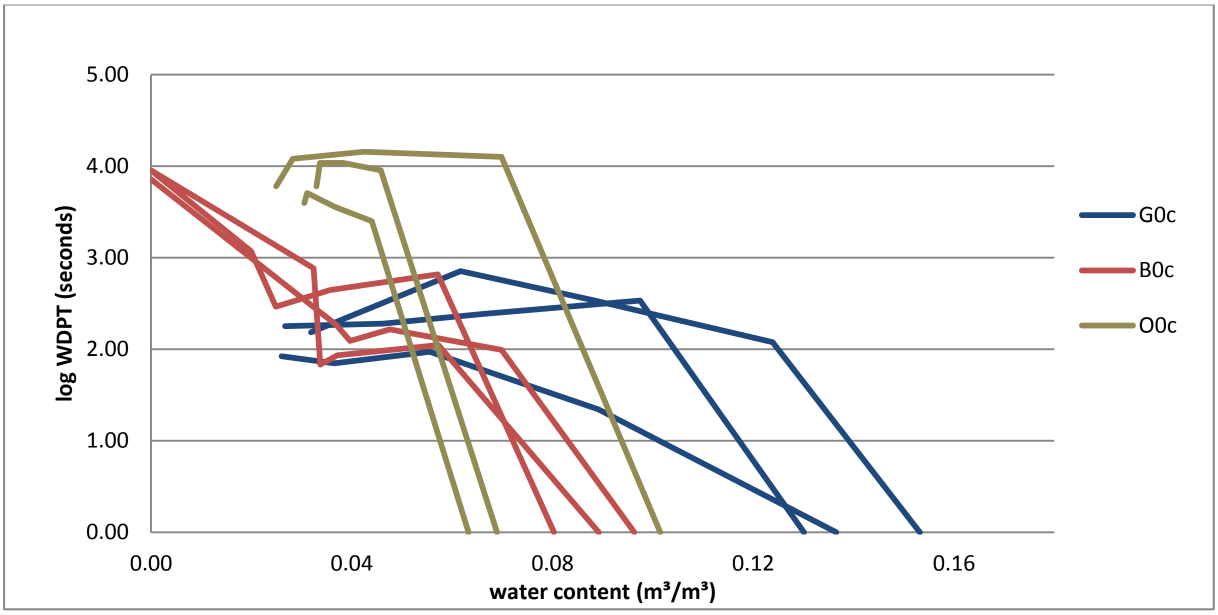


Figure 54: Soil water repellency curves, expressed by water droplet penetration times, 1st drying cycle, disturbed samples, Taranaki soils

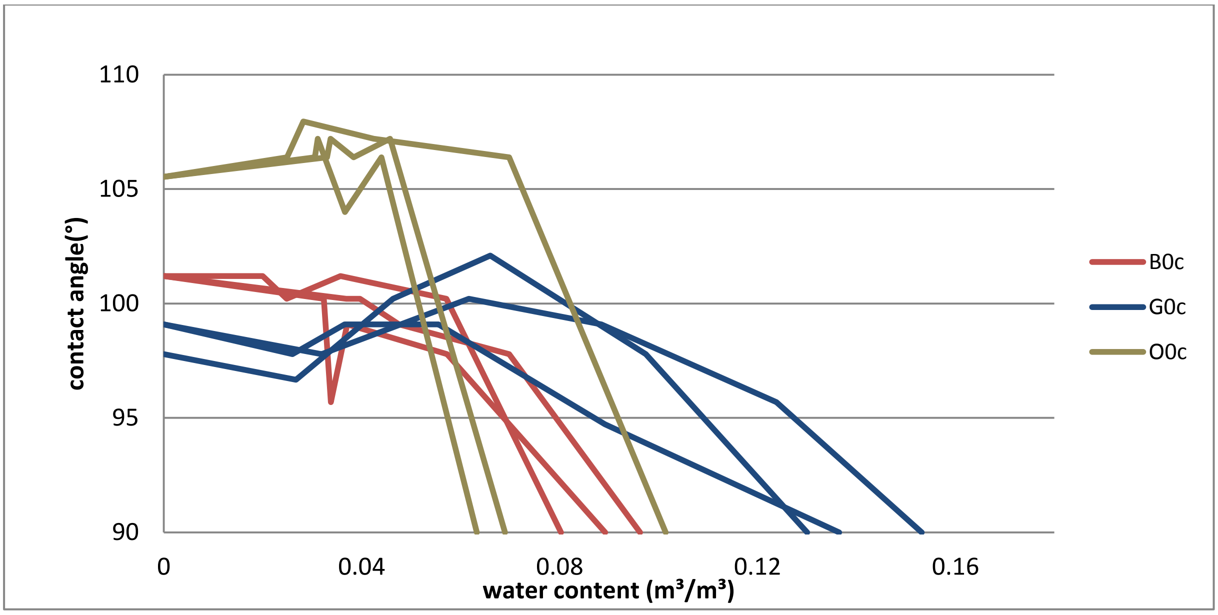


Figure 55: Soil water repellency curves, expressed by contact angles, 1st drying cycle, disturbed samples, Taranaki soils

4.2.6 Re- establishment of soil water repellency- comparison of different drying cycles for the disturbed samples

On the disturbed samples soil water repellency tests were executed during three drying cycles. The SWR- curves differ from those obtained from the undisturbed samples as they were much less homogeneous: on the undisturbed samples, SWR- curves maintained the same shape and magnitude from 2nd to 4th drying cycle; on the disturbed samples, however, there could not be observed a continuous pattern for the SWR- curves of different cycles. Instead, we could identify three possibilities for the development of soil water repellency curves throughout the different drying cycles: (1) some samples showed a complete re- establishment of soil water repellency throughout all cycles (figures 56 and 57), (2) some samples showed decreasing levels of soil water repellency with an increasing number of cycles (figures 58 to 59) as also reported by (Quyum, 2000), and (3) others completely lost water repellency from one cycle onwards (one of the replicates in figures 58 and 59). Table 9 gives an overview on how many samples fulfilled each of the three possibilities.

Table 9: development of SWR- curves during different drying cycles on disturbed samples

Complete re- establishment of SWR throughout all cycles	8 samples
Decreasing levels of SWR with increasing No. of cycles	6 samples
Complete loss of SWR	3 samples

The SWR- levels obtained by the MED- and the WDPT- tests were in close agreement to each other for all drying- cycles. The complete set of graphs for all tested samples can be found in 0.

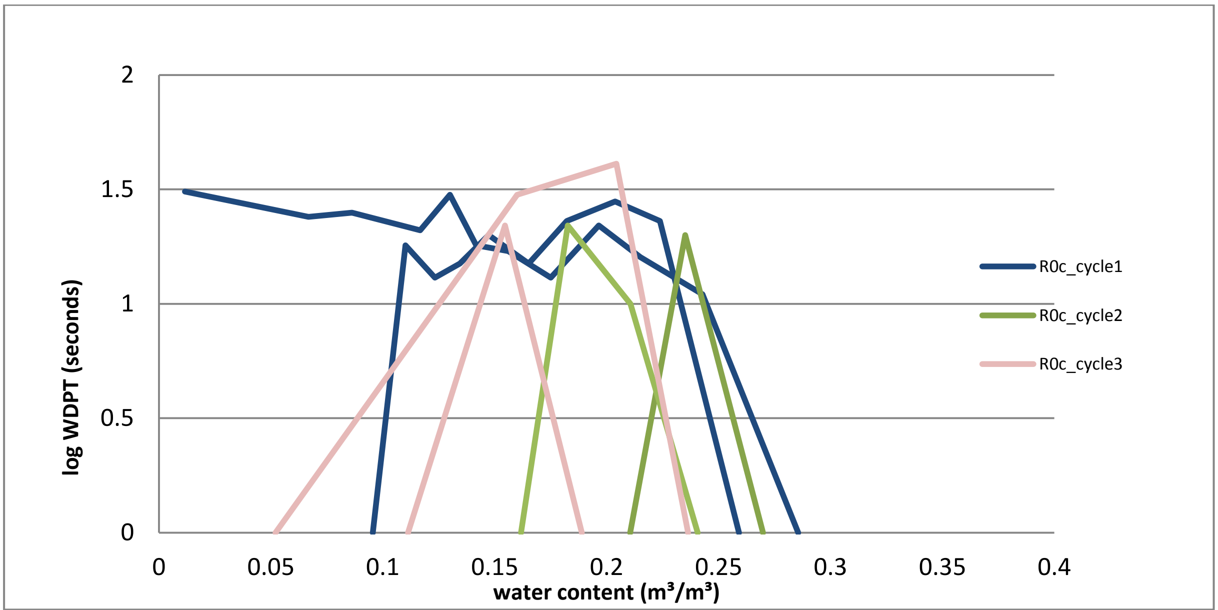


Figure 56: Soil water repellency curves, expressed by water droplet penetration times, disturbed samples, different drying cycles, site R0c

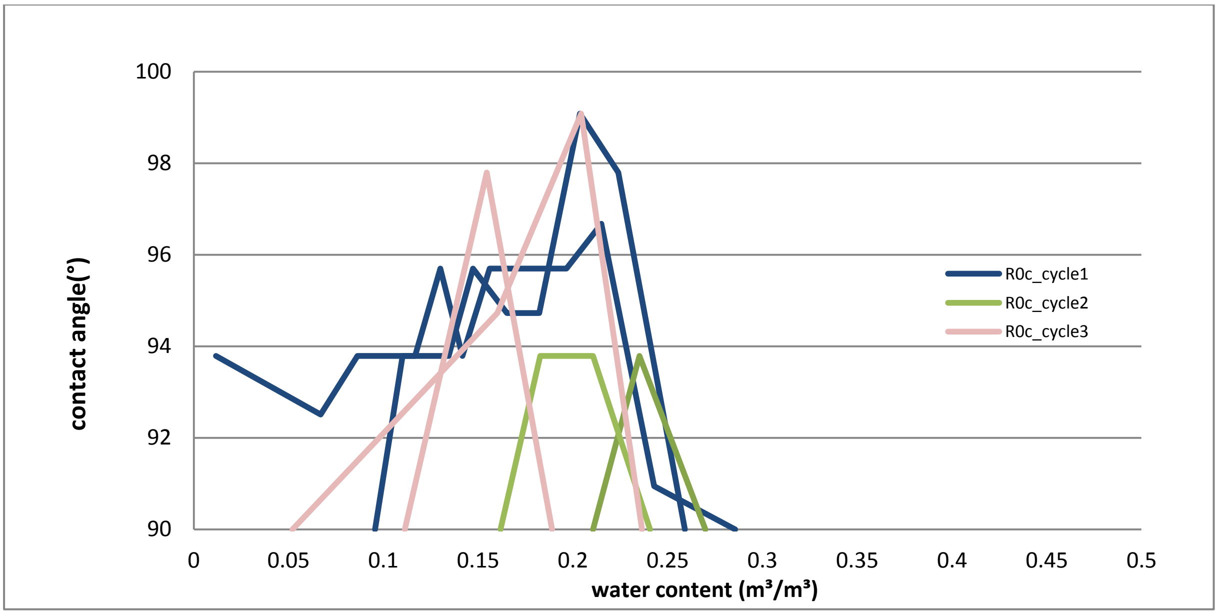


Figure 57: Soil water repellency curves, expressed by contact angles, disturbed samples, different drying cycles, site R0c

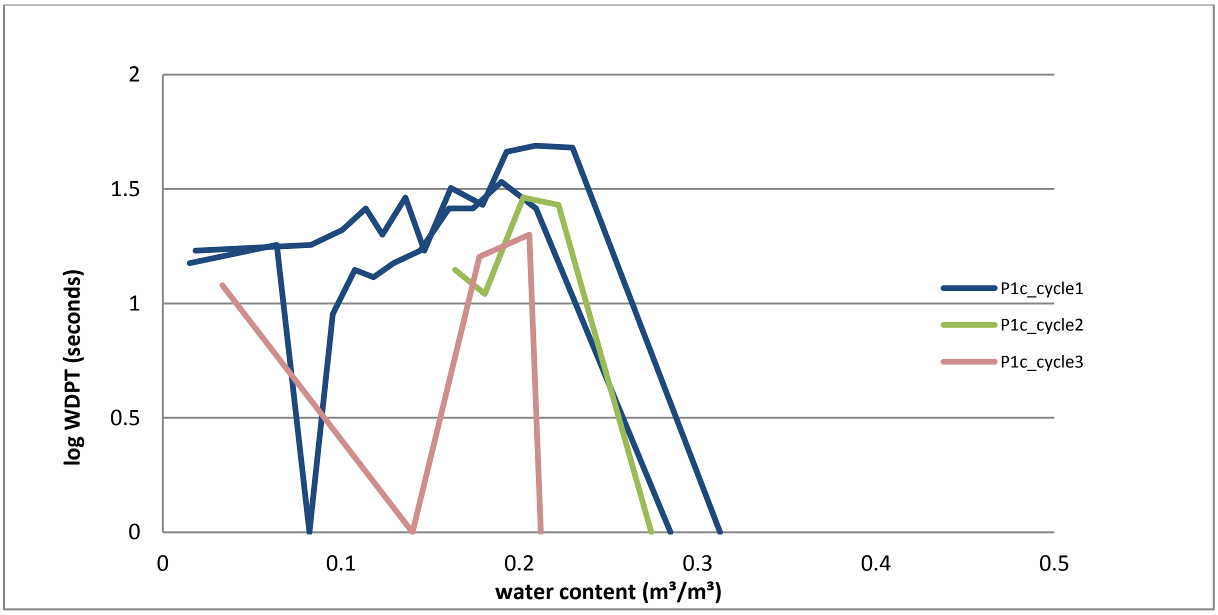


Figure 58: Soil water repellency curves, expressed by water droplet penetration times, disturbed samples, different drying cycles, site P1c

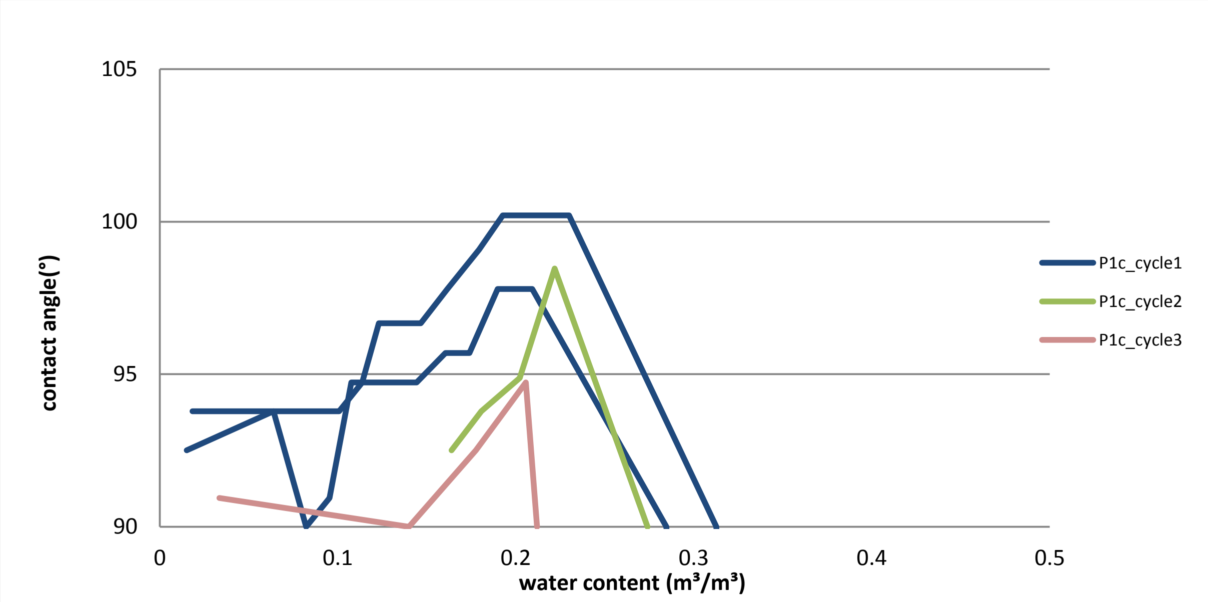


Figure 59: Soil water repellency curves, expressed by contact angles, disturbed samples, different drying cycles, site P1c

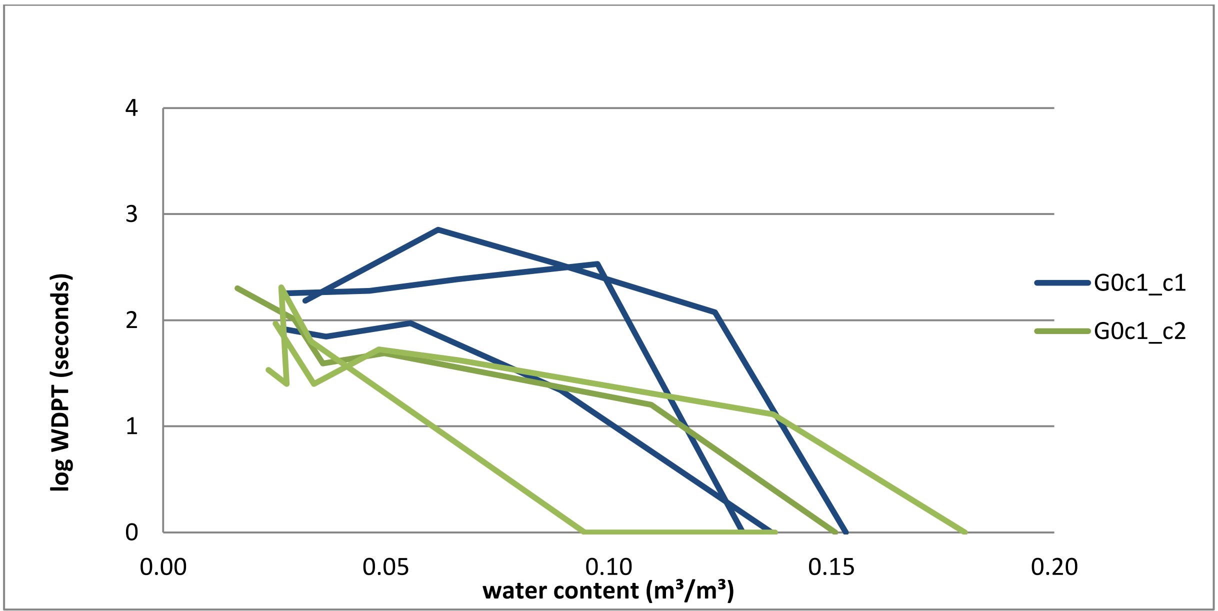


Figure 60: Soil water repellency curves, expressed by water droplet penetration times, disturbed samples, different drying cycles, site G0c

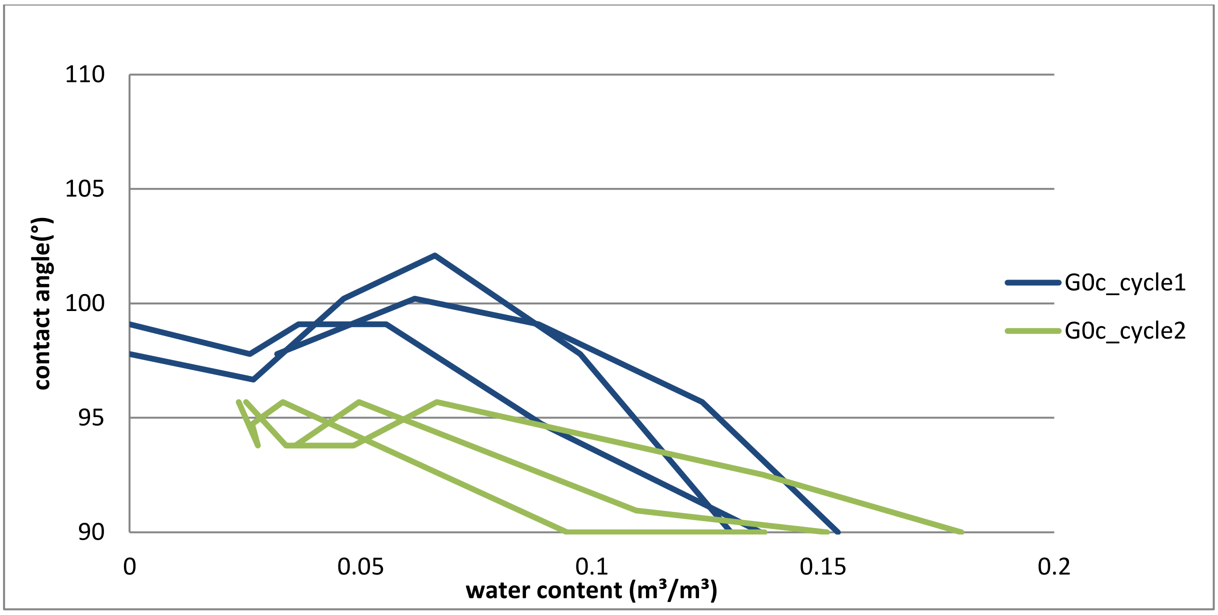


Figure 61: Soil water repellency curves, expressed by contact angles, disturbed samples, different drying cycles, site G0c

4.2.7 Comparison of water repellency curves from undisturbed and disturbed samples

We compared the 1st drying cycle of the disturbed samples with the 2nd drying cycle of the undisturbed samples. They are thought to correspond to each other because they have both undergone one drying cycle. While the pallic and recent soils (examples: site P1c and site R0c in figures 62 to 65) exhibited lower values for the disturbed than for the undisturbed samples, the organic, brown and gley soils (example: site O0c in figures 66 and 67) showed significantly higher soil water repellency for the disturbed than for the undisturbed samples.

As stated by Graber et al. (2006) the observed differences in the SWR measurements between the disturbed and undisturbed samples could be due to modifications in the surface roughness, pore size connectivity or bulk density. Furthermore the organic material which is responsible for the water repellent behaviour could be differently distributed or orientated. The sieving process could have led to abrasion of the water repellent coatings (Ma'shum et al., 1988). As already stated in section 4.2.6 the critical water contents differ extremely between the disturbed and undistbured samples. The disturbed samples started to act water repellent at much lower moisture content than the undisturbed samples throughout all drying cycles. The water repellency curves for the disturbed samples generally showed a total shift towards lower soil water contents as presented in figures 62 to 67.

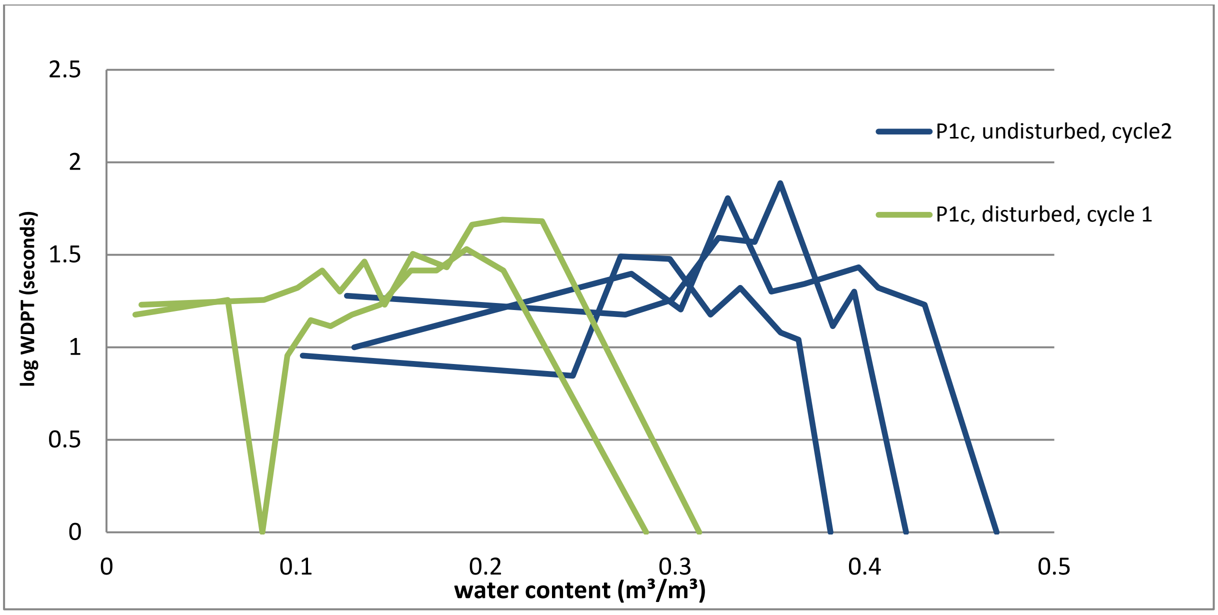


Figure 62: comparison of soil repellency curves for disturbed & undisturbed samples, WDPT test results, site P1c

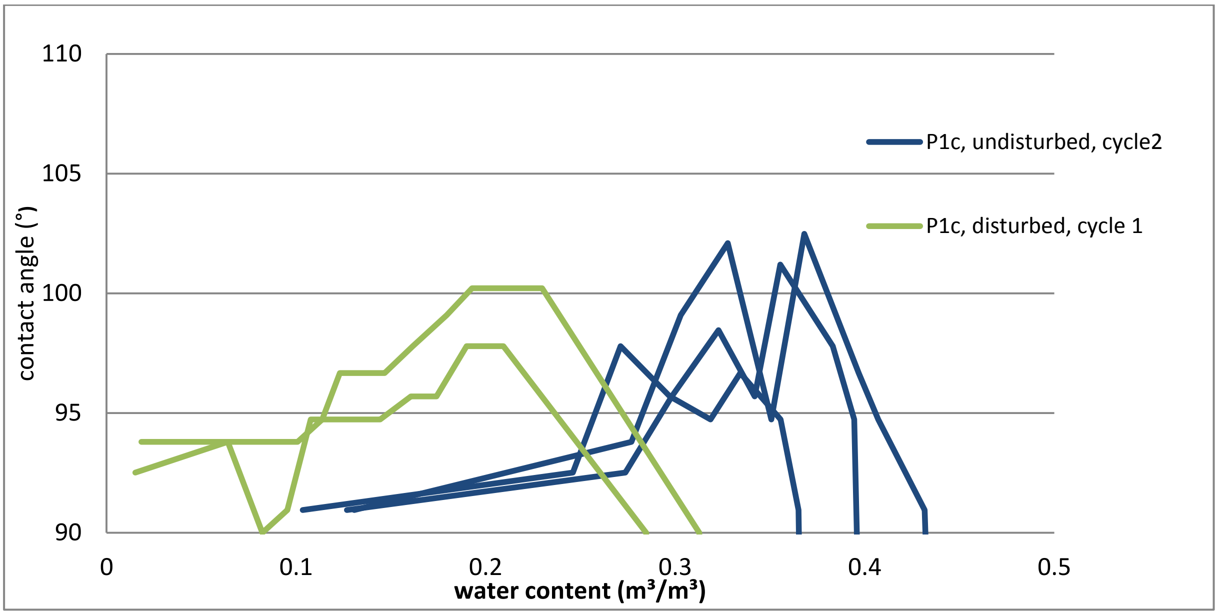


Figure 63: comparison of soil repellency curves for disturbed & undisturbed samples, MED test results, site P1c

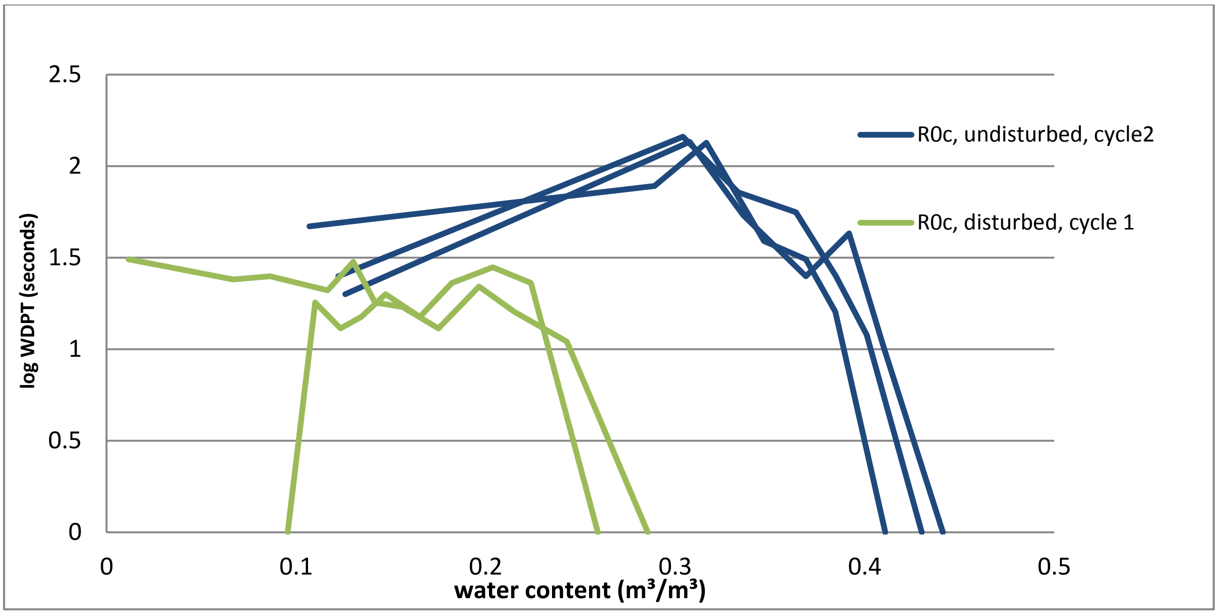


Figure 64: Comparison of soil repellency curves for disturbed & undisturbed samples, WDPT test results, site R0c

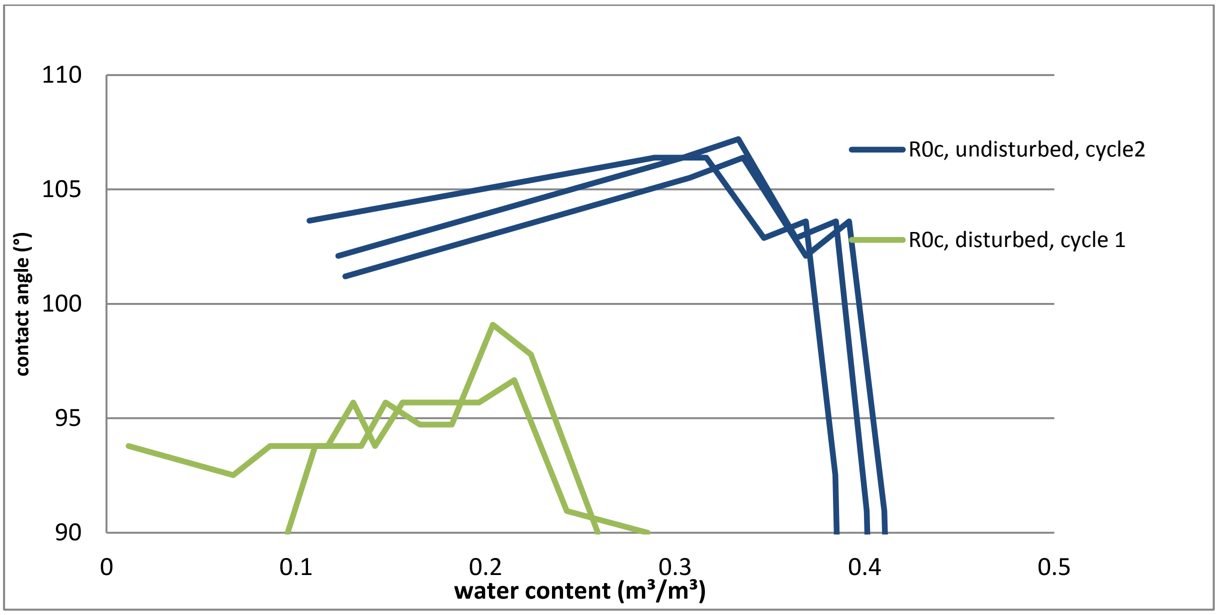


Figure 65: Comparison of soil repellency curves for disturbed & undisturbed samples, MED test results, site R0c

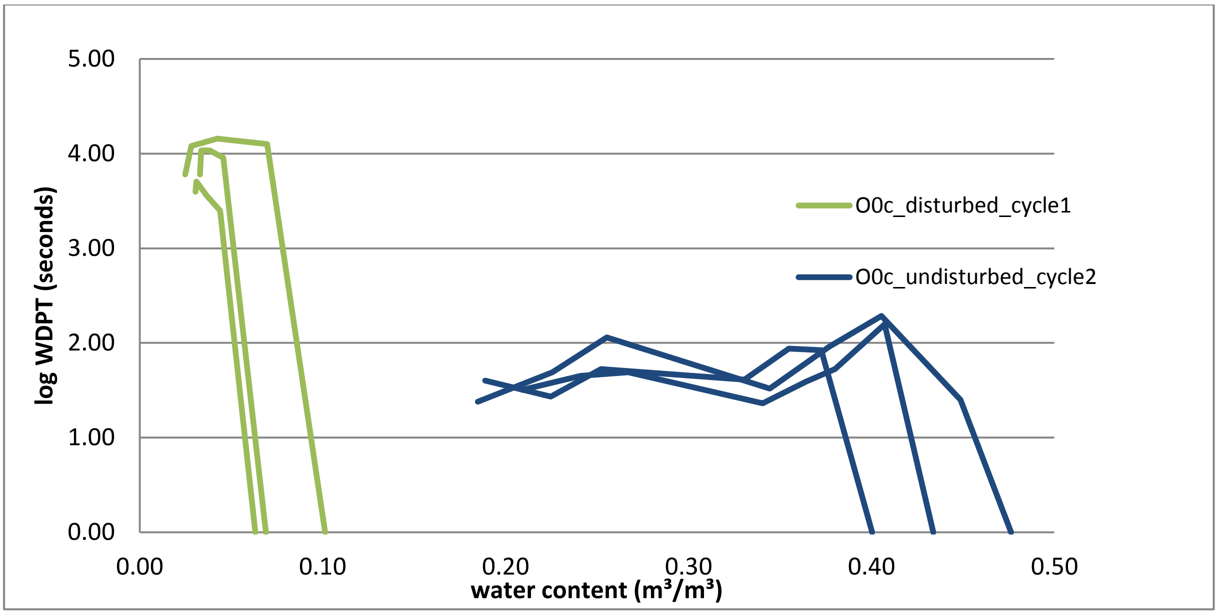


Figure 66: Comparison of soil repellency curves for disturbed & undisturbed samples, WDPT test results, site O0c

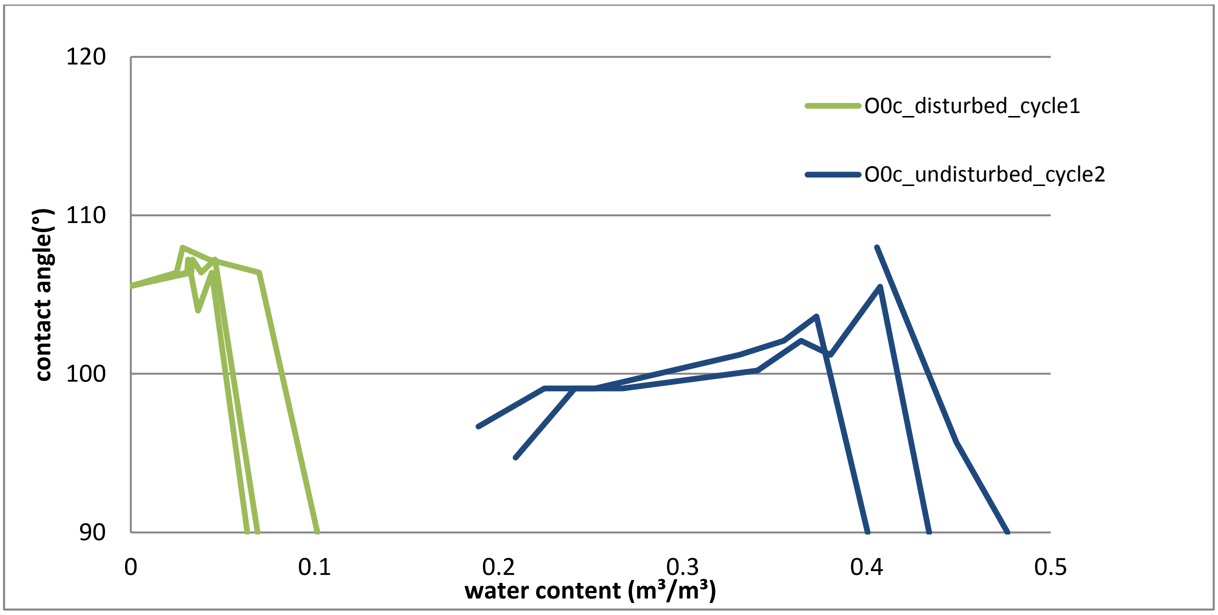


Figure 67: Comparison of soil repellency curves for disturbed & undisturbed samples, MED test results, site O0c

4.2.8 The critical water content

The existence of critical water content or rather a critical transition zone below which soil water repellency occurs could be confirmed in this study. It could also be observed that critical water content levels were much lower for the disturbed than for the undisturbed samples. The question arising was then which of those critical water content levels corresponds best to the actual situation in the field. As presented in section 4.2.5, soil water repellency measurements on the disturbed samples were not consistent (i.e. the shape of the water repellency curves and even the occurrence of SWR differed between replicates from the same study site). The critical water contents obtained on disturbed samples are thus neglected for further analysis. All critical transition zones obtained on the undisturbed samples during the different drying cycles are presented in Annex G for further analysis.

The critical water contents obtained in the first cycle on the undisturbed samples ranged between 0.39- and 0.65 (m^3/m^3). These values, though, seem to be too high because they exceed field capacity and are close to saturation as can be seen in Table 10. When taking the samples from the field, all of them, but the organic ones, were wettable. The critical water content can thus be expected to be found below field capacity. The overestimations of the critical water content in the 1st cycle may be due to inhomogeneous moisture distribution in the samples. Depending on the precipitation- evaporation- regime of the days before the field sampling took place, it could be possible that the top layers of the soil samples were drier than the bottom layers. As soil water repellency measurements were only executed on the samples' surfaces, this could have led to an over- estimation of the critical water contents. It would be of use to avoid this problem by measuring the soil moisture only in the top soil layer (~ 1 cm) and not for the whole sample.

After the 1st drying cycle was finished, both the top and the lower part of the sample were dry. The sample was then continuously re- wetted both from above and from below during a period of two days. In this manner, homogeneous water distribution within the sample could be achieved and also maintained until the CWC was reached (see section 3.2.6).

It can thus be concluded that the water distribution within the soil sample is more homogeneous during the 2nd, 3rd and 4th test cycle than during the 1st, where the soil was exposed to the arbitrary impact of present weather conditions.

Table 10: critical water contents in 1st test cycle, field capacity and degree of saturation in 1st test cycle for samples of all study sites (except for samples of study site O0c which were already water repellent at the start of the 1st test cycle)

	P1c	P2b	P2d	PS	PN	R0c	R2b	B0c	G0c
CWC, 1st drying cycle (m^3/m^3)	0.48	0.50	0.60	0.65	0.57	0.52	0.39	0.57	0.64
field capacity (m^3/m^3)	0.41	0.43	0.42	0.48	0.48	0.38	0.34	0.39	0.49
degree of saturation (m^3/m^3)	0.72	0.86	0.92	0.92	0.91	0.75	0.61	0.75	0.81

The decrease of the critical water content levels with the number of drying cycles is very pronounced between the 1st and 2nd cycle, while it does not really change from the 2nd to 4th cycle. The critical water contents found in the 2nd drying cycles of the undisturbed samples are all very close to field capacity and appear to be closest to the real situation in the field: (I) the water distribution in the samples in the 2nd cycle is homogeneous which makes the results more reliable than those obtained in the 1st cycle and (II) the samples are undisturbed and no destruction of hydrophobic particles could have possibly taken place (see section 4.2.5) which makes the results more reliable than those obtained from the disturbed samples. Furthermore, also the water repellency curve for the 2nd drying cycle appears to be realistic. Regalado & Ritter (2005), King, (1981) and De Jonge et al. (1999) found that the peak of soil water repellency is reached close to the wilting point and the state of wettability occurs when the moisture content approaches field capacity. These conditions are both fulfilled for the 2nd cycle of the undisturbed samples.

As described in section 2.3.4, the water drop penetration times and the contact angles were fitted into a classification system with 6 respectively 4 classes ranging from class 0 = 'wettable' to class 4 respectively 6= 'extremely hydrophobic'. The critical water content is thus the transition from class 0 to class 1. Figures 68 to 72 show the relationship between the persistence of SWR and the soil water content found in the second drying cycle on the undisturbed samples with the transition zone between 'wettable' and 'hydrophobic' indicated in blue. Each of the five graphs presents a different soil order.

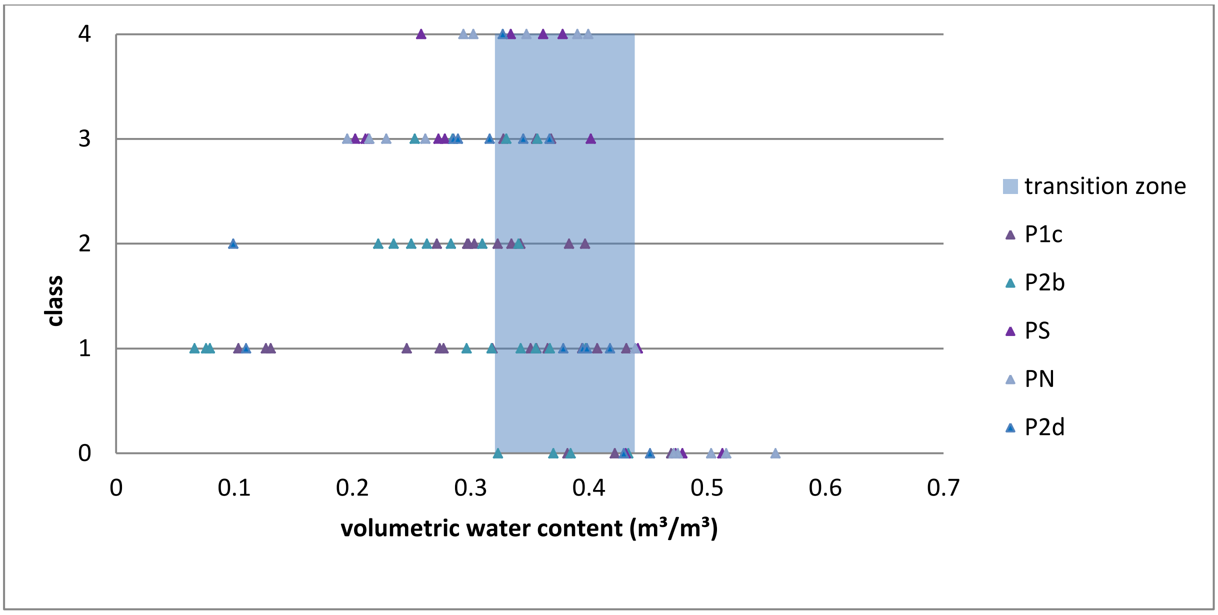


Figure 68: WDPT- classes, 2nd drying cycle, undisturbed samples, pallic soils; the transition zone is indicated in blue

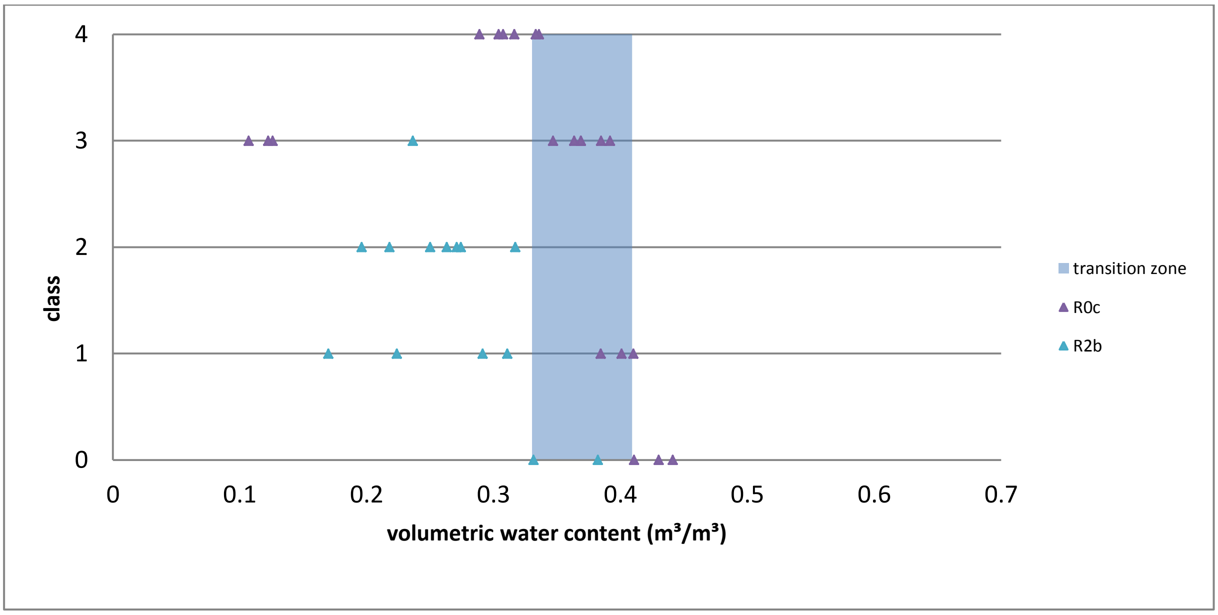


Figure 69: WDPT- classes, 2nd drying cycle, undisturbed samples, recent soils; the transition zone is indicated in blue

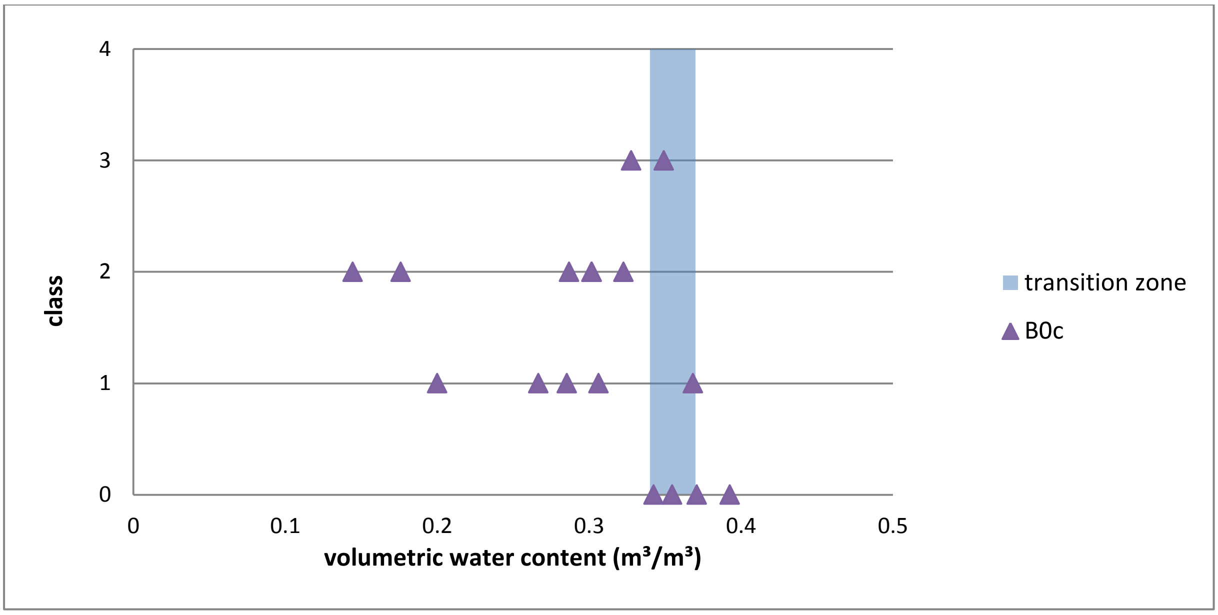


Figure 70: WDPT- classes, 2nd drying cycle, undisturbed samples, brown soil; the transition zone is indicated in blue

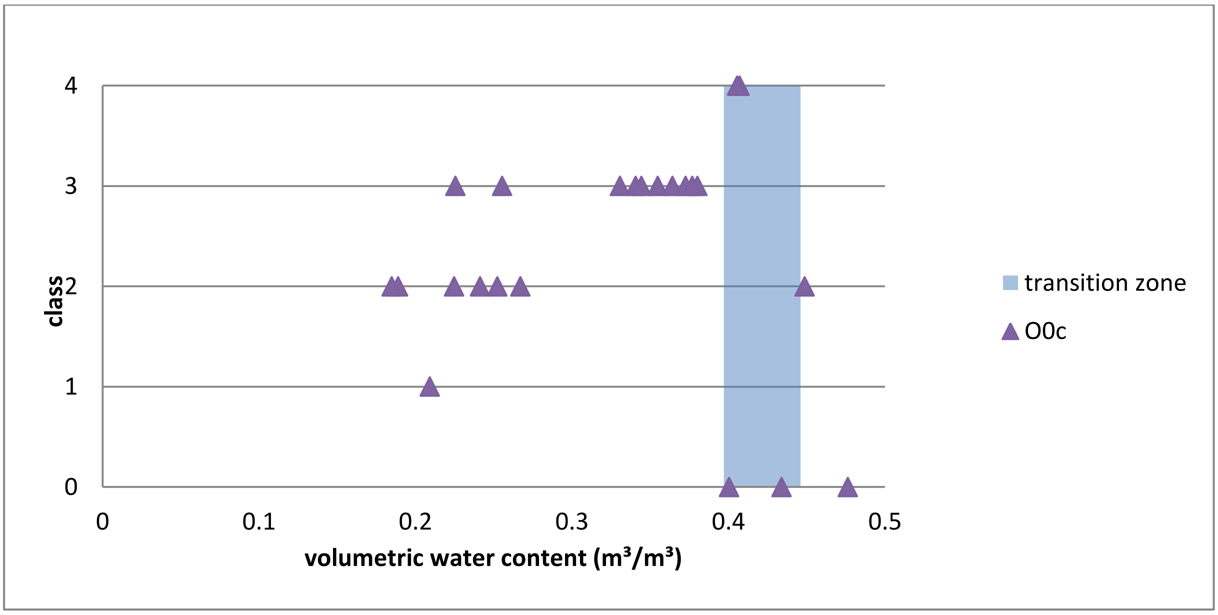


Figure 71: WDPT- classes, 2nd drying cycle, undisturbed samples, organic soil; the transition zone is indicated in blue

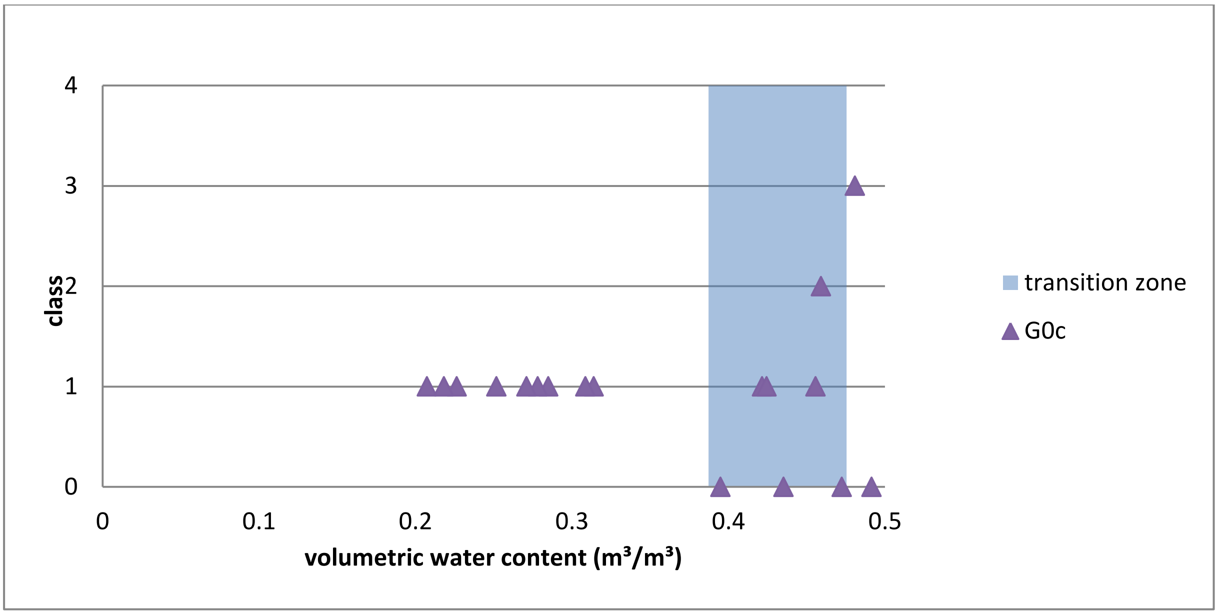


Figure 72: WDPT- classes, 2nd drying cycle, undisturbed samples, gley soil; the transition zone is indicated in blue

The critical water contents ranged between 0.33 and 0.44 (m^3/m^3) for pallic soil, 0.29 and 0.44 (m^3/m^3) for recent soil, 0.34 and 0.37 (m^3/m^3) for brown soil, 0.40 and 0.45 (m^3/m^3) for organic soil and 0.39 and 0.47 (m^3/m^3) for gley soil. These results coincide well with the results obtained by Doerr et al. (2000) on a comparable study site in the UK. He found slightly lower transition zones for loamy soils which are in our case the recent and brown soils and higher ones for clayey soils (pallic and gley soil). The organic soil stands out with an extremely high transition zone and this, once again, coincides well with the fact that the organic soil has been the only soil which was water repellent at the time of sampling. Deurer et al. (2011) gave a very approximate critical water content of 0.45 (m^3/m^3) for all soil orders of the New Zealand North Island which lies within the range of our results (Table 11).

The water balance model requires in lieu of a transition zone a defined single critical water content as an input- parameter. We calculated the mean critical water content as an average of the replicate samples and furthermore determined maximum and minimum values as well as the standard deviation (Table 11). The standard deviation ranges between 0.01 and 0.04 for all soil orders except for the gley soil where it is extremely high with 0.09. This is due to the very low critical water content measured in one replicate sample of gley soil. The reason, however, could not be identified.

Table 11: mean maximum and minimum critical water contents for each sampling site for the 2nd drying cycle of the undisturbed samples. The standard deviation is given as a parameter of reliability.

	P1c	P2b	P2d	PS	PN
Mean CWC	**0.41**	**0.38**	**0.42**	**0.43**	**0.45**
Max CWC	0.45	0.42	0.43	0.46	0.46
Min CWC	0.37	0.36	0.41	0.42	0.43
Standard Dev.	0.04	0.03	0.02	0.02	0.01

	R0c	R2b	B0c	O0c	G0c
Mean CWC	**0.41**	**0.34**	**0.36**	**0.42**	**0.44**
Max CWC	0.43	0.35	0.38	0.46	0.50
Min CWC	0.40	0.32	0.34	0.39	0.34
Standard Dev.	0.01	0.02	0.02	0.04	0.09

Furthermore we wanted to find out if there is a significant difference in the critical water content between the different soil orders. We decided to exclude the CWC- value obtained by the first replicate of gley soil from this comparison because of its great deviation in respect to the other results. Taking the critical water contents of all replicate samples from all other soil types, an ANOVA test was performed (see Annex H:II). We chose the 0, 95% confidence interval and got a p- value of p= 0,004 < 0, 05 which indicates that there is a significant difference between the critical water contents of the different soil orders. While gley and organic soils were observed to be water repellent already at high water contents of about 0.45 m^3/m^3, pallic soils drop hydrophobic at an intermediate level of about 0.41 m^3/m^3 and recent and brown soils are repellent only below a water content of ~ 0.38 m^3/m^3.

Another ANOVA test was performed to find out if there is a difference in the critical water contents for the same soil order which was taken from different regions. In this study this is the case for the pallic soil from Hawke's Bay and Tararua region. The resulting p- value of p= 0.03 < 0,05 indicates that there is a significant difference in the critical water content for soils with the same soil order, but from different regions. The results of the ANOVA test are presented in Annex G: section II.

4.3. Model Results

We applied the water balance model on each sampling site for the time between April 2008 and April 2012. Because of the high number of estimated input- parameters, the measurement uncertainties and the generally abstract character of the model, we only want to discuss the tendency of the model results and do not comment on any exact numbers.

Before presenting the model results, there is given an overview about the used input- parameters and their influence on the model outcomes.

4.3.1 Input- Parameters

4.3.1.1 Rain Data

As described in section 3.3.1, 10- minute rain data measured at the 3 climatic stations Waipawa EWS, Stratford EWS and Palmerston North EWS was used as input- parameter in the water balance model for the different study sites. The climatic station Waipawa EWS did not record any ten minute data between the 16th and the 21st of November 2011. We assumed the rainfall to be 0 during this time. However, regarding the results in the course of one year, this will not have any essential influence on the outcomes of the model.

Table 12 shows the annual rain rates for the selected years from April 2008 to April 2012 as well as the long- term averages in different study regions. Comparatively wet years are indicated in blue, comparatively dry years in red and average years in green colour.

For all three stations the precipitation patterns were relatively stable in the course of the year and do not show any seasonal fluctuations. However, they are located in different regions of New Zealand and are thus exposed to quite different precipitation amounts. Figure 73 shows the cumulated rainfall rates in the course of an average year for the different study regions.

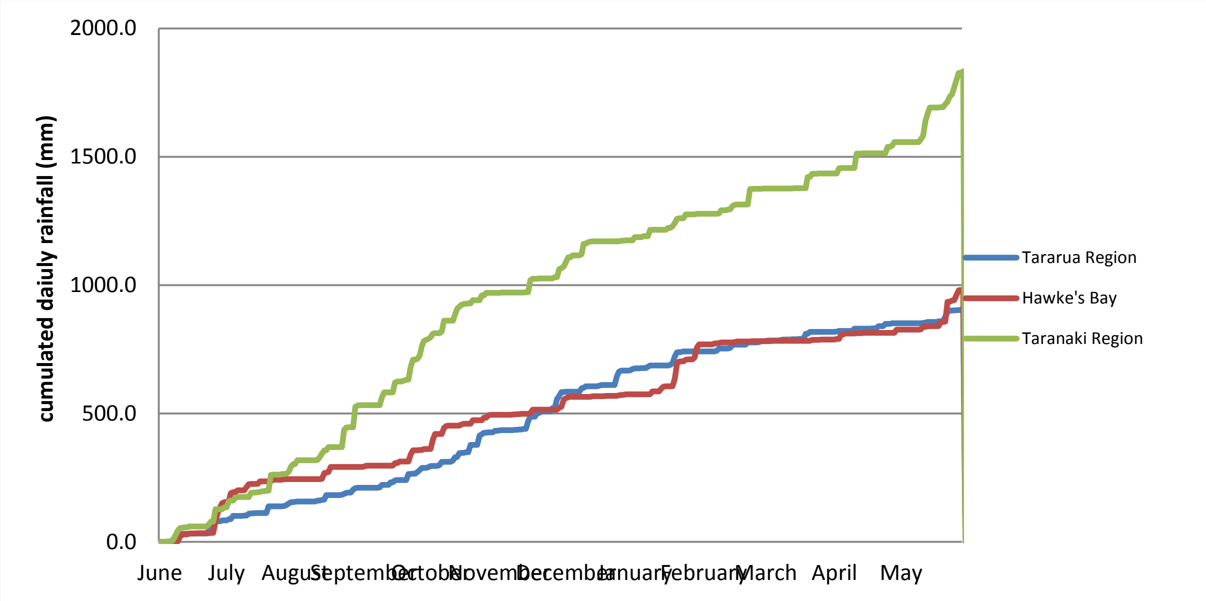


Figure 73: Cumulated daily rain rates for the different regions, from June 2009 to june 2010

Table 12: Annual rainfall for selected years for the selected regions and long- term averages, red= dry year, blue= wet year, green= average year

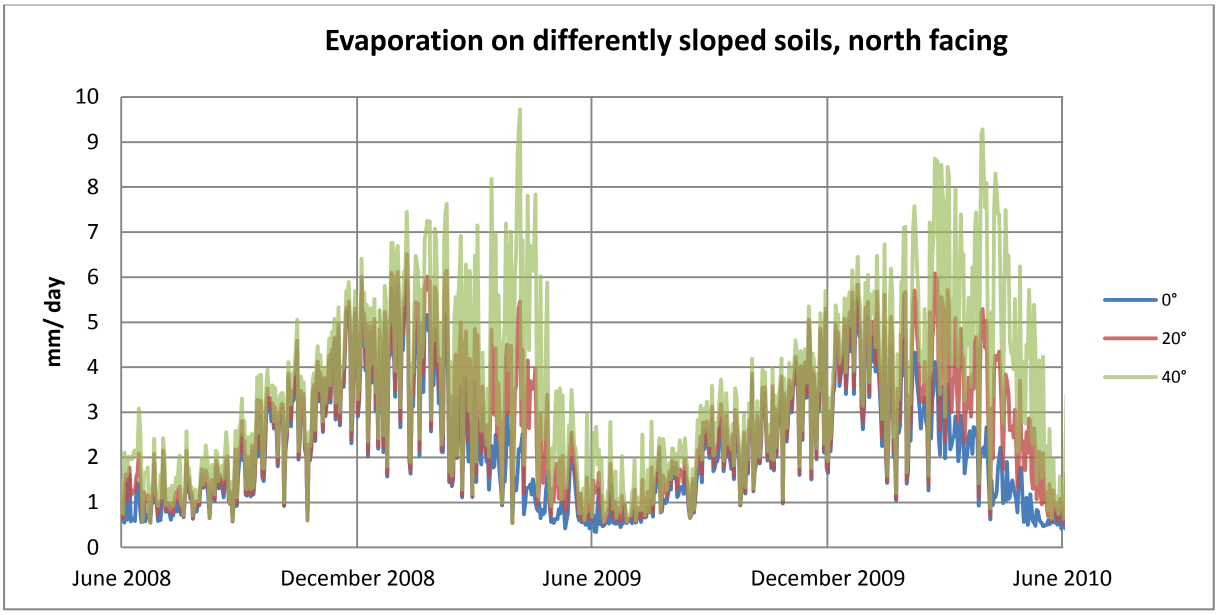
Annual rainfall (mm)	Tararua Region	Hawke's Bay	Taranaki Region
01/04/2008- 31/03/2009	1135	571	2142
01/04/2009- 31/03/2010	904	987	1831
01/04/2010- 31/03/2011	1073	1014	2292
01/04/2011- 31/03/2012	972	807	2143
long- term average (mm)	**935**	**920**	**1975**

While the precipitation regime in Hawke's Bay and the Tararua region is very similar, the Taranaki region is much wetter and exhibits more than the double amount of annual rainfall.

4.3.1.2 Evaporation

Evaporation is a function of the input parameters temperature, relative humidity, wind speed, radiation, aspect and slope. The evaporation rate in the course of the year shows the typical sine curve fluctuations with little evaporation in winter and a high evaporation rate in summer.

Figure 74 show the influence of different slope angles combined with north respectively south aspect on the reference crop evapotranspiration rate. While slope and aspect have hardly any influence on the evaporation rate in autumn (June to December), the impact in spring (December to June) is somewhat more important. In this period, evaporation on north- facing slopes is much higher, while it is much lower on south- facing ones. In the model there can occur negative evaporation on south- facing slopes. The outgoing radiation is then greater than the incoming radiation. The idea behind it is that plants take up water from the air. This water must be evaporated- a process which requires energy - before any evaporation of soil water can take place (see Figure 74). This phenomenon is also present in the south- facing study sites PS in the Tararua Region and R0c in Hawke's Bay.



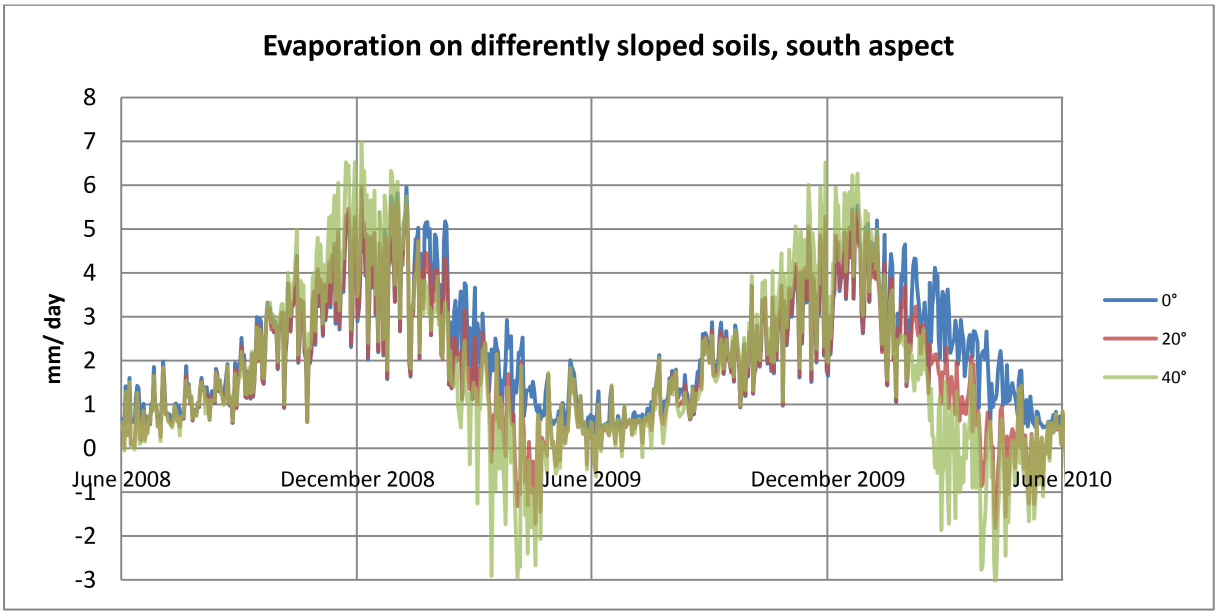


Figure 74: The influence of the slope on the reference crop evapotranspiration in the course of one year with otherwise constant parameters.

The two sampling sites in the Tararua region have the same climate and soil input parameters; the only differences are firstly their aspect with one site being north facing, and the other south facing and secondly slightly different CWC thresholds. We will thus compare the results obtained on these two sites as to quantify the differences caused by different slope aspects.

4.3.2 Simulated soil water content in top- soil (0-50 mm)

Figure 75 presents an example for the simulated water content in the top- soil layer (0-50 mm) on the Alfredton site in the Tararua region from April 2008 to April 2012. Soil water contents showed seasonal fluctuations which were comparatively low during the summer season and much higher in the winter season. These seasonal fluctuations are mainly caused by seasonal differences in evapotranspiration because the rainfall regime stays the same all year round. In the following we thus also want to present soil water repellency in its seasonal context.

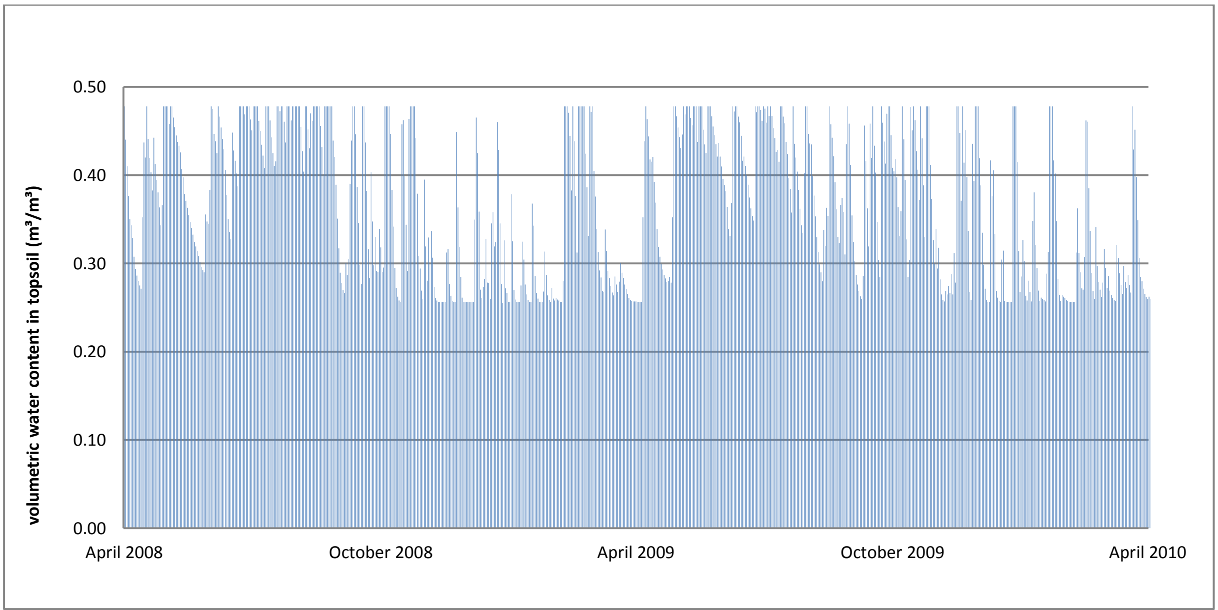


Figure 75: Modelled soil water content in top soil layer (0-50mm), site PN, from April 2008 to April 2010.

4.4. Questions, answered with the help of the model

4.3.1 Question 1: How many days per year can we expect the soil to be hydrophobic?

For each sampling site, we determined the number of days per year when the soil water content fell below the critical water content, meaning the days per year when the soil was in a hydrophobic state. As a simulation period we chose the time between April 2009 and April 2010, because this is a period of average rainfall for all three regions (Table 12). We ran the model not only for the mean critical water content, but also for the maximum and minimum one, meaning the upper and lower value of the transition zone, as to observe the sensitivity of the results on the chosen critical water content.

Figure 76 presents the number of days per year, when the soil water content fell below the critical water content. The red bars are the results obtained for the mean CWC, the blue bars for the maximum CWC and the green bars for the minimum CWC.

Generally, the sampled soils appear to be water repellent during two to three thirds of the year. Soil water repellency thus appears to be rather the norm than the exception. The influence of the chosen critical water content is rather marginal and can be neglected.

The influence of the different soil orders can be observed for the Taranaki sites: While brown soil appears to be water repellent at only two thirds of the year, organic soil acts hydrophobic all year round. This is mainly caused by differences in the critical water content: While water contents fall quite often below the CWC of organic soil of 0.42 m^3/m^3, this is less often the case for the threshold of brown soil of 0.36 m^3/m^3.

When comparing the results of the two Tararua sites, water repellent days appear to be slightly more frequent on the slope which faces north. This is caused by different amounts of annual evaporation from the top soil. While the annual mean evaporation from the top soil on the 20°-north- facing slope amounts to approximately 500 m/a, it is only about 400 mm/a on the 20° south-facing slope. However, the difference in the number of days when hydrophobicity is likely to occur is so small that it can be regarded negligible.

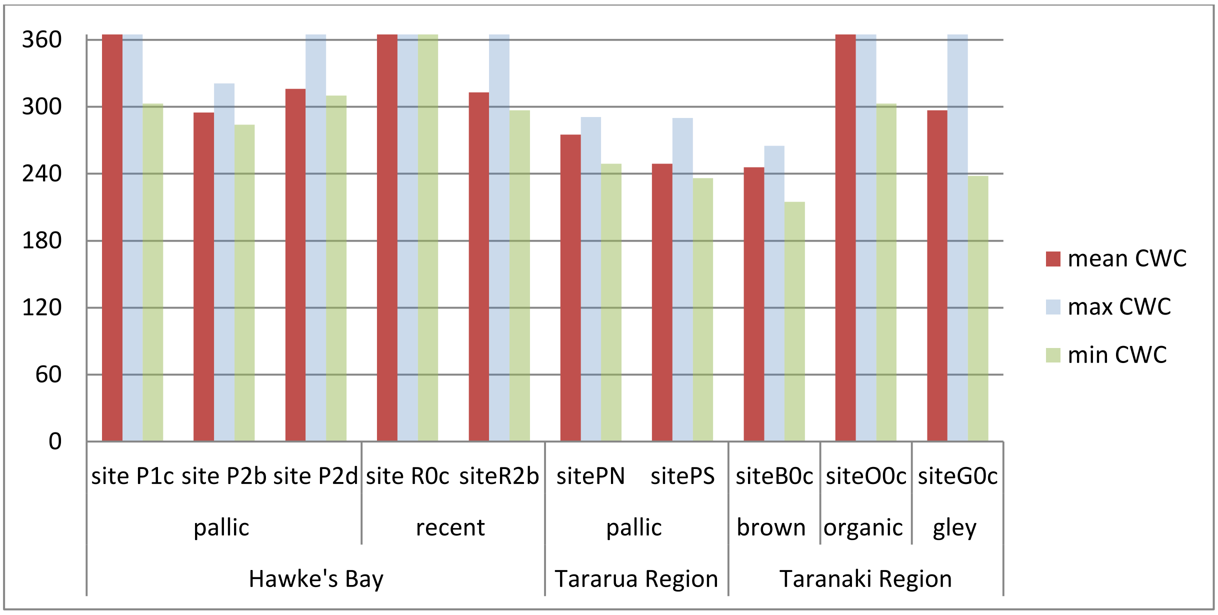


Figure 76: Number of days when the soil water content in the 5 cm- top soil falls below the critical water content and the soil is expected to be hydrophobic. The red bars show the results for the mean critical water content, while the blue bars indicate results for the maximum and the green bars for the minimum critical water content.

4.3.2 Question 2: How many days per year can we expect the occurrence of surface runoff due to soil water repellency?

Soil water repellency by itself does not cause any major troubles. Problems will arise, if water is prevented from infiltrating into the soil due to repellency- induced limited infiltration capacity. One main question is thus the average occurrence of surface runoff due to soil water repellency in the course of a year. In the model, surface runoff due to soil water repellency happens, if (I) the soil water content is lower than the critical water content and (II) the rainfall intensity is higher than the set maximum infiltration capacity for hydrophobic soils. With the help of the model we thus tried to identify the number of days when surface runoff due to soil water repellency is likely to occur.

Figure 77 presents the number of days per year, when surface runoff due to soil water repellency is expected to occur. The red bars are the results obtained for the mean CWC, the blue bars for the maximum CWC and the green bars for the minimum CWC.

Repellency- induced surface runoff is expected to occur between approximately 15 and 60 days of the year. While it appears to be a rather minor problem for dry Hawke’s Bay, it seems to be of moderate importance for Tararua Region and potentially becomes a considerable issue in the wet Taranaki Region. In dry Hawke’s Bay, the major parameter of influence is the number of days, when the rainfall intensity exceeds the set maximum infiltration capacity. In the wet Taranaki Region, high rainfall intensities are a common phenomenon and the parameter of importance is the number of days, when the soil water content falls below the critical water content. Simulated surface runoff thus occurred more often on the very hydrophobic organic soil than on the less hydrophobic brown soil.

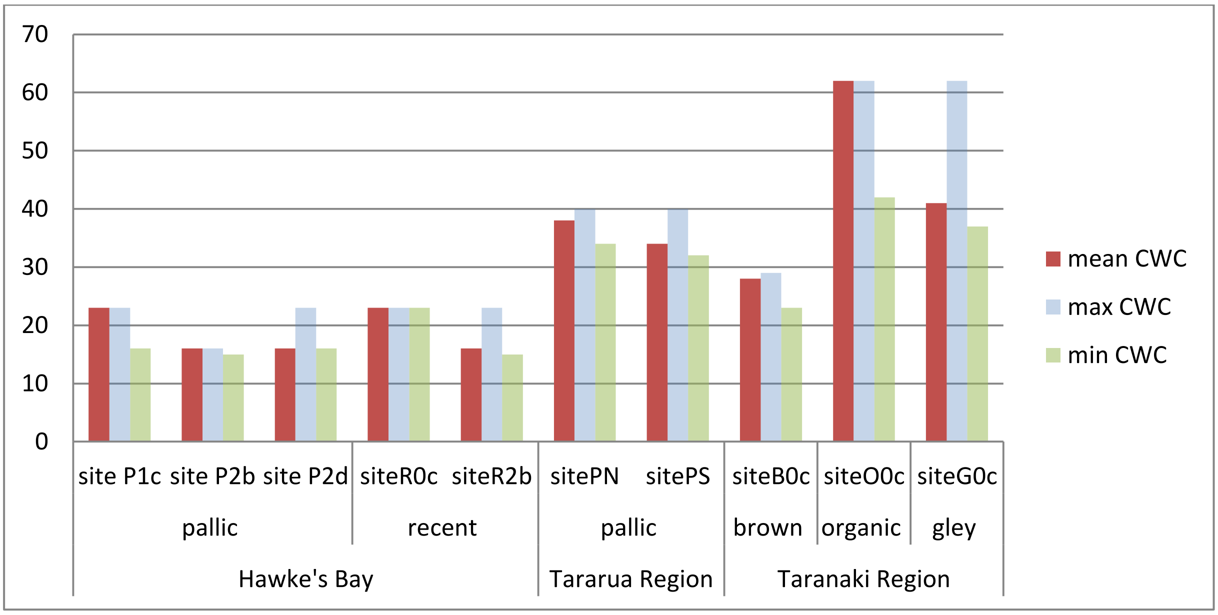


Figure 77: Number of days when soil water repellency- induced surface runoff is expected. The red bars show the results for the mean critical water content, while the blue bars indicate results for the maximum and the green bars for the minimum critical water content.

4.3.3 Question 3: Is the presence of soil water repellency and SWR- induced runoff a seasonal phenomenon?

In order to face soil hydrophobicity in an appropriate way, it is important to know when during the year the phenomenon most probably occurs, so that the necessary actions can be taken. It was thus a major question to find out if soil hydrophobicity is a seasonal phenomenon. Figure 78 shows the model results for those days during the year when the soil water content fell below the critical water content meaning when the soil was hydrophobic. Results are presented for four individual years, from 2008 to 2012, starting and ending with April. The graph only presents four selected sites (three pallic soil sites and the brown soil site) because the other sampling sites appear to be hydrophobic all year round and no seasonal influence can be detected.

There could be detected a seasonal influence on the occurrence of soil water repellency. Throughout all sampling sites and throughout all years, soils appeared to be less hydrophobic in the winter months from May to October and most hydrophobic in the summer months between November and January. However, soils appear to have the potential to be water repellent all year round.

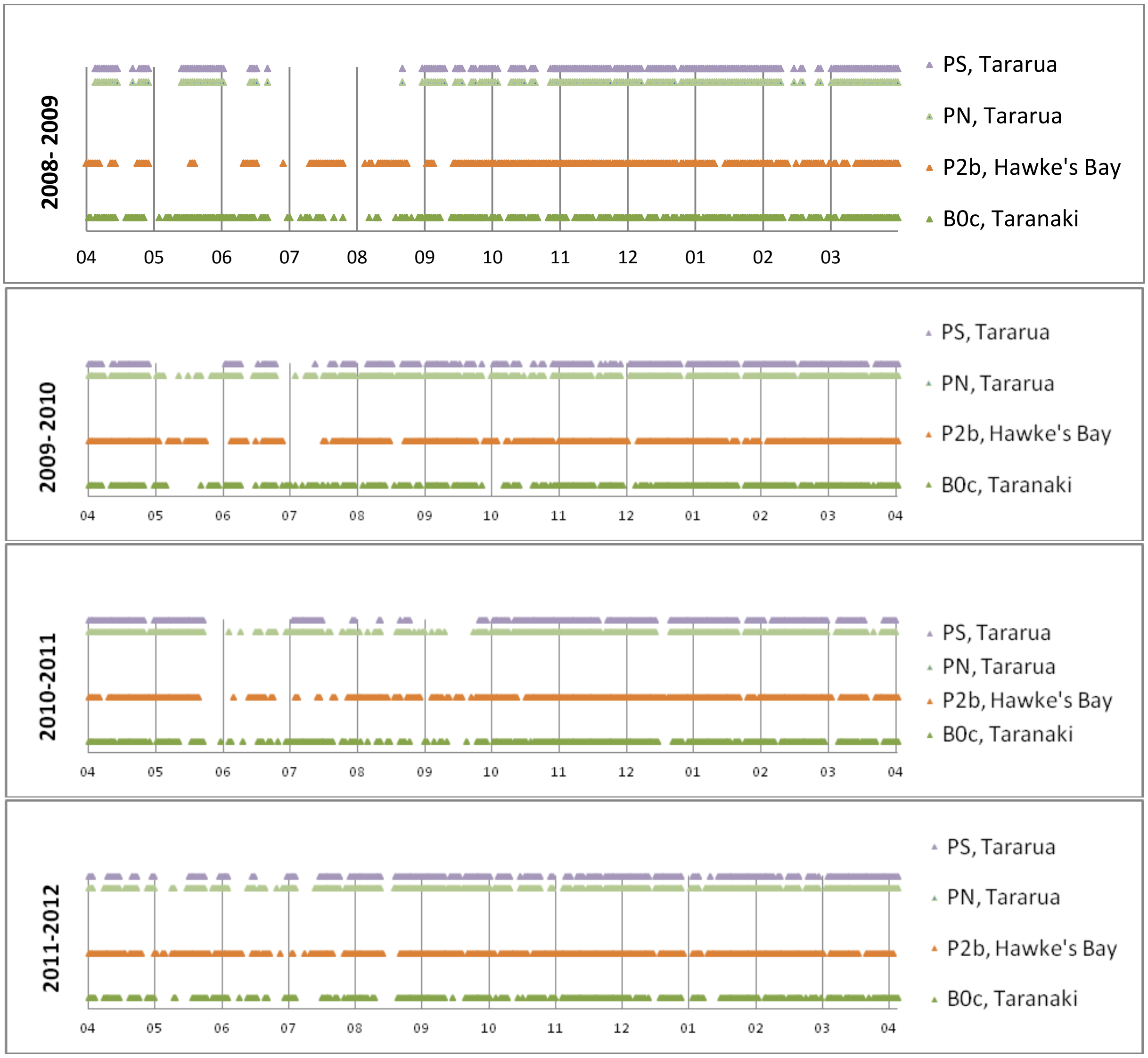


Figure 78: Temporal distribution of soil water repellency throughout all 4 examined years for the 2 pallic soil sites in Tararua, for one pallic soil site in Hawke's Bay and for the brown soil site in Taranaki

A further question was then to find out if also soil water repellency induced surface runoff is a seasonal phenomenon. Figure 79 presents the temporal distribution of surface runoff due to soil water repellency from April 2008 to April 2012. There is, however, no seasonal influence detectable. This is caused by the fact, that the limiting factor of surface runoff is more often rainfall intensity than soil water repllency because the sampled soils appeared to be water repellent practically all year round. There cannot be detected any seasonal rainfall pattern, and surface runoff due to soil water repellency is therefore a phenomenon which occurs at arbitrary times throughout the year.

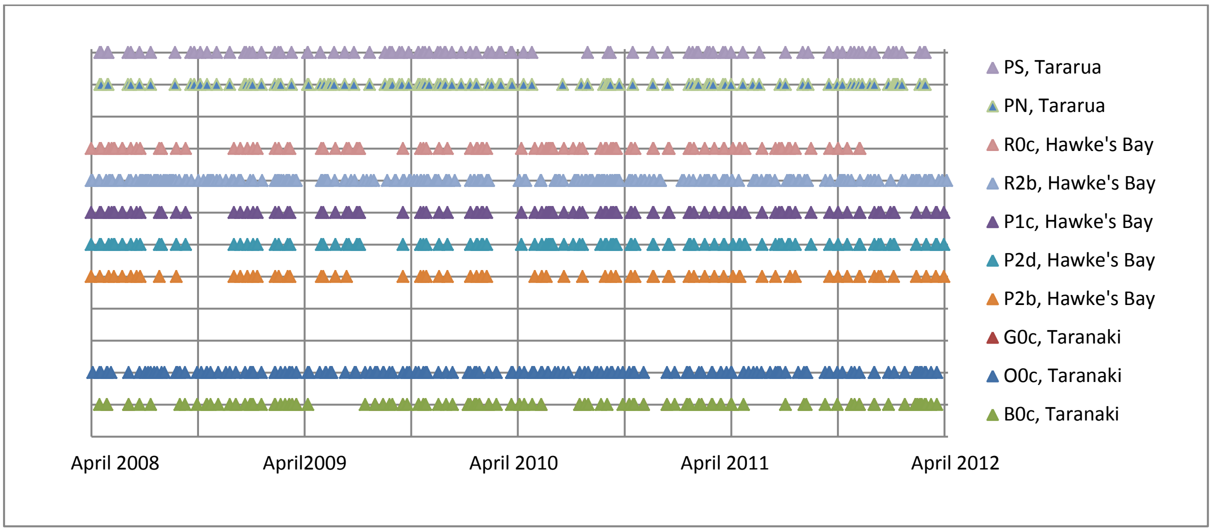


Figure 79: Temporal distribution of soil water repellency- induced surface runoff throughout all four examined years for all sampling sites

4.3.4 Question 4: How big is the influence of yearly climate fluctuations on the number of days when soil water repellency or SWR- induced runoff occurs?

It can be expected that the occurrence of soil water repellency depends much on the amounts of rain per year. Figure 80 presents the number of days per year when the soil water content in the top soil falls below the critical water content for an average, wet and dry year. For the Tararua region and the Taranaki region there was no dry year between 2008 and 2012 and we thus only compared an average with a wet year. An ANOVA test showed that there is no significant difference in the average number of soil water repellent days for years with different amounts of rainfall (p- values: 0,69 resp. 0,73; see 0 section III).

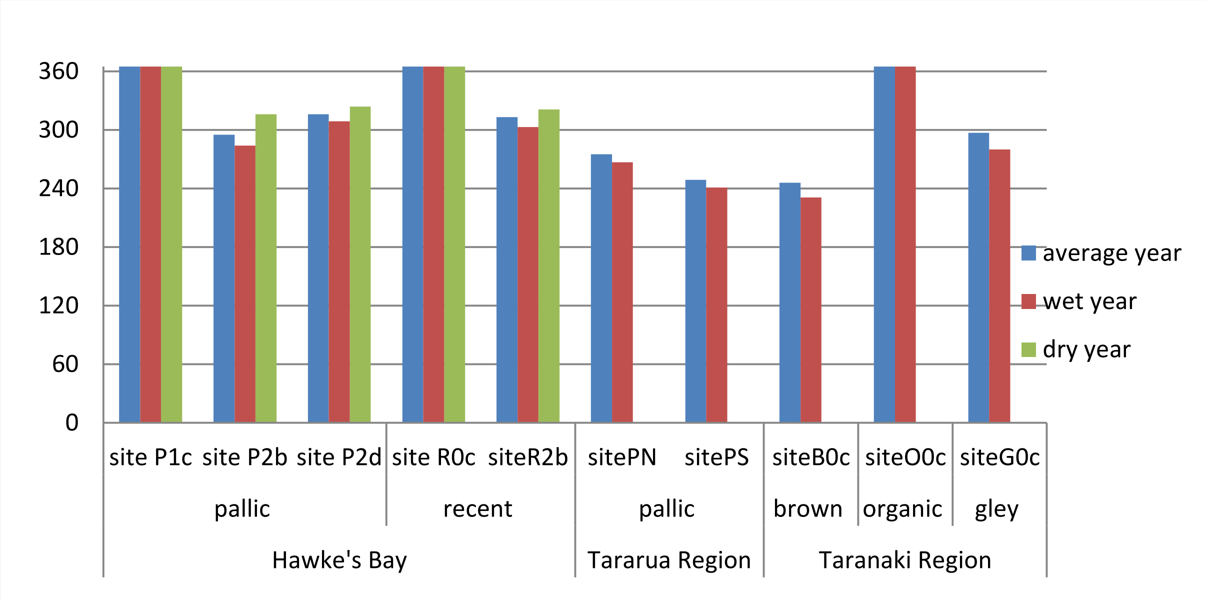


Figure 80: Number of days when the soil water content in the top soil falls below the critical water content and the soil is expected to be hydrophobic for years with different amounts of rain.

Figure 77 shows the influence of climate fluctuations on the number of days when surface runoff due to SWR is likely to occur. Table 13 presents the number of days when the rainfall intensity exceeds the set maximum infiltration rate of $1mm.10min^{-1}$. If the water content is lower than the CWC on these days, surface runoff due to SWR occurs. The results in table 13 show that the number of days per year with high rainfall intensities does not automatically increase if the total amount of rain per year is high. This is the case for the selected dry year in Hawke's Bay, where the number of days per year with high rainfall intensities is higher than for an average year. It is also the case for the selected wet year in the Tararua region, where the number of days per year with high rainfall intensities only increases by two days from 54 to 56 in comparison to the average year. Thus, these comparisons must be taken with care.

Still, there can be seen a general tendency: On sampling sites where soil hydrophobicity is present throughout the year and where the soil water content is generally low (e.g. sites P1c and R0c), wet years will increase the number of days when surface runoff due to SWR occurs because wet years go along with higher rainfall intensities. On sites where soil hydrophobicity does not occur throughout the year (e.g. sites PS, PN and G0c) and is limited to dry days, wet years will decrease the number of days when surface runoff due to SWR is likely to occur. However, as most of the sampling sites were very hydrophobic, even at little soil water contents, wet years tended to rather increase than decrease the repellency- induced surface runoff. An ANOVA test showed that there is no significant difference in the average number of days of repellency- induced surface runoff for years with different amounts of rainfall (p- values: 0,50 resp. 0,64; see 0 section III).

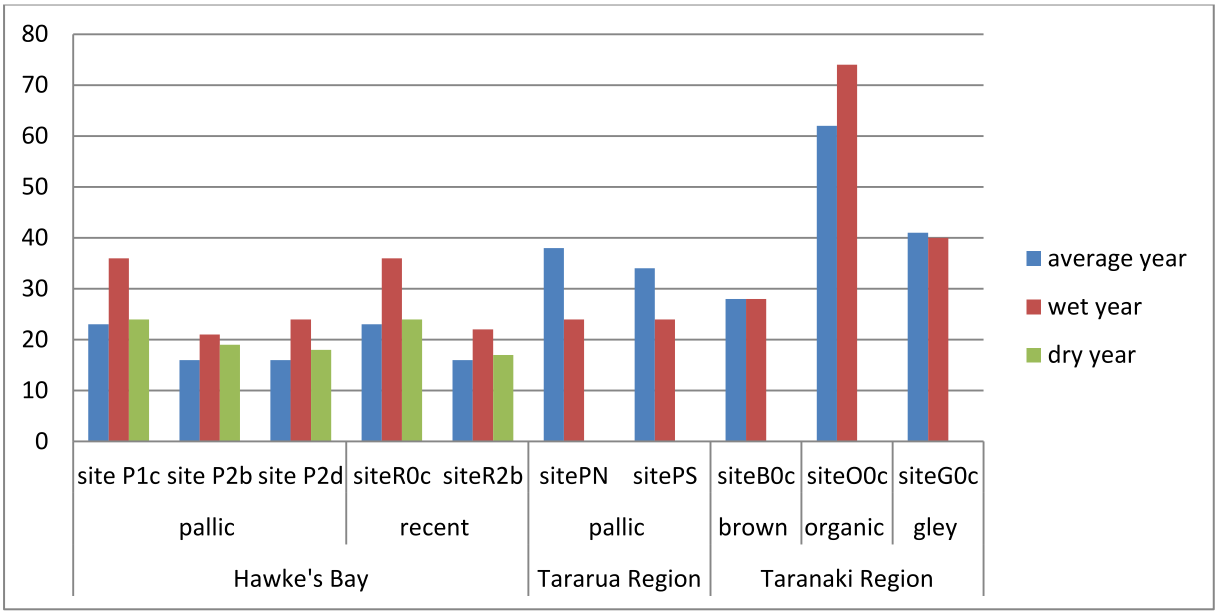


Figure 81: Number of days when soil water repellency- induced surface runoff occurs for years with different amounts of rain.

Table 13: Number of days when the rainfall intensity exceeds 1mm.10min^{-1}

Number of days of high rainfall intensity (rainfall intensity > 1mm.10min^{-1})			
	Hawke's Bay	**Tararua Region**	**Taranaki Region**
average year	23	54	62
wet year	36	56	74
dry year	24		

4.3.5 Question 5: How many days per year and when can we expect moderately persistent soil water repellency to appear in a year of average rainfall?

As presented in sections 4.2.3- 4.2.7, soil water repellency is low at low water contents; it then increases up to a peak value and in the following decreases again until the soil turns hydrophilic at the critical water content. The problem of soil hydrophobicity is most important, when the soil water repellency moves around the peak value and when this peak value is of high dimension. Figure 82 shows an example for the appearance of moderately persistent soil water repellency within the repellency curve.

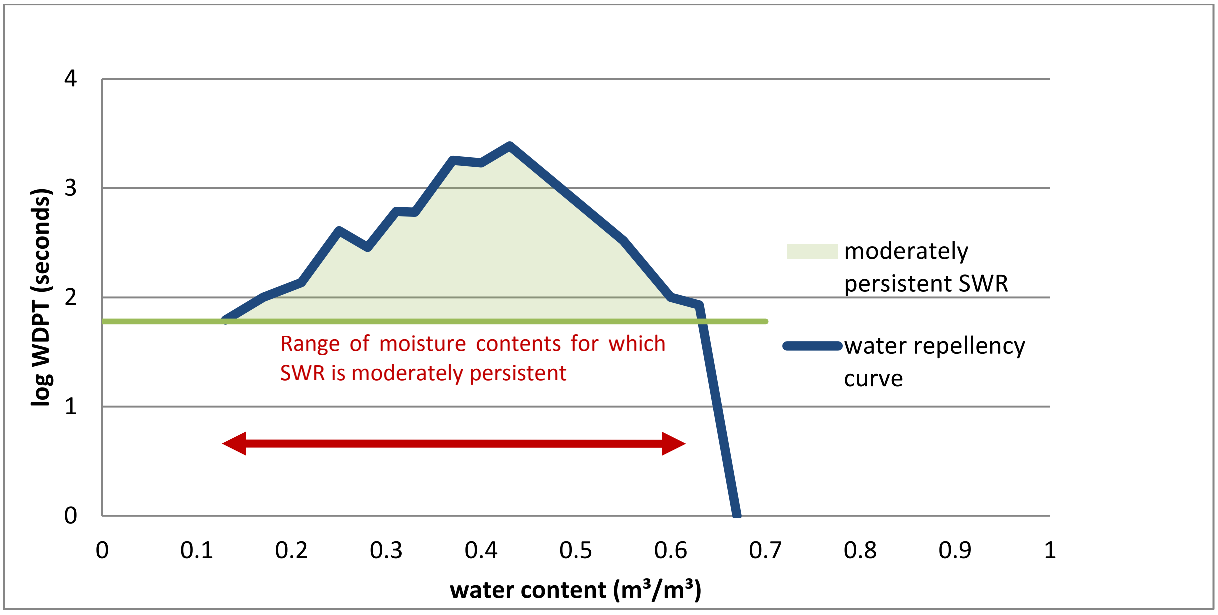


Figure 82: Example: range of moisture content when soil water repellency is moderately persistent

It was tried to find out on how many days per year the top soil layers exhibit soil water contents which lie in the range indicating moderately persistent SWR. The results are presented in Figure 83. Corresponding to the classification system in section 3.2.4, soil water repellency was considered to be moderately persistent when the measured water drop penetration times showed values greater than 60 seconds or WDPT classes ≥ 3. It is remarkable that the proneness to moderate soil water repellency does not correspond to the general proneness to soil water repellency of the different soil orders and is generally very variable for the different sites. On the sites P2d, R2b and G0c water drop penetration times never exceeded one minute suggesting that soil water repllency at these sites did not show moderate level of persistency. The number of days of moderately persistent soil water repellency for the sampling sites P1c and P2b amounted to approximately two weeks, for site B0c to one month and for site O0c to three months. Extremely high values have been found for the sampling sites in the Tararua Region as well as for site R0c, where moderately persistent water repellency appears to occur within six to seven months per year. On the sites in Tararua region these high values are explained by the fact that the soil already starts to act moderately water repellent at relatively high water contents of about $0.4m^3/m^3$ and keeps this state down to very low water contents. On site R0c the range of moisture contents for which soil water repellency is moderately persistent ranges between $0.21m^3/m^3$ and $0.33m^3/m^3$ and is thus not very large, but top soil water contents are frequently found in this range.

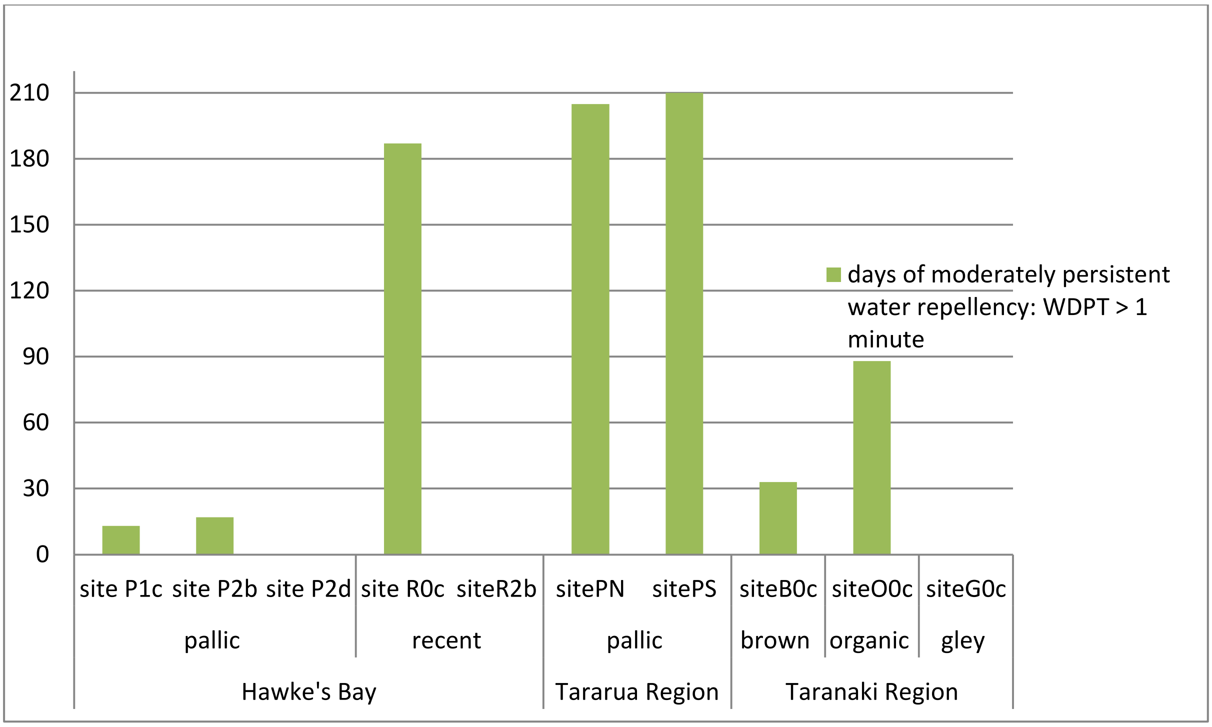
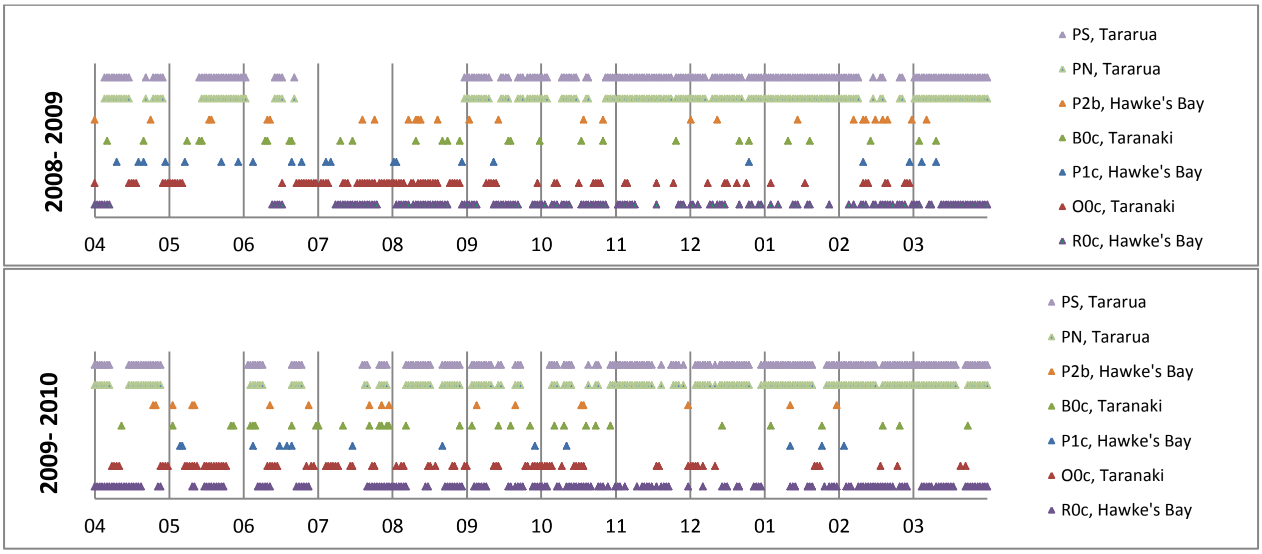


Figure 83: Number of days when the soil water repellency is moderately persistent in a year of average rainfall.

It was also tried to find out if there can be detected a seasonal pattern in the appearance of moderately persistent soil water repellency. Figure 84 presents the days per year, when the soil water content was in the range where the soil water repellency was moderately persistent. However, there could not be detected any seasonal influence on the appearance of moderately persistent water repellency and the days of occurrence are distributed randomly throughout the year.



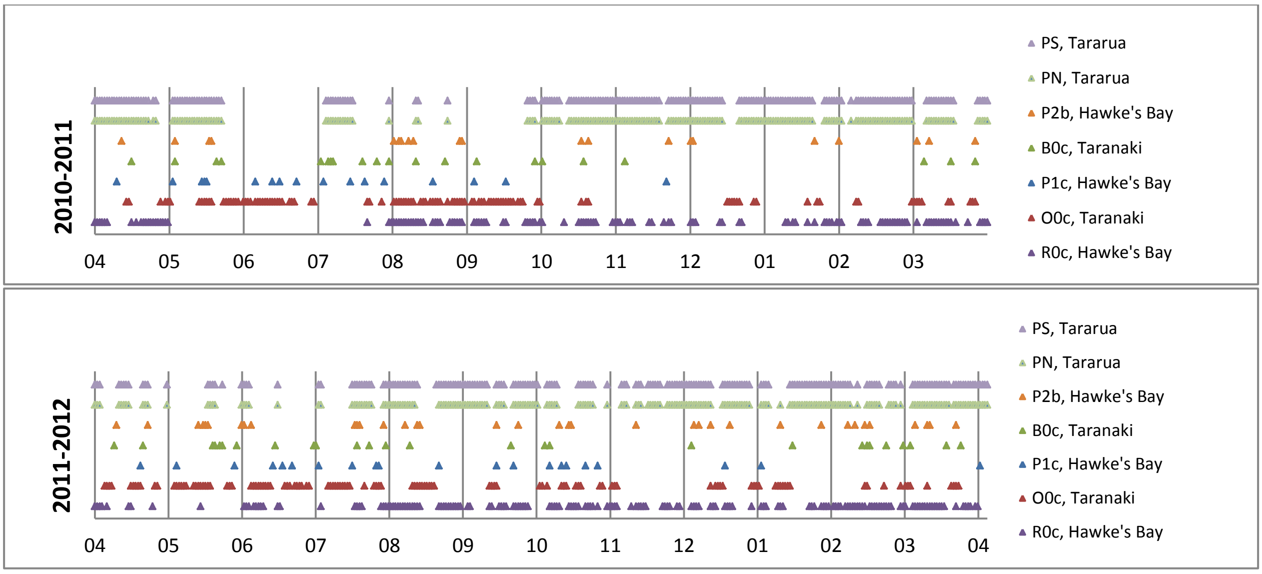


Figure 84: Temporal distribution of moderately persistent soil water repellency throughout all 4 examined years

4.3.6 Question 6: How many dry days does it take the soil to reach moderately persistent water repellency after a rainfall event at the different sites in an average year?

Right after a rainfall event, the top soil layer is saturated with water. If there is no further rainfall in the following days, the water content in the top soil decreases continually. At one specific point it reaches the critical moisture content, when moderately persistent water repellency starts to occur. In order to adjust irrigation and land management, it would be of use to determine after how many days after a rainfall event the soil reaches this state of moderate water repellency. The water balance model showed that this number of days between the rainfall event and the occurrence of moderately persistent water repellency is different for summer and winter months. In Hawke's Bay and the Tararua Region, it takes the soil in average two days to reach moderately persistent water repellency during the winter months between April and September and one day during the summer months between October and March. In the Taranaki the soil reached moderate water repellency already after one day during the winter months; in summer, the top soil water content hardly ever exceeded the critical water content for moderate water repellency if there was no rain at the same time so that the average number of days was zero. Even though this is a very rough approximation, it can be said that after two days of dry weather, the soils on the various study sites are likely to be water repellent.

4.3.7 Question 7: How big is the difference in the number of days of soil hydrophobicity per year for critical water contents from different drying cycles?

The number of days per year when the soil water content falls below the critical water content was evaluated in section 4.3.3 for the critical water content obtained in the 2nd drying cycle of the undisturbed samples. The 2nd cycle of the undisturbed samples has been classified to be the most realistic one; however, it would be interesting to find out on how many days per year the soil is expected to be hydrophobic for the critical water contents obtained in the 3rd respectively the 4th drying cycles. Figure 85 presents the number of days when the soil is expected to be hydrophobic for critical water contents obtained for the 2nd, 3rd and 4th cycles of the undisturbed samples.

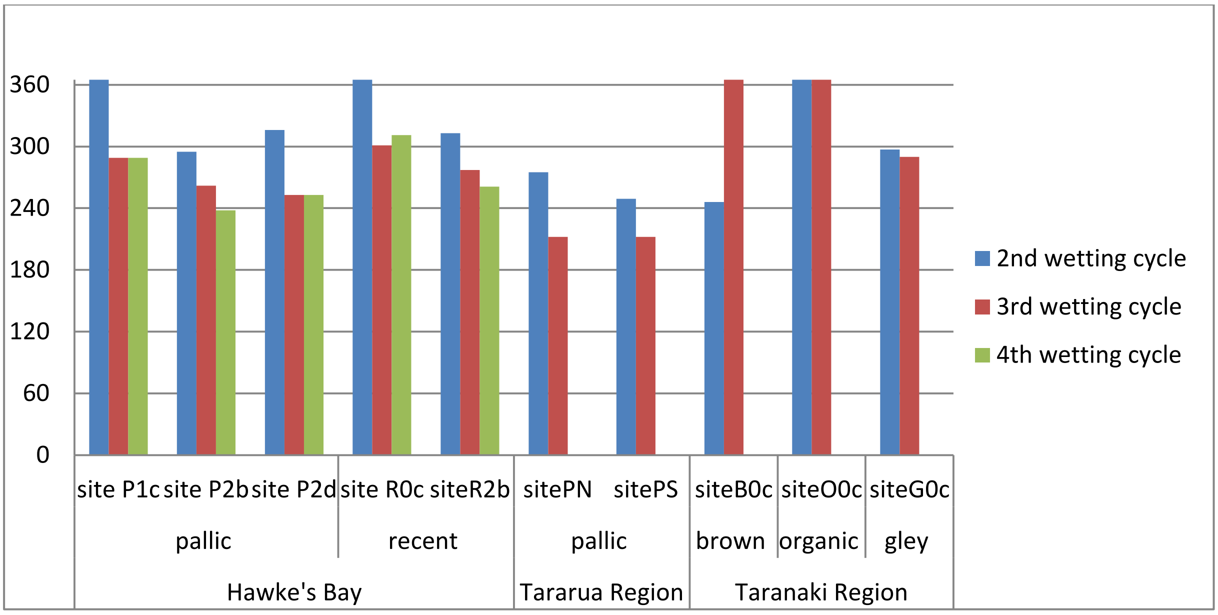


Figure 85: Number of days when the water content in the top soil falls below the critical water content, for critical water contents from different drying cycles

The number of days when soil appear to be hydrophobic decreases between 30 and 80 days between the 2nd and 3rd cycles for the Hawke's Bay and Tararua Region. For the Taranaki Region the number of days remains the same for the organic and gley soil sites and increases for the brown soil site. There is no big difference in the number of days between the 3rd and 4th cycles. An ANOVA test shows (0 section IV) that the difference in the number of days between the 2nd and 3rd drying cycle is not significant (p- value= 0, 25).

In any case, an exact number of days when hydrophobicity is likely to occur cannot be determined by means of the used water balance model due to the great amount of uncertainties. The variation between the results for different critical water contents is not too big. The use of the critical water content of the 2nd drying cycle may thus be considered to be appropriate to detect the approximate temporal extent of hydrophobicity throughout a year at a specific site.

4.5. Test methods: problems and possible improvements

The implementation of both the WDPT and the MED tests is very easy and rapid. However, it is not clear, how well the results of the tests correspond to the real situation in the field.

The main problem is the limited reliability of the correspondence between water contents and soil water repellency: The moisture distribution in the undisturbed samples in the first cycle does not appear to be homogeneous, but to increase vertically from top to bottom layer. Water repellency, though, is determined on the sample's surface. The critical water content, determined for the whole sample, is then over- estimated. To reduce the variance of the soil water content within the soil sample, it would be of use to merely measure the water content in the top 1cm of the soil sample.

A problem of the two test methods is the relatively broad variance of the test results. The soil surface of the samples (especially of the undisturbed ones) is inhomogeneous. The test results therefore depend much on the droplet placement. The values of the three droplet replicates which are conducted at each test- run may vary strongly.

When a droplet is placed on the soil surface, it sometimes occurs that tiny soil particles cover the droplet surface. It is then very difficult to observe the exact time of the droplet infiltration.

The ethanol solutions used for the MED test should be replaced every month as to avoid possible changes in the compositions which are due to microbial growth, ethanol decomposition and volatilization (Roy & MacGill, 2002). In this study, however, we worked with the same solutions over a period of 3 months to avoid too much time and effort. In order to keep changes in the composition to a minimum, they were stored in a fridge and only taken out for a few minutes as to refill small flasks which were used for the SWR- tests and changed every three days.

During the process of drying, clayey soils are subject to shrinkage and develop little cracks on the soil surface. In the present study this could be observed especially on the pallic soil samples. Water drop penetration times are easily underestimated if the drops infiltrate these cracks. The droplets must thus be placed very carefully on the soil surface as to avoid distortion and as to measure the real infiltration time. When spreading, however, the drops sometimes slip into one of those cracks so that the fulfilment of this condition is not always possible.

The rewetting processes led to mould formation on some of the pallic soil samples. Mould, however, can possibly influence both the results of the MED and the WDPT test.

The disturbed samples of the organic soil were so water repellent that the rewetting process was a very difficult procedure and took long time. It was then also difficult to achieve homogeneous wetting within those samples.

SWR varies not only in time, but also in space. The MED and WDPT- tests, however, can only measure SWR on a very small scale. The results are therefore merely representative for the sampled site.

In order to overcome these difficulties and quantify soil water repellency at a larger scale as well as in the field there has been developed a runoff measurement apparatus (ROMA) by Jeyakumar, et al. (2011) which will be of use in future studies.

All model results are merely a first approximation of the situation. A better match with reality could be achieved by improving the model structure and using more detailed rainfall intensity and runoff data. The model performance should be improved by its calibration and validation using the field measurements of SWR, soil water content and surface runoff.

5. Summary and Conclusions

The objective of this thesis was the analysis of the relationship between water repllency and soil water content in hydrophobic soils in New Zealand. In the experimental part, the critical water content for soil water repellency was identified for ten selected sites with five different soil types under pastural land use in the north island of New Zealand. In the theoretical part, the experimentally determined results were implemented into a water balance model which simulates the frequency and time periods at which critical soil water content levels are reached indicating the potential occurrence of soil water repellency at the study sites.

The sampling sites were selected from 50 sites which were examined in a previous study by Deurer et al. (2011) and chosen based on their representativity for New Zealand. The studied soil orders are pallic, recent, brown, gley and organic soil and were sampled in the three different regions Hawke's Bay, Taranaki and Tararua in the New Zeland North Island. Hawke's Bay is characterised by a dry climate, Taranaki is a relatively wet region and Tararua features an average rainfall regime. Undisturbed soil samples were taken at the beginning of April from five sites in Hawke's Bay and at the beginning of June from two sites in the Tararua region as well as from three sites in Taranaki.

Bulk density, field capacity and wilting point were determined for one soil sample of each study site. Soil water repellency (SWR) was measured with the Water Droplet Penetration Time Test (WDPT) and the Molarity of Ethanol Droplet Test (MED). SWR- measurements were started on nearly saturated samples and repeated every day, while the samples were air- drying. When the samples reached a dry state, they were rewetted and another test cycle started. In this manner SWR- measurements were carried out during 4 drying cycles on 3 replicates each of disturbed and undisturbed soil samples of different soil orders from different study sites.

Soil water repellency could be measured on all undisturbed and on all but one disturbed samples. Immediately after the oven- drying of the disturbed samples, the potential water repellency was measured. It is thought to be the maximum possible water repellency which can be reached, but this was not true for all analysed samples. The results, however, were in line with those given by Deurer et al. (2011) and Holzinger (2012) who examined the potential water repellency on samples from the same study sites. There could be found a moderately close relationship between the test results from WDPT and MED- tests with coefficients of determination of 0.67 for undisturbed samples and 0.75 for disturbed ones. SWR- measurements on disturbed samples did not provide good results; the outcomes differed much even between two replicates of the same sampling site and were thus rejected. SWR- measurements on undisturbed samples led to plausible results; water repellency generally started to appear at a certain level, increased rapidly up to a peak value and finally decreased slowly when the water content approached zero. The critical water contents were very high in the first drying cycle and stabilized at a rather constant level during the 2nd, 3rd and 4th test cycle. This phenomenon may be due to inhomogeneous soil water distributions within the field moist samples which were used in the 1st drying cycle and it was thus chosen to take the critical water contents from the 2nd, 3rd and 4th test cycle for further purposes. The critical water contents appeared to differ between the various soil orders and showed values between 0.32m^3/m^3 and 0.50m^3/m^3. Water repellency never existed at water contents higher than 0.50m^3/m^3.

In the modelling part, a water balance model was used to calculate the volumetric water content in the top- soil layer (upper 50 mm). This model was fed with climate and geographic data from the sampling sites, with the site- specific physical soil properties such as the previously measured field capacity and wilting point and with the critical water contents obtained in the experimental part of the study. The model was run for four years, from April 2008 to April 2012. Soil water repellency was found to be the rule rather than the exception and to occur during two to three thirds of an average year. Repellency induced surface runoff was found to be a considerable issue especially in regions where high rainfall intensities are combined with high critical water contents as it is the case for organic soil in the Taranaki region. Even though having the potential to occur all year round, soil water repellency was found to appear more likely in the summer months between November and January and less likely in the winter months between May and October. The occurrence of water repellency was compared for average, wet and dry years. The differences, however, were not significant. This is caused by the fact that critical water contents are high and even during wet years, the water content in the top soil layer rarely exceeds the critical water content. Using a water drop penetration time of 60 seconds as the threshold for moderately persistent soil water repellency, it was evaluated on how many days per year this moderately persistent soil water repellency was reached on the different sampling sites. The results showed big variances between the different regions and also between the different soil orders presenting values between 0 and 7 months per year of moderate soil water repellency. It was not possible to detect any seasonal pattern in the occurrence of moderate soil water repellency. An additional task was to identify the number of dry days it takes the soil to reach moderately persistent water repellency after a rainfall event at the different sites in an average year. In winter it takes the soil longer to regain the state of moderately persistent water repellency than in summer. Generally, after two dry days after the rainfall event, moderately persistent water repellency can be expected.

The biggest problem in the experimental part was the inaccurate measurement of the water content. While SWR- tests were carried out on soil samples' surfaces, the water content was determined for the whole sample, neglecting possible inhomogeneous water distributions. It was thus difficult to identify the real critical water content. Furthermore, both WDPT and the MED tests are very easy and rapid to implement. The closeness of the agreement between the obtained results and the real situation in the field is, however, not clear. The results obtained in the modelling part should generally be regarded with caution and are only a coarse approximation of the real situation. For more realistic results, both the model structure and the input data must be improved.

There has been an increased awareness of the problem of soil water repellency in recent years which led to many publications on this subject. Still, the exact causes of soil water repellency are not clear and further investigation on the source and evolution of SWR is needed. Moreover, research on soil water repellency mostly took place under laboratory conditions; SWR-measurements in the field have rarely been performed and the extent of the issue on agriculture is not at all clear. Additional research would thus be needed with respect to large- scale investigations on soil water repellency in the field. In addition, it would be of use if there were developed efficient and affordable mitigation techniques to overcome this problem.

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Annex A: Soil water repellency results, WDPT and MED tests on undisturbed samples

The results are presented as: volumetric soil moisture (m³/m³), molarity (mol/l), average molarity (mol/l), water droplet penetration times (hh:mm:ss), contact angles (°), and SWR- classes (Tables 2 and 3)

Table 14: Soil water repllency results, WDPT & MED test, undisturbed samples, 1st cycle

Undisturbed samples. cycle 1

R0c1							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.60	0	0	0	00:00:00	90.00	0	0
0.56	0	0	0	00:00:00	90.00	0	0
0.52	1.368	1.71	1.54	00:02:29	99.08	3	2
0.41	3.932	4.445	4.19	00:12:55	105.50	4	4
0.37	3.419	3.932	3.68	00:03:20	104.54	4	3
0.33	2.393	2.798	2.60	00:03:54	102.17	4	3
0.30	2.393	2.795	2.59	00:02:47	102.17	3	3
0.28	1.71	2.052	1.88	00:01:48	100.20	3	3
0.21	1.026	1.368	1.20	00:01:05	97.79	3	2
0.20	1.71	2.052	1.88	00:00:42	100.20	2	3
0.19	2.393	2.735	2.56	00:01:12	102.09	3	3
0.17	1.368	1.71	1.54	00:02:04	99.08	3	2
0.14	1.368	1.71	1.54	00:00:51	99.08	2	2

R0c2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.55	0	0	0	00:00:00	90.00	0	0
0.52	0	0	0	00:00:00	90.00	0	0
0.47	1.71	2.052	1.88	00:02:41	100.20	3	3
0.35	3.932	4.445	4.19	00:09:05	105.50	4	4
0.32	3.419	3.932	3.68	00:10:48	104.54	4	3
0.29	2.393	2.798	2.60	00:03:02	102.17	4	3
0.26	2.393	2.795	2.59	00:03:22	102.17	4	3
0.24	2.735	3.075	2.91	00:02:52	102.91	3	3
0.17	1.026	1.368	1.20	00:01:11	97.79	3	2
0.16	1.71	2.052	1.88	00:01:29	100.20	3	3
0.15	2.052	1.393	1.72	00:02:13	99.70	3	2
0.13	1.368	1.71	1.54	00:01:21	99.08	3	2
0.10	1.368	1.71	1.54	00:01:51	99.08	3	2

R0c3							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.59	0	0	0	00:00:00	90.00	0	0
0.56	0	0	0	00:00:00	90.00	0	0
0.50	1.026	1.368	1.20	00:00:47	97.79	2	2
0.38	3.932	4.445	4.19	00:09:13	105.50	4	4
0.35	3.419	3.932	3.68	00:04:18	104.54	4	3
0.31	2.393	2.798	2.60	00:02:18	102.17	3	3
0.29	3.077	3.416	3.25	00:04:07	103.67	4	3
0.26	2.735	3.075	2.91	00:04:53	102.91	4	3
0.19	2.052	2.393	2.22	00:01:20	101.20	3	3
0.18	1.71	2.052	1.88	00:01:45	100.20	3	3
0.17	1.71	2.052	1.88	00:01:49	100.20	3	3
0.15	1.368	1.71	1.54	00:00:58	99.08	2	2
0.12	1.71	2.052	1.88	00:01:38	100.20	3	3

R2b1							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.44	0	0	0.00	00:00:00	90.00	0	0
0.40	0	0.171	0.09	00:00:26	90.94	2	1
0.29	2.393	2.795	2.59	00:03:07	102.17	4	3
0.25	0.684	0.855	0.77	00:01:02	95.83	3	2
0.23	0.171	0.342	0.26	00:00:43	92.51	2	1
0.21	0.171	0.342	0.26	00:00:31	92.51	2	1
0.19	0.342	0.613	0.48	00:00:36	94.12	2	1
0.14	0.855	1.026	0.94	00:00:48	96.67	2	2
0.13	0.855	1.026	0.94	00:00:28	96.67	2	2
0.12	1.026	1.368	1.20	00:00:51	97.79	2	2
0.11	1.368	1.71	1.54	00:00:37	99.08	2	2
0.09	0.634	0.855	0.74	00:00:32	95.70	2	2

R2b2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.39	0	0	0.00	00:00:00	90.00	0	0
0.34	0.171	0.342	0.26	00:00:51	92.51	2	1
0.22	2.393	2.795	2.59	00:01:55	102.17	3	3
0.19	0.684	0.855	0.77	00:01:52	95.83	3	2
0.16	0	0.171	0.09	00:01:06	90.94	3	1
0.15	0.171	0.342	0.26	00:01:08	92.51	3	1
0.13	0.342	0.613	0.48	00:00:37	94.12	2	1
0.09	1.026	1.368	1.20	00:00:58	97.79	2	2

0.09	1.026	1.368	1.20	00:00:46	97.79	2	2
0.08	1.026	1.368	1.20	00:00:40	97.79	2	2
0.07	1.368	1.71	1.54	00:00:43	99.08	2	2
0.05	0.855	1.026	0.94	00:00:25	96.67	2	2

P1c1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.48	0	0	0.00	00:00:00	90.00	0	0
0.46	0	0	0.00	00:00:00	90.00	0	0
0.43	3.419	3.932	3.68	00:02:17	104.54	3	3
0.33	1.71	2.052	1.88	00:03:26	100.20	4	3
0.31	0.684	0.855	0.77	00:01:40	95.83	3	2
0.28	0	0.171	0.09	00:00:54	90.94	2	1
0.26	0.684	0.855	0.77	00:01:11	95.83	3	2
0.25	0.342	0.513	0.43	00:01:02	93.79	3	1
0.20	0.855	1.026	0.94	00:01:00	96.67	3	2
0.19	1.026	1.368	1.20	00:00:53	97.79	2	2
0.18	0.855	1.026	0.94	00:01:10	96.67	3	2
0.17	0.513	0.634	0.57	00:00:44	94.73	2	1
0.13	0.342	0.513	0.43	00:00:32	93.79	2	1

P1c2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.51	0	0	0.00	00:00:00	90.00	0	0
0.50	1.71	2.052	1.88	00:05:40	100.20	4	3
0.46	3.932	4.446	4.19	00:05:07	105.51	4	4
0.34	2.052	2.393	2.22	00:06:06	101.20	4	3
0.31	0.855	1.026	0.94	00:02:38	96.67	3	2
0.28	0.171	0.342	0.26	00:00:42	92.51	2	1
0.26	1.026	1.368	1.20	00:01:08	97.79	3	2
0.24	0.342	0.513	0.43	00:01:10	93.79	3	1
0.19	0.855	1.026	0.94	00:00:52	96.67	2	2
0.18	0.513	0.634	0.57	00:00:57	94.73	2	1
0.17	1.368	1.71	1.54	00:00:39	99.08	2	2
0.16	1.026	1.368	1.20	00:01:05	97.79	3	2
0.13	0.855	1.026	0.94	00:00:35	96.67	2	2

P1c3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.50	0	0	0.00	00:00:00	90.00	0	0
0.48	1.026	1.368	1.20	00:03:03	97.79	4	2
0.43	3.419	3.932	3.68	00:02:33	104.54	3	3

0.32	2.052	2.393	2.22	00:02:35	101.20	3	3
0.29	0.684	0.855	0.77	00:04:53	95.83	4	2
0.26	0.342	0.513	0.43	00:02:01	93.79	3	1
0.24	1.026	1.368	1.20	00:00:44	97.79	2	2
0.23	0.342	0.513	0.43	00:00:30	93.79	2	1
0.17	0.613	0.684	0.65	00:00:19	95.17	1	2
0.17	1.368	1.71	1.54	00:00:36	99.08	2	2
0.16	1.368	1.71	1.54	00:00:47	99.08	2	2
0.15	1.026	1.368	1.20	00:00:40	97.79	2	2
0.12	0.634	0.855	0.74	00:00:27	95.70	2	2

P2b1							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.54	0	0	0.00	00:00:00	0.00	0	0
0.47	0.513	0.684	0.00	00:01:41	0.60	3	1
0.35	3.077	3.419	0.00	00:06:36	3.25	4	3
0.32	3.077	3.419	0.00	00:03:02	3.25	4	3
0.28	0.684	0.855	0.00	00:01:55	0.77	3	2
0.26	0.684	0.855	0.00	00:00:45	0.77	2	2
0.23	0.684	0.855	0.00	00:00:21	0.77	1	2
0.17	0.171	0.342	0.00	00:00:33	0.26	2	1
0.15	0	0.171	0.00	00:00:26	0.09	2	1
0.15	0.342	0.513	0.00	00:00:25	0.43	2	1
0.14	0.342	0.513	0.00	00:00:11	0.43	1	1

P2b2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.53	0	0	0.00	00:00:00	90.00	0	0
0.47	0.171	0.342	0.26	00:00:35	92.51	2	1
0.36	3.077	3.419	3.25	00:02:33	103.67	3	3
0.33	3.077	3.419	3.25	00:01:03	103.67	3	3
0.29	0	0.171	0.09	00:00:30	90.94	2	1
0.26	0	0.171	0.09	00:01:18	90.94	3	1
0.24	0.855	1.368	1.11	00:00:40	97.44	2	2
0.17	0	0	0.00	00:00:07	90.00	0	0
0.16	0	0	0.00	00:00:05	90.00	0	0
0.15	0.171	0.342	0.26	00:00:34	92.51	2	1
0.14	0.342	0.513	0.43	00:00:21	93.79	1	1

P2b3							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.55	0	0	0.00	00:00:00	90.00	0	0

0.48	1.026	1.368	1.20	00:03:55	97.79	4	2
0.35	3.419	3.932	3.68	00:08:46	104.54	4	3
0.32	4.445	4.958	4.70	00:12:29	106.39	4	4
0.28	3.419	3.932	3.68	00:04:20	104.54	4	3
0.25	3.419	3.932	3.68	00:02:28	104.54	3	3
0.23	1.368	1.71	1.54	00:02:32	99.08	3	2
0.16	0.342	0.613	0.48	00:00:35	94.12	2	1
0.15	0.342	0.613	0.48	00:00:49	94.12	2	1
0.14	1.026	1.368	1.20	00:01:19	97.79	3	2
0.13	0.634	0.855	0.74	00:01:00	95.70	3	2
0.11	0.171	0.342	0.26	00:00:33	92.51	2	1

P2d1							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.59	0	0	0.00	00:00:00	90.00	0	0
0.56	2.052	2.393	2.22	00:01:54	101.20	3	3
0.44	3.932	4.446	4.19	00:12:12	105.51	4	4
0.40	3.932	4.446	4.19	00:09:26	105.51	4	4
0.36	3.419	3.392	3.41	00:06:08	104.00	4	3
0.33	2.735	3.077	2.91	00:01:12	102.91	3	3
0.31	2.693	2.735	2.71	00:01:20	102.46	3	3
0.23	0.684	0.855	0.77	00:01:00	95.83	3	2
0.22	1.026	1.368	1.20	00:00:52	97.79	2	2
0.20	1.368	1.71	1.54	00:00:48	99.08	2	2
0.19	1.71	2.052	1.88	00:00:54	100.20	2	3
0.14	1.026	1.368	1.20	00:00:35	97.79	2	2

P2d2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.65	0	0	0.00	00:00:00	90.00	0	0
0.60	1.026	1.368	1.20	00:01:00	97.79	3	2
0.46	3.932	4.446	4.19	00:10:49	105.51	4	4
0.42	3.932	4.446	4.19	00:10:16	105.51	4	4
0.37	4.446	4.958	4.70	00:10:59	106.39	4	4
0.34	4.446	4.958	4.70	00:04:54	106.39	4	4
0.30	2.735	3.077	2.91	00:02:26	102.91	3	3
0.22	0.855	1.026	0.94	00:01:08	96.67	3	2
0.21	1.71	2.052	1.88	00:01:11	100.20	3	3
0.19	1.71	2.052	1.88	00:00:49	100.20	2	3
0.18	1.71	2.052	1.88	00:00:54	100.20	2	3
0.14	1.026	1.368	1.20	00:00:31	97.79	2	2

B0c1

soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.59	0	0	0.00	00:00:00	90.00	0	0
0.55	5.471	5.994	5.73	00:00:28	107.98	2	4
0.43	3.047	3.419	3.23	00:02:07	103.64	3	3
0.40	2.735	3.047	2.89	00:00:45	102.88	2	3
0.38	2.052	2.393	2.22	00:02:20	101.20	3	3
0.35	1.71	2.052	1.88	00:01:02	100.20	3	3
0.33	0.855	1.026	0.94	00:01:11	96.67	3	2
0.31	0.855	1.026	0.94	00:01:31	96.67	3	2
0.28	0.634	0.855	0.74	00:01:57	95.70	3	2
0.24	0.634	0.855	0.74	00:01:00	95.70	3	2
0.21	0.634	0.855	0.74	00:00:17	95.70	1	2
0.15	0.634	0.855	0.74	00:00:25	95.70	2	2

B0c2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.55	0	0	0.00	00:00:00	90.00	0	0
0.52	5.471	5.994	5.73	00:00:23	107.98	1	4
0.41	2.735	3.047	2.89	00:00:26	102.88	2	3
0.39	1.368	1.71	1.54	00:00:20	99.08	1	2
0.37	2.052	2.393	2.22	00:00:28	101.20	2	3
0.34	1.71	2.052	1.88	00:00:18	100.20	1	3
0.32	0.855	1.026	0.94	00:00:30	96.67	2	2
0.31	0.855	1.026	0.94	00:00:47	96.67	2	2
0.28	0.634	0.855	0.74	00:00:28	95.70	2	2
0.25	0.634	0.855	0.74	00:00:15	95.70	1	2
0.21	0	0	0.00	00:00:00	90.00	0	0
0.16	0.634	0.855	0.74	00:00:13	95.70	1	2

B0c3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.61	0	0	0.00	00:00:00	90.00	0	0
0.57	2.735	3.047	2.89	00:00:26	102.88	2	3
0.45	2.735	3.047	2.89	00:00:15	102.88	1	3
0.43	2.052	2.393	2.22	00:00:20	101.20	1	3
0.40	1.026	1.368	1.20	00:01:47	97.79	3	2
0.37	1.71	2.052	1.88	00:00:23	100.20	1	3
0.35	0	0.171	0.09	00:00:10	90.94	1	1
0.33	0	0.171	0.09	00:00:16	90.94	1	1
0.30	0.171	0.342	0.26	00:00:23	92.51	1	1
0.27	0.513	0.634	0.57	00:00:15	94.73	1	1

0.23	0	0	0.00	00:00:00	90.00	0	0
0.18	0.513	0.634	0.57	00:00:11	94.73	1	1

O0c1							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.71	1.368	1.71	1.54	00:00:56	99.08	2	2
0.68	6.496	7.18	6.84	00:02:19	109.49	3	4
0.54	7.18	7.864	7.52	00:21:36	110.34	3	4
0.51	6.496	7.18	6.84	00:15:28	109.49	3	4
0.49	4.958	5.471	5.21	00:07:54	107.21	3	4
0.45	3.932	4.475	4.20	00:06:35	105.53	3	4
0.43	3.41	3.932	3.67	00:03:16	104.54	3	3
0.40	2.393	2.735	2.56	00:04:22	102.09	3	3
0.37	2.393	2.735	2.56	00:01:32	102.09	3	3
0.32	1.71	2.052	1.88	00:01:55	100.20	3	3
0.29	1.368	1.71	1.54	00:01:00	99.08	3	2
0.23	1.368	1.71	1.54	00:01:25	99.08	3	2

O0c2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.67	1.368	1.71	1.54	00:00:28	99.08	2	2
0.64	6.496	7.18	6.84	00:02:34	109.49	3	4
0.51	7.18	7.864	7.52	00:09:43	110.34	3	4
0.48	6.496	7.18	6.84	00:04:08	109.49	3	4
0.45	4.958	5.471	5.21	00:13:48	107.21	3	4
0.42	3.932	4.475	4.20	00:03:37	105.53	3	4
0.40	3.41	3.932	3.67	00:02:58	104.54	3	3
0.37	3.41	3.932	3.67	00:04:43	104.54	3	3
0.31	2.052	2.393	2.22	00:02:39	101.20	3	3
0.27	1.368	1.71	1.54	00:01:24	99.08	3	2
0.22	1.368	1.71	1.54	00:01:01	99.08	3	2

O0c3							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.66	1.368	1.71	1.54	00:00:38	99.08	2	4
0.62	5.934	6.496	6.22	00:01:10	108.66	3	4
0.49	6.496	7.18	6.84	00:21:57	109.49	3	4
0.46	6.496	7.18	6.84	00:10:43	109.49	3	4
0.43	4.958	5.471	5.21	00:05:59	107.21	3	4
0.40	3.932	4.475	4.20	00:04:38	105.53	3	4
0.37	3.41	3.932	3.67	00:06:59	104.54	3	4
0.35	2.735	3.047	2.89	00:02:48	102.88	3	4

0.32	3.047	3.41	3.23	00:05:01	103.63	3	4
0.28	1.71	2.052	1.88	00:02:02	100.20	3	4
0.25	1.368	1.71	1.54	00:00:57	99.08	2	4
0.20	1.71	2.052	1.88	00:01:43	100.20	3	4

G0c1							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.64	0	0	0.00	00:00:00	90.00	0	0
0.60	2.735	3.047	2.89	00:00:26	102.88	2	3
0.48	3.047	3.419	3.23	00:01:33	103.64	3	3
0.44	2.735	3.047	2.89	00:01:15	102.88	3	3
0.43	3.047	3.419	3.23	00:01:03	103.64	3	3
0.39	2.735	3.047	2.89	00:00:46	102.88	2	3
0.37	0.634	0.855	0.74	00:00:23	95.70	1	2
0.35	0.513	0.634	0.57	00:00:27	94.73	2	1
0.32	0.171	0.342	0.26	00:00:16	92.51	1	1
0.28	0.513	0.634	0.57	00:00:13	94.73	1	1
0.24	0.171	0.342	0.26	00:00:11	92.51	1	1
0.20	0	0.171	0.09	00:00:09	90.94	0	1

G0c2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.72	0	0	0.00	00:00:00	90.00	0	0
0.69	3.047	3.419	3.23	00:00:22	103.64	1	3
0.57	3.932	4.445	4.19	00:02:52	105.50	3	4
0.54	3.419	3.932	3.68	00:01:47	104.54	3	3
0.51	2.735	3.047	2.89	00:00:39	102.88	2	3
0.47	2.735	3.047	2.89	00:01:18	102.88	3	3
0.45	0.634	0.855	0.74	00:01:11	95.70	3	2
0.43	1.026	1.368	1.20	00:00:44	97.79	2	2
0.40	1.026	1.368	1.20	00:00:43	97.79	2	2
0.36	0.855	1.026	0.94	00:00:12	96.67	1	2
0.31	0.342	0.513	0.43	00:00:23	93.79	1	1
0.25	0.513	0.634	0.57	00:00:51	94.73	2	1

G0c3							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.68	0	0	0.00	00:00:00	90.00	0	0
0.64	0	0	0.00	00:00:00	90.00	0	0
0.51	2.393	2.735	2.56	00:04:06	102.09	3	3
0.49	3.419	3.932	3.68	00:02:52	104.54	3	3
0.47	2.735	3.047	2.89	00:01:38	102.88	3	3

0.43	2.735	3.047	2.89	00:02:27	102.88	3	3
0.41	0.634	0.855	0.74	00:03:08	95.70	3	2
0.39	1.026	1.368	1.20	00:02:01	97.79	3	2
0.36	2.052	2.393	2.22	00:01:26	101.20	3	3
0.33	0.855	1.026	0.94	00:01:27	96.67	3	2
0.28	0.171	0.342	0.26	00:00:29	92.51	2	1
0.22	0.634	0.855	0.74	00:00:41	95.70	2	2

PS1							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.67	0	0	0.00	00:00:00	90.00	0	0
0.63	5.417	5.984	5.70	00:01:25	107.93	3	4
0.60	5.984	6.496	6.24	00:01:28	108.69	3	4
0.55	6.496	6.496	6.50	00:05:30	109.04	3	4
0.43	7.18	7.864	7.52	00:40:28	110.34	3	4
0.40	6.496	7.18	6.84	00:28:18	109.49	3	4
0.37	6.496	7.18	6.84	00:29:48	109.49	3	4
0.33	5.471	5.984	5.73	00:10:01	107.97	3	4
0.31	3.932	4.445	4.19	00:10:08	105.50	3	4
0.28	3.932	4.445	4.19	00:04:46	105.50	3	4
0.25	3.932	4.445	4.19	00:06:47	105.50	3	4
0.21	2.393	2.735	2.56	00:02:16	102.09	3	3
0.17	2.735	3.047	2.89	00:02:02	102.88	3	3
0.13	2.052	2.393	2.22	00:01:02	101.20	3	3

PS2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.66	0	0	0.00	00:00:00	90.00	0	0
0.62	6.496	6.496	6.50	00:02:25	109.04	3	4
0.58	6.496	6.496	6.50	00:02:31	109.04	3	4
0.54	6.496	6.496	6.50	00:12:05	109.04	3	4
0.43	7.864	8.548	8.21	00:43:03	111.14	3	4
0.40	7.18	7.864	7.52	00:28:53	110.34	3	4
0.38	6.496	7.18	6.84	00:36:40	109.49	3	4
0.35	7.18	7.864	7.52	00:38:54	110.34	3	4
0.33	5.471	5.984	5.73	00:20:43	107.97	3	4
0.31	5.984	6.496	6.24	00:15:45	108.69	3	4
0.28	2.984	6.496	4.74	00:02:17	106.45	3	4
0.24	2.984	6.496	4.74	00:07:02	106.45	3	4
0.19	2.984	6.496	4.74	00:03:19	106.45	3	4
0.14	2.984	6.496	4.74	00:03:58	106.45	3	4

PS3

soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.68	0	0	0.00	00:00:00	90.00	0	0
0.63	5.984	6.496	6.24	00:01:48	108.69	3	4
0.59	6.496	6.496	6.50	00:02:04	109.04	3	4
0.54	6.496	6.496	6.50	00:09:35	109.04	3	4
0.42	5.984	6.496	6.24	00:29:50	108.69	3	4
0.39	6.496	7.18	6.84	00:13:41	109.49	3	4
0.36	6.496	7.18	6.84	00:15:42	109.49	3	4
0.32	5.9784	6.496	6.24	00:16:25	108.69	3	4
0.30	3.932	4.445	4.19	00:12:41	105.50	3	4
0.28	3.932	4.445	4.19	00:11:14	105.50	3	4
0.25	4.446	4.958	4.70	00:09:43	106.39	3	4
0.20	2.393	2.735	2.56	00:03:14	102.09	3	3
0.16	2.393	2.735	2.56	00:03:06	102.09	3	3
0.12	2.735	3.047	2.89	00:03:18	102.88	3	3

PN1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.62	0	0	0.00	00:00:00	90.00	0	0
0.56	6.496	6.496	6.50	00:03:09	109.04	3	4
0.53	6.496	6.496	6.50	00:04:28	109.04	3	4
0.48	6.496	6.496	6.50	00:08:25	109.04	3	4
0.36	2.735	3.047	2.89	00:03:05	102.88	3	3
0.33	2.052	2.393	2.22	00:01:17	101.20	3	3
0.31	2.052	2.393	2.22	00:01:09	101.20	3	3
0.28	2.052	2.393	2.22	00:01:02	101.20	3	3
0.26	2.052	2.393	2.22	00:01:14	101.20	3	3
0.24	1.026	1.368	1.20	00:01:04	97.79	3	2
0.21	1.026	1.368	1.20	00:01:09	97.79	3	2
0.18	1.026	1.368	1.20	00:01:01	97.79	3	2
0.15	1.71	2.052	1.88	00:01:04	100.20	3	3
0.11	1.026	1.368	1.20	00:01:10	97.79	3	2

PN2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.59	0	0	0.00	00:00:00	90.00	0	0
0.54	6.496	6.496	6.50	00:02:32	109.04	3	4
0.51	6.496	6.496	6.50	00:05:52	109.04	3	4
0.47	6.496	6.496	6.50	00:11:53	109.04	3	4
0.34	4.445	4.958	4.70	00:25:28	106.39	3	4
0.31	5.471	5.984	5.73	00:25:49	107.97	3	4

0.29	4.445	4.958	4.70	00:16:38	106.39	3	4
0.26	3.932	4.445	4.19	00:08:46	105.50	3	4
0.24	2.052	2.393	2.22	00:04:45	101.20	3	3
0.22	2.735	3.047	2.89	00:04:13	102.88	3	3
0.20	2.393	2.735	2.56	00:01:56	102.09	3	3
0.17	2.052	2.393	2.22	00:01:47	101.20	3	3
0.14	1.71	2.052	1.88	00:01:06	100.20	3	3
0.11	1.026	1.368	1.20	00:01:10	97.79	3	2

PN3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.59	0	0	0.00	00:00:00	90.00	0	0
0.54	5.984	6.496	6.24	00:01:22	108.69	3	4
0.51	6.496	6.496	6.50	00:05:37	109.04	3	4
0.46	5.984	6.496	6.24	00:06:22	108.69	3	4
0.34	2.735	3.047	2.89	00:01:29	102.88	3	3
0.31	2.052	2.393	2.22	00:00:48	101.20	2	3
0.29	3.047	3.419	3.23	00:00:55	103.64	2	3
0.26	2.052	2.393	2.22	00:01:30	101.20	3	3
0.24	2.052	2.393	2.22	00:01:30	101.20	3	3
0.22	1.71	2.052	1.88	00:00:49	100.20	2	3
0.20	1.71	2.052	1.88	00:00:43	100.20	2	3
0.17	2.393	2.735	2.56	00:00:38	102.09	2	3
0.14	1.368	1.71	1.54	00:00:17	99.08	1	2
0.10	0.855	1.026	0.94	00:00:27	96.67	2	2

Table 15: Soil water repllency results. WDPT & MED test. undisturbed samples. 2nd cycle

undisturbed samples. cycle 2

R0c1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.44	0	0	0.00	00:00:00	90.00	0	0
0.41	0	0.171	0.09	00:00:10	90.94	1	1
0.39	3.047	3.393	3.22	00:00:43	103.61	2	3
0.37	2.393	2.735	2.56	00:00:25	102.09	2	3
0.34	4.445	4.958	4.70	00:00:54	106.39	2	4
0.31	3.932	4.445	4.19	00:02:16	105.50	3	4
0.13	2.052	2.393	2.22	00:00:20	101.20	1	3

R0c2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class

(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.41	0	0	0.00	00:00:00	90.00	0	0
0.38	0.171	0.342	0.26	00:00:16	92.51	1	1
0.37	3.047	3.393	3.22	00:00:31	103.61	2	3
0.35	2.735	3.047	2.89	00:00:39	102.88	2	3
0.32	4.445	4.958	4.70	00:02:14	106.39	3	4
0.29	4.445	4.958	4.70	00:01:18	106.39	3	4
0.11	3.047	3.419	3.23	00:00:47	103.64	2	3

R0c3							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.43	0	0	0.00	00:00:00	90.00	0	0
0.40	0	0.171	0.09	00:00:12	90.94	1	1
0.38	3.047	3.393	3.22	00:00:25	103.61	2	3
0.36	2.735	3.047	2.89	00:00:56	102.88	2	3
0.33	4.958	5.471	5.21	00:01:12	107.21	3	4
0.30	4.445	4.958	4.70	00:02:25	106.39	3	4
0.12	2.393	2.735	2.56	00:00:25	102.09	2	3

R2b1							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.33	0	0	0.00	00:00:00	90.00	0	0
0.32	0.634	0.855	0.74	00:00:14	95.70	1	2
0.29	0.513	0.634	0.57	00:00:08	94.73	0	1
0.27	0.855	1.026	0.94	00:00:27	96.67	2	2
0.25	0.855	1.026	0.94	00:00:19	96.67	1	2
0.22	0	0.171	0.09	00:00:08	90.94	0	1
0.20	0	0	0.00	00:00:04	90.00	0	0
0.08	0	0	0.00	00:00:00	90.00	0	0

R2b2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.38	0	0	0.00	00:00:00	90.00	0	0
0.31	0	0.171	0.09	00:00:15	90.94	1	1
0.27	0.634	0.855	0.74	00:00:18	95.70	1	2
0.26	0.634	0.855	0.74	00:00:20	95.70	1	2
0.24	3.047	3.419	3.23	00:00:51	103.64	2	3
0.22	0.634	0.855	0.74	00:00:19	95.70	1	2
0.20	0.634	0.855	0.74	00:00:32	95.70	2	2
0.17	0	0.171	0.09	00:00:09	90.94	0	1
0.15	0	0	0.00	00:00:07	90.00	0	0
0.05	0	0	0.00	00:00:00	90.00	0	0

P1c1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.42	0	0	0	00:00:00	0	0	0
0.39	0.513	0.634	0.57	00:00:20	94.73	1	1
0.38	1.026	1.368	1.20	00:00:13	97.79	1	2
0.36	2.052	2.393	2.22	00:01:17	101.20	3	3
0.34	0.634	0.855	0.74	00:00:37	95.70	2	2
0.32	1.026	1.71	1.37	00:00:39	98.46	2	2
0.30	0.634	0.855	0.74	00:00:18	95.70	1	2
0.27	0.171	0.342	0.26	00:00:15	92.51	1	1
0.13	0	0.171	0.09	00:00:19	90.94	1	1

P1c2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.47	0	0	0	00:00.00	0	0	0
0.43	0	0.171	0.09	00:00:17	90.94	1	1
0.41	0.513	0.634	0.57	00:00:21	94.73	1	1
0.40	0.855	1.026	0.94	00:00:27	96.67	2	2
0.37	2.393	3.047	2.72	00:00:22	102.48	1	3
0.35	0.513	0.634	0.57	00:00:20	94.73	1	1
0.33	2.393	2.735	2.56	00:01:04	102.09	3	3
0.30	1.368	1.71	1.54	00:00:16	99.08	1	2
0.28	0.342	0.513	0.43	00:00:25	93.79	2	1
0.13	0	0.171	0.09	00:00:10	90.94	1	1

P1c3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.38	0	0	0.00	00:00:00	90.00	0	0
0.37	0	0.171	0.09	00:00:11	90.94	1	1
0.36	0.513	0.634	0.57	00:00:12	94.73	1	1
0.33	0.855	1.026	0.94	00:00:21	96.67	1	2
0.32	0.513	0.634	0.57	00:00:15	94.73	1	1
0.30	0.634	0.855	0.74	00:00:30	95.70	2	2
0.27	1.026	1.368	1.20	00:00:31	97.79	2	2
0.25	0.171	0.342	0.26	00:00:07	92.51	0	1
0.10	0	0.171	0.09	00:00:09	90.94	0	1

P2b1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.38	0	0	0.00	00:00:00	90.00	0	0

0.36	1.71	2.052	1.88	00:00:18	100.20	1	3
0.34	0.342	0.513	0.43	00:00:09	93.79	0	1
0.32	0.513	0.634	0.57	00:00:20	94.73	1	1
0.28	0.855	1.026	0.94	00:00:45	96.67	2	2
0.25	1.71	2.052	1.88	00:00:50	100.20	2	3
0.08	0.171	0.342	0.26	00:00:12	92.51	1	1

P2b2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.37	0	0	0.00	00:00:00	90.00	0	0
0.34	1.026	1.368	1.20	00:00:13	97.79	1	2
0.32	0	0	0.00	00:00:07	90.00	0	0
0.30	0.513	0.634	0.57	00:00:29	94.73	2	1
0.26	1.026	1.71	1.37	00:00:28	98.46	2	2
0.23	1.026	1.368	1.20	00:00:14	97.79	1	2
0.08	0.513	0.634	0.57	00:00:14	94.73	1	1

P2b3							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.43	0	0	0.00	00:00:00	90.00	0	0
0.40	0	0.171	0.09	00:00:14	90.94	1	1
0.37	0	0.171	0.09	00:00:15	90.94	1	1
0.36	0	0.171	0.09	00:00:13	90.94	1	1
0.33	2.052	2.393	2.22	00:00:39	101.20	2	3
0.31	0.855	1.026	0.94	00:00:13	96.67	1	2
0.28	3.419	3.932	3.68	00:00:49	104.54	2	3
0.25	1.026	1.71	1.37	00:01:04	98.46	3	2
0.22	1.026	1.368	1.20	00:00:42	97.79	2	2
0.07	0.513	0.634	0.57	00:00:13	94.73	1	1

P2d1							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.43	0	0	0.00	00:00:00	90.00	0	0
0.39	0.171	0.342	0.26	00:00:24	92.51	1	1
0.38	0.171	0.342	0.26	00:00:19	92.51	1	1
0.34	2.735	3.047	2.89	00:01:35	102.88	3	3
0.32	3.047	3.419	3.23	00:01:27	103.64	3	3
0.29	2.393	2.735	2.56	00:00:56	102.09	2	3
0.10	0.855	1.026	0.94	00:00:39	96.67	2	2

P2d2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**

(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.45	0	0	0.00	00:00:00	90.00	0	0
0.42	0.171	0.342	0.26	00:00:17	92.51	1	1
0.40	0.342	0.634	0.49	00:00:15	94.19	1	1
0.37	3.047	3.419	3.23	00:00:58	103.64	2	3
0.33	4.445	4.958	4.70	00:01:13	106.39	3	4
0.29	3.419	3.932	3.68	00:01:40	104.54	3	3
0.11	0.342	0.513	0.43	00:00:22	93.79	1	1

B0c1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.35	0	0	0.00	00:00:00	90.00	0	0
0.33	2.393	2.735	2.56	00:01:47	102.09	3	3
0.30	1.368	1.71	1.54	00:00:40	99.08	2	2
0.29	1.368	1.71	1.54	00:00:37	99.08	2	2
0.27	0.171	0.342	0.26	00:00:23	92.51	1	1
0.20	0.171	0.342	0.26	00:00:20	92.51	1	1
0.18	0.342	0.513	0.43	00:00:30	93.79	2	1
0.14	0.171	0.342	0.26	00:00:35	92.51	2	1

B0c2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.39	0	0	0.00	00:00:00	90.00	0	0
0.37	1.368	1.71	1.54	00:00:16	99.08	1	2
0.34	0	0	0.00	00:00:00	90.00	0	0
0.32	0	0	0.00	00:00:00	90.00	0	0
0.30	0.342	0.513	0.43	00:00:28	93.79	2	1
0.23	0	0	0.00	00:00:00	90.00	0	0
0.21	0	0	0.00	00:00:00	90.00	0	0
0.17	0	0	0.00	00:00:00	90.00	0	0

B0c3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.37	0	0	0.00	00:00:00	90.00	0	0
0.35	2.052	2.393	2.22	00:01:18	101.20	3	3
0.32	1.71	2.052	1.88	00:00:34	100.20	2	3
0.31	0.342	0.513	0.43	00:00:11	93.79	1	1
0.29	0.171	0.342	0.26	00:00:11	92.51	1	1
0.22	0	0	0.00	00:00:00	90.00	0	0
0.20	0	0	0.00	00:00:00	90.00	0	0
0.16	0	0	0.00	00:00:00	90.00	0	0

O0c1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.43	0	0	0.00	00:00:00	90.00	0	0
0.41	3.932	4.445	4.19	00:02:37	105.50	3	4
0.38	2.052	2.393	2.22	00:00:53	101.20	2	3
0.36	2.393	2.735	2.56	00:00:39	102.09	2	3
0.34	1.71	2.052	1.88	00:00:23	100.20	1	3
0.27	1.368	1.71	1.54	00:00:49	99.08	2	2
0.24	1.368	1.71	1.54	00:00:45	99.08	2	2
0.21	0.513	0.634	0.57	00:00:32	94.73	2	1

O0c2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.40	0	0	0.00	00:00:00	90.00	0	0
0.37	3.047	3.41	3.23	00:01:24	103.63	3	3
0.35	2.393	2.735	2.56	00:01:27	102.09	3	3
0.33	2.052	2.393	2.22	00:00:41	101.20	2	3
0.25	1.368	1.71	1.54	00:00:53	99.08	2	2
0.22	1.368	1.71	1.54	00:00:27	99.08	2	2
0.19	0.855	1.026	0.94	00:00:40	96.67	2	2

O0c3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.48	0	0	0.00	00:00:00	90.00	0	0
0.45	0.634	0.855	0.74	00:00:25	95.70	2	2
0.41	5.471	5.984	5.73	00:03:13	107.97	3	4
0.38	3.41	3.932	3.67	00:01:31	104.54	3	3
0.34	2.052	2.393	2.22	00:00:33	101.20	2	3
0.26	1.71	2.052	1.88	00:01:54	100.20	3	3
0.23	2.052	2.393	2.22	00:00:49	101.20	2	3
0.18	0.634	0.855	0.74	00:00:24	95.70	1	2

G0c1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.55	0	0	0.00	00:00:00	90.00	0	0
0.52	0	0	0.00	00:00:00	90.00	0	0
0.47	0	0	0.00	00:00:00	90.00	0	0
0.44	0	0	0.00	00:00:00	90.00	0	0
0.39	0	0	0.00	00:00:00	90.00	0	0
0.28	0	0.171	0.09	00:00:10	90.94	1	1

0.25	0.171	0.342	0.26	00:00:18	92.51	1	1
0.21	0	0.171	0.09	00:00:10	90.94	1	1

G0c2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.54	0	0	0.00	00:00:00	90.00	0	0
0.52	0	0	0.00	00:00:00	90.00	0	0
0.48	1.71	2.052	1.88	00:00:23	100.20	1	3
0.46	0	0.171	0.09	00:00:08	90.94	0	1
0.42	0.513	0.634	0.57	00:00:44	94.73	2	1
0.31	0.171	0.342	0.26	00:00:12	92.51	1	1
0.28	0.342	0.513	0.43	00:00:18	93.79	1	1
0.23	0.171	0.342	0.26	00:00:11	92.51	1	1

G0c3							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.56	0	0	0.00	00:00:00	90.00	0	0
0.54	0	0	0.00	00:00:00	90.00	0	0
0.49	0	0	0.00	00:00:00	90.00	0	0
0.46	1.026	1.368	1.20	00:00:17	97.79	1	2
0.42	0.513	0.634	0.57	00:00:37	94.73	2	1
0.31	0.342	0.513	0.43	00:00:23	93.79	1	1
0.27	0.342	0.513	0.43	00:00:13	93.79	1	1
0.22	0.342	0.513	0.43	00:00:13	93.79	1	1

PS1							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.48	0	0	0.00	00:00:00	90.00	0	0
0.44	0	0.171	0.09	00:00:10	90.94	1	1
0.36	5.471	5.984	5.73	00:01:17	107.97	3	4
0.27	3.418	3.932	3.68	00:04:16	104.54	3	3
0.21	3.418	3.932	3.68	00:04:47	104.54	3	3

PS2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.43	0	0	0.00	00:00:00	90.00	0	0
0.40	2.393	3.047	2.72	00:00:32	102.48	2	3
0.33	5.984	6.496	6.24	00:05:58	108.69	3	4
0.26	4.445	4.958	4.70	00:04:39	106.39	3	4
0.20	3.047	3.418	3.23	00:05:07	103.64	3	3

PS3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.51	0	0	0.00	00:00:00	90.00	0	0
0.47	0	0	0.00	00:00:00	90.00	0	0
0.38	4.958	5.471	5.21	00:01:18	107.21	3	4
0.28	3.418	3.932	3.68	00:02:05	104.54	3	3
0.21	2.735	3.047	2.89	00:02:55	102.88	3	3

PN1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.56	0	0	0.00	00:00:00	90.00	0	0
0.50	0	0	0.00	00:00:00	90.00	0	0
0.40	5.471	5.984	5.73	00:01:39	107.97	3	4
0.30	3.932	4.445	4.19	00:01:54	105.50	3	4
0.23	2.735	3.047	2.89	00:01:06	102.88	3	3

PN2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.52	0	0	0.00	00:00:00	90.00	0	0
0.48	0	0	0.00	00:00:00	90.00	0	0
0.39	5.471	5.984	5.73	00:00:53	107.97	2	4
0.29	6.496	7.18	6.84	00:05:11	109.49	3	4
0.21	3.047	3.419	3.23	00:03:49	103.64	3	3

PN3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.47	0	0	0.00	00:00:00	90.00	0	0
0.44	0	0.171	0.09	00:00:11	90.94	1	1
0.35	5.471	5.984	5.73	00:01:57	107.97	3	4
0.26	3.047	3.418	3.23	00:01:08	103.64	3	3
0.20	2.735	3.047	2.89	00:00:44	102.88	2	3

Table 16: Soil water repllency results. WDPT & MED test. undisturbed samples. 3rd cycle

undisturbed samples. cycle 3

R0c1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.37	0	0	0.00	00:00:00	90.00	0	0

0.35	1.71	2.052	1.88	00:00:16	100.20	1	3
0.33	3.047	3.419	3.23	00:00:49	103.64	2	3
0.31	2.393	2.735	2.56	00:00:48	102.09	2	3
0.29	1.026	1.368	1.20	00:00:30	97.79	2	2
0.27	0.855	1.026	0.94	00:00:47	96.67	2	2
0.23	0.634	0.855	0.74	00:00:20	95.70	1	2
0.21	0.855	1.026	0.94	00:00:37	96.67	2	2
0.17	1.368	1.71	1.54	00:00:23	99.08	1	2

R0c2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.46	0	0	0.00	00:00:00	90.00	0	0
0.43	0	0	0.00	00:00:00		0	0
0.40	0	0	0.00	00:00:00		0	0
0.37	0	0.171	0.09	00:00:12	90.94	1	1
0.34	1.71	2.052	1.88	00:00:36	100.20	2	3
0.31	2.052	2.735	2.39	00:00:58	101.66	2	3
0.26	0.855	1.026	0.94	00:00:43	96.67	2	2
0.25	1.026	1.368	1.20	00:00:40	97.79	2	2
0.18	1.368	1.71	1.54	00:00:41	99.08	2	2

R0c3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.39	0	0	0.00	00:00:00	90.00	0	0
0.37	0	0	0.00	00:00:00	0	0	0
0.35	3.047	3.419	3.23	00:00:43	103.64	2	3
0.33	3.419	3.932	3.68	00:01:30	104.54	3	3
0.30	2.052	2.735	2.39	00:01:39	101.66	3	3
0.28	2.393	3.047	2.72	00:01:43	102.48	3	3
0.25	2.052	2.393	2.22	00:01:06	101.20	3	3
0.23	0.855	1.026	0.94	00:00:21	96.67	1	2
0.15	1.368	1.71	1.54	00:00:49	99.08	2	2

R2b1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.31	0	0	0.00	00:00:00	90.00	0	0
0.28	0.855	1.026	0.94	00:00:23	96.67	1	2
0.26	0.513	0.634	0.57	00:00:23	94.73	1	1
0.23	0	0.171	0.09	00:00:09	90.94	0	1
0.21	0	0	0.00	00:00:00	90.00	0	0
0.19	0	0	0.00	00:00:00	90.00	0	0
0.17	0	0	0.00	00:00:00	90.00	0	0

0.16	0	0	0.00	00:00:00	90.00	0	0
0.15	0	0.171	0.09	00:00:11	90.94	1	1
0.10	0	0	0.00	00:00:00	90.00	0	0

R2b2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.36	0	0	0.00	00:00:00	90.00	0	0
0.25	1.026	1.368	1.20	00:00:20	97.79	1	2
0.23	1.026	1.368	1.20	00:00:24	97.79	1	2
0.20	1.026	1.368	1.20	00:00:24	97.79	1	2
0.18	0.684	0.855	0.77	00:00:27	95.83	2	2
0.16	0	0.171	0.09	00:00:11	90.94	1	1
0.15	0	0	0.00	00:00:00	90.00	0	0
0.13	0	0	0.00	00:00:00	90.00	0	0
0.12	0	0.171	0.09	00:00:16	90.94	1	1
0.08	0	0.171	0.09	00:00:08	90.94	0	1

P1c1							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.39	0	0	0.00	00:00:00	90.00	0	0
0.37	0	0	0.00	00:00:00	90.00	0	0
0.35	0.342	0.513	0.43	00:00:39	93.79	2	1
0.32	2.052	2.393	2.22	00:00:34	101.20	2	3
0.30	0.513	0.684	0.60	00:00:27	94.88	2	1
0.28	0.171	0.342	0.26	00:00:25	92.51	2	1
0.26	0	0.171	0.09	00:00:09	90.94	0	1
0.24	0	0.171	0.09	00:00:19	90.94	1	1
0.23	0	0.171	0.09	00:00:11	90.94	1	1
0.18	0	0	0.00	00:00:00	90.00	0	0

P1c2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.37	0	0	0.00	00:00:00	90.00	0	0
0.35	0.855	1.026	0.94	00:00:16	96.67	1	2
0.33	0.855	1.026	0.94	00:00:14	96.67	1	2
0.30	1.026	1.368	1.20	00:00:47	97.79	2	2
0.28	0.342	0.513	0.43	00:00:21	93.79	1	1
0.26	0	0.171	0.09	00:00:14	90.94	1	1
0.24	0	0.171	0.09	00:00:10	90.94	1	1
0.22	0	0.171	0.09	00:00:14	90.94	1	1
0.21	0	0.171	0.09	00:00:13	90.94	1	1
0.16	0	0	0.00	00:00:00	90.00	0	0

P1c3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.36	0	0	0.00	00:00:00	90.00	0	0
0.34	0	0	0.00	00:00:00	90.00	0	0
0.32	0.342	0.513	0.43	00:00:10	93.79	1	1
0.30	1.026	1.368	1.20	00:00:25	97.79	2	2
0.27	0.171	0.342	0.26	00:00:10	92.51	1	1
0.25	0	0.171	0.09	00:00:09	90.94	0	1
0.23	0	0.171	0.09	00:00:13	90.94	1	1
0.21	0	0	0.00	00:00:00	90.00	0	0
0.20	0	0	0.00	00:00:00	90.00	0	0

P2b1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.35	0	0	0.00	00:00:00	90.00	0	0
0.32	0.171	0.342	0.26	00:00:13	92.51	1	1
0.29	0.342	0.513	0.43	00:00:26	93.79	2	1
0.26	2.735	3.047	2.89	00:00:26	102.88	2	3
0.23	0.684	0.855	0.77	00:00:19	95.83	1	2
0.21	0.855	1.026	0.94	00:00:19	96.67	1	2
0.19	0	0.171	0.09	00:00:18	90.94	1	1
0.17	0.513	0.684	0.60	00:00:12	94.88	1	1
0.12	0	0	0.00	00:00:00	90.00	0	0

P2b2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.32	0	0	0.00	00:00:00	90.00	0	0
0.31	0	0.171	0.09	00:00:11	90.94	1	1
0.28	0	0.171	0.09	00:00:12	90.94	1	1
0.25	0.684	0.855	0.77	00:00:12	95.83	1	2
0.23	0	0	0.00	00:00:00	90.00	0	0
0.21	0	0	0.00	00:00:00	90.00	0	0
0.19	0	0.171	0.09	00:00:10	90.94	1	1
0.18	0.171	0.342	0.26	00:00:10	92.51	1	1
0.14	0	0	0.00	00:00:00	90.00	0	0

P2b3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.35	0	0	0.00	00:00:00	90.00	0	0
0.34	0.342	0.513	0.43	00:00:15	93.79	1	1

0.31	0.342	0.513	0.43	00:00:23	93.79	1	1
0.28	2.052	2.393	2.22	00:00:20	101.20	1	3
0.25	0.342	0.513	0.43	00:00:18	93.79	1	1
0.22	0	0.171	0.09	00:00:19	90.94	1	1
0.20	0	0.171	0.09	00:00:24	90.94	1	1
0.18	0.855	1.026	0.94	00:00:13	96.67	1	2
0.14	0	0	0.00	00:00:00	90.00	0	0

P2d1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.36	0	0	0.00	00:00:00	90.00	0	0
0.33	1.368	1.71	1.54	00:00:16	99.08	1	2
0.31	2.735	3.047	2.89	00:00:35	102.88	2	3
0.28	3.047	3.419	3.23	00:01:40	103.64	3	3
0.26	2.393	2.735	2.56	00:00:21	102.09	1	3
0.24	0.855	1.026	0.94	00:00:15	96.67	1	2
0.22	0.342	0.513	0.43	00:00:19	93.79	1	1
0.20	0	0	0.00	00:00:00		0	0
0.19	0.855	1.026	0.94	00:00:19	96.67	1	2
0.14	0.513	0.634	0.57	00:00:12	94.73	1	1

P2d2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.39	0	0	0.00	00:00:00	90.00	0	0
0.35	0	0	0.00	00:00:00	90.00	0	0
0.33	2.393	2.735	2.56	00:00:26	102.09	2	3
0.29	2.735	3.047	2.89	00:00:59	102.88	2	3
0.26	3.149	3.932	3.54	00:01:00	104.28	3	3
0.24	2.052	2.735	2.39	00:00:40	101.66	2	3
0.22	0	0.171	0.09	00:00:12	90.94	1	1
0.20	0.342	0.513	0.43	00:00:17	93.79	1	1
0.19	0.855	1.026	0.94	00:00:14	96.67	1	2
0.14	0.342	0.513	0.43	00:00:15	93.79	1	1

B0c1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.45	0	0	0.00	00:00:00	90.00	0	0
0.40	0.634	0.855	0.74	00:00:19	95.70	1	2
0.34	0.634	0.855	0.74	00:00:41	95.70	2	2
0.33	0.342	0.513	0.43	00:00:25	93.79	2	1
0.31	0.342	0.513	0.43	00:00:43	93.79	2	1
0.29	0.342	0.513	0.43	00:00:12	93.79	1	1

0.28	0.171 0.342	0.26	00:00:10	92.51	1	1

B0c3						
soil moisture	**Molarity**	**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)			(hh:mm:ss)	(°)	(-)	(-)
0.47	0 0	0.00	00:00:00	90.00	0	0
0.42	0.342 0.513	0.43	00:00:20	93.79	1	1
0.37	0.171 0.342	0.26	00:00:17	92.51	1	1
0.35	0 0	0.00	00:00:00	90.00	0	0
0.33	0 0	0.00	00:00:00	90.00	0	0
0.31	0 0	0.00	00:00:00	90.00	0	0
0.30	0 0	0.00	00:00:00	90.00	0	0

O0c1						
soil moisture	**Molarity**	**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)			(hh:mm:ss)	(°)	(-)	(-)
0.48	0 0	0.00	00:00:00	90.00	0	0
0.42	3.047 3.418	3.23	00:01:16	103.64	3	3
0.37	2.735 3.047	2.89	00:01:03	102.88	3	3
0.36	2.052 2.393	2.22	00:00:32	101.20	2	3
0.34	1.368 1.71	1.54	00:00:20	99.08	1	2
0.32	1.368 1.71	1.54	00:00:32	99.08	2	2
0.31	1.368 1.71	1.54	00:00:14	99.08	1	2

O0c2						
soil moisture	**Molarity**	**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)			(hh:mm:ss)	(°)	(-)	(-)
0.42	0 0	0.00	00:00:00	90.00	0	0
0.38	3.047 3.418	3.23	00:01:25	103.64	3	3
0.33	2.393 2.735	2.56	00:00:18	102.09	1	3
0.32	1.71 2.052	1.88	00:00:26	100.20	2	3
0.31	1.026 1.368	1.20	00:00:19	97.79	1	2
0.29	1.026 1.368	1.20	00:00:16	97.79	1	2
0.28	1.026 1.368	1.20	00:00:27	97.79	2	2

O0c3						
soil moisture	**Molarity**	**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)			(hh:mm:ss)	(°)	(-)	(-)
0.46	0 0	0.00	00:00:00	90.00	0	4
0.40	3.047 3.418	3.23	00:02:34	103.64	3	4
0.35	2.735 3.047	2.89	00:02:33	102.88	3	4
0.33	2.735 3.047	2.89	00:02:03	102.88	3	4
0.32	1.368 1.71	1.54	00:00:19	99.08	1	4
0.30	1.368 1.71	1.54	00:00:29	99.08	2	4
0.29	1.368 1.71	1.54	00:00:52	99.08	2	4

G0c1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.60	0	0	0.00	00:00:00	90.00	0	0
0.54	0	0	0.00	00:00:00	90.00	0	0
0.46	0	0	0.00	00:00:00	90.00	0	0
0.44	0	0	0.00	00:00:00	90.00	0	0
0.40	0	0	0.00	00:00:00	90.00	0	0
0.37	0.342	0.513	0.43	00:00:08	93.79	0	1
0.35	0	0	0.00	00:00:00	90.00	0	0

G0c2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.55	0	0	0.00	00:00:00	90.00	0	0
0.50	0	0	0.00	00:00:00	90.00	0	0
0.44	0.171	0.342	0.26	00:00:18	92.51	1	1
0.42	0.342	0.513	0.43	00:00:12	93.79	1	1
0.40	0.171	0.342	0.26	00:00:34	92.51	2	1
0.37	0.634	0.855	0.74	00:00:23	95.70	1	2
0.36	0.342	0.513	0.43	00:00:13	93.79	1	1

G0c3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.61	0	0	0.00	00:00:00	90.00	0	0
0.55	0	0	0.00	00:00:00	90.00	0	0
0.47	0.171	0.342	0.26	00:00:10	92.51	1	1
0.45	0	0	0.00	00:00:00	90.00	0	0
0.41	0.342	0.513	0.43	00:00:17	93.79	1	1
0.39	0.342	0.513	0.43	00:00:32	93.79	2	1
0.37	0.342	0.513	0.43	00:00:13	93.79	1	1

PS1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.49	0	0	0.00	00:00:00	90.00	0	0
0.44	0	0	0.00	00:00:00	90.00	0	0
0.37	2.052	2.393	2.22	00:00:23	101.20	1	3
0.35	2.735	3.047	2.89	00:00:37	102.88	2	3
0.32	4.958	5.471	5.21	00:01:07	107.21	3	4
0.30	4.958	5.471	5.21	00:01:31	107.21	3	4
0.28	3.418	3.932	3.68	00:00:25	104.54	2	3

PS2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.43	0	0	0.00	00:00:00	90.00	0	0
0.38	3.047	3.418	3.23	00:00:20	103.64	1	3
0.33	5.984	6.496	6.24	00:02:30	108.69	3	4
0.32	5.984	6.496	6.24	00:04:38	108.69	3	4
0.29	5.984	6.496	6.24	00:06:04	108.69	3	4
0.27	3.932	4.445	4.19	00:03:26	105.50	3	4
0.26	3.932	4.445	4.19	00:01:19	105.50	3	4

PS3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.42	0	0	0.00	00:00:00	90.00	0	0
0.37	3.047	3.418	3.23	00:00:35	103.64	2	3
0.30	4.445	4.958	4.70	00:02:50	106.39	3	4
0.29	3.932	4.445	4.19	00:02:21	105.50	3	4
0.27	3.418	3.932	3.68	00:00:50	104.54	2	3
0.25	3.047	3.418	3.23	00:01:19	103.64	3	3
0.24	1.71	2.052	1.88	00:01:05	100.20	3	3

PN1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.44	0	0	0.00	00:00:00	90.00	0	0
0.39	2.052	2.393	2.22	00:00:24	101.20	1	3
0.32	3.932	4.445	4.19	00:01:19	105.50	3	4
0.30	2.735	3.047	2.89	00:01:46	102.88	3	3
0.28	1.026	1.368	1.20	00:00:52	97.79	2	2
0.26	2.393	2.735	2.56	00:01:39	102.09	3	3
0.25	1.71	2.052	1.88	00:00:56	100.20	2	3

PN2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.44	0	0	0.00	00:00:00	90.00	0	0
0.39	2.052	2.393	2.22	00:00:17	101.20	1	3
0.33	5.471	5.984	5.73	00:01:29	107.97	3	4
0.31	5.984	6.496	6.24	00:02:47	108.69	3	4
0.28	4.958	5.471	5.21	00:01:58	107.21	3	4
0.25	4.445	4.958	4.70	00:01:34	106.39	3	4
0.24	3.932	4.445	4.19	00:02:03	105.50	3	4

PN3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.40	0	0	0.00	00:00:00	90.00	0	0
0.35	1.71	2.052	1.88	00:00:17	100.20	1	3
0.28	3.047	3.41	3.23	00:01:39	103.63	3	3
0.27	2.393	2.735	2.56	00:00:58	102.09	2	3
0.25	0.513	0.634	0.57	00:00:19	94.73	1	1
0.23	1.71	2.052	1.88	00:00:46	100.20	2	3
0.22	1.71	2.052	1.88	00:00:32	100.20	2	3

Table 17: Soil water repllency results. WDPT & MED test. undisturbed samples. 4th cycle

undisturbed samples. cycle 4

R0c1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.44	0	0	0.00	00:00:00	0	0	0
0.40	0	0	0.00	00:00:00	90.00	0	0
0.37	0.171	0.342	0.26	00:00:12	92.51	1	1
0.34	0.855	1.026	0.94	00:00:24	96.67	1	2
0.28	3.047	3.41	3.23	00:01:46	103.63	3	3
0.23	1.026	1.368	1.20	00:00:39	97.79	2	2
0.16	0.634	0.855	0.74	00:00:17	95.70	1	2

R0c2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.39	0	0	0.00	00:00:00	90.00	0	0
0.35	0	0.171	0.09	00:00:11	90.94	1	1
0.33	1.026	1.368	1.20	00:00:23	97.79	1	2
0.30	2.052	2.393	2.22	00:01:35	101.20	3	3
0.25	3.047	3.41	3.23	00:01:33	103.63	3	3
0.21	1.026	1.368	1.20	00:00:27	97.79	2	2
0.13	0.855	1.026	0.94	00:00:39	96.67	2	2

R0c3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.39	0	0	0.00	00:00:00	90.00	0	0
0.36	0	0.171	0.09	00:00:44	90.94	2	1
0.34	0.634	0.855	0.74	00:00:28	95.70	2	2
0.32	0.855	1.026	0.94	00:02:03	96.67	3	2
0.27	3.41	3.932	3.67	00:03:13	104.54	4	3

0.23	2.052	2.393	2.22	00:00:34	101.20	2	3
0.16	1.368	1.71	1.54	00:00:48	99.08	2	2

R2b1							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.38	0	0	0.00	00:00:00	0	0	0
0.34	0	0	0.00	00:00:00	0	0	0
0.31	0	0	0.00	00:00:00	90.00	0	0
0.28	0.513	0.634	0.57	00:00:18	94.73	1	1
0.22	0	0	0.00	00:00:00	90.00	0	0
0.18	0.634	0.855	0.74	00:00:47	95.70	2	2
0.12	0.171	0.342	0.26	00:00:34	92.51	2	1

R2b2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.29	0	0	0.00	00:00:00	90.00	0	0
0.25	0.342	0.513	0.43	00:00:19	93.79	1	1
0.23	0.513	0.634	0.57	00:00:13	94.73	1	1
0.21	1.368	1.71	1.54	00:00:22	99.08	1	2
0.16	0.342	0.513	0.43	00:00:55	93.79	2	1
0.13	0.855	1.026	0.94	00:00:14	96.67	1	2
0.09	0.171	0.342	0.26	00:00:29	92.51	2	1

P1c1							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.37	0	0	0.00	00:00:00	90.00	0	0
0.34	0.513	0.634	0.57	00:00:11	94.73	1	1
0.32	0.634	0.855	0.74	00:00:17	95.70	1	2
0.27	0	0.171	0.09	00:00:13	90.94	1	1
0.23	0	0	0.00	00:00:00	90.00	0	0

P1c2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.42	0	0	0.00	00:00:00	90.00	0	0
0.37	0.342	0.513	0.43	00:00:14	93.79	1	1
0.34	0.634	0.855	0.74	00:00:24	95.70	1	2
0.31	0.342	0.513	0.43	00:00:22	93.79	1	1
0.25	0	0	0.00	00:00:00	90.00	0	0

P1c3							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**

(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.31	0	0	0.00	00:00:00	90.00	0	0
0.25	1.368	1.71	1.54	00:00:38	99.08	2	2
0.21	0	0	0.00	00:00:00	90.00	0	0

P2b1							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.35	0	0	0.00	00:00:00	90.00	0	0
0.28	0.171	0.342	0.26	00:00:11	92.51	1	1
0.26	0.342	0.513	0.43	00:00:13	93.79	1	1
0.23	0.342	0.513	0.43	00:00:25	93.79	2	1
0.18	0.342	0.513	0.43	00:00:18	93.79	1	1
0.14	0.171	0.342	0.26	00:00:10	92.51	1	1
0.10	0.171	0.342	0.26	00:00:11	92.51	1	1

P2b2							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.37	0	0	0.00	00:00:00	90.00	0	0
0.33	0	0	0.00	00:00:00	90.00	0	0
0.31	0	0	0.00	00:00:00	90.00	0	0
0.28	0	0	0.00	00:00:00	90.00	0	0
0.23	0.634	0.855	0.74	00:00:22	95.70	1	2
0.19	0.171	0.342	0.26	00:00:24	92.51	1	1
0.09	0	0	0.00	00:00:00	90.00	0	0

P2b3							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.40	0	0	0.00	00:00:00		0	0
0.36	0	0	0.00	00:00:00	90.00	0	0
0.33	0	0.171	0.09	00:00:14	90.94	1	1
0.31	0	0	0.00	00:00:00	90.00	0	0
0.24	1.368	1.71	1.54	00:00:28	99.08	2	2
0.19	0.171	0.342	0.26	00:00:15	92.51	1	1
0.13	0	0	0.00	00:00:00	90.00	0	0

P2d1							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.35	0	0	0.00	00:00:00	90.00	0	0
0.30	2.393	2.735	2.56	00:00:45	102.09	2	3
0.28	2.393	2.735	2.56	00:00:55	102.09	2	3
0.26	3.41	3.932	3.67	00:01:24	104.54	3	3

0.21	1.368	1.71	1.54	00:00:20	99.08	1	2
0.18	0.634	0.855	0.74	00:00:14	95.70	1	2
0.11	0.171	0.342	0.26	00:00:18	92.51	1	1

P2d2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.37	0	0	0.00	00:00:00	90.00	0	0
0.33	0.342	0.513	0.43	00:00:21	93.79	1	1
0.30	2.052	2.393	2.22	00:00:34	101.20	2	3
0.28	3.042	3.41	3.23	00:00:51	103.62	2	3
0.22	3.047	3.41	3.23	00:01:17	103.63	3	3
0.18	0.855	1.026	0.94	00:00:14	96.67	1	2
0.13	0.513	0.634	0.57	00:00:38	94.73	2	1

Annex B: Soil water repllency results. WDPT and MED tests on disturbed samples

The results are presented as: volumetric soil moisture (m³/m³), molarity (mol/l), average molarity (mol/l), water droplet penetration times (hh:mm:ss), contact angles (°), and SWR- classes (Tables 2 and 3). Potential soil water repellency is indicated with red background color

Table 18: Soil water repllency results. WDPT & MED test. disturbed samples. 1st cycle

Disturbed samples. cycle 1

R0c1:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.00	0	0	0.00	0	<90	0	0
0.47	0	0	0.00	0	<90	0	0
0.43	0	0	0.00	0	<90	0	0
0.41	0	0	0.00	0	<90	0	0
0.37	0	0	0.00	0	<90	0	0
0.26	0	0	0.00	0	<90	0	0
0.22	1.026	1.368	1.20	00:00:23	97.79	1	2
0.20	1.368	1.71	1.54	00:00:28	99.08	2	2
0.18	0.513	0.634	0.57	00:00:23	94.73	1	1
0.17	0.513	0.634	0.57	00:00:15	94.73	1	1
0.15	0.634	0.855	0.74	00:00:20	95.70	1	2
0.13	0.342	0.513	0.43	00:00:15	93.79	1	1
0.12	0.342	0.513	0.43	00:00:13	93.79	1	1
0.11	0.342	0.513	0.43	00:00:18	93.79	1	1
0.10	0	0	0.00	00:00:00	<90	0	0

0.08	0	0	0.00	00:00:00	<90	0	0
0.03	0	0	0.00	00:00:00	<90	0	0

R0c2:							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.00	0	0	0.00	0	<90	0	0
0.51	0	0	0.00	0	<90	0	0
0.47	0	0	0.00	0	<90	0	0
0.45	0	0	0.00	0	<90	0	0
0.41	0	0	0.00	0	<90	0	0
0.29	0	0	0.00	0	<90	0	0
0.24	0	0.171	0.09	00:00:11	90.94	1	1
0.22	0.855	1.026	0.94	00:00:16	96.67	1	2
0.20	0.634	0.855	0.74	00:00:22	95.70	1	2
0.18	0.634	0.855	0.74	00:00:13	95.70	1	2
0.16	0.634	0.855	0.74	00:00:17	95.70	1	2
0.14	0.342	0.513	0.43	00:00:18	93.79	1	1
0.13	0.634	0.855	0.74	00:00:30	95.70	2	2
0.12	0.342	0.513	0.43	00:00:21	93.79	1	1
0.09	0.342	0.513	0.43	00:00:25	93.79	2	1
0.07	0.171	0.342	0.26	00:00:24	92.51	1	1
0.01	0.342	0.513	0.43	00:00:31	93.79	2	1

P1c1:							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.00	0	0	0.00	00:00:00	<90	0	0
0.37	0	0	0.00	00:00:00	<90	0	0
0.34	0	0	0.00	00:00:00	<90	0	0
0.32	0	0	0.00	00:00:00	<90	0	0
0.28	0	0	0.00	00:00:00	<90	0	0
0.21	1.026	1.368	1.20	00:00:26	97.79	2	2
0.19	1.026	1.368	1.20	00:00:34	97.79	2	2
0.17	0.634	0.855	0.74	00:00:26	95.70	2	2
0.16	0.634	0.855	0.74	00:00:26	95.70	2	2
0.14	0.513	0.634	0.57	00:00:17	94.73	1	1
0.13	0.513	0.634	0.57	00:00:15	94.73	1	1
0.12	0.513	0.634	0.57	00:00:13	94.73	1	1
0.11	0.513	0.634	0.57	00:00:14	94.73	1	1
0.10	0	0.171	0.09	00:00:09	90.94	0	1
0.08	0	0	0.00	00:00:00	90.00	0	0
0.06	0.342	0.513	0.43	00:00:18	93.79	1	1
0.02	0.171	0.342	0.26	00:00:15	92.51	1	1

P1c2:							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.00	0	0	0.00	00:00:00	<90	0	0
0.40	0	0	0.00	00:00:00	<90	0	0
0.37	0	0	0.00	00:00:00	<90	0	0
0.35	0	0	0.00	00:00:00	<90	0	0
0.31	0	0	0.00	00:00:00	<90	0	0
0.23	1.71	2.052	1.88	00:00:48	100.20	2	3
0.21	1.71	2.052	1.88	00:00:49	100.20	2	3
0.19	1.71	2.052	1.88	00:00:46	100.20	2	3
0.18	1.368	1.71	1.54	00:00:27	99.08	2	2
0.16	1.026	1.368	1.20	00:00:32	97.79	2	2
0.15	0.855	1.026	0.94	00:00:17	96.67	1	2
0.14	0.855	1.026	0.94	00:00:29	96.67	2	2
0.12	0.855	1.026	0.94	00:00:20	96.67	1	2
0.11	0.513	0.634	0.57	00:00:26	94.73	2	1
0.10	0.342	0.513	0.43	00:00:21	93.79	1	1
0.08	0.342	0.513	0.43	00:00:18	93.79	1	1
0.02	0.342	0.513	0.43	00:00:17	93.79	1	1

P2b1:							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.00	0	0	0.00	00:00:00	<90	0	0
0.44	0	0	0.00	00:00:00	<90	0	0
0.40	0	0	0.00	00:00:00	<90	0	0
0.37	0	0	0.00	00:00:00	<90	0	0
0.34	0	0	0.00	00:00:00	<90	0	0
0.24	0	0	0.00	00:00:00	90.00	0	0
0.21	0	0.171	0.09	00:00:18	90.94	1	1
0.18	1.368	1.71	1.54	00:00:15	99.08	1	2
0.15	1.026	1.368	1.20	00:00:20	97.79	1	2
0.14	0.634	0.855	0.74	00:00:16	95.70	1	2
0.12	0.855	1.026	0.94	00:00:17	96.67	1	2
0.11	0.855	1.026	0.94	00:00:21	96.67	1	2
0.09	0.634	0.855	0.74	00:00:17	95.70	1	2
0.08	0.342	0.513	0.43	00:00:14	93.79	1	1
0.07	0.342	0.513	0.43	00:00:12	93.79	1	1
0.05	0.171	0.342	0.26	00:00:12	92.51	1	1
0.01	0	0.171	0.09	00:00:09	90.94	0	1

P2b2:							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**

(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.00	0	0	0.00	00:00:00	<90	0	0
0.33	0	0	0.00	00:00:00	<90	0	0
0.30	0	0	0.00	00:00:11	<90	1	0
0.28	0	0	0.00	00:00:10	<90	1	0
0.25	0	0.171	0.09	00:00:10	90.94	1	1
0.17	0.855	1.026	0.94	00:00:25	96.67	2	2
0.15	1.71	2.052	1.88	00:00:29	100.20	2	3
0.13	2.052	2.393	2.22	00:00:21	101.20	1	3
0.11	0.855	1.026	0.94	00:00:28	96.67	2	2
0.10	0.634	0.855	0.74	00:00:25	95.70	2	2
0.08	1.368	1.71	1.54	00:00:20	99.08	1	2
0.08	1.368	1.71	1.54	00:00:23	99.08	1	2
0.07	0.855	1.026	0.94	00:00:24	96.67	1	2
0.06	0.513	0.634	0.57	00:00:16	94.73	1	1
0.05	0.634	0.855	0.74	00:00:21	95.70	1	2
0.04	0.634	0.855	0.74	00:00:17	95.70	1	2
0.02	0.634	0.855	0.74	00:00:23	95.70	1	2

R2b1:							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.00	0.342	0.613	0.48	00:01:14	94.12	3	1
0.41	0	0	0.00	00:00:00	<90	0	0
0.38	0	0	0.00	00:00:00	<90	0	0
0.35	0	0	0.00	00:00:00	<90	0	0
0.23	2.393	2.735	2.56	00:01:01	102.09	3	3
0.20	2.735	3.077	2.91	00:01:07	102.91	3	3
0.19	1.026	1.3687	1.20	00:00:50	97.80	2	2
0.16	0.855	1.026	0.94	00:00:19	96.67	1	2
0.15	0.634	0.855	0.74	00:00:25	95.70	2	2
0.14	0.855	1.026	0.94	00:00:18	96.67	1	2
0.13	0.634	0.855	0.74	00:00:16	95.70	1	2
0.12	0.634	0.855	0.74	00:00:17	95.70	1	2
0.11	0.342	0.513	0.43	00:00:14	93.79	1	1
0.10	0.171	0.342	0.26	00:00:14	92.51	1	1
0.08	0.342	0.513	0.43	00:00:11	93.79	1	1
0.03	0.171	0.342	0.26	00:00:21	92.51	1	1

R2b2:							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.02	0.342	0.613	0.48	00:01:50	94.12	3	1
0.38	0	0	0.00	00:00:00	<90	0	0
0.35	0	0	0.00	00:00:00	<90	0	0

0.32	0	0	0.00	00:00:00	<90	0	0
0.20	0.513	0.634	0.57	00:00:18	94.73	1	1
0.19	0.634	0.855	0.74	00:00:14	95.70	1	2
0.17	0.855	1.026	0.94	00:00:19	96.67	1	2
0.14	0.855	1.026	0.94	00:00:15	96.67	1	2
0.14	0.513	0.634	0.57	00:00:15	94.73	1	1
0.13	0.855	1.026	0.94	00:00:14	96.67	1	2
0.12	0.634	0.855	0.74	00:00:23	95.70	1	2
0.11	0.634	0.855	0.74	00:00:18	95.70	1	2
0.10	0.171	0.342	0.26	00:00:13	92.51	1	1
0.09	0.342	0.513	0.43	00:00:13	93.79	1	1
0.07	0.342	0.513	0.43	00:00:22	93.79	1	1
0.00	0.171	0.342	0.26	00:00:19	92.51	1	1

PS1:							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.00	0.855	1.026	0.94	00:03:51	96.67	4	2
0.36	0	0	0.00	00:00:00	90.00	0	0
0.29	0	0	0.00	00:00:00	90.00	0	0
0.20	0	0	0.00	00:00:00	90.00	0	0
0.14	0.634	0.855	0.74	00:00:41	95.70	2	2
0.10	1.026	1.368	1.20	00:00:35	97.79	2	2

PS2:							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.00	1.026	1.368	1.20	00:06:21	97.79	4	2
0.33	0	0	0.00	00:00:00	90.00	0	0
0.30	0	0	0.00	00:00:00	90.00	0	0
0.23	0	0	0.00	00:00:00	90.00	0	0
0.17	0.634	0.855	0.74	00:00:27	95.70	2	2
0.12	0.634	0.855	0.74	00:00:26	95.70	2	2
0.08	1.368	1.71	1.54	00:00:41	99.08	2	2

PS3:							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.00	0.513	0.634	0.57	00:03:40	94.73	4	1
0.42	0	0	0.00	00:00:00	90.00	0	0
0.39	0	0	0.00	00:00:00	90.00	0	0
0.33	0	0	0.00	00:00:00	90.00	0	0
0.26	0	0	0.00	00:00:00	90.00	0	0
0.17	0	0	0.00	00:00:00	90.00	0	0
0.11	1.368	1.71	1.54	00:01:34	99.08	3	2

PN1:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.00	0.513	0.634	0.57	00:01:34	94.73	3	1
0.34	0	0	0.00	00:00:00	90.00	0	0
0.31	0	0	0.00	00:00:00	90.00	0	0
0.23	0	0	0.00	00:00:00	90.00	0	0
0.17	0.513	0.634	0.57	00:00:14	94.73	1	1
0.09	0	0.171	0.09	00:00:10	90.94	1	1
0.08	0	0.171	0.09	00:00:15	90.94	1	1

PN2:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.00	1.026	1.368	1.20	00:31:40	97.79	5	2
0.23	0	0	0.00	00:00:00	90.00	0	0
0.20	1.026	1.368	1.20	00:00:50	97.79	2	2
0.16	1.368	1.71	1.54	00:01:25	99.08	3	2
0.12	0.855	1.026	0.94	00:00:36	96.67	2	2
0.10	0.634	0.855	0.74	00:01:04	95.70	3	2
0.07	1.026	1.368	1.20	00:00:51	97.79	2	2

PN3:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.00	1.026	1.368	1.20	00:07:43	97.79	4	2
0.25	0	0	0.00	00:00:00	90.00	0	0
0.22	0	0.171	0.09	00:00:12	90.94	1	1
0.17	1.026	1.368	1.20	00:00:44	97.79	2	2
0.13	1.026	1.368	1.20	00:00:39	97.79	2	2
0.10	0.634	0.855	0.74	00:00:46	95.70	2	2
0.07	1.026	1.368	1.20	00:00:32	97.79	2	2

B0c1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.00	2.052	2.393	2.22	02:00:00	101.20	6	3
0.10	0	0	0.00	00:00:00	90.00	0	0
0.07	1.026	1.368	1.20	00:01:38	97.79	3	2
0.05	1.368	1.71	1.54	00:02:45	99.08	3	2
0.04	1.71	2.052	1.88	00:02:03	100.20	3	3
0.04	1.71	2.052	1.88	00:03:04	100.20	4	3

B0c2

soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.00	2.052	2.393	2.22	02:30:00	101.20	6	3
0.09	0	0	0.00	00:00:00	90.00	0	0
0.06	1.026	1.368	1.20	00:01:51	97.79	3	2
0.04	1.368	1.71	1.54	00:01:26	99.08	3	2
0.03	0.634	0.855	0.74	00:01:08	95.70	3	2
0.03	1.71	2.052	1.88	00:12:44	100.20	5	3

B0c3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.00	2.052	2.393	2.22	02:30:00	101.20	6	3
0.08	0	0	0.00	0	90.00	0	0
0.06	1.71	2.052	1.88	00:10:55	100.20	5	3
0.04	2.052	2.393	2.22	00:07:23	101.20	4	3
0.02	1.71	2.052	1.88	00:04:52	100.20	4	3
0.02	2.052	2.393	2.22	00:19:35	101.20	5	3

O0c1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.00	3.932	4.475	4.20	02:30:00	105.53	6	4
0.10	0	0	0.00	00:00:00	90.00	0	0
0.07	4.445	4.958	4.70	03:30:00	106.39	6	4
0.04	4.958	5.471	5.21	04:00:00	107.21	6	4
0.03	5.471	5.958	5.71	03:20:00	107.95	6	4
0.02	4.445	4.958	4.70	01:40:00	106.39	6	4

O0c2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.00	3.932	4.475	4.20	03:30:00	105.53	6	4
0.06	0	0	0.00	00:00:00	90.00	0	0
0.04	4.445	4.958	4.70	00:41:33	106.39	5	4
0.04	3.41	3.393	3.40	01:00:00	103.99	6	3
0.03	4.958	5.471	5.21	01:24:40	107.21	6	4
0.03	4.445	4.958	4.70	01:06:00	106.39	6	4

O0c3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.00	3.932	4.475	4.20	03:30:00	105.53	6	4
0.07	0	0	0.00	00:00:00	90.00	0	0

0.05	4.958	5.471	5.21	02:30:00	107.21	6	4
0.04	4.445	4.958	4.70	03:00:00	106.39	6	4
0.03	4.958	5.471	5.21	03:00:00	107.21	6	4
0.03	4.445	4.958	4.70	01:40:00	106.39	6	4

G0c1							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.00	1.026	1.368	1.20	00:45:27	97.79	5	2
0.13	0	0	0.00	00:00:00	90.00	0	0
0.10	1.026	1.368	1.20	00:05:40	97.79	4	2
0.07	2.393	2.735	2.56	00:04:03	102.09	4	3
0.05	1.71	2.052	1.88	00:03:10	100.20	4	3
0.03	0.855	1.026	0.94	00:02:59	96.67	3	2

G0c2							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.00	1.368	1.71	1.54	02:00:00	99.08	6	2
0.14	0	0	0.00	00:00:00	90.00	0	0
0.09	0.513	0.634	0.57	00:00:22	94.73	1	1
0.06	1.368	1.71	1.54	00:01:34	99.08	3	2
0.04	1.368	1.71	1.54	00:01:10	99.08	3	2
0.03	1.026	1.368	1.20	00:01:24	97.79	3	2

G0c3							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.00	1.368	1.71	1.54	02:30:00	99.08	6	2
0.15			0.00	00:00:00	90.00	0	0
0.12	0.634	0.855	0.74	00:01:59	95.70	3	2
0.09	1.368	1.71	1.54	00:05:40	99.08	4	2
0.06	1.71	2.052	1.88	00:11:52	100.20	5	3
0.03	1.026	1.368	1.20	00:02:33	97.79	3	2

Table 19: Soil water repllency results. WDPT & MED test. disturbed samples. 2nd cycle

disturbed samples. cycle 2

R0c1:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.27	0	0	0	0	<90	0	0
0.24	0.342	0.513	0.43	00:00:20	93.79	1	1
0.21	0	0	0	0	<90	0	0

R0c2:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.24	0	0	0	00:00:00	90.00	0	0
0.21	0.342	0.513	0.43	00:00:10	93.79	1	1
0.18	0.342	0.513	0.43	00:00:22	93.79	1	1
0.16	0	0	0	00:00:00	90.00	0	0

R2b1:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.17	0	0	0	00:00:00	90.00	0	0
0.13	1.026	1.368	1.20	00:00:40	97.79	2	2
0.12	1.368	1.71	1.54	00:00:33	99.08	2	2
0.11	0.342	0.513	0.4275	00:00:34	93.79	2	1
0.09	0	0.171	0.0855	00:00:10	90.94	1	1

R2b2:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.11	0	0	0	00:00:00		0	0
0.06	1.026	1.368	1.20	00:00:17	97.79	1	2
0.05	0.171	0.342	0.26	00:00:10	92.51	1	1
0.03	0	0	0	00:00:00		0	0
0.02	0	0.171	0.0855	00:00:08	90.94	0	1
0.01	0	0	0	00:00:00	90.00	0	0

P1c1:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.00	0	0	0.00	00:00:00	<90	0	0

P1c2:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.27	0	0	0	00:00:00	90.00	0	0
0.22	1.026	1.71	1.37	00:00:27	98.46	2	2
0.20	0.513	0.684	0.60	00:00:29	94.88	2	1
0.18	0.342	0.513	0.4275	00:00:11	93.79	1	1
0.16	0.171	0.342	0.2565	00:00:14	92.51	1	1

P2b1:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)

0.00	0	0	0.00	00:00:00	<90	0	0

P2b2:								
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.17	0	0	0	0	90.00	0	0
0.15	0.171	0.342	0.26	00:00:13	92.51	1	1
0.13	0	0	0	0	90.00	0	0

B0c1:								
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.10	0	0	0.00	00:00:00	90.00	0	0
0.06	1.026	1.368	1.20	00:01:06	97.79	3	2
0.04	1.026	1.368	1.20	00:01:25	97.79	3	2
0.04	0.855	1.026	0.94	00:00:59	96.67	2	2
0.04	0.855	1.026	0.94	00:01:01	96.67	3	2

B0c2:								
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.10	0	0	0.00	00:00:00	90.00	0	0
0.05	0.513	0.634	0.57	00:00:52	94.73	2	1
0.03	0.634	0.855	0.74	00:01:18	95.70	3	2
0.03	0.634	0.855	0.74	00:01:00	95.70	3	2
0.03	0.634	0.855	0.74	00:01:08	95.70	3	2

B0c3:								
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.09	0	0	0.00	00:00:00	90.00	0	0
0.05	2.052	2.393	2.22	00:04:55	101.20	3	3
0.02	1.026	1.368	1.20	00:04:01	97.79	3	2
0.02	1.368	1.71	1.54	00:03:22	99.08	3	2
0.02	1.026	1.368	1.20	00:02:58	97.79	3	2

O0c1:								
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.08	0	0	0.00	00:00:00	90.00	0	0
0.04	4.445	4.958	4.70	04:00:00	106.39	3	4
0.02	3.932	4.445	4.19	04:00:00	105.50	3	4

O0c2:								
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class

(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.05	0	0	0.00	00:00:00	90.00	0	0
0.04	3.047	3.418	3.23	00:05:11	103.64	3	3
0.03	2.393	2.735	2.56	00:10:00	102.09	3	3

O0c3:							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.08	0	0	0.00	00:00:00	90.00	0	4
0.04	3.932	4.445	4.19	00:11:22	105.50	3	4
0.04	2.735	3.047	2.89	00:20:00	102.88	3	4

G0c1:							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.15	0	0	0.00	00:00:00	90.00	0	0
0.11	0	0.171	0.09	00:00:16	90.94	1	1
0.05	0.634	0.855	0.74	00:00:49	95.70	2	2
0.04	0.342	0.513	0.43	00:00:39	93.79	2	1
0.03	2.735	3.047	2.89	00:01:42	102.88	3	3
0.02	2.735	3.047	2.89	00:03:20	102.88	3	3

G0c2:							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.14	0	0	0.00	00:00:00	90.00	0	0
0.09	0	0	0.00	00:00:00	90.00	0	0
0.03	0.634	0.855	0.74	00:01:03	95.70	3	2
0.03	0.513	0.634	0.57	00:03:25	94.73	3	1
0.03	0.342	0.513	0.43	00:00:25	93.79	2	1
0.02	0.634	0.855	0.74	00:00:34	95.70	2	2

G0c3:							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m³/m³)				(hh:mm:ss)	(°)	(-)	(-)
0.18	0	0	0.00	00:00:00	90.00	0	0
0.14	0.171	0.342	0.26	00:00:13	92.51	1	1
0.07	0.634	0.855	0.74	00:00:42	95.70	2	2
0.05	0.342	0.513	0.43	00:00:53	93.79	2	1
0.03	0.342	0.513	0.43	00:00:25	93.79	2	1
0.03	0.634	0.855	0.74	00:01:33	95.70	3	2

Table 20: Soil water repllency results. WDPT & MED test. disturbed samples. 3rd cycle

disturbed samples. cycle 3

R0c1:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.24	0	0	0.00	00:00:00	90.00	0	0
0.20	1.368	1.71	1.54	00:00:41	99.08	2	2
0.16	0.513	0.634	0.57	00:00:30	94.73	2	1
0.05	0	0	0.00	00:00:00	90.00	0	0

R0c2:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.19	0	0	0.00	00:00:00	90.00	0	0
0.15	1.026	1.368	1.20	00:00:22	97.79	1	2
0.11	0	0	0.00	00:00:00	90.00	0	0

P1c1:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.00	0	0	0.00	00:00:00	<90	0	0

P1c2:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.21	0	0	0.00	00:00:00	90.00	0	0
0.21	0.513	0.634	0.57	00:00:20	94.73	1	1
0.18	0.171	0.342	0.26	00:00:16	92.51	1	1
0.14	0	0	0.00	00:00:00	90.00	0	0
0.03	0	0.171	0.09	00:00:12	90.94	1	1

P2b1:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.14	0	0	0.00	00:00:00	90.00	0	0
0.10	0	0.171	0.09	00:00:09	90.94	0	1
0.02	0	0	0.00	00:00:00	90.00	0	0

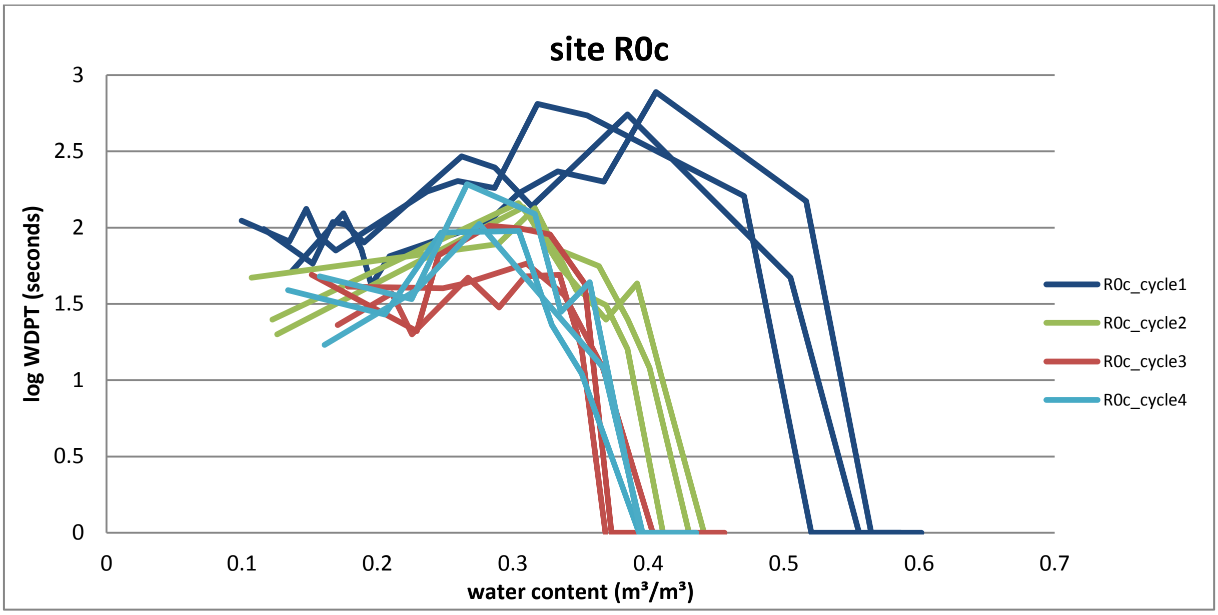
P2b2:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.00	0	0	0.00	00:00:00	<90	0	0

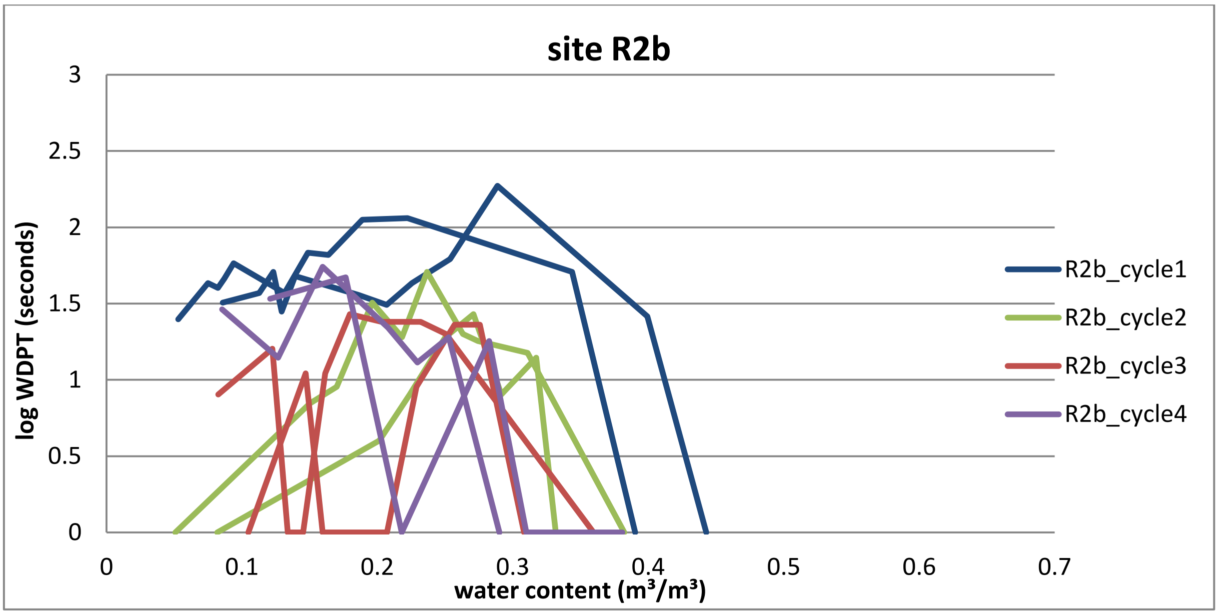
R2b1:							
soil moisture	Molarity		Average M	WDPT- average	Contact angles	WDPT class	CA class
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)

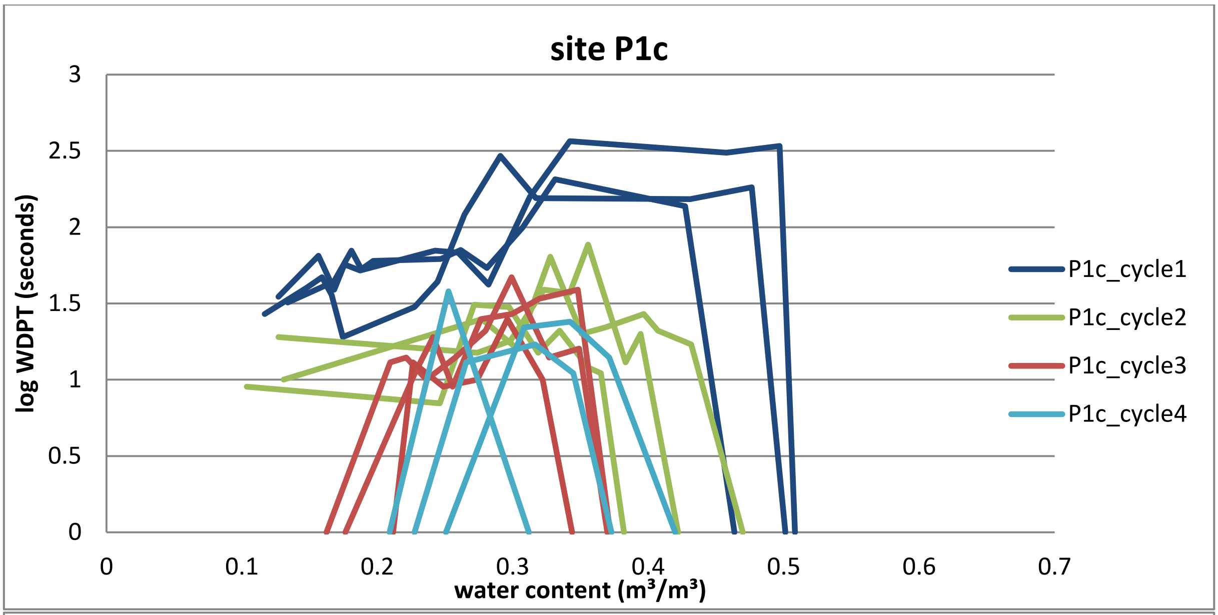
0.16	0	0	0.00	00:00:00	90.00	0	0
0.12	1.026	1.368	1.20	00:00:30	97.79	2	2
0.09	0.342	0.513	0.43	00:00:27	93.79	2	1
0.09	0	0	0.00	00:00:00	90.00	0	0
0.07	0	0	0.00	00:00:00	90.00	0	0
0.05	0	0.171	0.09	00:00:10	90.94	1	1
0.03	0	0	0.00	00:00:00	90.00	0	0

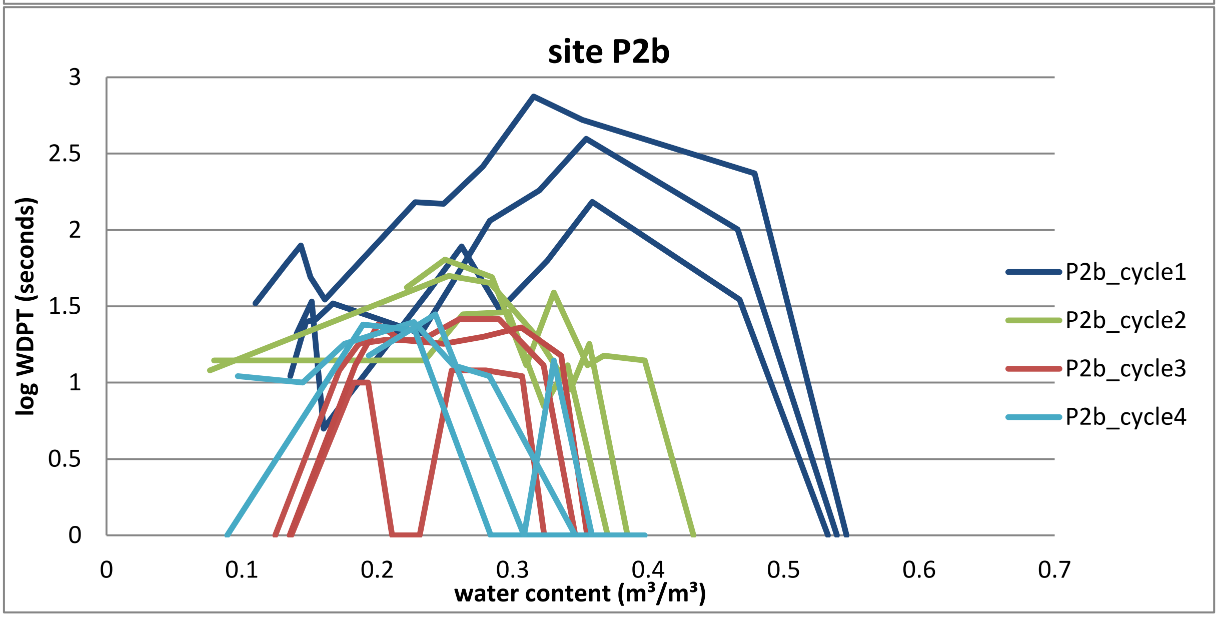
R2b2:							
soil moisture	**Molarity**		**Average M**	**WDPT- average**	**Contact angles**	**WDPT class**	**CA class**
(m^3/m^3)				(hh:mm:ss)	(°)	(-)	(-)
0.04	0	0	0.00	00:00:00	90.00	0	0
0.01	0	0.171	0.09	00:00:10	90.94	1	1
0.00	0	0	0.00	00:00:00	90.00	0	0

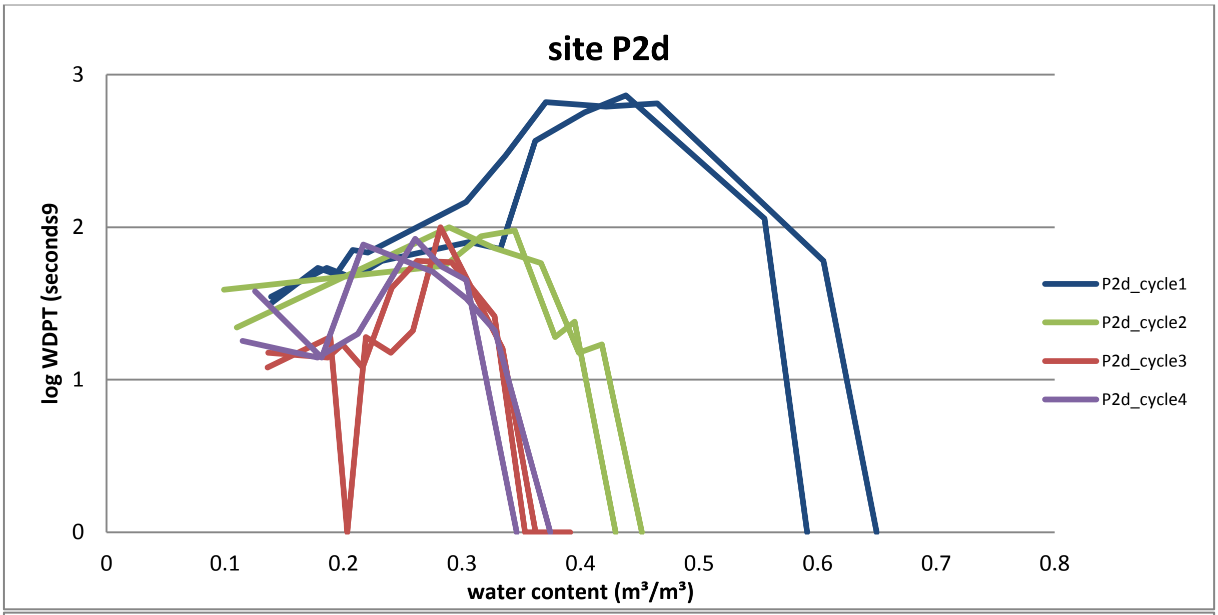
Annex C: Soil water repellency curves (SWR expressed by WDPT) for different drying cycles on undisturbed samples

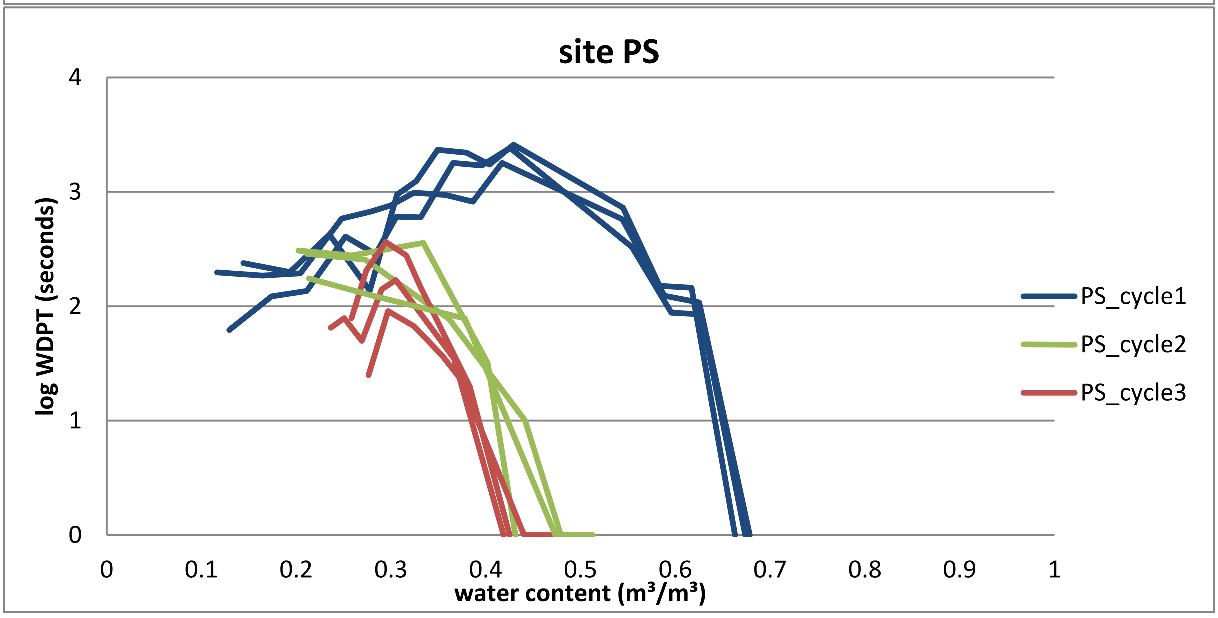


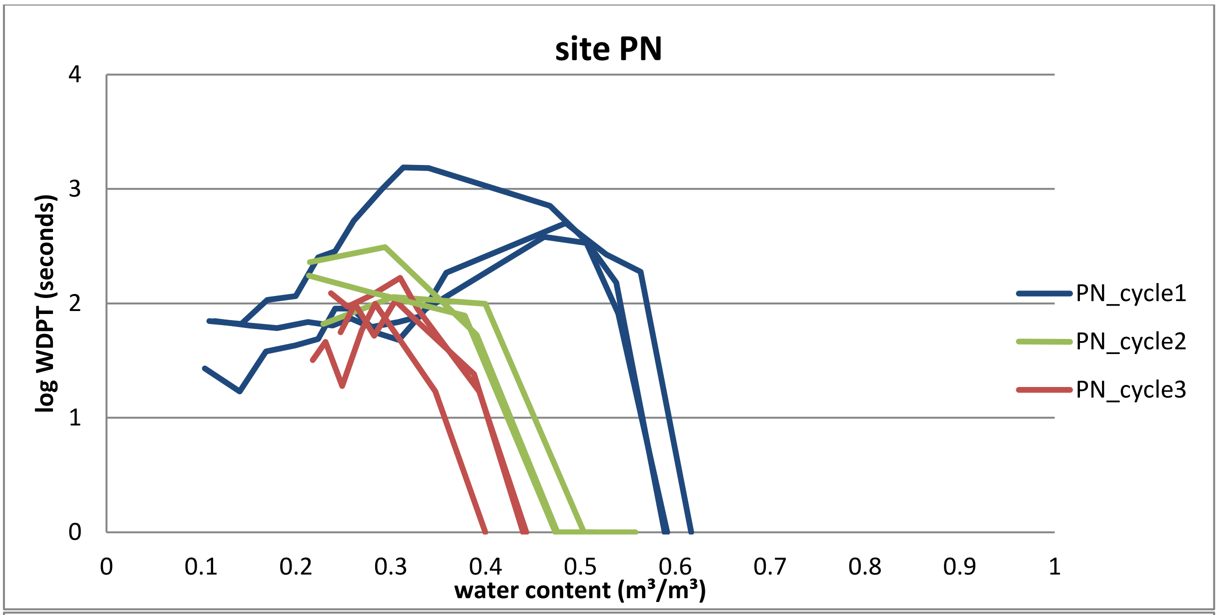


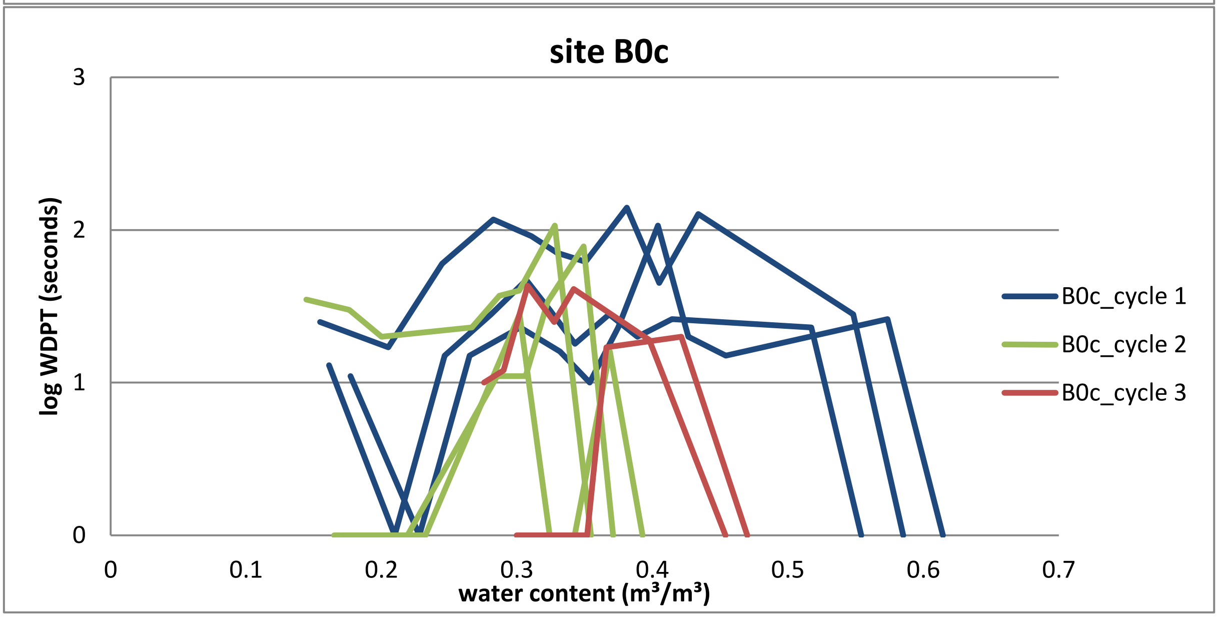

site P1c
log WDPT (seconds)
3
2.5
2
1.5
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
water content (m³/m³)
P1c_cycle1
P1c_cycle2
P1c_cycle3
P1c_cycle4

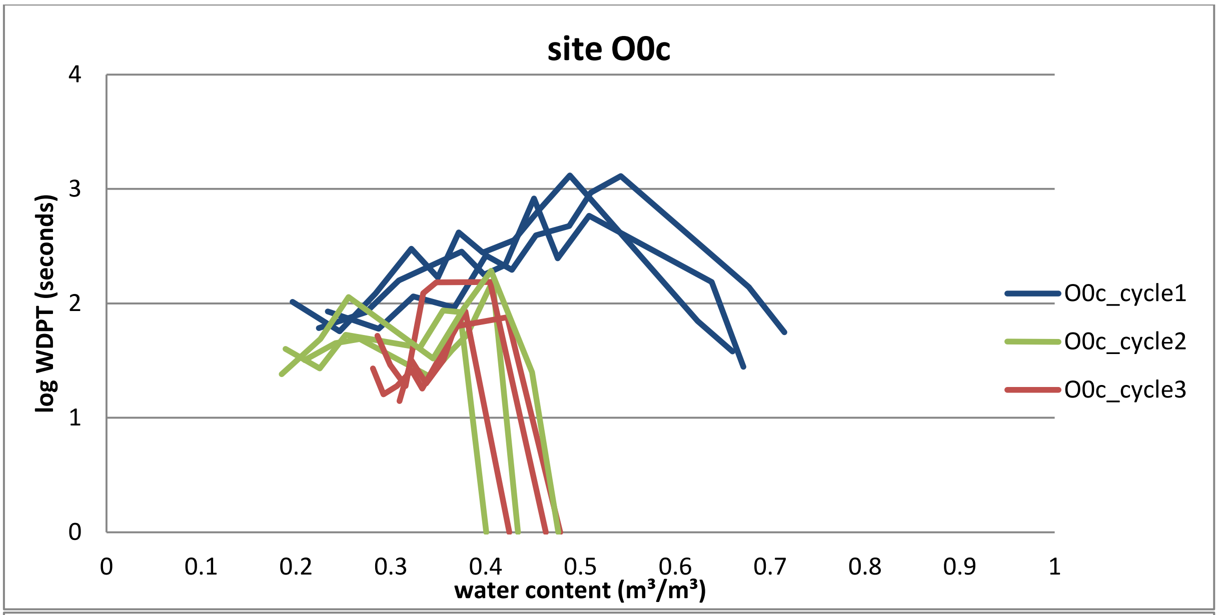

site P2b
log WDPT (seconds)
3
2.5
2
1.5
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
water content (m³/m³)
P2b_cycle1
P2b_cycle2
P2b_cycle3
P2b_cycle4

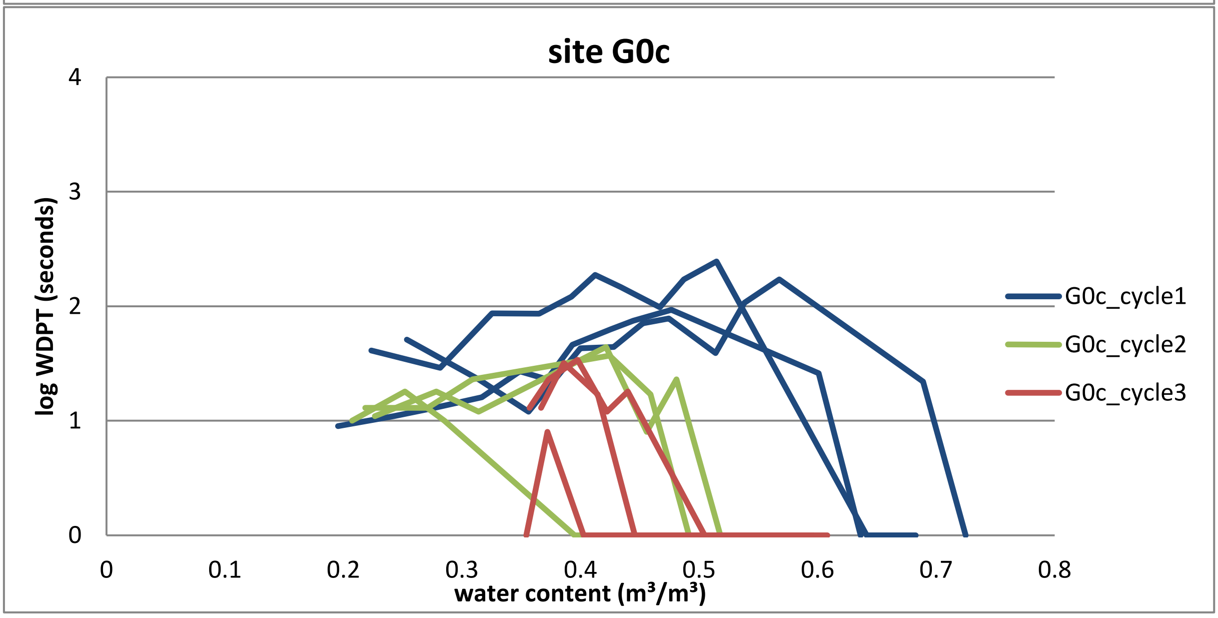

site P2d
log WDPT (seconds9
water content (m³/m³)
0
1
2
3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
P2d_cycle1
P2d_cycle2
P2d_cycle3
P2d_cycle4


site PS
log WDPT (seconds)
water content (m³/m³)
0
1
2
3
4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
PS_cycle1
PS_cycle2
PS_cycle3

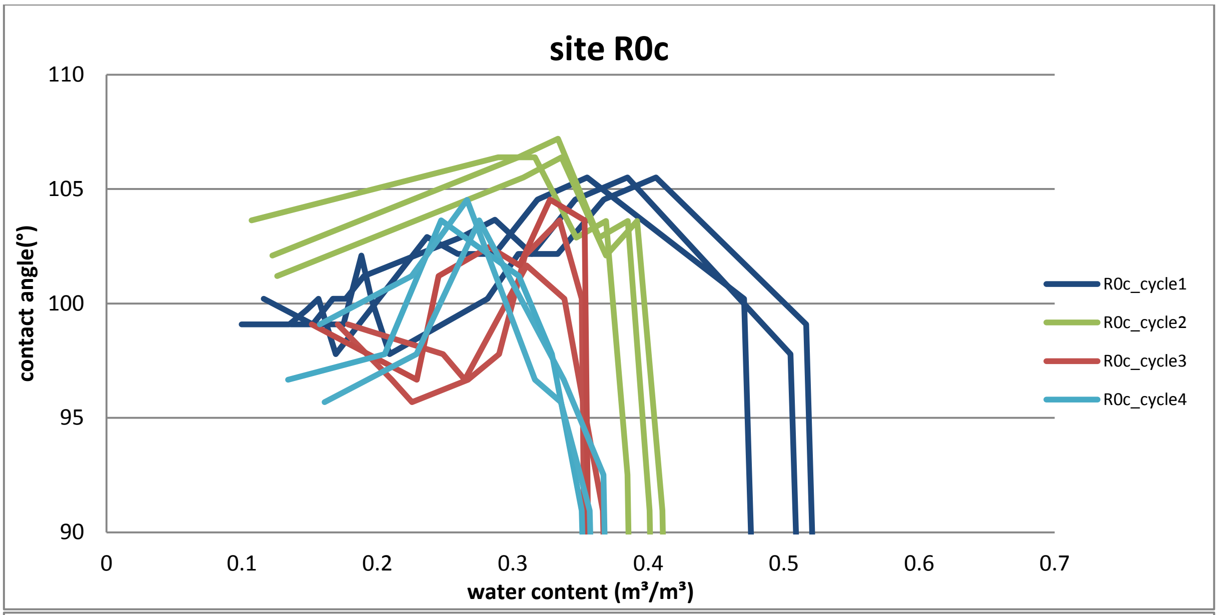

site PN
log WDPT (seconds)
4
3
2
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
water content (m³/m³)
PN_cycle1
PN_cycle2
PN_cycle3

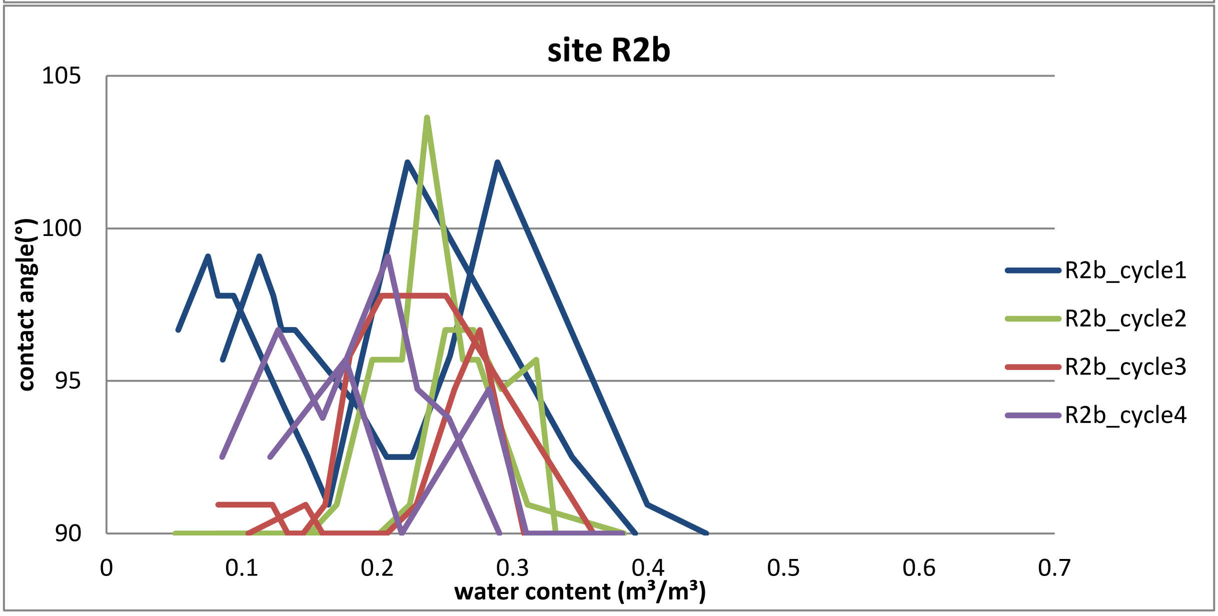

site B0c
log WDPT (seconds)
3
2
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
water content (m³/m³)
B0c_cycle 1
B0c_cycle 2
B0c_cycle 3

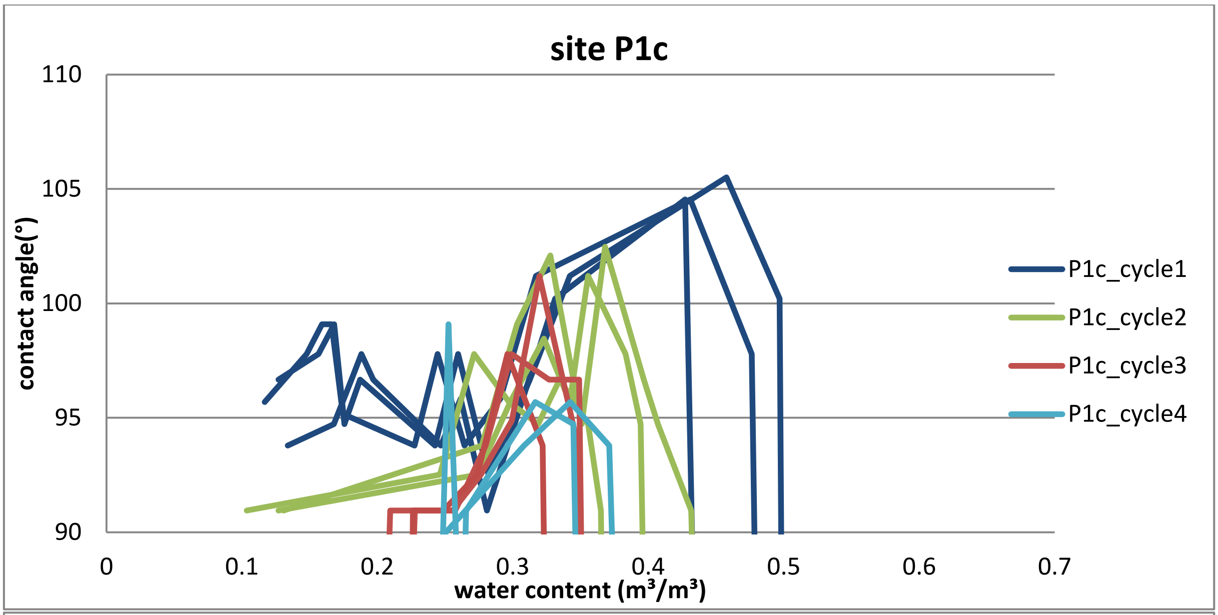

site O0c
log WDPT (seconds)
water content (m³/m³)
O0c_cycle1
O0c_cycle2
O0c_cycle3

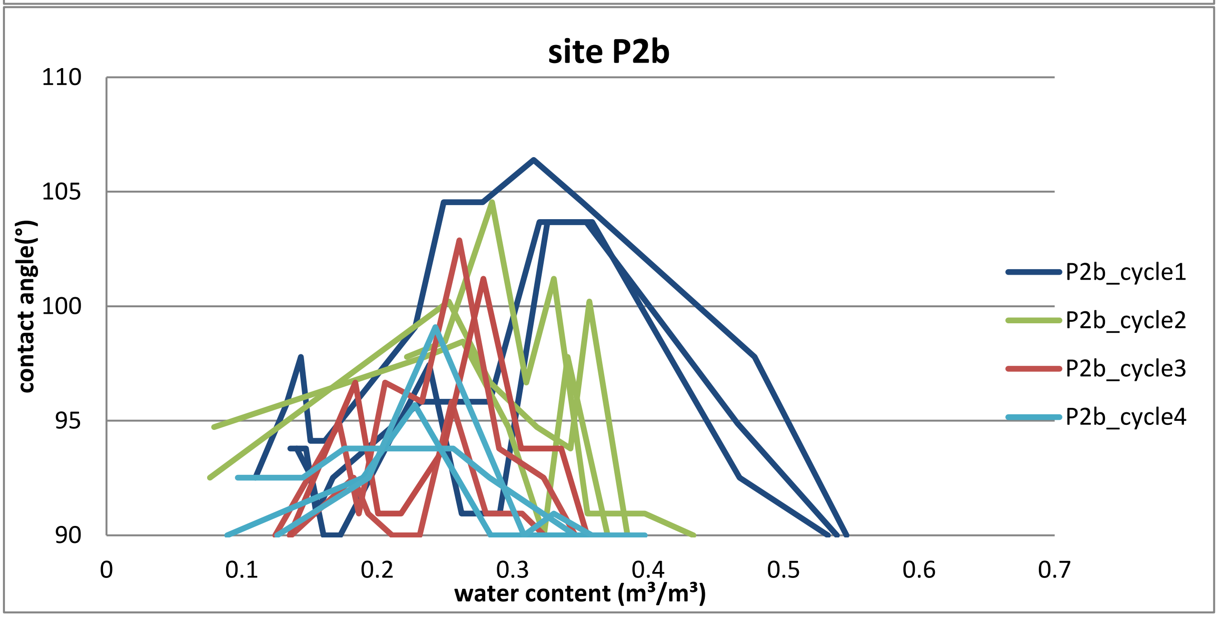

site G0c
log WDPT (seconds)
water content (m³/m³)
G0c_cycle1
G0c_cycle2
G0c_cycle3

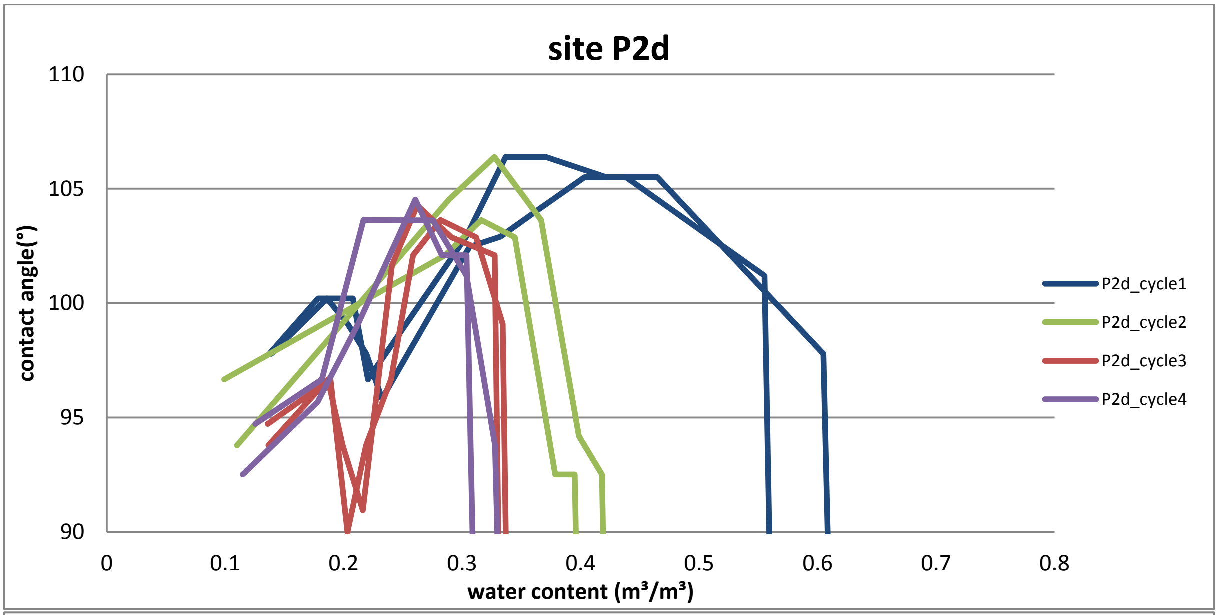
Annex D: Soil water repellency curves (SWR expressed by CA) for different drying cycles for undisturbed samples

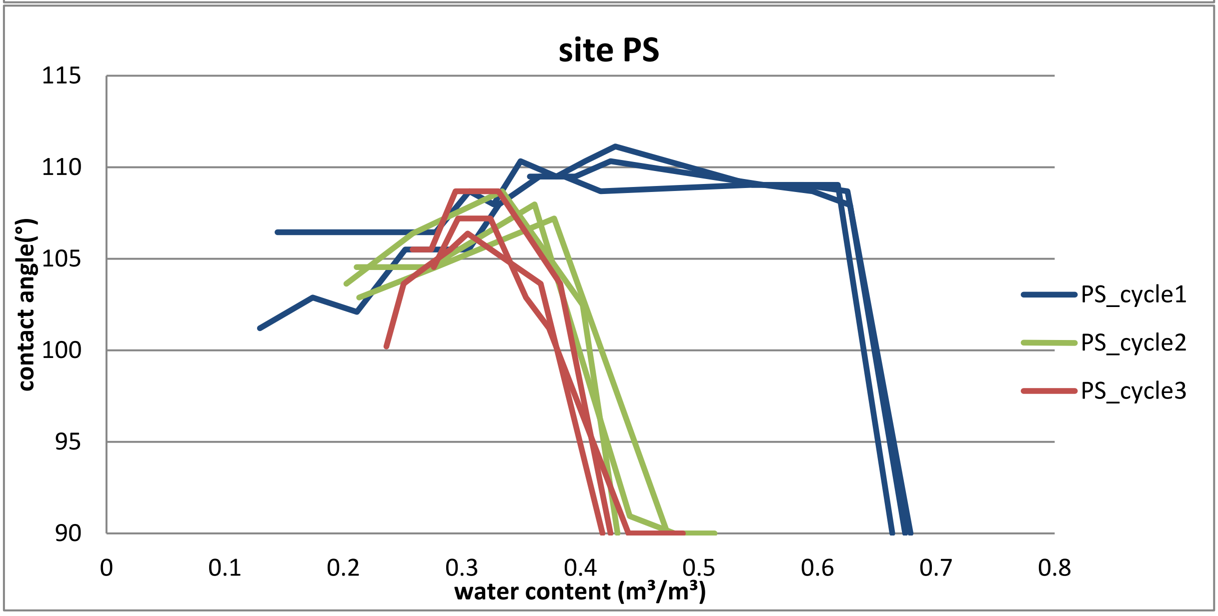


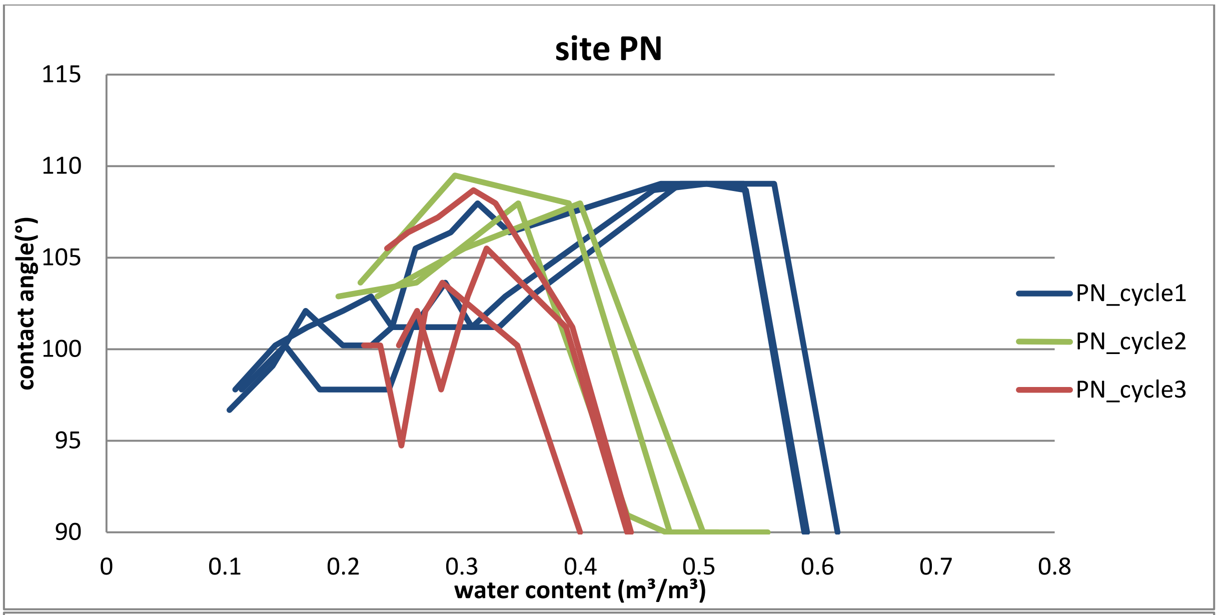


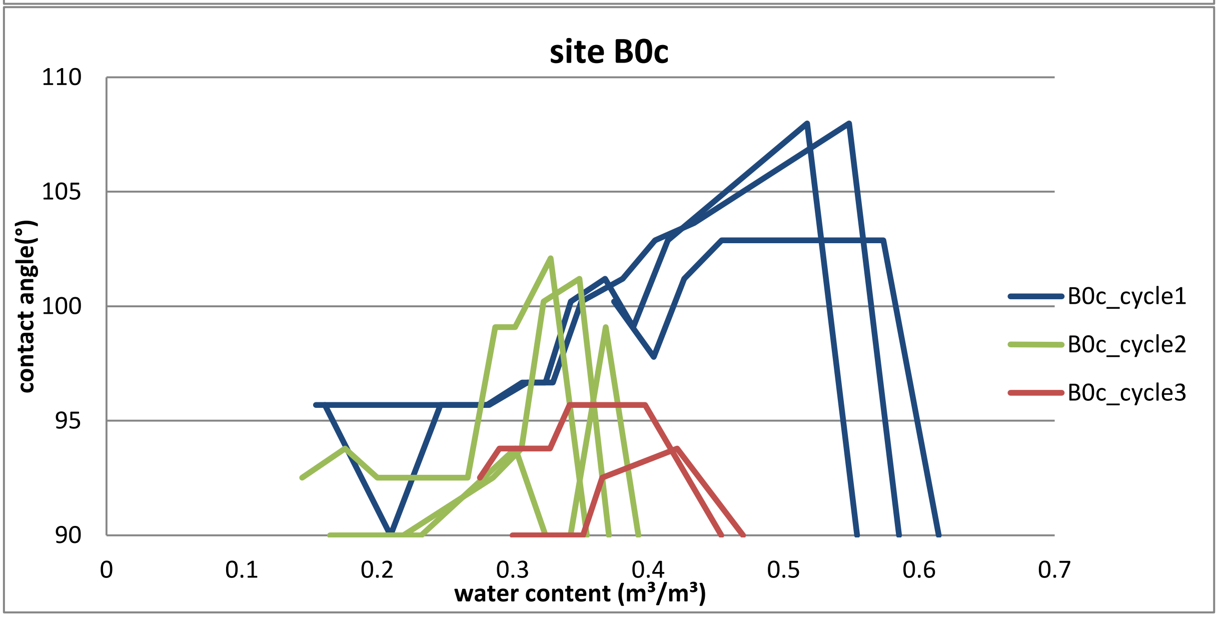

site P1c
contact angle(°)
110
105
100
95
90
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
water content (m³/m³)
P1c_cycle1
P1c_cycle2
P1c_cycle3
P1c_cycle4

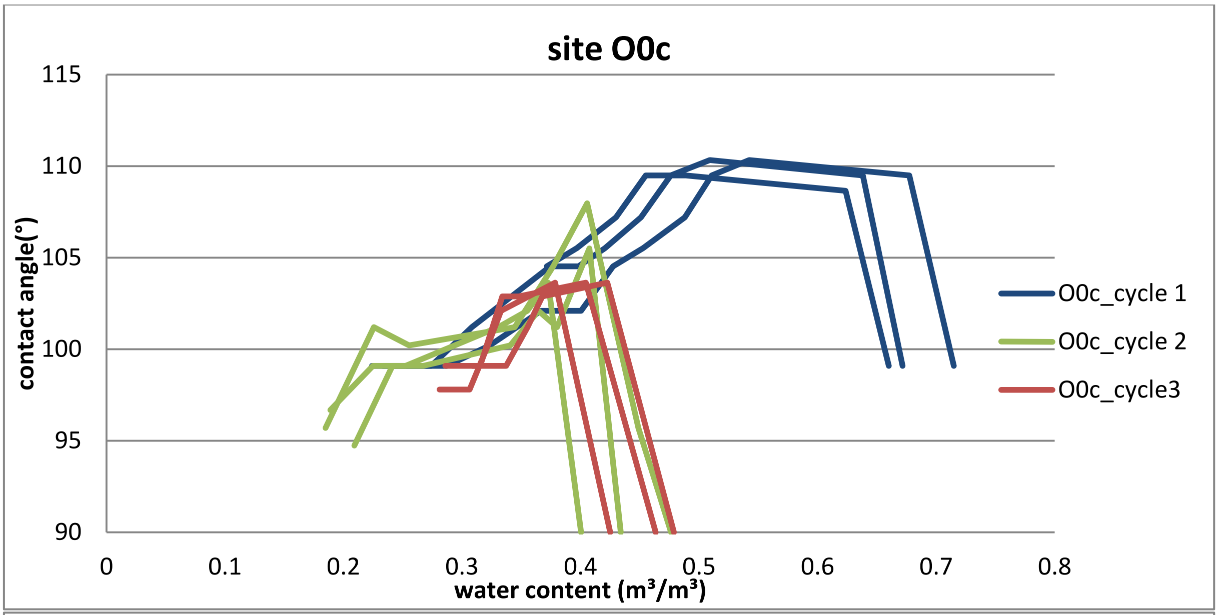

site P2b
contact angle(°)
110
105
100
95
90
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
water content (m³/m³)
P2b_cycle1
P2b_cycle2
P2b_cycle3
P2b_cycle4

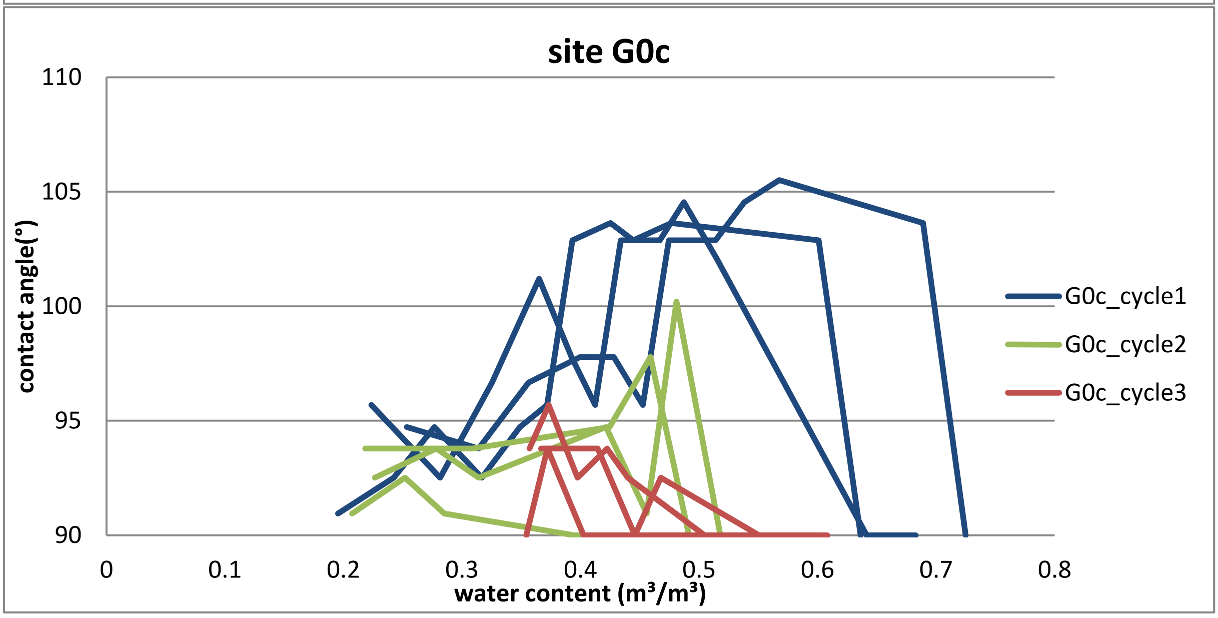

site P2d
contact angle(°)
110
105
100
95
90
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
water content (m³/m³)
P2d_cycle1
P2d_cycle2
P2d_cycle3
P2d_cycle4


site PS
contact angle(°)
115
110
105
100
95
90
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
water content (m³/m³)
PS_cycle1
PS_cycle2
PS_cycle3

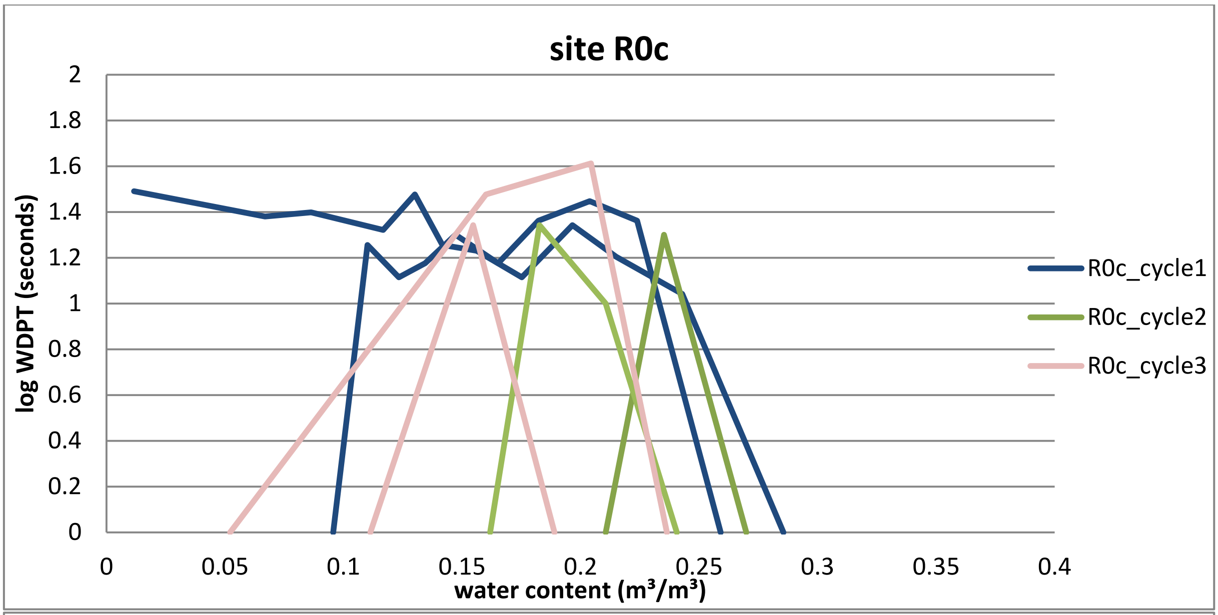

site PN
115
110
105
100
95
90
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
contact angle(°)
water content (m³/m³)
PN_cycle1
PN_cycle2
PN_cycle3

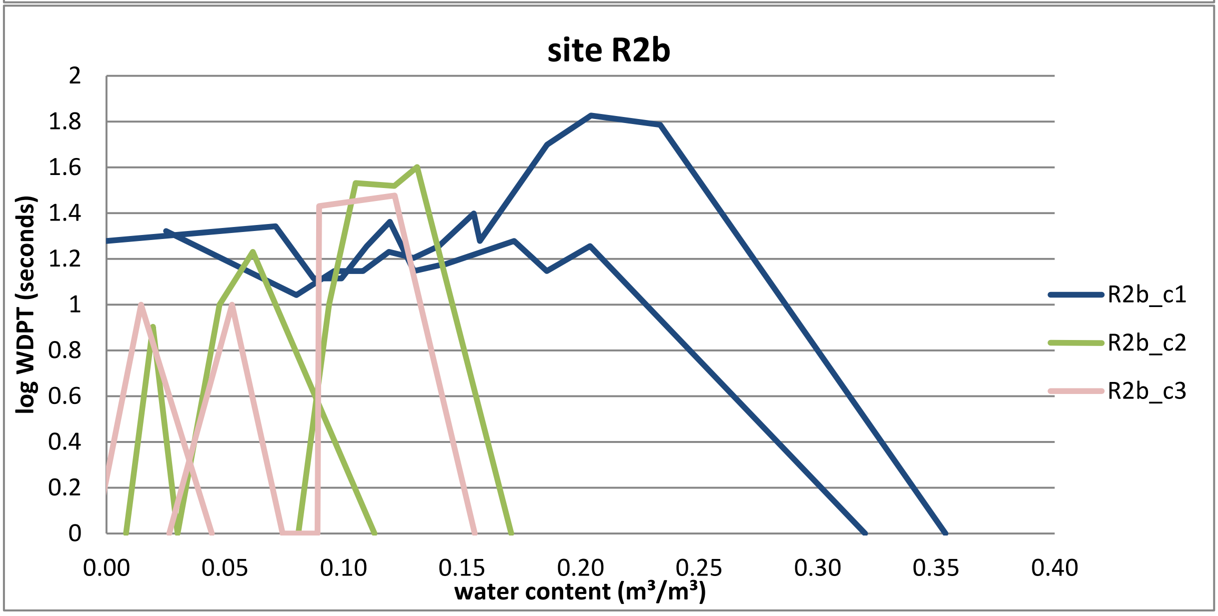

site B0c
110
105
100
95
90
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
contact angle(°)
water content (m³/m³)
B0c_cycle1
B0c_cycle2
B0c_cycle3

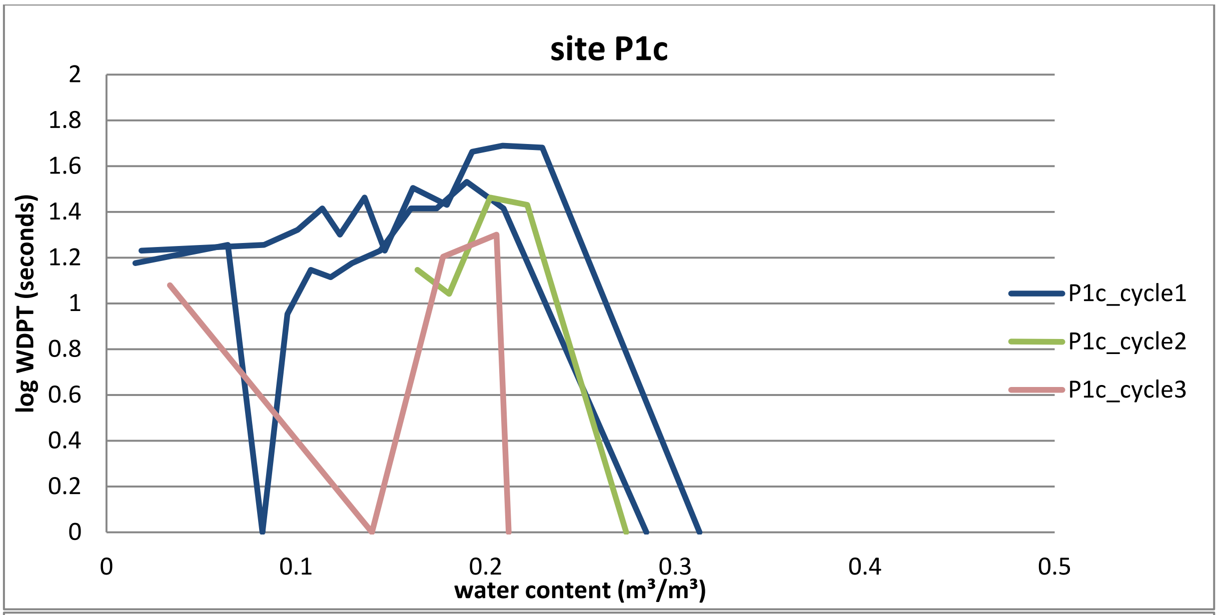

site O0c
115
110
105
100
95
90
contact angle(°)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
water content (m³/m³)
O0c_cycle 1
O0c_cycle 2
O0c_cycle3

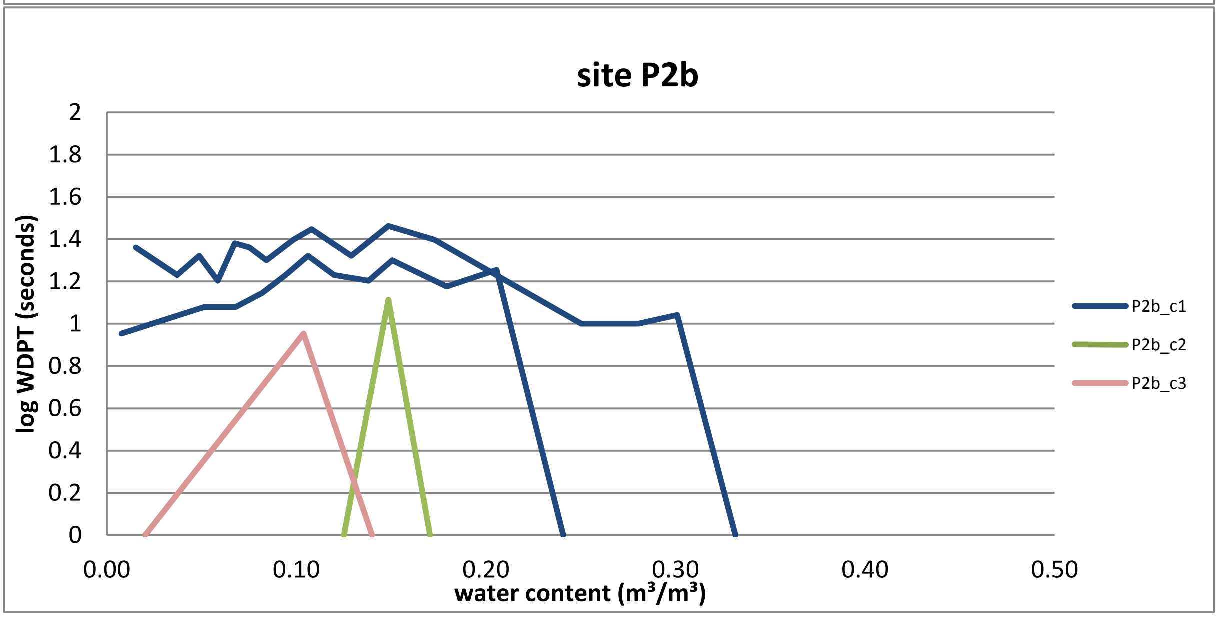

site G0c
110
105
100
95
90
contact angle(°)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
water content (m³/m³)
G0c_cycle1
G0c_cycle2
G0c_cycle3

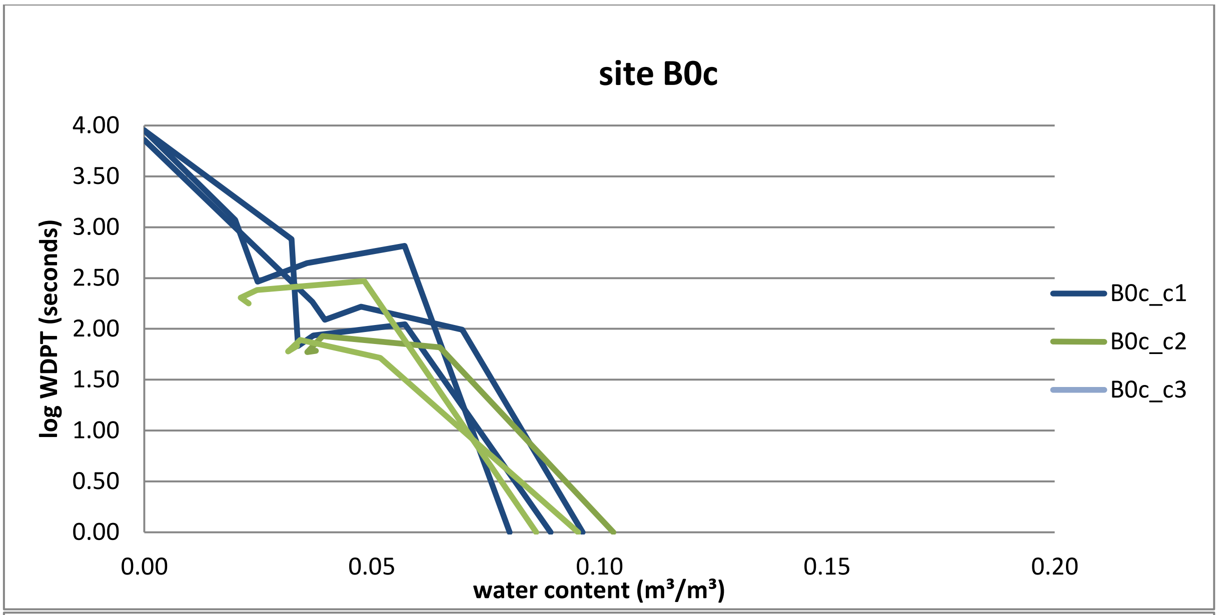
Annex E: Soil water repellency curves (SWR expressed by WDPT) for different drying cycles for disturbed samples

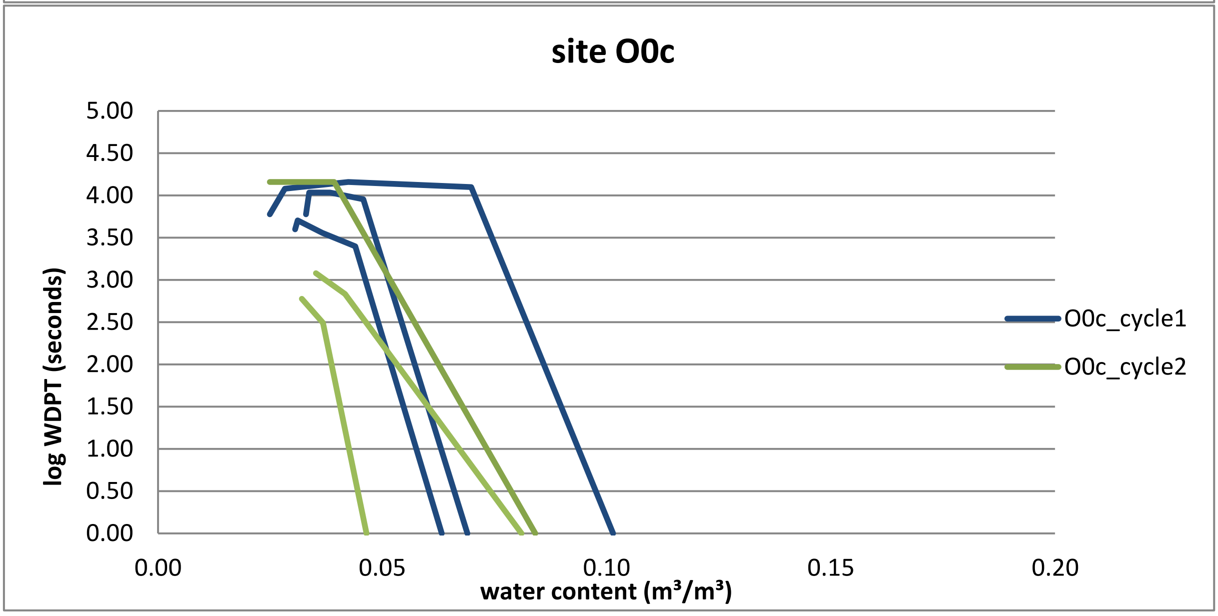


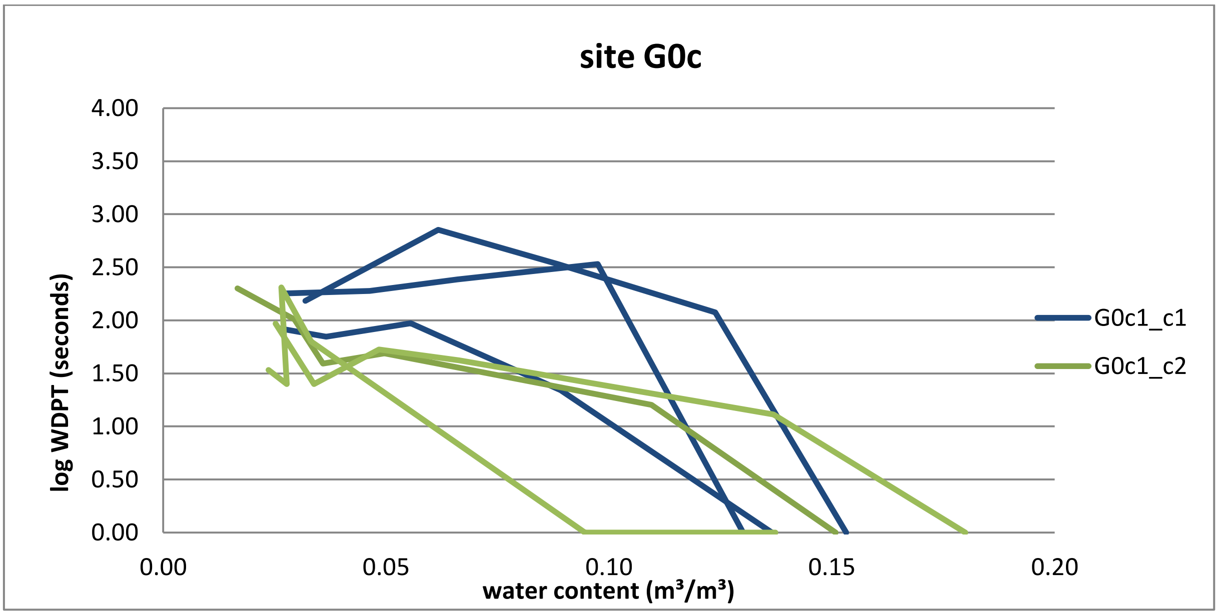



site P1c
log WDPT (seconds)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
water content (m³/m³)
P1c_cycle1
P1c_cycle2
P1c_cycle3

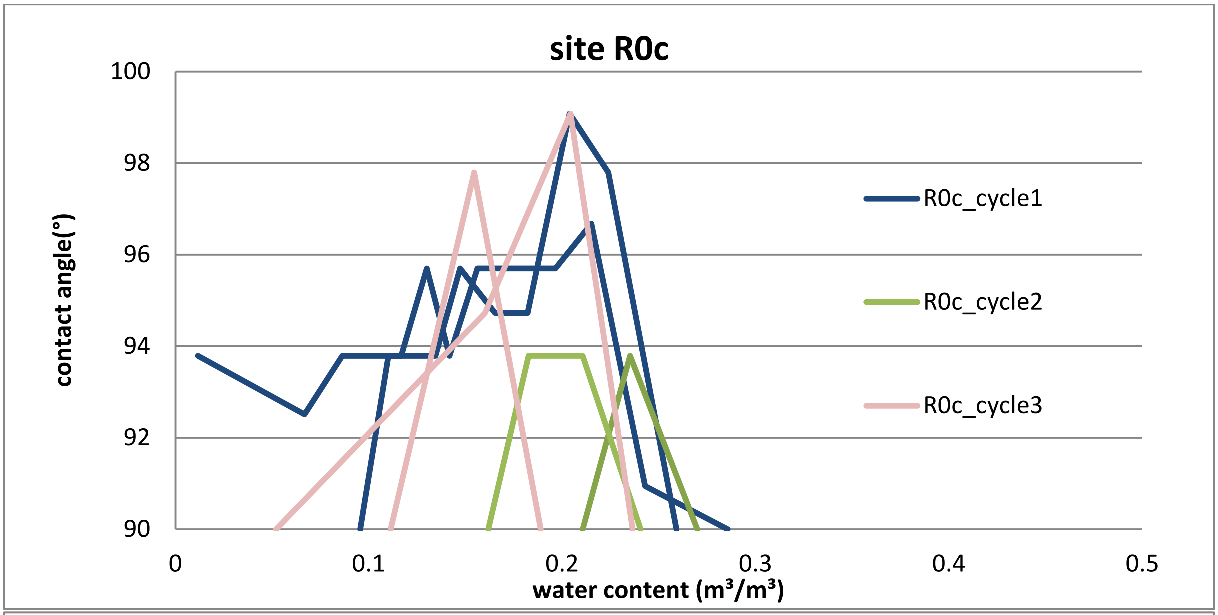

site P2b
log WDPT (seconds)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.00
0.10
0.20
0.30
0.40
0.50
water content (m³/m³)
P2b_c1
P2b_c2
P2b_c3

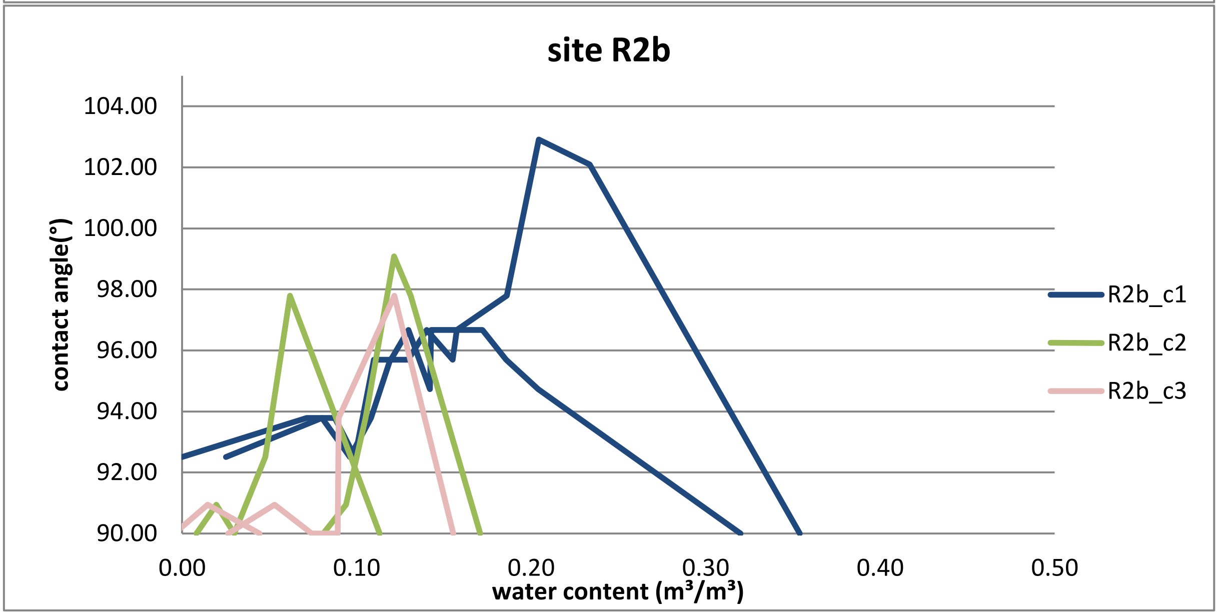

site B0c
log WDPT (seconds)
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
0.05
0.10
0.15
0.20
water content (m³/m³)
B0c_c1
B0c_c2
B0c_c3

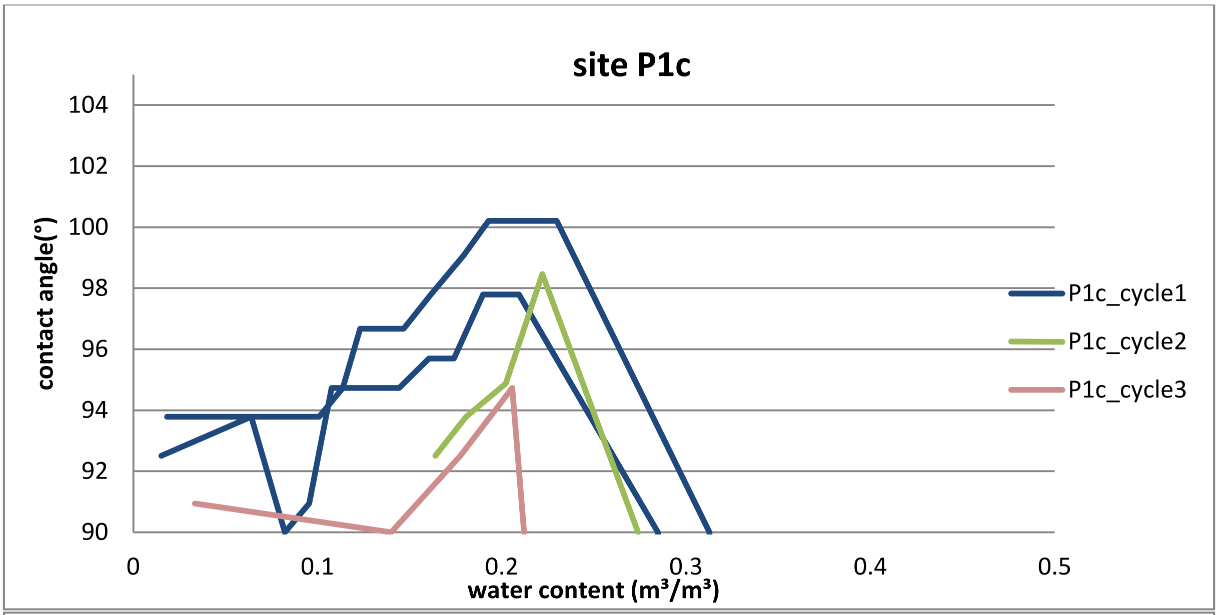

site O0c
log WDPT (seconds)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
0.05
0.10
0.15
0.20
water content (m³/m³)
O0c_cycle1
O0c_cycle2

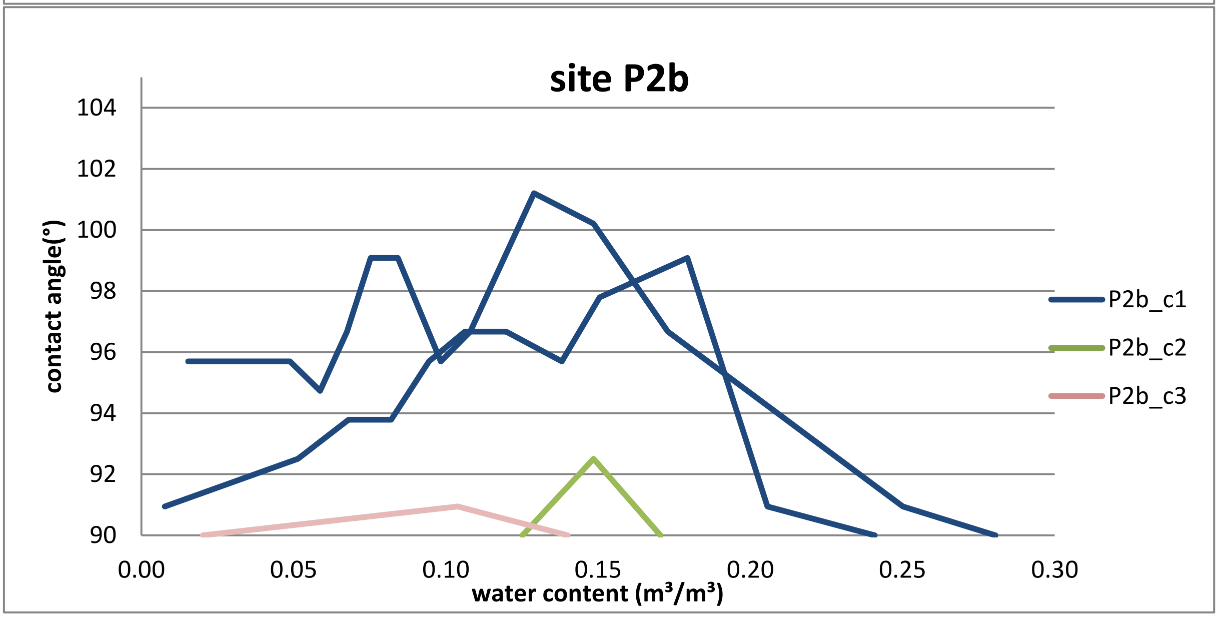

site G0c
log WDPT (seconds)
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
0.05
0.10
0.15
0.20
water content (m³/m³)
G0c1_c1
G0c1_c2

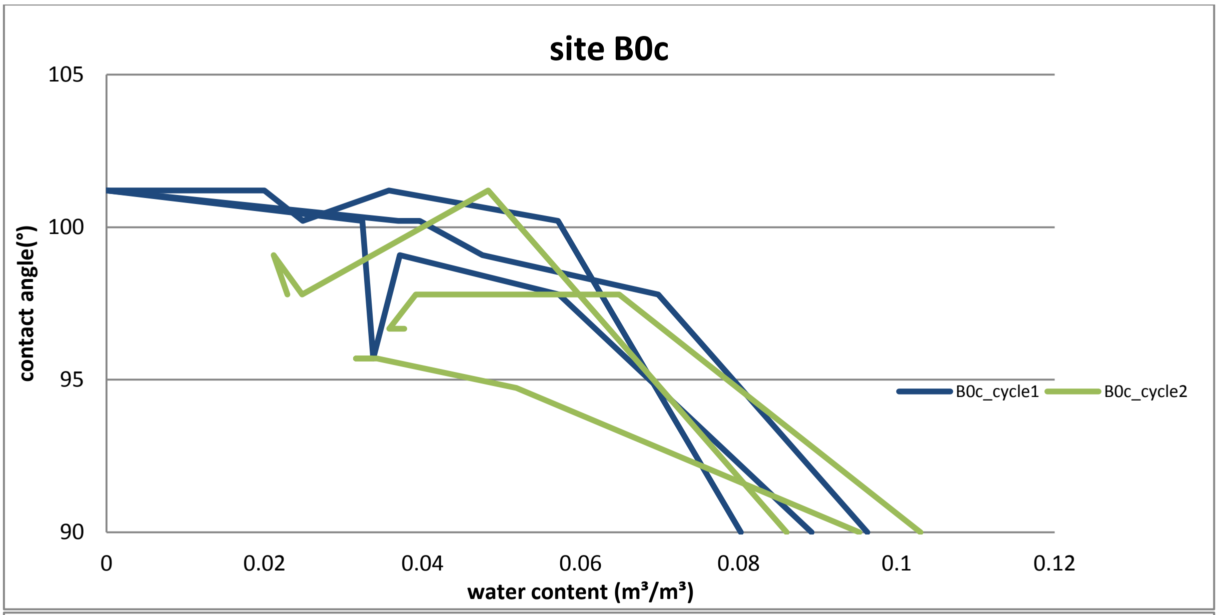
Annex F: Soil water repellency curves (SWR expressed by CA) for different drying cycles for disturbed samples

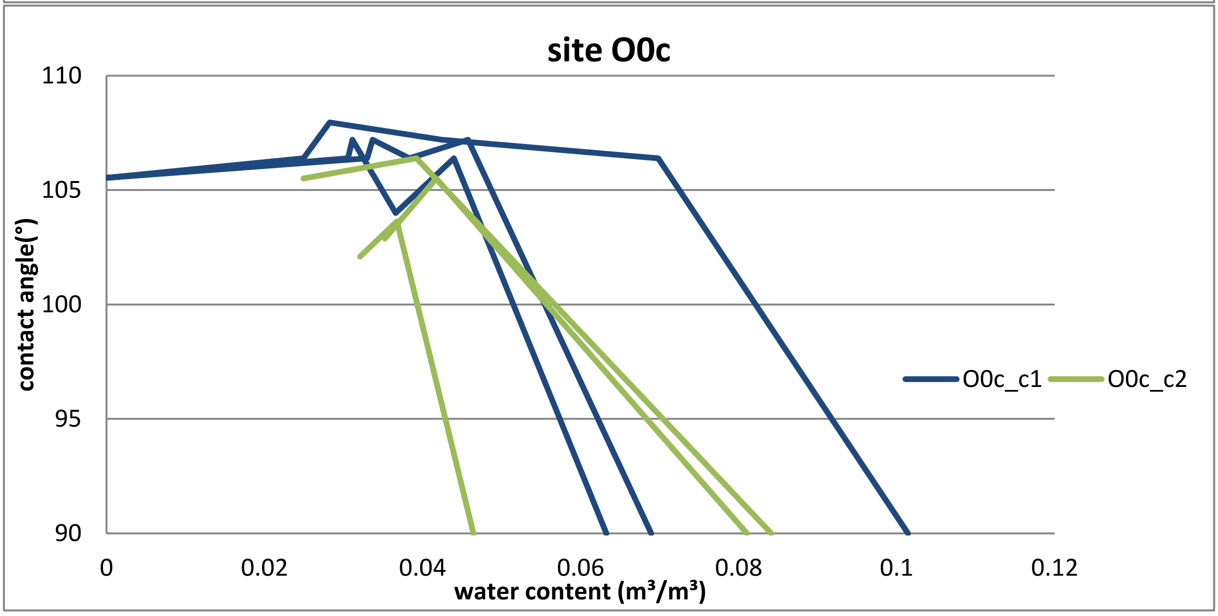


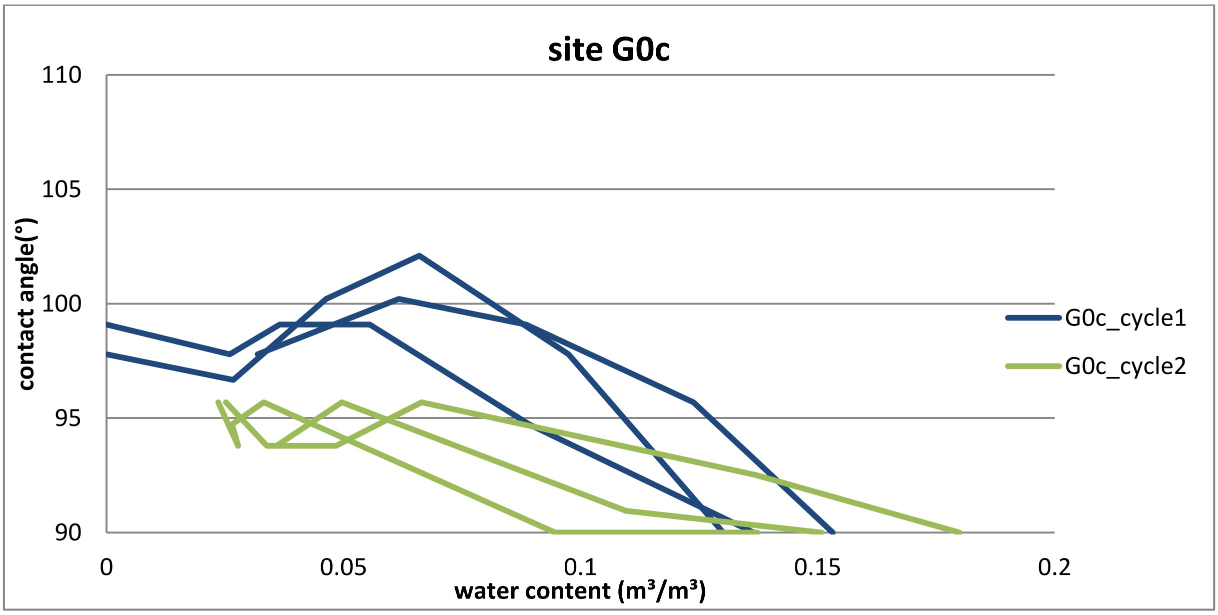



site P1c
contact angle(°)
104
102
100
98
96
94
92
90
0
0.1
0.2
0.3
0.4
0.5
water content (m³/m³)
P1c_cycle1
P1c_cycle2
P1c_cycle3


site P2b
contact angle(°)
104
102
100
98
96
94
92
90
0.00
0.05
0.10
0.15
0.20
0.25
0.30
water content (m³/m³)
P2b_c1
P2b_c2
P2b_c3


site B0c
105
100
95
90
contact angle(°)
0
0.02
0.04
0.06
0.08
0.1
0.12
water content (m³/m³)
B0c_cycle1
B0c_cycle2


site O0c
110
105
100
95
90
contact angle(°)
0
0.02
0.04
0.06
0.08
0.1
0.12
water content (m³/m³)
O0c_c1
O0c_c2


site G0c
110
105
100
95
90
contact angle(°)
0
0.05
0.1
0.15
0.2
water content (m³/m³)
G0c_cycle1
G0c_cycle2

Annex G: Critical water contents obtained for the undisturbed samples during different drying cycles

Table 21: Critical water contents and upper/lower boundaries of transition zones obtained for the undisturbed samples during different drying cycles

cycle1					
	P1c	**P2b**	**P2d**	**PS**	**PN**
Mean CWC	**0,48**	**0,50**	**0,60**	**0,65**	**0,57**
Max CWC (upper boundary)	0,50	0,51	0,63	0,65	0,59
Min CWC (lower boundary)	0,45	0,50	0,57	0,64	0,56
Standard Deviation	2,99	0,66	3,83	0,01	0,01
	R0c	**R2b**	**B0c**	**O0c**	**G0c**
Mean CWC	**0,52**	**0,39**	**0,57**		**0,64**
Max CWC (upper boundary)	0,54	0,42	0,59		0,71
Min CWC (lower boundary)	0,50	0,37	0,54		0,58
Standard Deviation	2,36	3,82	0,03		0,06

cycle2					
	P1c	**P2b**	**P2d**	**PS**	**PN**
Mean CWC	**0,41**	**0,38**	**0,42**	**0,43**	**0,45**
Max CWC (upper boundary)	0,45	0,42	0,43	0,46	0,46
Min CWC (lower boundary)	0,37	0,36	0,41	0,42	0,43
Standard Deviation	0,04	0,03	0,02	0,02	0,01
	R0c	**R2b**	**B0c**	**O0c**	**G0c**
Mean CWC	**0,41**	**0,34**	**0,36**	**0,42**	**0,44**
Max CWC (upper boundary)	0,43	0,35	0,38	0,46	0,50
Min CWC (lower boundary)	0,40	0,32	0,34	0,39	0,34
Standard Deviation	0,01	0,02	0,02	0,04	0,09

cycle3					
	P1c	**P2b**	**P2d**	**PS**	**PN**
Mean CWC	**0,35**	**0,33**	**0,34**	**0,40**	**0,40**
Max CWC (upper boundary)	0,36	0,35	0,35	0,41	0,41
Min CWC (lower boundary)	0,33	0,31	0,34	0,39	0,39
Standard Deviation	1,54	1,53	0,55	0,01	0,01
	R0c	**R2b**	**B0c**	**O0c**	**G0c**
Mean CWC	**0,37**	**0,30**	**0,44**	**0,43**	**0,43**
Max CWC (upper boundary)	0,38	0,31	0,45	0,45	0,47

Min CWC (lower boundary)	0,36	0,29	0,43	0,40	0,39
Standard Deviation	1,37	0,93	0,01	0,02	0,04

Annex H: ANOVA- test results

I) Comparison of potential water repellency measured on samples from the same three sampling sites in Taranaki region in the course of different studies

i) Comparison of potential water repellency expressed by contact angles

Table 22: ANOVA results, comparison of potential water repellencey (expressed by contact angles) on organic soil

CA- organic
Anova: Single Factor

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
Deurer, January 2010	5	517.715098	103.54302	0.45656123
Holzinger, April 2011	2	206.38	103.19	0.245
Holzinger, August 2011	1	101.72	101.72	
present study, June 2012	3	316.594332	105.531444	3.0292E-28

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	14.3607247	3	4.78690822	16.1778828	0.0015721	4.3468314
Within Groups	2.07124492	7	0.29589213			
Total	16.4319696	10				

Table 23: ANOVA results, comparison of potential water repellency (expressed by contact angles) on brown soil

CA- brown
Anova: Single Factor

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
Deurer, January 2010	5	492.967303	98.5934607	9.70107179
Holzinger, April 2011	2	199.75	99.875	3.30245
Holzinger, August 2011	1	100.01	100.01	
present study, June 2012	3	303.593148	101.197716	0

ANOVA						

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	12.9958602	3	4.33195339	0.72016204	0.57096016	4.3468314
Within Groups	42.1067372	7	6.01524817			
Total	55.1025973	10				

Table 24: ANOVA results, comparison of potential water repellency (expressed by contact angles) on gley soil

CA- gley

Anova: Single Factor

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
Deurer, January 2010	5	490.624947	98.1249895	4.33537283
Holzinger, April 2011	2	194.61	97.305	1.32845
Holzinger, August 2011	1	97.76	97.76	
present study, June 2012	3	295.963351	98.6544505	0.55449338

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.30319292	3	0.76773097	0.2717092	0.84405925	4.3468314
Within Groups	19.7789281	7	2.82556115			
Total	22.082121	10				

ii) Comparison of potential water repellency expressed by water droplet penetration times

Table 25: ANOVA results, comparison of potential water repellencey (expressed by water droplet penetration times) on organic soil

WDPT- organic soil

Anova: Single Factor

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
Deurer, January 2010	5	0.74322917	0.14864583	0.00181967
Holzinger, April 2011	2	0.28002315	0.14001157	0.00022825
Holzinger, August 2011	1	0.07993056	0.07993056	
present study, June 2012	3	0.39583333	0.13194444	0.0005787

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.00402407	3	0.00134136	1.08369605	0.41622964	4.3468314
Within Groups	0.00866432	7	0.00123776			
Total	0.01268839	10				

Table 26: ANOVA results, comparison of potential water repellency (expressed by water droplet penetration times) on brown soil

WDPT- brown

Anova: Single Factor

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
Deurer, January 2010	5	0.20893133	0.04178627	0.00464556
Holzinger, April 2011	2	0.10572917	0.05286458	0.00024769
Holzinger, August 2011	1	0.03596065	0.03596065	
present study, June 2012	3	0.29166667	0.09722222	0.00014468

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.00646638	3	0.00215546	0.78916207	0.5372004	4.3468314
Within Groups	0.01911929	7	0.00273133			
Total	0.02558567	10				

Table 27: ANOVA results, comparison of potential water repellency (expressed by water droplet penetration times) on gley soil

WDPT- gley

Anova: Single Factor

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
Deurer, January 2010	5	0.0739159	0.01478318	3.6709E-05
Holzinger, April 2011	2	0.02106481	0.01053241	3.5303E-05
Holzinger, August 2011	1	0.01063657	0.01063657	
present study, June 2012	3	0.2190625	0.07302083	0.0013976

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.00784048	3	0.00261349	6.14455072	0.02256443	4.3468314
Within Groups	0.00297735	7	0.00042534			
Total	0.01081782	10				

II) Comparison of critical water content for different soil orders

Table 28: ANOVA results, comparison of critical water contents for different soil orders

Anova: Einfaktorielle Varianzanalyse

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
pallic	14	5.862724	0.418766	0.001097
recent	5	1.909859	0.381972	0.001965
brown	3	1.081889	0.36063	0.000388
organic	3	1.26974	0.423247	0.001451
gley	2	0.974738	0.487369	0.000292

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.024783	4	0.006196	5.224821	0.004103	2.816708
Within Groups	0.026089	22	0.001186			
Total	0.050872	26				

Table 29: ANOVA results, comparison of critical water contents for pallic soil from different regions

Anova: Single Factor

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
Hawke' s Bay	8	3,220547	0,402568	0,001108
Tararua	6	2,642177	0,440363	0,000321

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0,004897	1	0,004897	6,277475	0,027636	4,747225
Within Groups	0,009362	12	0,00078			
Total	0,014259	13				

III) Comparison of frequency of SWR and SWR- induced surface runoff within wet, average and dry years

Table 30: ANOVA results, comparison of frequency of soil water repellency for average and dry years

Anova: Single Factor

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
average	5	1654	330,8	1039,2
dry	5	1691	338,2	606,7

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	136,9	1	136,9	0,16635276	0,69407098	5,31765507
Within Groups	6583,6	8	822,95			
Total	6720,5	9				

Table 31: ANOVA results, comparison of frequency of soil water repellency for average and wet years

Anova: Single Factor

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
average	10	3086	308,6	2059,6
wet	10	3010	301	2526,88889

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	288,8	1	288,8	0,12593511	0,72680841	4,41387342
Within Groups	41278,4	18	2293,24444			
Total	41567,2	19				

Table 32: ANOVA results, comparison of frequency of surface runoff for average and dry years

Anova: Single Factor

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
dry	5	102	20,4	11,3
average	5	94	18,8	14,7

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6,4	1	6,4	0,49230769	0,50279719	5,31765507
Within Groups	104	8	13			
Total	110,4	9				

Table 33: ANOVA results, comparison of frequency of surface runoff for average and wet years

Anova: Single Factor

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
average	10	297	29,7	212,677778
wet	10	329	32,9	253,433333

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	51,2	1	51,2	0,21969011	0,64490265	4,41387342
Within Groups	4195	18	233,055556			

Total	4246,2	19				

IV) Comparison of frequency of soil water repellencey obtained with critical water content from different drying cycles

Table 34: ANOVA results, comparison of frequency of soil water repellency obtained with critical water contents from 2nd and 3rd drying cycles

Anova: Single Factor

SUMMARY				
Groups	*Count*	*Sum*	*Average*	*Variance*
2nd drying cycle	10	3086	308,6	2059,6
3rd drying cycle	10	2826	282,6	2812,71111

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3380	1	3380	1,38743193	0,254178376	4,413873419
Within Groups	43850,8	18	2436,15556			
Total	47230,8	19				