CHALMERS

Testing of Remotely Controlled Soil Moisture Sensors and Analysis of Soil Moisture Data

Master of Science Thesis

ROBERTO MONTES CAÑIZARES

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CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

A theoretical study and analysis of soil moisture data at Remningstorp area from spring 2006 to winter 2009 has been performed. Water volume content has been compared with the precipitation in the area, as well as the ground temperature has been compared with the air temperature in the same area. One sensor was located in an open field and the second sensor was located inside the forest.
Installation and testing of remotely controlled soil moisture sensor at Mölnlycke has also been completed in this master thesis work. An analysis of the water volume content data has been done to try to identify rainfall.
The output data from the soil moisture measurement given by Aquaflex sensors consisted of three variables, which are related primarily to the real and imaginary components of the dielectric permittivity and temperature of the ground in degrees.

The field sensor is surrounded by clay soils or clay-rich loams. This compacted soil absorbs and store moisture and retains water. The forest sensor is surrounded by silt, sand or sandy-loams. The ground in the open field is more easily heated, there is no vegetation or tree canopy and therefore the sun rays can easily heat the area. For those reasons the field sensor shows a stronger variation in its water volume content.

The aquaflex sensor uses a direct method to measure the volumetric water content in the ground as well as the temperature. The results were accurate measurement of the water volume content and the temperature on the ground. The new remotely controlled soil moisture sensor allowed a fast and easy data access; however some problems were experienced with Aquaflex software installation in Windows Vista.

ACKNOWLEDGEMENTS

This Master’s Thesis is the last part of my Master of Science studies within Electrical Engineering, specialization in Radio and Space Science. This Master’s Thesis has been written at the Department of Radio and Space Science at Chalmers University of Technology.

I wish to thank my supervisor Leif Eriksson for his feedback and support. I also want to thank Gunnar Rasmussen at Inverva, for guiding me during the Aquaflex software installation and Peter Hedborg at the division for GeoEngineering at the Department for Civil and Environmental Engineering at Chalmers University of Technology for the analysis and identification of the soils type taken at Remningstorp and Benareby. I would like to thank Gustaf Sandberg, Ph.D. student at the Department of Radio and Space Science at Chalmers University of Technology for helping me with Matlab.
Finally, I would like to thank my girlfriend for her support and understanding.

The research project in Remningstorp is carried out by researchers at the Department of Forest Resource Management at the Swedish University of Agriculture Sciences in Umeå, in collaboration with Chalmers University of Technology in Gothenburg and the Swedish Defense Research Agency in Linköping. In the project, data is used from Remningstorp collected with economical support from Hildur and Sven Wingquists foundation for forest scientific research and the Swedish National Space Board.

Meteorological data (air temperature and precipitation) from the meteorological station in Remningstorp have been supplied to Chalmers by the Swedish Meteorological and Hydrological Institute (SMHI) within the project "Evaluation of forestry applications using new SAR and optical images".

TABLE OF CONTENT

ABBREVIATIONS AND ACRONYMS

AMR	Adaptative Multi-rate.
ASAR	Advanced Synthetic Aperture Radar.
CSD	Circuit Switched Data.
EFR	Enhanced Full Rate.
FR	Full Rate.
GPRS	General Packet Radio Service.
GSM	Global System for Mobile Communication.
SMS	Short Message Service
HR	Half Rate.
Imp	Maximum Power Current.
Isc	Short Circuit Current.
MW	Micro Wave.
SAR	Synthetic Aperture Radar.
ScanSAR	Scanning Synthetic Aperture Radar.
SLU	Swedish Univ. of Agriculture Sciences.
SMC	Soil Moisture Content.
SMHI	Swedish Meteorological and Hydrological Institute.
TDR	Time Domain Reflectrometry.
TDT	Time Domain Transmission.
Vmp	Maximum Power Voltage.
Voc	Open Circuit Voltage.

1 Introduction

Imaging radar shows potential for forestry, hydrological, agricultural and many other applications. Radar is independent of the weather and light condition.

According to Álvarez-Mozos, et al., (2007) the knowledge of the moisture content of the soil over a field or a catchment can be very helpful for hydrological, agronomic and meteorological applications. The possibility of achieving its estimation by means of remote sensing observations is very interesting for many applications. This is also confirmed by Pathe, et al., (2007), the knowledge of the soil moisture content is essential for hydrologic and climatologic modeling as well as in meteorology. Soil moisture is the limiting factor for plant growth and thus important for agriculture.

Already in the beginning of the eighty's the importance of radar imaging was clear. Ulaby, et al., (1981) wrote that imaging radar has been used extensively and successfully, throughout the world on a commercial basis. As he explained radar was used to survey vast tracts of previously unmapped land, much of it covered by woodland. Radar did permit also the classification of vegetation classes.

Churchill, et al., (1984) states that Synthetic Aperture Radar has potential in woodland analysis. It is possible to delineate woodland from non-woodland and that it is possible to make broad and sometimes specific species and age determinations. Imaging radar can be used to make woodland determinations; woodland from non woodland, forest boundary delineation, species classification and age classification.

According to Pampaloni and Paloscia (1984) in agriculture Soil Moisture Content is an important parameter for the estimation of evapotranspiration, the knowledge of which is fundamental for correct irrigation scheduling. Microwave radiometry is a good way to study the dielectric properties of soil and vegetation in their natural environment. Most of the studies try to show a relationship between microwave emission and SMC.

Microwave sensors offer a relatively direct means of assessing soil moisture since they exploit, like many in situ observation techniques, the strong relationship between the moisture content and dielectric constant of the soil, Wagner, et al., (2004). This is also noticed by Álvarez-Mozos, et al., (2007) where the backscattering coefficient obtained from radar sensors is directly related to the dielectric properties of the soil surface being observed, which is mainly dependent on its moisture content.

Wang and Schmugge (1980) states that the dielectric properties of soils have shown that the variation of dielectric constant with moisture content depends on soil types. The microwave dielectric constant of soil is strongly dependent on the soil moisture content and to a lesser extent on the soil textural composition. Therefore the knowledge of the dielectric constant of materials is important in microwave remote sensing.

Krul, L. (1984) wrote that the radar signal is also the combined result of spectral, structural and material influences. Therefore it is important to develop suitable models that can describe the interaction between the electromagnetic waves and the objects. According to him, in any estimation of received signal level it is necessary to consider the coefficients of reflection and transmission as the wave passes through the dielectric to the target.

Soil moisture can be measured by various methods, Active remote sensing techniques and direct methods. SAR can provide us with information regarded to soil moisture. A SAR antenna radiates short coherent microwave pulses towards the Earth's surface. The phase and amplitude of the backscattered signals are received by the SAR antenna. The strength of the returned signals depends on the technical configuration of the SAR sensor (frequency, polarization, look angle) as well as the geometrical and dielectrical properties of the Earth's surface. The intensity of the signal returned increase with the amount of water in the soil (Pathe, et al., 2007). Several difficulties obstruct the operational estimation of soil moisture based on space borne sensors. According to Pathe, et al., (2007) SAR system measurements are very sensitive to the geometric distribution of scatterers called "speckle". The influence of surface roughness on the backscattered signal is in the same order or larger than the influence of soil moisture. Álvarez-Mozos, et al., (2007) explain that roughness strongly influence the backscattering coefficient and hinder the soil moisture inversion. For Mattia, et al., (2007) the backscatter often depends not only on soil roughness, soil moisture and plant water content but also on crop structure.

Precipitation can modify the soil surface shape causing an overall reduction on its roughness. These surface roughness variations can introduce errors in the estimation of soil moisture that are difficult to evaluate (Álvarez-Mozos, et al., 2007).

The method we analyzed here, is however a direct method which use the Time Domain Transmission technique. Aquaflex humidity sensors are installed approximately 30 cm under the ground. These sensors measure the dielectric constant in different soil moisture with TDT technique and provide us with volumetric water content expressed in percent and temperature of the ground expressed in degrees Celsius.

Direct methods to measure soil moisture are accurate and can provide estimates over the entire root zone, but they are point measurements and therefore in situ measurements are usually rather limited. The main reason of remote sensing methods is that they provide average estimates over areas that may range from a few square meters to thousands of square kilometers Wagner, et al., (2004). Remote sensing can provide extended spatial data at different temporal and spatial scales (Pathe, et al., 2007). Microwave sensors can acquire imagery unaffected by cloud cover during day and night but cannot provide soil moisture information when the soil is frozen or snow covered (Wagner, et al., 2004).

The purpose of this master thesis was to analyze soil moisture and temperature measurements of the soil, recorded by Aquaflex sensors placed at the Remningstorp area. These data will be further compared with precipitation and temperature records of the area supplied by Swedish Meteorological and Hydrological Institute.

Further, a new updated Aquaflex system with remotely controlled soil moisture sensors was installed and tested at Benareby, Mölnlycke area.

2 Background and Theory

2.1 Test Site

Forest and field data have been collected at the Remnigstorp test site, figure 1. (Lat. 58º30’ N, Long. 13º40’ E) a property located in the area of Västergötland located in the south of Sweden between Skara and Skövde. The estate covers about 1200ha of productive forest land divided into 340 stands. The prevailing tree species are Norway spruce (Picea abies), Scots pine (Pinus sylvestris) and birch (Betula spp). The dominant soil type is till (i.e. a mixture of glacial debris) with a field layer consisting of different herbs, blueberry (Vaccinium myrtillus) and narrow-leaved grass (e.g. Deschampsia flexuosa). In denser old spruce stands the field layers is absent. The property’s wood producing ability is very high. The ground is in many places very compact but in a bigger perspective is the landscape flat with small height variations, around 130 meters above the sea. (Johan Fransson, 2006).

A new updated Aquaflex humidity sensor system has been installed and tested at Benareby, Mölnlycke, figure 1. (Lat. 57º38’N, Long. 12º10’O). Mölnlycke is located south west of Gothenburg city, only 15 minutes by car from the city.

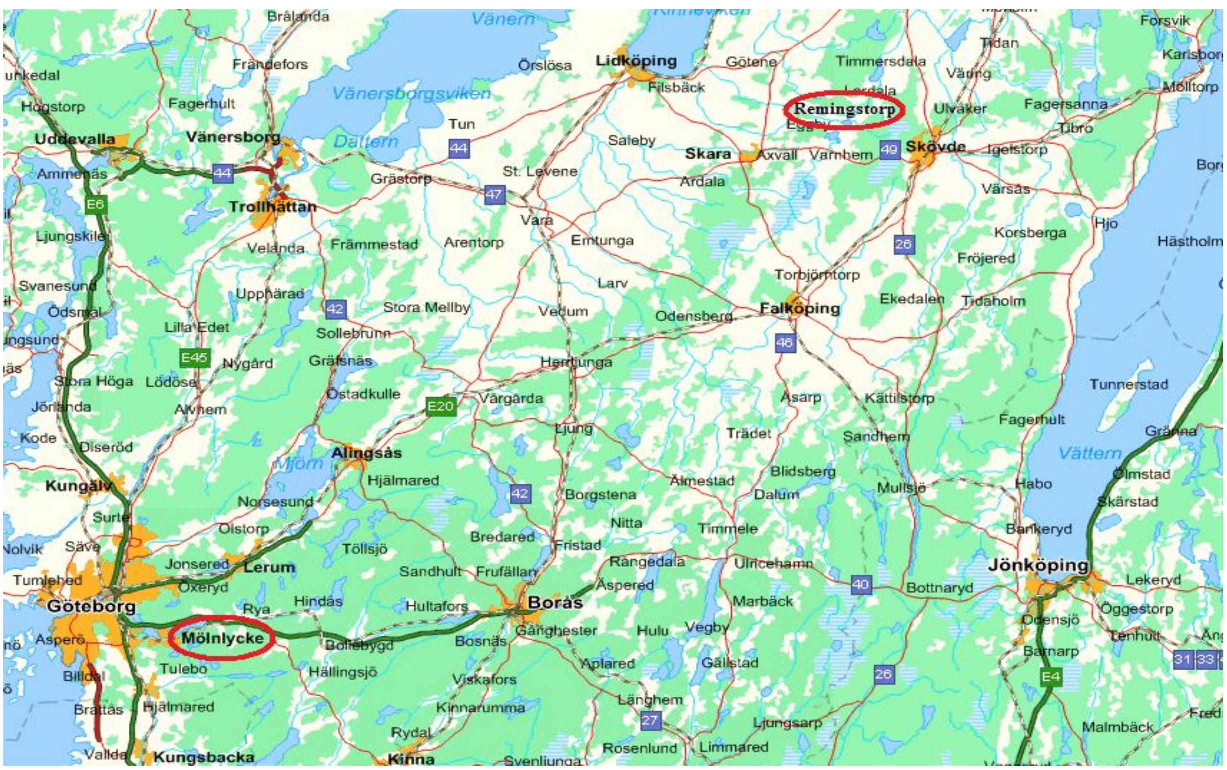

Figure 1.
Reminingstorp and Mölnlycke location.

In Remningstorp an extensive research is going on to examine how remote sensing can be used to help today’s and tomorrow’s forest investment. The fast development in remote sensing techniques has made it possible to reproduce forest in a more detailed way. Information about the big areas in the forest received from remote sensing techniques can today be complemented with information of individual trees.

Remote sensing is used to evaluate the possibility to get information of wood storage, tree height, the diameter of tree trunks and what type of tree it is. The data used by remote sensing techniques are collected with many different sensors (optics, radar and laser sensors) from satellites, air planes or helicopters. Together with measurements on the ground is it possible to use remote sensing in an effective way to get a detailed picture about the condition of the forest, both for individual trees as well as for stands.

An evaluation of the different remote sensing techniques requires detailed information of the forest (wood storage, tree height, the diameter of tree trunk and wood type). This information is usually collected by sensitive measurements on the ground. In Remningstorp field material is available for analysis of bigger similar forest areas, groups or individual trees.

To retrieve information from the forest with remote sensing techniques, field data is also required. After that, the data collected with remote sensing techniques is connected to the data collected with sensors on the ground, e.g. for individual trees or groups of trees. When the connection has been established, the data collected with remote sensing can be used to get information about the forest where only remote sensing data is present.

The Radar Remote Sensing Group at Chalmers University of Technology has contributed with radar pictures taken from different air planes and satellites. The group has also contributed with field measurements taken on the ground, e.g. humidity and temperature measurements for different soil moisture. These field measurements have used soil moisture sensors (Aquaflex).

2.2 Electromagnetic Waves Propagation. Importance of the Dielectric Constant.

Krul, L (1984) tells us that remote sensing systems depend on the use of electromagnetic waves to cover the distance between the sensor and the object to be observed. In microwave remote sensing the physical and biological quantities have to be extracted from the electromagnetic wave parameters.

Electromagnetic wave propagation is based on the ideas of the theoretical physicist; James Clerk Maxwell (1831-1879). Electromagnetic fields propagate in a vacuum with the speed of light.

$$c = (\mu_0 \varepsilon_0)^{-1/2} = 3 \times 10^8 \, m/s$$

ε_0 is the dielectric permittivity of the material in vacuum and μ_0 the permeability in vacuum. Their values are the following;

$$\mu_0 = 4\pi \times 10^{-7} \, H/m$$
$$\varepsilon_0 = 8.851 \times 10^{-12} \, As/Vm$$

The electric field **E** caused by a charge Q is a vector with the following definition.

$$E \equiv \frac{F}{q}(N/C) \qquad [1]$$

Where **F** is the Coulomb force between two charges and q is a test charge used to determine the direction of the field due to the charge Q. By placing the test charge in different locations it is possible to develop a plot of the electric field due to the charge Q. The electric field in this region as a result of the charge Q is written as;

$$E = \frac{Q}{4\pi\varepsilon_0 R^2} u_R \qquad [2]$$

Where u_R is the unit vector in the direction from $Q_1(r')$ to $Q_2(r)$. The direction of the electric field depends on the sign of the charge (Lonngren, et al., 2007).

The propagation of an electromagnetic field E_0 in a xyz-coordinate system, originating at z=0, t=0 in a conducting dielectric can be described by $E(r,t)$ at a distance, r and time t by:

$$E(r,t) = E_0 e^{-\alpha r} e^{j(\omega t - \beta r)} \qquad [3]$$

According to David J. Daniels (2004) the first exponential function is the attenuation term and the second the propagation term.

The parameters α and β can be related to σ and jωε.

$$\alpha = \omega\sqrt{\left[\frac{\mu\varepsilon'}{2}\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right]} \quad [4]$$

$$\beta = \omega\sqrt{\frac{\mu\varepsilon'}{2}\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}+1} \quad [5]$$

k is the phase constant; $k = \frac{w}{v}$ and kλ=2π [6]

Which give us ω=$\frac{2\pi v}{\lambda}$

λ is the wave length, v is the velocity of the propagation

According to Guru and Hiziroglu (2004) one of the numerous applications of electromagnetic field, is the transmission, reception and propagation of energy. The propagation of a wave may either be in an unbounded region (free space) or in a bounded region (waveguide or a coaxial transmission line).

Materials consist of atoms and according to Lonngren, et al., (2007) these atoms can be considered to be a large collection of randomly oriented small electric dipoles. Figure below shows the random orientation of the atoms just before the application of electric field.

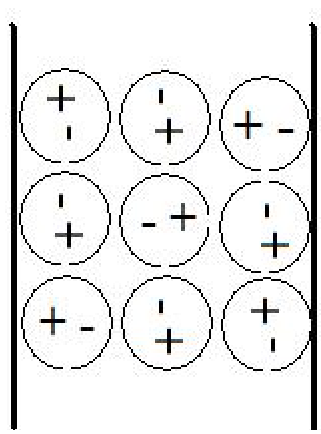

Figure 2.
Random orientation, before E-field application.

Each pair of charges acts as an electric dipole and if an external electric field is applied, the dipoles may reorient themselves. After the application of the electric field between the two electrodes, the atoms are reoriented.

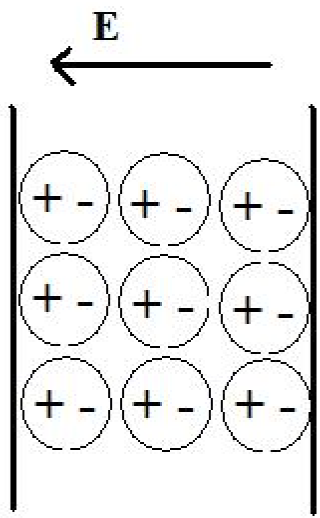

Figure 3.
Reorientation after E-field application

An electromagnetic field depends on space and time and therefore $\boldsymbol{E} = \boldsymbol{E}(r, t)$ and $\boldsymbol{H} = \boldsymbol{H}(r, t)$. Where $\boldsymbol{E}$ is the electric field intensity and $\boldsymbol{H}$ is the magnetic field intensity.

According to equations [a1], [a2] (see Appendix D, Maxwell´s equations), if we perturb either the electric or magnetic field, the other field would automatically be affected.

The polarization of the electric field $\boldsymbol{E}$ is determined by the polarization introduced with the excitation mechanism. This could be an antenna with a particular radiation characteristic, a laser or a waveguide with a certain physical orientation. The polarization of an electromagnetic wave is determined by the electric field component rather than by the magnetic field component (Lonngren, et al., 2007). The polarization can be Linear, Circular and/or Elliptical.

David J. Daniels (2004) states that electromagnetic waves propagating through natural media experience losses, to both the electric and magnetic fields. This causes attenuation of the original electromagnetic wave. In the case of lossy dielectric materials, absorption of electromagnetic radiation is caused by both conduction and dielectric effect. It is also important to consider the effect of interface between two media. How much of the energy of the incoming wave is transmitted into the second medium or reflected back into the first medium.

Wang and Schmugge (1980) states that the dielectric properties of soils have shown that the variation of dielectric constant with moisture content depends on soil types.
The microwave dielectric constant of soil is strongly dependent on the soil moisture content and to a lesser extent on the soil textural composition. In models for the reflection or emission of complicated targets, e.g., vegetation, the dielectric properties of the component parts (stems, leaves) must be known. As the electromagnetic wave propagates it can hit different objects or pass through different materials/medium, soil types. These objects could be either another dielectric or a conductor. Some components of the electric field will be reflected back when the electric field pass from a medium to another and some other components of the electric field will be transmitted from a medium to the other, (Lonngren, et al., 2007)

The real and imaginary part of the dielectric constant for the soil moisture content, determines the magnitudes of the polarized Fresnel reflection coefficients for the air-soil boundary and also the penetration depth in the soil medium (Ulaby, et al., 1982). Fresnel´s equations describe the reflection and transmission of electromagnetic waves at different interfaces. Depending on the plane of incidence for the electromagnetic wave (parallel or perpendicular) Fresnel´s equations give us the reflection and transmission coefficients. (See Appendix E).

According to Krul, L (1984) at a given incidence angle, the scattered energy will depend on wavelength. The spectral signature of the electromagnetic wave is the result of the interaction between waves and objects. This interaction can occur in two ways; material interaction and structural interaction. The material interaction way means that some energy of the incident wave is absorbed by the object material. From the electromagnetic point of view absorbing materials can be characterized by a complex dielectric constant. The structural interaction way is divided in frequency regions which have to do with dimensional scales relative to wavelength.

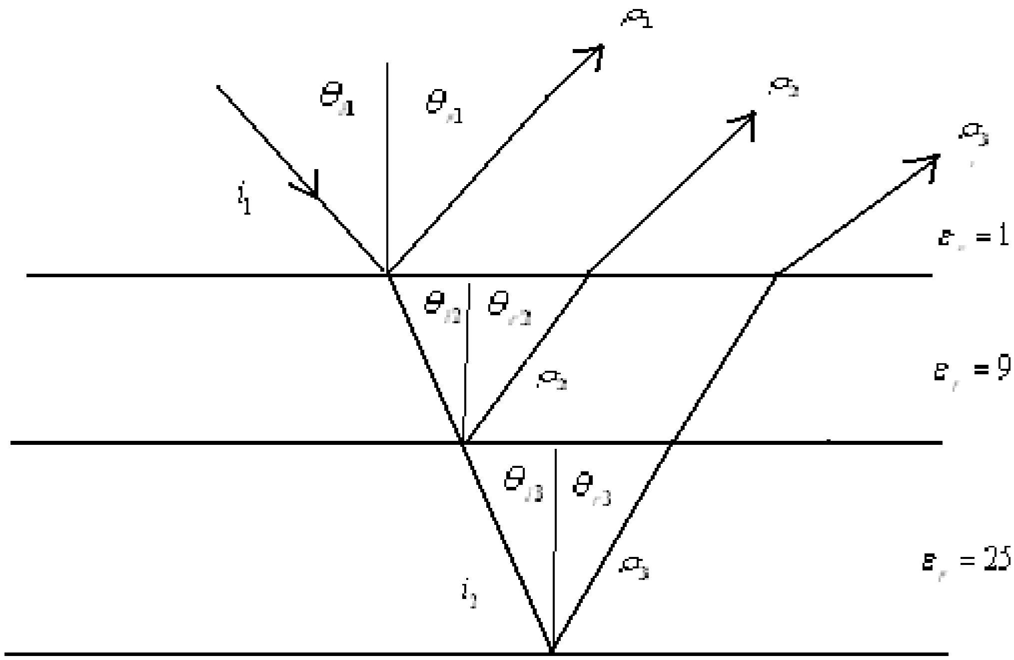

Figure 4.
Multi-layer dielectric
Electromagnetic wave propagates through different materials/medium
Source: David J. Daniels (2004). Ground Penetrating Radar, 2nd Edition

Figure 4; shows the reflection and transmission of electromagnetic waves, propagating through different medium. i_1 is the incident wave and ρ_1 is the reflected wave after it passed the dielectric medium with $\varepsilon_r = 1$ where ε_r is the relative permittivity, ρ_2 is the second reflected wave after it passed the dielectric medium with $\varepsilon_r = 9$ and ρ_3 is the third reflected wave after it passed the dielectric medium with $\varepsilon_r = 25$.
$\theta_{i1}, \theta_{i2}, \theta_{i3}$ are the incidence angles and $\theta_{r1}, \theta_{r2}, \theta_{r3}$ the reflection angles.

ε refers to the absolute dielectric permittivity of the material and μ refers as the *permeability*. These are properties of the medium ε consist of a real part $\varepsilon^{'}$ and an imaginary part $\varepsilon^{''}$.

$$\varepsilon = \varepsilon^{'} - j\varepsilon^{''} \qquad [7]$$

$\varepsilon^{'}$ is referred to as the permittivity of the material and $\varepsilon^{''}$ as the dielectric loss factor of the material.

The dielectric constant ε_{r} is related to the complex index of refraction n by;

$$\varepsilon = n^{2} \qquad [8]$$

According to the equation [8] the index of refraction presented in the figure 4, for the dielectric medium $\varepsilon_{r} = 1$, $\varepsilon_{r} = 9$ and $\varepsilon_{r} = 25$ are n=1, n=3 and n=5 respectively.

With n defined as

$$n = n^{'} - jn^{''} \qquad [9]$$
$$\varepsilon^{'} = \left(n^{'}\right)^{2} - \left(n^{''}\right)^{2} \qquad [10]$$
$$\varepsilon^{''} = 2n^{'}n^{''} \qquad [11]$$

David J. Daniels (2004) states that the complex dielectric constant and the loss factor of a soil are affected by both temperature and water content. Increasing the water content also increases the value of the loss factor.

For Lonngren, et al., (2007) the electric field components of the incident, reflected and the transmitted electromagnetic wave are the following;

$$\boldsymbol{E}_{y,i}(z,t) = \boldsymbol{A}_{i}e^{j(wt-k_{1}z)} \qquad [12]$$
$$\boldsymbol{E}_{y,r}(z,t) = \boldsymbol{B}_{r}e^{j(wt+k_{1}z)} \qquad [13]$$
$$\boldsymbol{E}_{y,t}(z,t) = \boldsymbol{A}_{t}e^{j(wt-k_{2}z)} \qquad [14]$$

Where k_1 represents the wave number in the region or medium 1 and k_2 represents the wave number in the region or medium 2.
i, r and t indicates the incident, the reflected and the transmitted terms respectively. A and B indicates the terms that propagate to increasing and decreasing values of the coordinate z.

According to Lonngren, et al., (2007), the magnetic field intensities for the three field components can be write as;

$$\boldsymbol{H}_{x,i}(z,t) = -\frac{A_i}{Z_{c,1}} e^{j(wt-k_1 z)} \quad [15]$$

$$\boldsymbol{H}_{x,r}(z,t) = \frac{B_r}{Z_{c,1}} e^{j(wt+k_1 z)} \quad [16]$$

$$\boldsymbol{H}_{r,t}(z,t) = -\frac{A_t}{Z_{c,2}} e^{j(wt-k_2 z)} \quad [17]$$

If we place the interface between the two media at z = 0, then we have;

$e^{j(wt \pm kz)}|_{z=0} = e^{jwt}$ and we obtain that;

$$A_i + B_r = A_t \quad [18]$$

$$\frac{A_i}{Z_{c,1}} - \frac{B_r}{Z_{c,1}} = \frac{A_t}{Z_{c,2}} \quad [19]$$

According to Ulaby, et al., (1986) in remote sensing the materials of interest can be classified into different dielectric groups. Homogeneous Substances, Electrolytic Solutions or Heterogeneous Mixtures. Wet soil and vegetation canopy belong to the group Heterogeneous Mixtures. Most natural materials, such as soil, vegetation and snow are mixtures of bulk material, air and water. In the absence of water in liquid form, the relative permittivity $\varepsilon_m^{'}$ rarely exceeds 7 and $\varepsilon_m^{''}$ rarely exceeds 1. In contrast, $\varepsilon_w^{'}$ of liquid water is one order of magnitude larger than that of dry materials and $\varepsilon_w^{''}$ of water is typically two orders of magnitude larger that of dry materials. The dielectric constant of the mixture tends to be dominated by the dielectric behavior of water. In the absence of liquid water, the real part of the dielectric constant of soil $\varepsilon_{soil}^{'}$ varies between 2 and 4 and is independent of temperature and frequency. The imaginary part $\varepsilon_{soil}^{''}$ is typically < 0.05. A wet soil medium is a mixture of soil particles, air pockets and liquid water. The water contained in the soil usually is divided into two fractions: bound water and free water. The complex dielectric constants of bound and free water are functions of the electromagnetic frequency f, the physical temperature T and the salinity S. Bound water are the water molecules surrounding the soil particles. Free water is the water molecules which are located several molecular layers away from soil particles. The dielectric constant of the soil mixture is a function of f, T and S, the total volumetric water content m_v, soil texture, the density of the soil/air mixture ρ_b, the shape of the soil particles and the shape of the water inclusions.

2.3 TDT & TDR Transmission Line Techniques

According to J.M Blonquist Jr. et al (2005) Time Domain Reflectrometry, TDR and TDT transmission line techniques can be used to estimate dielectric permittivity from the travel time of an electromagnetic signal propagating along a probe buried in a dielectric, which could be any liquid or porous medium. In general, the total travel time includes the travel time through the medium under examination and through connecting cables. According to Masbruch and Ferré (2003) the total one-way travel time is then:

$$t_T = t_{cables} + t_{medium} + t_{air} \qquad [20]$$

Where t_{cables} is the time for the electromagnetic signal through the connecting cables, t_{medium} the time through the medium and t_{air} refers to a section of the probe that maybe extend outside the medium, depending on the length of the sample. As we will see later an *Aquaflex's Soil Moisture Probe* is located inside the medium without any parts outside and therefore t_{air} could be neglected.

TDR can be defined as an electrical measurement technique to determine the spatial location and nature of various objects. By measuring the time from the transmitted pulse until the echo returns, the distance to the reflecting object may be easily calculated. TDR is widely used in hydrology and soil science for measurement of soil water content (Cataldo et al 2005).

From Harlow et al (2003), in typical TDT applications, the travel time is defined as the time taken for an electromagnetic signal to travel one way along a transmission line and the measured travel time is the sum of the time taken to travel along the connecting cables and the transmission line.

In the figure below both TDT and TDR sensors are presented.

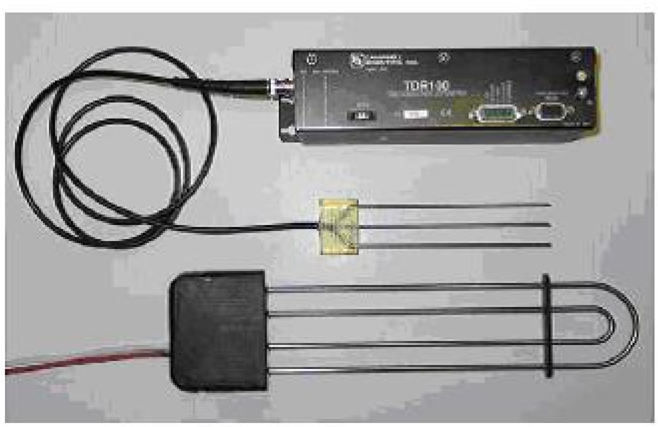

Figure 5.
TDR (Above) and TDT (below) sensors.
Source: Journal of Hydrology 314 (2005) page 238.
Title: A time domain transmission sensor with TDR performance characteristics.

Cataldo et al (2005) states that a Time Domain Reflectometer transmits the incident signal, an ultra short rise time (200ps), step voltage pulse, along the transmission line and records the travel time and the magnitude of all reflected signals (echo). Changes in impedances causes electromagnetic discontinuities and can be located in the reflected voltage, particularly for liquid level and dielectric properties monitoring purposes. The above mentioned discontinuities result from impedance changes produced by changes in the dielectric constant. According to David J. Daniels (2004) this impedance is called the intrinsic impedance of the materials. He defines this intrinsic impedance by;

$$\eta = \frac{E}{H} = \sqrt{\frac{\mu}{\varepsilon}} \qquad [21]$$

where E is the Electric field and H is the Magnetic field.

μ is the absolute magnetic susceptibility of medium, $\mu = \mu_0 \mu_r$

ε is the absolute dielectric permittivity of medium $\varepsilon = \varepsilon_0 \varepsilon_r$

ε_r is the relative permittivity, with a values between 1 to 80 for most geological materials and μ_r is the relative magnetic susceptibility, with a value 1 for nonmagnetic geological materials.

According to Lonngren, et al., (2007) if we assume that the amplitude of the incident electric field intensity $A_i$is known, then we can write;

$$\Gamma \equiv \frac{B_r}{A_i} = \frac{Z_{c,2} - Z_{c,1}}{Z_{c,1} - Z_{c,2}} \qquad [22]$$

$$\mathrm{T} \equiv \frac{A_t}{A_i} = \frac{2Z_{c,2}}{Z_{c,1} + Z_{c,2}} \qquad [23]$$

Where Γ are the reflection coefficient and T the transmission coefficient. These coefficients can be compared with those in Appendix E where **E**-field is parallel and perpendicular to the plane of incidence.

David J.Daniels (2004) also state that at the boundary between two media, some energy will be reflected and the remainder transmitted. The reflected field is described by the reflection coefficient, r

$$r = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \qquad [24]$$

Where η_1 and η_2 are the different impedances of medium 1 and 2. If we know the characteristic impedance of the materials, we can then determine the propagation characteristics and amplitudes of both the wave that is transmitted into the second material and the wave that is reflected at the interface and consequently propagates back in the first material. A special case is when both sides of the materials have the same characteristic impedance, then all the incident electromagnetic energy is transmitted into material 2 and none is reflected back into material 1.

This is called matching the media. The reflection and transmission coefficients can be mentioned in terms of the relative dielectric constant of the two dielectric materials.

$$Z_c = \sqrt{\frac{\mu}{\varepsilon}} \qquad [25]$$

Which is the same as the impedance in equation [21].

$$\Gamma = \frac{\sqrt{\varepsilon_1}-\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1}+\sqrt{\varepsilon_2}} \qquad [26]$$

$$\mathrm{T} = 1 + \Gamma = \frac{2\sqrt{\varepsilon_1}}{\sqrt{\varepsilon_1}+\sqrt{\varepsilon_2}} \qquad [27]$$

According to Cataldo et al (2005) the TDR signal velocity propagation v is related to the relative dielectric permittivity ε of the medium by the following equation:

$$v = \frac{c}{\sqrt{\varepsilon\mu}} \qquad [28]$$

where c is the speed of light $\left(3x10^8\, ms^{-1}\right)$ in vacuum. Most of the materials are non-magnetic, thus μ is equal to one. For Cataldo et al (2005) the travel time t is the time consumed by the TDR signal to travel forth and back in the waveguide of length L and can be written:

$$t = \frac{2L}{c}\sqrt{\varepsilon} \Rightarrow \varepsilon = \left(\frac{ct}{2L}\right)^2 \qquad [29]$$

In the case of TDT the pulse travels the length of the probe once and the transmitted signal is sampled.

$$t = \frac{L}{c}\sqrt{\varepsilon} \Rightarrow \varepsilon = \left(\frac{ct}{L}\right)^2 \qquad [30]$$

As mention above, the propagating signal along the probe encounters an impedance break, causing the TDR and TDT signal to be reflected.

The ratio between the reflected signal amplitude and primary pulse amplitude give the reflection coefficient Γ. The dielectric change is related with the reflection coefficient through the equation:

$$\varepsilon = \left(\frac{1-\Gamma}{1+\Gamma}\right)^2 \qquad [31]$$

The length of the transmission system up to the point where the mismatch occurred is given by:

$$D = \frac{D_a}{\sqrt{\varepsilon}} \qquad [32]$$

Where D is the distance of the signal trip up to the mismatch point in the new medium, D_a is the corresponding distance for an air dielectric (Cataldo et al 2005).

J.M. Blonquist Jr. et al (2005) states that for most hydrological and environmental applications the determination of ε leads to a calculation of volumetric water content ϑ_v. There is a strong relationship between ε estimated by a transmission line sensor and ϑ_v and the reason is the strong contrast between the permittivities, for water $\varepsilon_w = 80$, air $\varepsilon_a = 1$ and mineral soil solids $\varepsilon_s = 2 - 9$.

For both TDR and TDT methods, the volumetric water content of the medium surrounding by sand can be calculated according of the measured travel time. The volumetric water content ϑ_v can be determined using the following equation (Harlow et al 2003).

$$\vartheta_{v,TDT} = 0{,}1256\left(\frac{ct}{L} - 1{,}756\right) \qquad \vartheta_{v,TDR} = 0{,}1256\left(\frac{ct}{2L} - 1{,}756\right) \qquad [33]$$

2.3.1 Advantages of disadvantages of use TDR Technique:

Advantages: Good precision and accuracy, high reliability of the measurement head, possibility of remotely acceding and transmitting data through existing telecommunication technologies, such as modem or cellular telephone (Cataldo et al 2005).

Disadvantages: Cost of the instrumentation and level of user-ability required. The length of cable that the probe can be attached to without signal attenuation compromising accurate permittivity and subsequently water content estimations. Sensor systems in field site locations must have coaxial cable running from the probe to the cable tester (J.M. Blonquist Jr. et al 2005).

2.3.2 Advantages and disadvantages of use TDT technique:

The TDT sensor offers the advantage of having the pulse generating and sampling electronics mounted in the head of the probe which reduces attenuation (J.M. Blonquist Jr. et al 2005). TDT waveform analysis is simpler than TDR waveform analysis. In TDR analysis, identification of the reflection from the ends of the probe can be complicated due to multiple reflections from the beginning of the probe and TDT method requires more expensive instruments than TDR-based methods (Masrbruch & Ferré 2003).

2.4 Soil moisture types

The dielectric properties of soils have been studied for many years and there is a large body of experimental data available as well as a large number of theoretical models. The difficulties are posed by the variability of the material. Some studies show that the permittivity increase with water content and at given water content a fall in permittivity with increasing frequency. Figure 6 below, show dielectric behavior of silty clay soil at a moisture content of 15% water over a wide range of frequencies (David J.Daniels 2004).

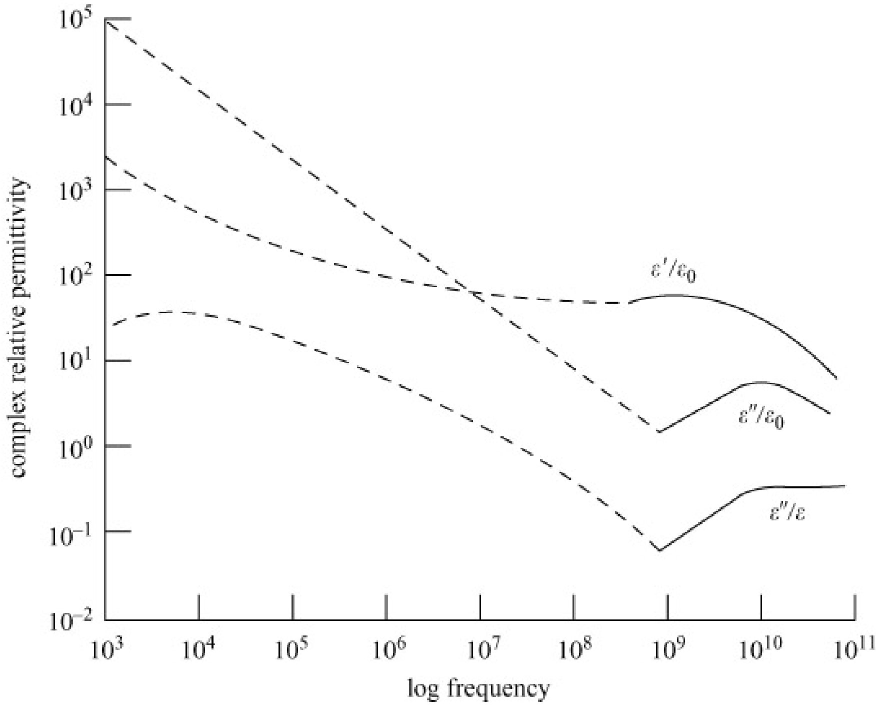

Figure 6.
Dielectric behavior of silty clay soil at a moisture content of 15% water.
Source: David J.Daniels (2004). Ground Penetrating Radar, 2nd Edition.

According to David J.Daniels (2004), soil is not only a mixture of dielectrics, even when the composition of a given sample is known in terms of its components and their individual properties, that alone is not sufficient to define its nature dielectrically. The particle sizes (see figure 7), the electrochemical nature of their boundaries and the way in which the water is distributed also affects the behavior.

According to Ulaby et al. (1986), soil is classified as sand, silt or clay according to size of the particles. All soils contain a distribution of particle size; it is convenient to classify a soil by the weight-percent of the soil within each specific size category; Sand, silt or clay. The soil´s texture class determined by the relative percentages of the three sizes, as shown in figure 8.

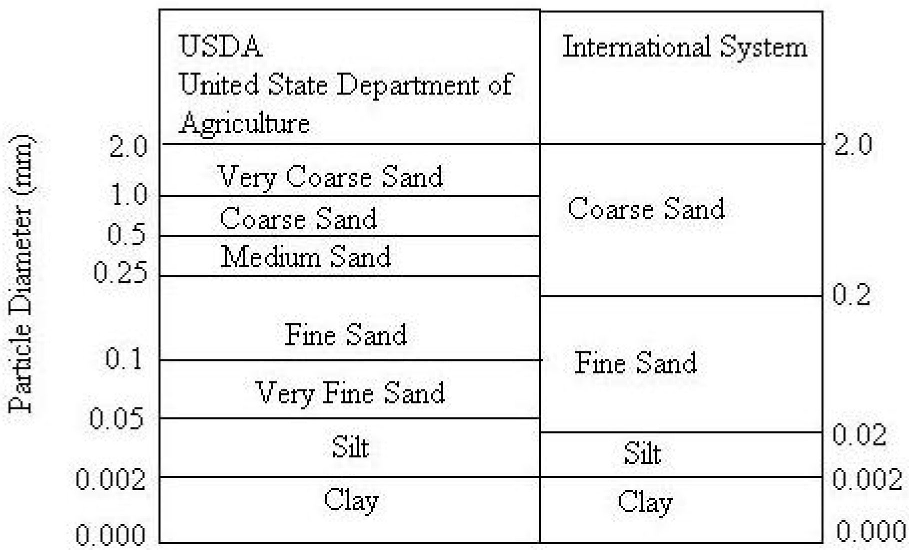

Figure 7.
Particle sizes classes.
Source: Ulaby, et al., (1986). Microwave Remote Sensing. Volume III

According to Ulaby, et al., (1986), there are two terms commonly used to characterize the moisture content of a soil sample; volumetric moisture m_v and gravimetric moisture m_g.
Here we focus on volumetric moisture which is given by;

$$m_v = \frac{v_w}{v_t} = \frac{v_w}{v_{dry}} = \frac{w_w \rho_b}{w_{dry} \rho_w} = \frac{w_w \rho_b}{w_{dry}} \text{ [g/cm3]} \qquad [34]$$

$$m_g = \frac{w_w}{w_{dry}} \times 100 = 100 \frac{m_v}{\rho_b} \text{ [\%]} \qquad [35]$$

v_w is the water volume. v_t is the total volume of the sample, which includes the volumes of air, soil and water and is equal to the volume of the dry sample v_{dry}. w_w and w_{dry} are the weights of the water in the sample and of the dry sample. ρ_b is the density of the soil/air mixture. ρ_w Is the density of water = 1g/cm3

In the picture below we show the soil types and their composition, Clay, Silt and Sand expressed in percent from 0% to 100%

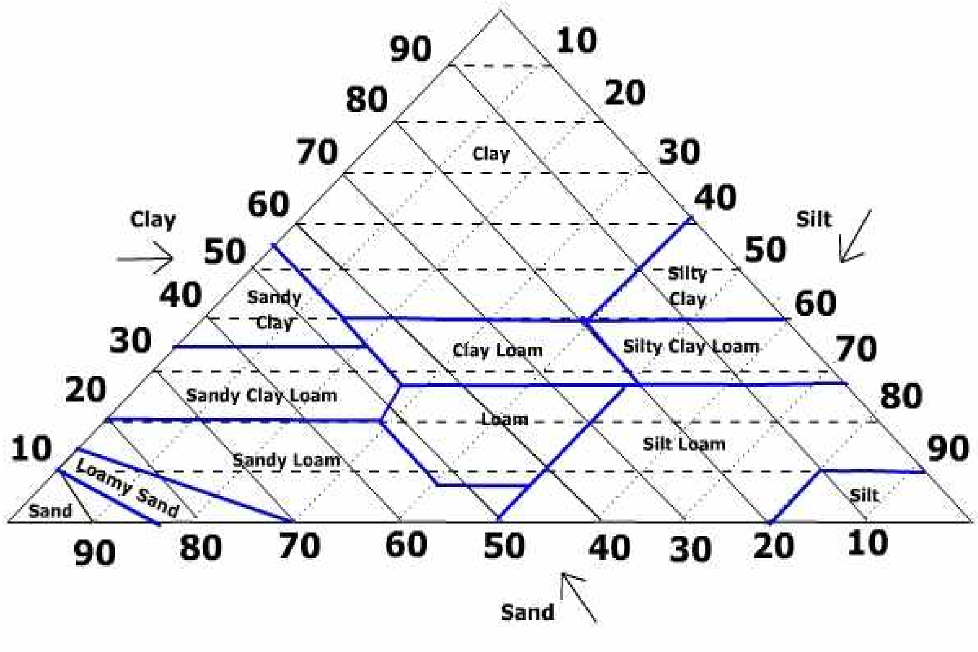

Figure 8.
Soil types and their composition; clay, silt and sand expressed in percent from 0% to 100%.
Available at: http://www.uwsp.edu/geo/faculty/ritter/glossary/s_u/soil_texture_triangle.html

According to Aquaflex PC software user manual version 4.13, the calibration types with their respective clay, silt and sand composition are expressed in percent as follow below.

Sand	(90% sand, 3% silt, 7% clay)
Sand Loam	(70% sand, 20% silt, 10% clay)
Loam	(40% sand, 40% silt, 20% clay)
Silt Loam	(25% sand, 60% silt, 15% clay)
Clay Loam	(35% sand, 30% silt, 35% clay)
Clay	(15% sand, 35% silt, 50% clay)

Table 1.
Clay, silt and sand composition expressed in percent.
(Source. AQUAFLEX PC Software User Manual, Version 4.13).

Where *Clay and Silt* S*oils* are made of very small particles according to figure 7. They feel slick and sticky when wet. Clay and Silt hold moisture well, but resist water infiltration, especially when they are dry. They easily become compacted. *Loam Soil* is a mix of sand, silt or clay and organic matter. Loam soils are loose and look rich. Loam soils normally absorb water and store moisture well. Loam soils can be sandy or clay based and will vary in moisture absorption and retention. *Sandy Soils* contain large particles which are visible to the eye and usually light in color. Sandy-Soils size is observable in the figure 7, in that we can see that the sand´s diameter particle can be between 0.02 to 2mm diameters. Sand feels coarse when wet or dry and will not form a ball when squeezed in your fist. Sandy soils stay loose and allow moisture to penetrate easily, but do not retain it for long term use.

The table below lists field capacity, refill point and permanent wilting point according to the different soil types.

SOIL TYPE	Field Capacity	Refill Point	Permanent W. Point
Clay	44%	36,5%	29%
Clay Loam	32%	25,5%	19%
Silt Loam	28%	19,5%	11%
Loam	26%	19,5%	13%
Sandy Loam	18%	13,5%	9%
Sand	14%	10,5%	7%

Table 2.
Soil Types and their respectively Field Capacity, Refill Point and Permanent W. Point
(Source: AQUAFLEX PC Software User Manuel. Version 4.13, page 33).

According to the Aquaflex PC software user manual, version 4.13, *Field Capacity* is the amount of water in a wetted soil after it has drained. It roughly corresponds to a matric potential of -30kPA = -30kN/m2 = -0, 3 bars in most soils and to -10kPA in sandy soils. *Refill Point,* means that when the soil moisture falls to this level, it should be irrigated so that the plants do not experience undue stress. This usually corresponds to half of the plant available water. *Permanent Wilting Point* means that the plant can no longer extract water from the soil and will begin to wilt. The plants will not fully recover after rewetting. This is the water content at a matric potential of -1,500kPa.

A soil type can be described according to its Compaction, Moisture, Soil Structure and Soil Temperature.

Compaction.

Compacted soils don't allow much air to circulate to the root zone and water tends to just run-off. This increase erosion and strips away vegetation and topsoil. A normal loosely compacted soil helps to absorb and retain water, releasing it slowly and allows the root zone of plants to breath. These soils are generally more productive, since plants can grow much more readily.

Moisture.

The amount of moisture found in soil varies greatly with the type of soil, climate and the amount of humus (organic material) in that soil. The types of organisms that can survive in the soil is largely determined by the amount of water available to them, since water acts as a means of nutrient transport and is necessary for cell survival.

Soil Structure.

Soil structure tells how the soil affects the movement of water, air and root penetration into the soil. Words such as blocky (the blocks of soil are large, with the same number of cracks going horizontal as vertical), granular (the blocks of soil are small, with the same number of cracks going horizontal as vertical), columns (the blocks of soil and related cracks are generally longer in the vertical direction than in the horizontal) and plate –like (the blocks of soil and related cracks are generally longer in the horizontal direction than in the vertical).

Soil Temperature
Has a significant role in helping to determine the rate of plant growth and whether a plant will ever survive. The temperature in the soil changes greatly with depth.

2.5 Aquaflex Soil Moisture Probe

Most of the text which follow below here, is extracted from the Aquaflex homepage (see References. AQUAFLEX Irrigation Management. 2005. Soil Moisture Meters).

There are many techniques available to measure and test soil moisture, from simple handheld soil moisture testers to sophisticated scanning systems. Aquaflex is a system for gauging soil moisture and temperature; it uses a patent technology (United States Patent; Patent Number: 5,148,125) to measure the dielectric constant of the soil in a process called TDT. As a direct method to measure soil moisture, Aquaflex humidity sensors are accurate and can provide estimates over the entire root zone, but they are point measurements and therefore in situ measurements are usually rather limited. The measurements can be converted to accurate measurements of volumetric soil moisture (the amount of water in a given volume of soil). The output data from the soil moisture measurement consisted of 2 variables, which are related primarily to the real and imaginary components of the dielectric permittivity, see equation [7]. These are called raw moisture and conductivity.

To relate the measurements to soil moisture (volume fraction, V in %) requires the use of empirical derived equations for different soil types. For clay soils and clay-rich loams (i.e. anything with above about 35% clay) the relationship used by Aquaflex is given below.

$$V=100*(1-0.32(b-a-0.36))(1.7875-0.3674a+0.01945a^2+0.0000512a^3-0.00001039a^4) \quad [36]$$

For the silt, sand and sandy loams, the equation used by Aquaflex is the following,

$$V=100*(1-0.30(b-a-0.30))(-2.282+0.6685a-0.07623a^2+0.003813a^3-0.00006361a^4) \quad [37]$$

a is defined as raw moisture and b is the conductivity thus the real and imaginary component of the dielectric permittivity.

The sensor of an Aquaflex soil moisture probe consists of a 3 meter long transmission line that extends to the end of the sensor ribbon and then returns back to the sensor electronics.

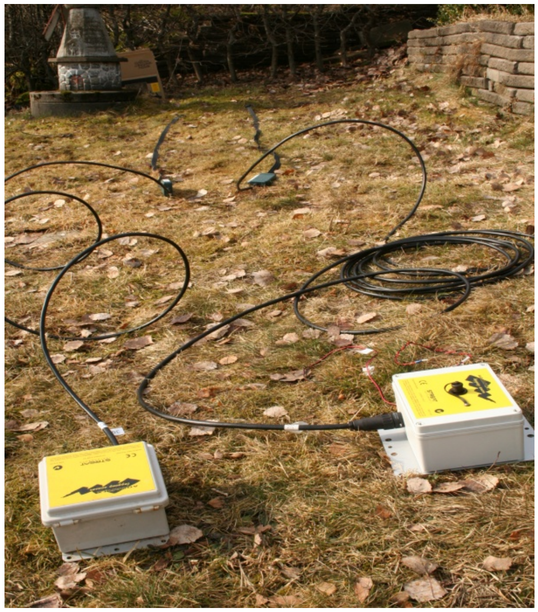

Figure 9.
AQUAFLEX Soil Moisture Probes.
Old(left) and new(right) electronic box.

This sensor measures the average soil moisture along its length and the soil temperature near the end of the sensor. To do that an electrical pulse is sent along the transmission line, which is embedded within the Aquaflex sensor. Aquaflex determines moisture by measuring the time it takes for this pulse to travel along its sensor cable. This electrical signal is influenced by the presence of water, therefore water has a much higher dielectric constant than most materials that constitute soil. The speed and shape of this pulse is affected by the dielectric properties of the medium so the electrical field around the transmission line interacts with the surrounding medium.

Aquaflex measures the original pulse and not a reflection from an open metal rod as in the case of TDR and extracts information from the shape of the pulse, which gives a good indication of soil conductivity. Increasing the conductivity of the soil has two independent effects: It will alter the speed of the pulse along the sensor cable and also the shape of the returned pulse will be altered in a known fashion. The Aquaflex pulse circulates many times through the sensor cable before the pulse delay is measured, resulting in high precision in the time delay measurement. Whereas TDR and other techniques measure a very small sample of soil, Aquaflex spatially averages over a 50x3000mm cylinder of soil. This represents a sample size of approximately 6 liters. The shape of the pulse used by the Aquaflex electronics differs from that used by traditional TDR instrumentation, with the consequence that losses and noise in the transmission are reduced.

Aquaflex measures and records continuously in time and the user can choose the interval between measurements and how often the data will download. The logging sensor is equipped with wrap-around memory, where the newest readings overwrite the oldest readings. The data capacity depends on the frequency of measurements (Sampling interval). The Aquaflex logging sensor can store nearly two months of data when taking a reading every hour. Aquaflex can even measure temperature and provide a temperature output signal. In most soils and growing conditions, soil moisture and temperature vary dramatically, often over quite short periods of time. Continuous monitoring is important because it provides a good picture that shows how widely and quickly these changes take place.

The Aquaflex soil moisture probe can be calibrated depending on the soil category and therefore it is necessary to know the approximate soil type at the location where the sensor is buried. According to Aquaflex PC Software User Manual with revision date 7th November 2003 the user can choose one of the following broad soil types;
Clay / Clay Loam / Silt Loam / Loam / Sandy Loam / Sand / Silt.

3 Equipment

The following section gives a brief exposition about the layout of the new Aquaflex humidity sensor and how the system works. It explains more in detail each part of the system and the characteristics for the different devices.

The new Aquaflex system differs from the old Aquaflex system. The sensor itself as well as the data processing is the same as before, however the new system is provided with solar panel, new rechargeable battery and telemetry device for remote data access.

Figure 10, shows the configuration of the new system.

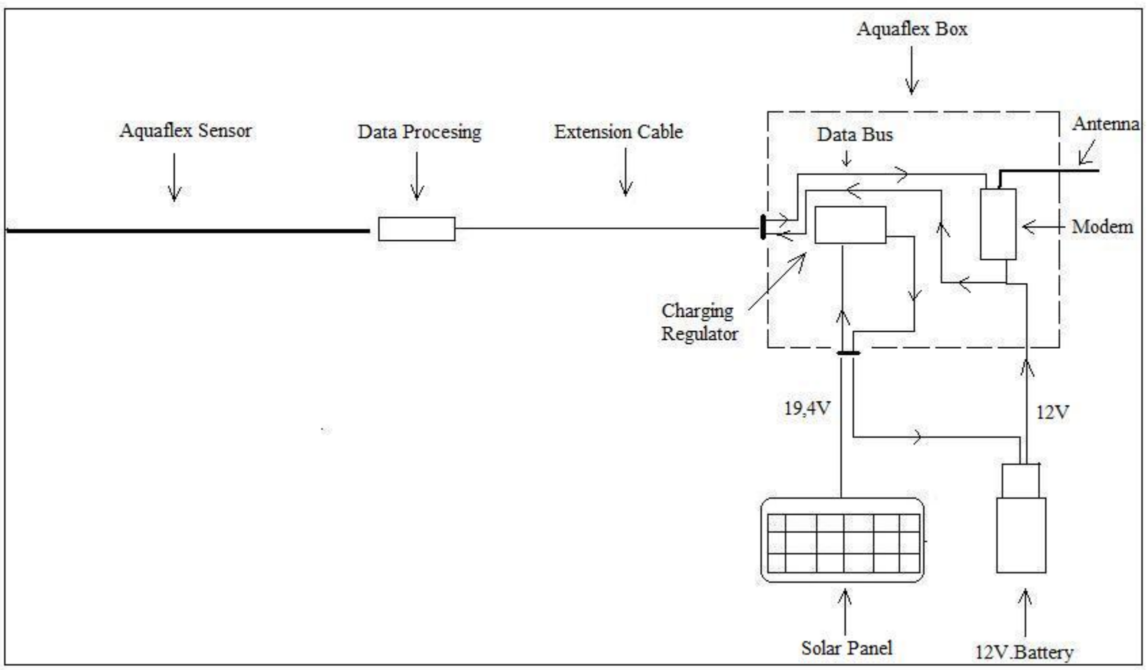

Figure 10.
Aquaflex´s new system configuration.

The 12V battery supplies power both to the telemetry device (modem) and the logging sensor. The sensors will in the future be placed in the forest under a closed forest canopy, a 10m extension cable connects, the cable sensor and the electric box. The 10m extension cable provide the system with extra flexibility to place both the electronic box and the solar panel in the right place (top of a tree or an open area) to guarantee that the solar panel get enough energy from the sun to run the system. In the case that longer distance is needed, the connection of the solar panel to the Aquaflex electronic box is a standard 2-wire cable used for electrical appliances at home with standard connectors, see figure 11. This connection could be extended as long as needed.

Figure 11.
Solar Panel/Aquaflex electronic box standar 2-wire cable connection.

3.1 Electrical Box

The new electrical box is presented in, figure 12 and 13.

Figure 12.
New Aquaflex electronic box. Front view.

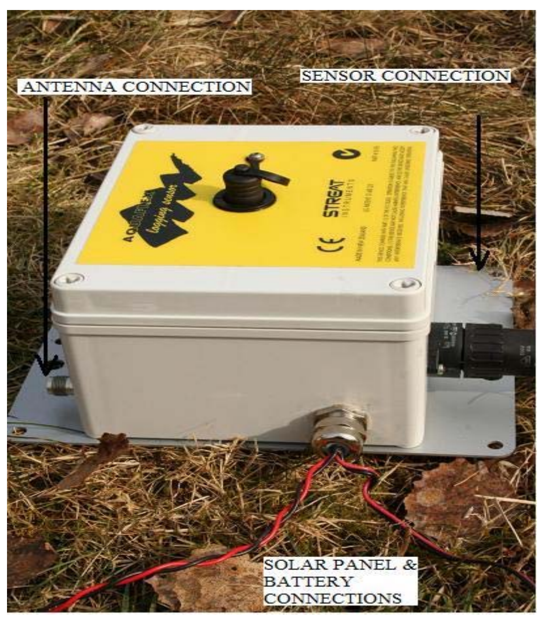

Figure 13.
New Aquaflex electronic box. Lateral view. Antenna, sensor, solar panel and battery connections are visible on the picture.

The size of the electronic box has changed and the new model is bigger than the old model. The box is still produced in plastic but is better water adapted than the old model. Four screws are placed in the corners of the box, to avoid water to come in. There are connections in three of the box´s sides, see Figure 11. These are one connection for the cable sensor, one connection for the solar panel and the battery and one connection for the modem antenna. Inside the electronic box we find the following devices; the charging-regulator and the modem.

3.2 The Charging-Regulator Module

The charging-regulator module is supplied by Kemo Electronics, see figure 14. The charging-regulator module controls the level of the battery and keeps it charged.
It is connected between the charging source and the device to be charged. According to the Charging-regulator supplier (see References. Kemo Electronic, 2008. *M083 Accu-charging regulator)*, the input voltage of the module must be approx. 16…20V.

Figure 14.
Kemo Electronics, charging regulator.

This regulator has been designed reverse-current proof to avoid the accumulator be discharged whenever the solar surface doesn´t supply voltage (by night). The module starts to charge the battery when the battery voltage falls below, 13.8…14.2V and switches off exceeding this voltage values.

3.3 Wavecom Modem

The modem inside the electronic box is supplied by Wavecom, see figure 15. Its function is to transfer the data recorded by the Aquaflex sensor. This modem model is called Fasttrack Supreme 10 and according to the modem suppliers (see References. Wavecom, 2009. *Products, Fasttrack Supreme)* the modem operates at 850/900/1800/1900 Mhz: GSM, SMS, CSD, GPRS and voice code FR/HR/EFR/AMR. The modem support even Class 10 GPRS. The class determines the speed at which data can be transferred and GPRS class 10 has the following max.data transfer speed. 16-24 kbps upload / 32-48kbps download and the input voltage of the modem is 5V-32V.

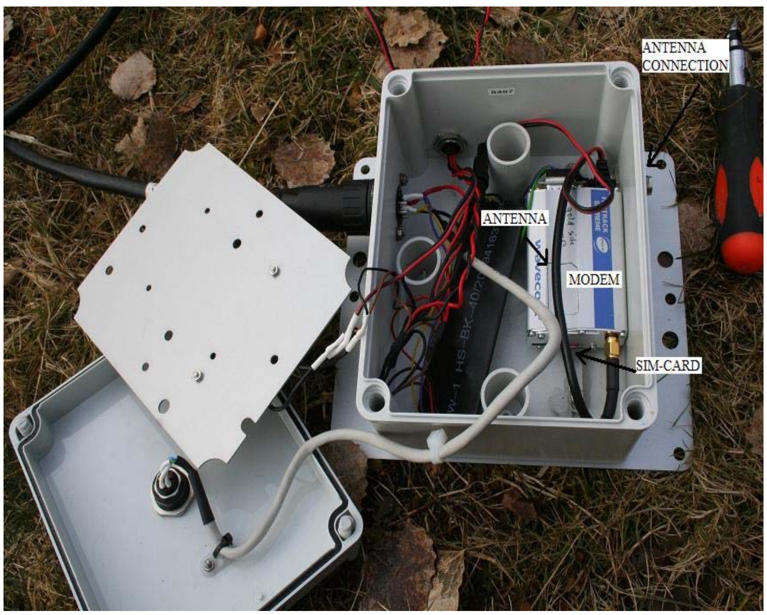

Figure 15.

Wawecom Fasttrack supreme 10 modem.

Figure 15; show us the Wavecom modem, the modem antenna, the antenna connection and the location of the SIM-card.

3.4 Battery

The battery is a rechargeable lead acid battery from Yuasa, model NP12-12, see figure 16.

Figure 16.
Rechargeable lead acid battery. Yuasa NP12-12

According to the battery suppliers (see References. Yuasa. Industrial batteries, automotive batteries, *Products. NP series.*), the nominal voltage is 12V and the nominal capacity expressed at 20, 10, 5 and 1 hr according to manufacturers is:

20hr. rate of 0.6A to 10.50V 12.0 Ah (C=20*0.6A)
10hr. rate of 1.1A to 10.50V 11.0 Ah (C=10*1.1A)
5hr. rate of 2.1A to 10.20V 10.5 Ah (C=5*2.1A)
1hr. rate of 7.2A to 9.60V 7.2Ah (C=1*7.2A)

The operating temperature range is; charge (-15ºC to 50ºC) and discharge (-20ºC to 60ºC) and the expected service life according to the manufacturers is five years in standby applications. After five years the percentage of capacity available is 40%.

3.5 Cable Sensor

The sensor is a 3m long cable in which electromagnetic waves travel, see figure 17.

Figure 17.
3 meters cable, Aquaflex humidity sensor.

An electrical pulse is sent along the transmission line, which is embedded within the Aquaflex sensor. Electromagnetic wave propagation, dielectric constant and soil types are basic moment to get an understanding of how TDT technique and Aquaflex humidity sensor work.
More details about how the TDT technique works is given in section 2.3 and 2.5.

3.6 Solar Panel

The solar module is a Silicium solar cell module supplied by Etsolar and the model is ET-M53930 with a maximum power of 30W, see figure 18.

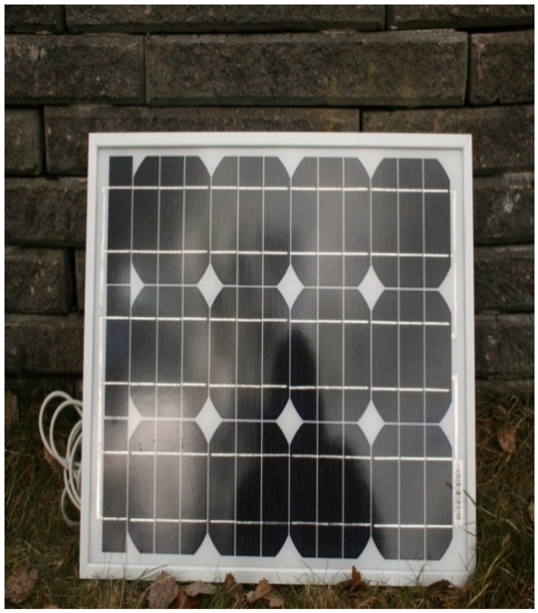

Figure 18.
Solar Module. ET_M53930. Max Power 30W

According to the manufacturers (see References. ET Solar. 2009. *ET Module catalog*.), the maximum possible voltage across the solar cell is 23.8V (Voc) and the current flowing in an external circuit that not has load or resistance is 1.74A (Isc). The voltage needed to reach the maximum power (Vmp) is 19,4V and the current needed to reach the maximum power (Imp) is 1,55A. Thus 19,4V*1,55A=30.07W

The Silicium solar cell has a band-gap of 1.1eV and therefore only absorb photons with an energy >=1.1eV. This energy gives us a wavelength of 1.13µm which corresponds to red light in the electromagnetic spectrum. Silicium solar cells transform red light effectively and they are sensitive to all visible light. They can ineffectively transform light with higher energy.

3.7 Multitech, Multimodem GPRS

The wireless modem used to establish the communication with the Wavecom modem is a Multitech, MultiModem GPRS class 10 wireless modem, which provides wireless data communication, see figure 19. This modem is connected to the computer where the data should be downloaded.

Figure 19.
Multitech GPRS modem.

According to the suppliers (see References. MultiTech Systems 2009. *MultiModem GPRS External Wireless Modem),* the MultiModem wireless modem, which can be desktop or panel mounted, is ideal for automated machine to machine, public transit, remote diagnostics, security systems, Telemetry/remote metering, etc. The MultiModem GPRS wireless supports GPRS Class 10 packet-switched cellular data. This enables mobile internet functionality by allowing interworking between the existing internet and the cellular network at speed up to 85.6Kbps. The MultiModem GPRS wireless also supports GSM circuit-switched cellular data connections to speeds up to 14.4 Kbps.

A 9600 baud GSM data transmission establishes the communication between the Multitech multimodem and the Wavecom modem. The data is presented in a Microsoft access file. In this file we have access to the real and imaginary part of the dielectric constant, soil moisture, temperature, date of the measurement, expressed as (yyyy-mm-dd-hh-mm-ss) and battery level. Configurations can be made to decide how often the data would be received/intervals in time of the measurements. The number of bytes exchanged per connection is in the order of 500. The memory capacity of the Aquaflex sensor is 1344 measurements, which means that if we configured the system to measure the soil water content every 60 minutes, the number of measurements per day is in order of 24. With this configuration, we could save 56 days data, before the sensor start to rewrite data, in earlier data records.

3.8 Telephone SIM-Card

To establish the communication between the Aquaflex sensor and the Multitech multimodem and allow the data transfer between them, two SIM telephone card are needed. There are several telephone companies that offer data transfer service, i.e. Telenor and Telia. Telia offer the best coverage. For that reason Telia´s data transfer service is chosen. According to Telia (see References. Telia.2009. *Telia Telematik*), Telia Telematik telephone subscription for companies provides machine to machine communication using the GSM/GPRS net. It is a product developed for surveillance, steering and reading of mobile or geographically spread devices. The price for a Telematik subscription is the following (see References. Telia 2009. *Telia Telematik Prislista*). Start charge of 100kr and a 40kr charge every month. There are several alternatives later on, depending of the quantity of the data to down load. One of these alternatives is what Telia called price agreement with package data-quantity. The customer pays a fixit monthly charge for the quantity of data to download, starting with a minimal data quantity of 2MB and a max data quantity of 500MB

Max 2 MB, a monthly charge of 16kr.
Max 4 MB, a monthly charge of 28kr.
Max 7 MB, a monthly charge of 42kr.
Max 10 MB, a monthly charge of 52kr

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Max 500 MB, a monthly charge of 300kr.

Another alternative is to pay a charge per MB. This charge is 9.60kr per MB, regardless of the time of the day. This alternative is the more economical, because the data amount per connection according to Aquaflex suppliers is only in order of 500bytes and therefore this alternative is the one chosen for our goal.

4 Methodology

Two Aquaflex humidity sensors were located at Remningstorp, between Skara and Skövde in Västergötland in the south of Sweden. The Aquaflex humidity sensors were placed approximately 100 meter from each other and 15cm deep in the ground. One was located inside the forest, surrounded by trees and canopy and the other was located in an open field. These sensors have recorded water volume content data and soil temperature data from spring 2006 until winter 2009.

In addition, the Radar and Remote Sensing Group at Chalmers University of Technology has received precipitation and temperature records from SMHI, collected at a meteorological station situated at Remningstorp. These records and the Aquaflex data are compared graphically to establish a relationship between precipitation, temperature and water volume content in the ground.

A sensor, called TinyTag, that measures temperature and relative humidity of the air was also placed near the Aquaflex Forest sensor. This sensor was placed on a tree, approximately 1,5m from the ground and at a distance of approximately 3m from the sensor located inside the forest. The TinyTag sensor data are also graphically presented and compared with the SMHI temperature data and Aquaflex temperature data in the ground, to establish differences between the air and the ground temperature.

The new and updated Aquaflex remotely controlled soil moisture sensor, was installed and tested at Benareby, Mölnlycke located south west of Gothenburg city about 15minutes by car from the city. The new Aquaflex system consists of an electrical box, a charging regulator module, a 12V rechargeable battery, a solar panel, two GPRS modems, two telephones SIM card and the 3 meters cable sensor. This new system has recorded water volume content data and temperature data from 20090316 to 20090525 at the Benareby location. These data are graphically presented in this thesis work.

The aquaflex system used equations [36] and [37] depending the soil type surrounding the sensor to calculate the water volume content. Those equations are used to make plots in Matlab of the water volume against the time and the soil temperature against the time. An analysis of the soil was necessary, to know which one of the two mentioned equations should be used, depending the sensor location. Three soil samples were taken, one sample was taken at the forest sensor location, the second sample was taken at the field sensor location and the third sample was taken at Benareby location.

5 Results

In this section soil moisture and temperature data from Remningstorp and Benareby are presented and analyzed. First data recorded from April 2006 to March 2009 by two Aquaflex humidity sensors placed in two different places at Remningstorp are presented. The Aquaflex humidity sensors are approximately 100 meter from each other, one is located inside the forest and the other is located in the open field. These sensors are called the Forest sensor and the Field sensor. The last reading recorded from the field sensor was at 10:00:00 am on 2 May 2007. We could detect that the electronic box on the field sensor had been taking in water due to the precipitations during the winter. However an attempt to install the field electronic box on the forest cable sensor showed that the box worked, so the conclusion was that the cable sensor for the field sensor did not work properly. According to the Aquaflex soil moisture specifications the temperature range of the system is -10ºC to 40ºC. SMHI meteorological station at Remningstorp recorded temperatures under winter 2007 below -10ºC and even below -15ºC. However the sensor worked correctly until the middle of the spring 2007 and therefore it is not believed that the cold temperature during winter was the reason why the sensor finished working properly.

The data have been collected with one hour interval and each reading contains information of the real and imaginary parts of the dielectric constant, date of the reading presented as follow; yyyy-mm-dd hh:mm:ss, sensor identification number and the temperature in the ground.

SMHI has supplied Chalmers with precipitation and temperature data from a meteorological station situated at Remningstorp and these data are also presented and analyzed in the results. The TinyTag temperature and humidity sensor has collected data from 20060601 to 20080929 with a sample interval of thirty minutes. However some data have been missed; data from 20060425 to 20060601, data from 20061116 to 20070318 and data from 20070904 to 20080413. For that reason we present only the temperature data for the available dates.

The Aquaflex humidity sensor represents a sample size of approximately 6 liters and the plots present the water content in volume fraction, in %. Both the temperature from the Aquaflex sensors, Remningstorp meteorological station and air temperature measured by the TinyTag sensor are presented in degrees Celsius. The precipitation data from Remningstorp meteorological station is presented in mm.

Further we plot data from the new updated Aquaflex humidity sensor. This sensor was placed in Benareby, Mölnlycke. The sensor was placed 30cm deep in the ground and it collected data from 20090316 to 20090525.

A soil analysis for samples from the field, forest and Benareby sensors was done by Mr. Peter Hedborg, who works at the division for GeoEngineering at the Department for Civil and Environmental Engineering at Chalmers University of Technology. The samples are the following; Sample nr 1 Benareby, sample nr 2 Remningstorp Field, and sample nr 3 Remningstorp Forest (see Appendix B). In the soil analysis, aspects like water quota and heat deficit were analyzed. The heat deficit allows us to know how much organic material there is in the ground and water quota the water amount in the ground. The water quota is achieved by weighing the humid soil sample + sample container and the dry soil sample + sample container. The difference between these two values gives us the water mass. We can calculate the water content of the test in percent by weighing the container alone. The relationship between the weight of water in the sample and the weight of the dry soil sample give us the water percent. The water quota and the heat deficit for the three soil samples were calculated.

According to the soil moisture protocol (See Appendix B) the results of the soil analysis are the following;

Sample nr 1, *Benareby*: Sandy humus. Root elements, i.e. Silt, Sand or Sandy-Loams.

Sample nr 2, *Remningstorp Field Sensor*: Dry crust clay, sand, plant rest elements, i.e. Clay Soils or Clay-Rich Loams.

Sample nr 3, *Remningstorp Forest Sensor*: Root elements, i.e. Silt, Sand or Sandy-Loams.

5.1 Analysis of Remningstorp Soil Moisture Data

5.1.1 Spring 2006

Data collected from 20060425 to 20060622. The plots showed below, represent the volumetric water content measured by Aquaflex humidity sensors located one in the field and one in the forest; Figure WSpring06. The precipitation at Remningstorp meteorological station; Figure PSpring06. The ground temperature measured by Aquaflex humidity sensors located one in the field and one in the forest; Figure TSpring06. Maximum, minimum and average temperature at Remningstorp meteorological station; Figure MmA06 and air temperature measured by TinyTag sensor, Figure TinySpring06.

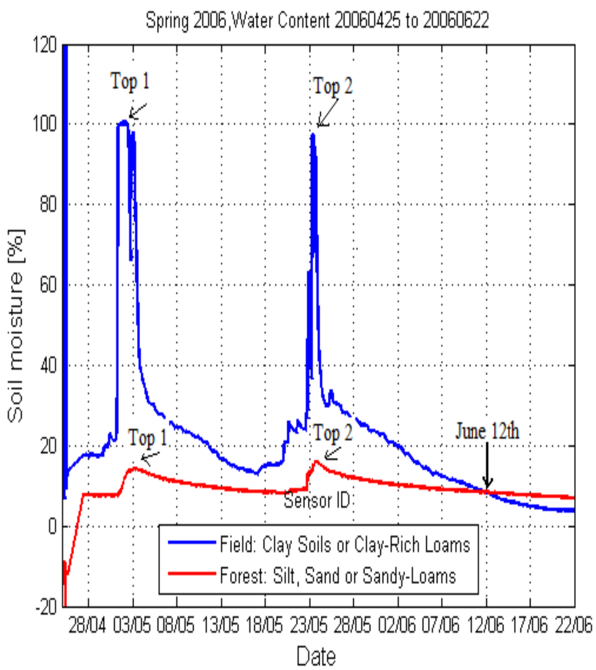


Figure. WSpring06.
Aquaflex-sensor, Water content (%)
20060425-20060622

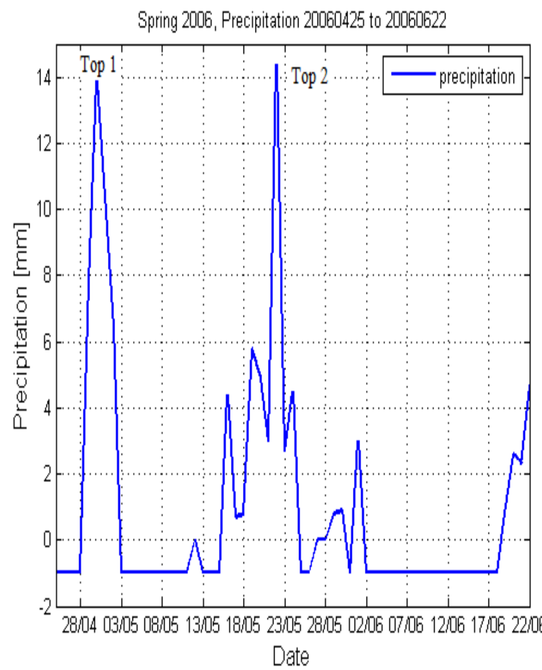


Figure. PSpring06.
SMHI data.Precipitation (mm)
20060425-20060622

In figure PSpring06 we observe two well defined tops; Top 1 on April 30th and Top 2 on May 22nd. These two precipitations tops were also recorded by the two Aquaflex sensors. Top 1 was recorded on May 2nd and Top 2 was recorded on May 23rd,

The precipitation tops are also indicated on the temperature graph from the Remningstorp meteorological station, figure MmA06 and on the temperature in the ground recorded by Aquaflex sensor, figure TSpring06.

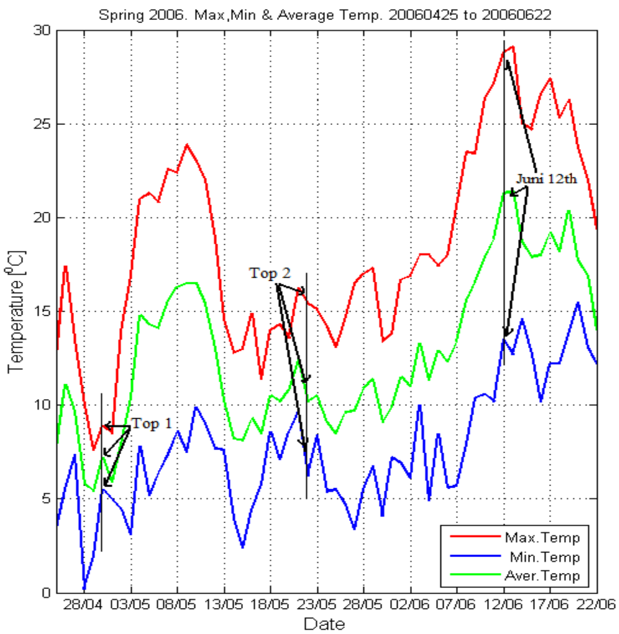


Figure. MmA06. SMHI data. Max, Min & Average Temperatures (ºC) 20060425-20060622

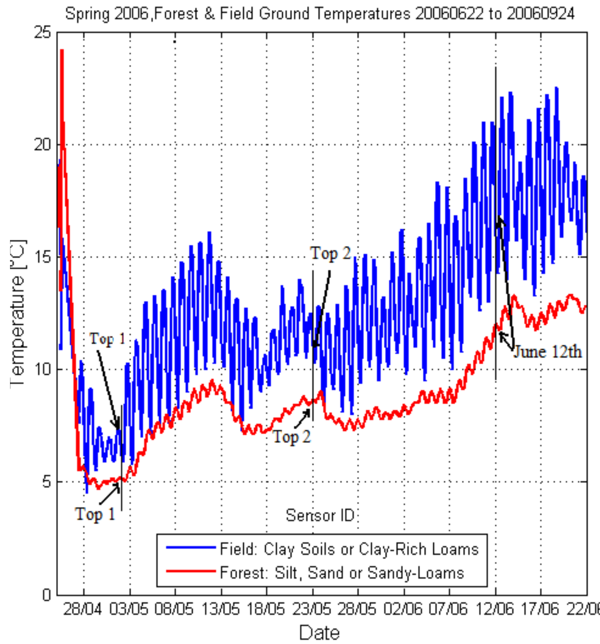


Figure. TSpring06. Aquaflex forest & field ground Temperatures (ºC) 20060425-20060622

In the Table 3 we present the following data for each precipitation top recorded: precipitation values at Remningstorp station, the maximum, minimum and average temperature values at Remningstorp, the Aquaflex sensors´ temperatures in field and forest ground and the Aquaflex sensors´ water volume content in the field and forest ground.

	Precipitation (mm)	**Max. Temp Remning Stat (ºC)**	**Min. Temp Remning Stat (ºC)**	**Aver.Temp Remning. Stat (ºC)**	**Forest.Sensor at 12h TinyTag (ºC)**	**Forest. Ground Temp At 12h (ºC)**	**Field. Ground Temp At 12h (ºC)**	**WVC. Forest (%)**	**WVC. Field (%)**
Top1	14	8,9	5,5	**7,2**	-	4,9	6,4	14	100
Top2	14	15,1	8,4	**10,5**	-	8,6	11,6	16	96

Table. 3. Precipitation at Remningstorp. Max, Min &Aver Temp at Remningstorp. Forest & Field Ground Temp. Forest & Field Water Volume Content.

Remningstorp meteorological station registered 14mm rain during Top 1 and 14mm rain during Top 2. The Aquaflex sensor situated on the field recorded 100% water volume content during Top 1 and the Aquaflex sensor placed on the forest recorded 14% water volume content. During Top 2 the Aquaflex sensor situated on the field registered 96% water volume content and the Aquaflex sensor placed on the forest registered 16% water volume content. There are large difference in the water volume between the two sensors during the two precipitation tops, 86% higher water volume for the sensor at field during Top 1 and 80% higher water volume for the sensor at field during Top 2. We know that the sensor on the field is surrounded by clay soils or clay-rich loams. These types of soil are, according to Table 1, composed of between 15% to 35% sand, between 30% to 35% silt and between 35% to 50% clay. This loosely compacted soil helps to absorb and store moisture well and retain water releasing it slowly. Therefore the precipitation could make the soil saturated; the water has not time to flow away. The sensor in the forest is surrounded by silt, sand or sandy loams soil. These types of soil are, according to table 1, composed of a majority of sand and in a minority of clay soil. Sandy soils stay loose and allow moisture to penetrate easily, but do not retain it for long time.

I believe that those are the reasons why the differences in water volume content between field and forest sensors are so large for Top 1 and Top 2. The remaining days during the spring 2006 the field sensor registered also higher water volume than the sensor on the forest, however the differences are not so high, just in order of 5 to 10% higher.

We also see in table 3 that the temperature recorded by the Remningstorp station at the two tops increased. The water volume content at the field sensor decreased. On the other hand the water volume at forest sensor increased 2%. On June 12th for the first time during the spring 2006, we observe that the water volume content in the forest becomes higher than in the field; figure WSpring06. A reason could be the increase of the temperature from the end of May to the middle of June registered by Remningstorp meteorological station; figure MmA06 and the temperature sensor situated close to Forest sensor; figure TinySpring06.

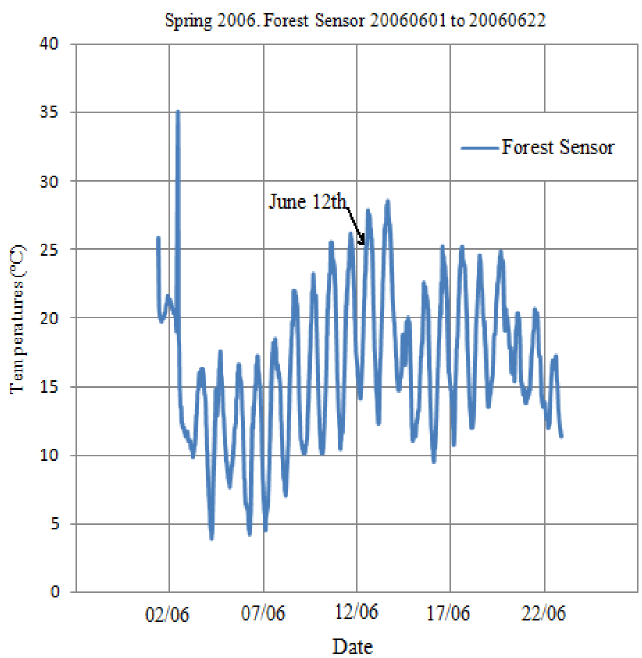


Figure TinySpring06. Temperature at Forest (ºC)
20060425-20060622

We observed that the highest temperature registered by Remningstorp station happened just between June 12th and June 13th, 27ºC to 29ºC, figure MmA06. The average temperature for June 12th was 21ºC and the minimum 13ºC, table 4.

	Max. Temp Remning Stat (ºC)	**Min. Temp Remning Stat (ºC)**	**Aver.Temp Remning. Stat (ºC)**	**Forest.Sensor at 12h TinyTag (ºC)**	**Forest. Ground Temp At 12h (ºC)**	**Field. Ground Temp At 12h (ºC)**
June 12th	28,8	13,5	**21,3**	25,2	11,7	18,2

Table. 4. Max, Min & Aver Temp at Remningstorp. TinyTag Sensor Temp. Forest & Field Ground Temp.

The differences between the air temperature measured by the TinyTag sensor and the temperature on the ground, measured by Aquaflex sensors vary significantly, i.e. On June 12th at 12:00h, the Aquaflex field sensor registered a temperature in the ground of 18,2ºC and the Aquaflex forest sensor a temperature in the ground of 11,7ºC. The same day at the same hour the sensor located in the forest location recorded a temperature of 25,2ºC. This means that the temperatures differ by 7,0ºC between the air temperature in the forest location and the temperature in the field ground and differ by 13,5ºC between the air temperature in the forest and the temperature in the forest ground.

The sun rays have to penetrate through the vegetation and the tree canopy and therefore the ground in the open area like the field area could be more easily heated, so that the water volume content on the field would decrease easier than in the forest area.

5.1.2 Summer 2006

Data collected from 20060622 to 20060924. The plots showed below, represent the volumetric water content measured by Aquaflex humidity sensor located one in the field and one in the forest; Figure WSummer06. The precipitation at Remningstorp meteorological station; Figure PSummer06. The ground temperature measured by Aquaflex humidity sensors located one in the field and one in the forest; Figure TSummer06. Maximum, minimum and average temperature at Remningstorp meteorological station; Figure MmAS06 and air temperature measured by TinyTag sensor, Figure TinySummer06.

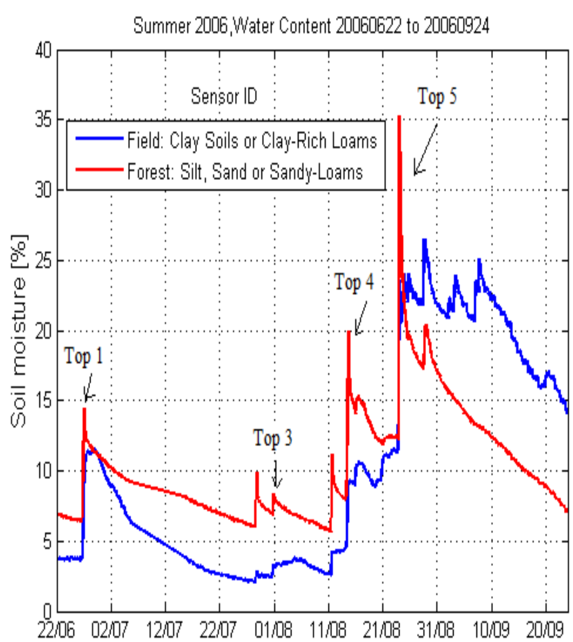


Figure. WSummer06.
Aquaflex-sensor.Water Content (%)
20060622-20060924

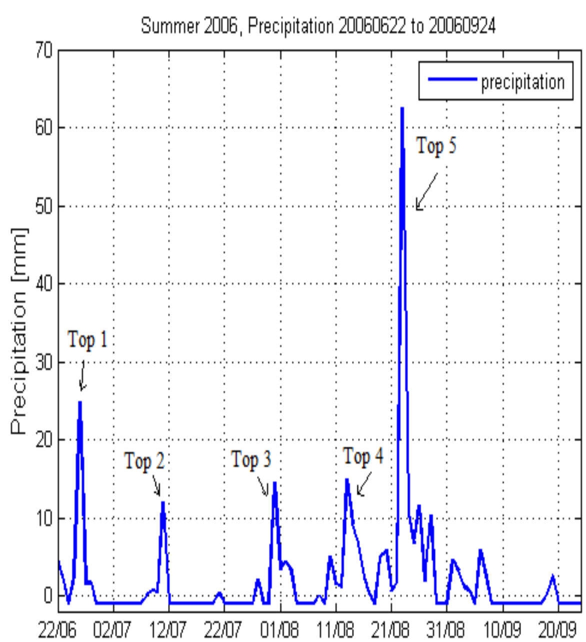


Figure. PSummer06.
SMHI data. Precipitation (mm)
20060622-20060924

In PSummer06 we observe five well defined tops. These are Top 1 on June 26th, Top 2 on July 11th, Top 3 on July 31st, Top 4 on August 13th and Top 5 on August 22nd.

Four of these precipitation tops recorded by Remningstorp meteorological station were also registered by two Aquaflex sensors. Those tops are visible on the figure WSummer06. Top 1 was recorded on June 27th. The missing Top 2 depend on missing data from the Aquaflex sensor, between July 5th at 14:00:00 and July 15th at 13:00:00. For that reason Top 2 is not showed in the figure WSummer06. Top 3 is appreciable on August 1st. Top 4 on August 13th and Top 5 on 22nd.

The precipitation tops are also indicated on the temperature graph at Remningstorp meteorological station, figure MmS6 and on the temperature graph at forest and field ground recorded by Aquaflex sensor, figure TSummer06.

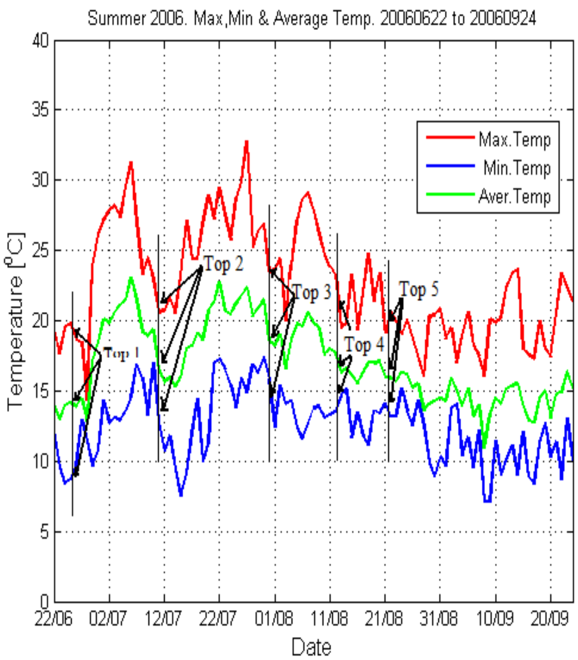


Figure. MmAS06. SMHI data. Max, Min & Average Temperatures (ºC) 20060622-20060924

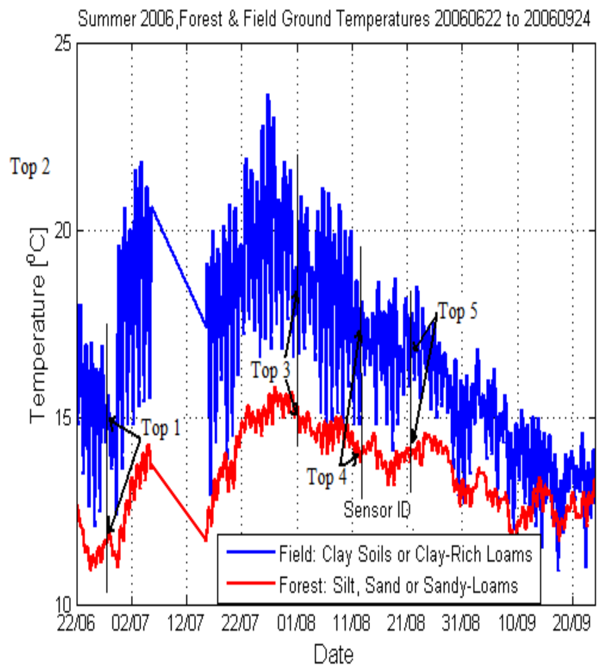


Figure. TinySummer06. Aquaflex forest & field ground Temperatures (ºC) 20060622-20060924

Below, in table 5 we present the data for each precipitation top recorded.

	Precipitation (mm)	Max. Temp Remning Stat (ºC)	Min. Temp Remning Stat (ºC)	Aver.Temp Remning. Stat (ºC)	Forest.Sensor at 12h TinyTag (ºC)	Forest. Ground Temp At 12h (ºC)	Field. Ground Temp At 12h (ºC)	WVC. Forest (%)	WVC. Field (%)
Top1	25	18.7	9.8	**13.9**	16,9	11,1	16,0	14,5	12,0
Top2	12	20.6	12.9	**16.5**	18,8	-	-	-	-
Top3	15	23.5	15.8	**18.6**	22,0	15,0	18,5	8,5	3,1
Top4	15	19.5	14.7	**16.3**	17,8	14,0	18,0	20,0	9,0
Top5	62	20.6	13.2	**15.9**	16,6	13,9	16,6	35,0	23,7

Table.5. Precipitation at Remningstorp. Max, Min &Aver Temp at Remningstorp. TinyTag Sensor Temp. Forest & Field Ground Temp. Forest & Field Water Volume Content.

There are not so large differences in the water volume between the two sensors during the precipitation tops, Top 1 and Top 3. However these differences become higher at Top 4, 11% higher water volume for the forest sensor and at Top 5, 11,3% higher water volume for the forest sensor.

We know that the sensor on the field is surrounded by soil that store moisture well and retain water releasing it slowly, while the sensor in the forest is surrounded by soil that allow moisture to penetrate easily, but do not retain it for long time. The precipitation at Tops 1, 3, 4 and 5 infiltrated easily the sandy soil in the forest and therefore the higher water volume values compare to the values at field ground. However we see in figure Wsummer06, that after the high precipitation at Top 5 table 5, the field ground retained higher water volume due to the clay soil retains the 62mm rain at Top 5 easier and releasing it slower than the sandy soil. We also see in table 5 that the temperatures recorded by the Remningstorp station at the five tops didn´t vary so much, likewise with the temperatures recorded by the TinyTag sensor, figure TinySummer06.

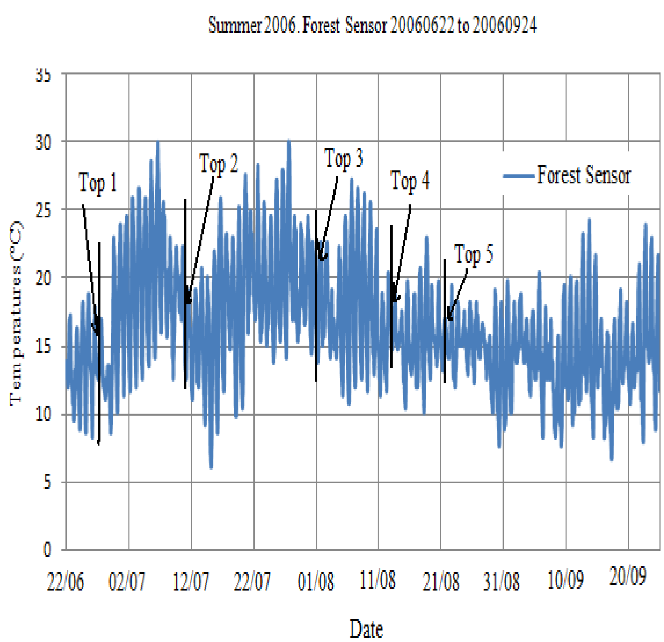


Figure TinySummer06. Temperature at Forest (ºC) 20060622-20060924

The temperatures recorded by the Aquaflex sensor and presented in figure TSummer06 are higher in the field ground than in the forest. At Top 1, the field ground temperature is 4,9ºC higher than the forest ground temperature. At Top 3, the field ground temperature is 3,5ºC higher than the forest ground temperature. At Top 4, the field ground temperature is 4,0ºC higher than the forest ground temperature and at Top 5, the field ground temperature is 2,7ºC higher than the forest ground temperature.

5.1.3 Autumn 2006

Data collected from 20060924 to 20061222. The plots showed below, represent the volumetric water content measured by Aquaflex humidity sensors located one in the field and one in the forest; Figure WAutumn06. The precipitation at Remningstorp meteorological station; Figure PAutumn06. The ground temperature measured by Aquaflex humidity sensors located one in the field and one in the forest; Figure TAutumn06. Maximum, minimum and average temperature at Remningstorp meteorological station; Figure MmAA06 and air temperature measured by TinyTag sensor, Figure TinyAutumn06.

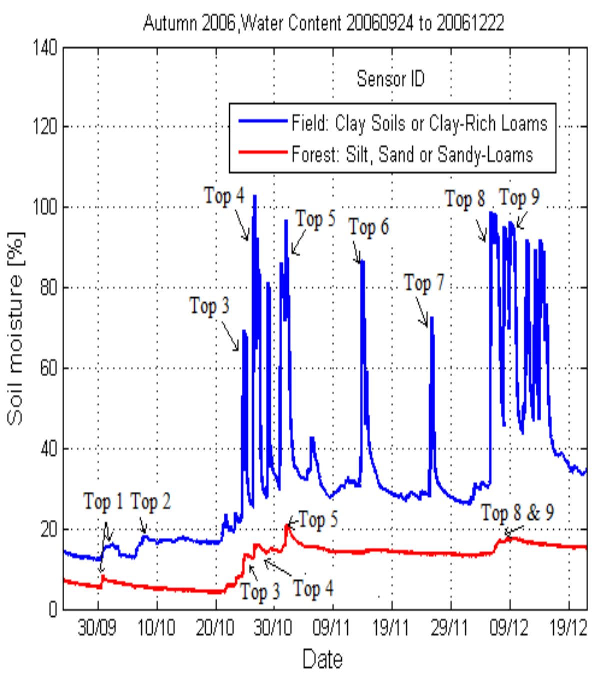


Figure. Wautumn06.
Aquaflex-sensor.Water Content (%)
20060924-20061222

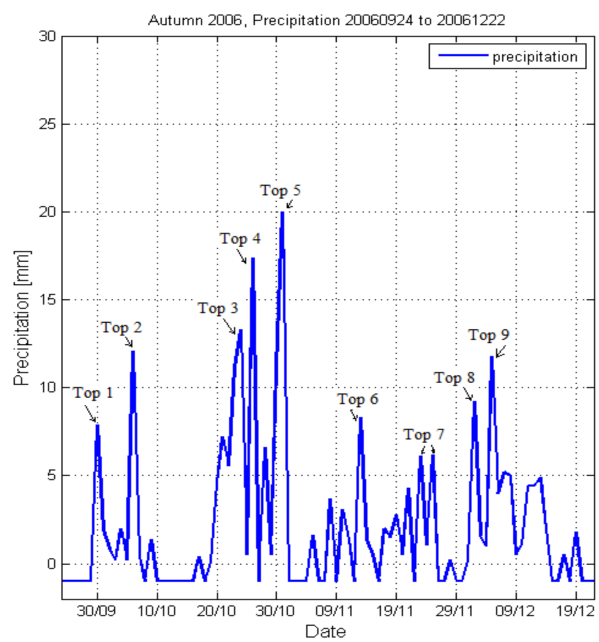


Figure. PAutumn06.
SMHI data. Precipitation (mm)
20060924-20061222

In figure PAutumn06 it is observed that the rain fall during the autumn has increased compared with the rain fall registered during the spring and summer 2006; figures PSpring06 and PSummer06. The time between the rainfalls is also shorter.

9 precipitation tops on the figure PAutumn06 were selected. These precipitation tops are; Top 1 on September 30th, Top 2 on October 6th, Top 3 on October 24th, Top 4 on October 26th, Top 5 on

October 31st, Top 6 on November 13th, Top 7 on November 23rd & 26th, Top 8 December 2nd and Top 9 on December 5th.

The precipitation tops recorded by Remningstorp meteorological station were also registered by two Aquaflex sensors. Those tops are visible on the figure WAutumn06. Top 1 was recorded on October 1st, Top 2 on October 6th, Top 3 on October 24th, Top 4 on October 26th, Top 5 on October 31st , Top 6 on November 13th,Top 7 on November 26th, Top 8 on December 6th and top 9 on December 9th. However the sensor placed in the forest seems to missed Top 2, Top 6 and Top 7.

The precipitation tops are also indicated on the temperature figure at Remningstorp meteorological station, figure MmAA06 and on the temperature in the ground recorded by the Aquaflex sensor, figure TAutumn06.

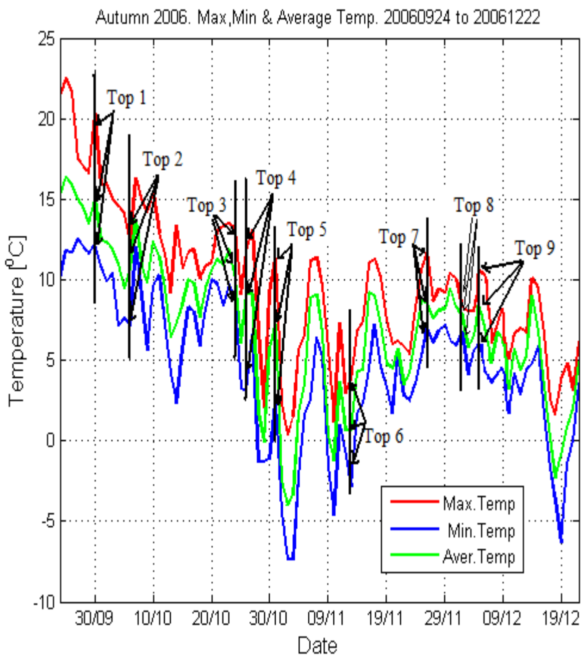


Figure. MmAA06. SMHI data. Max, Min & Average Temperatures (ºC) 20060924-20061222

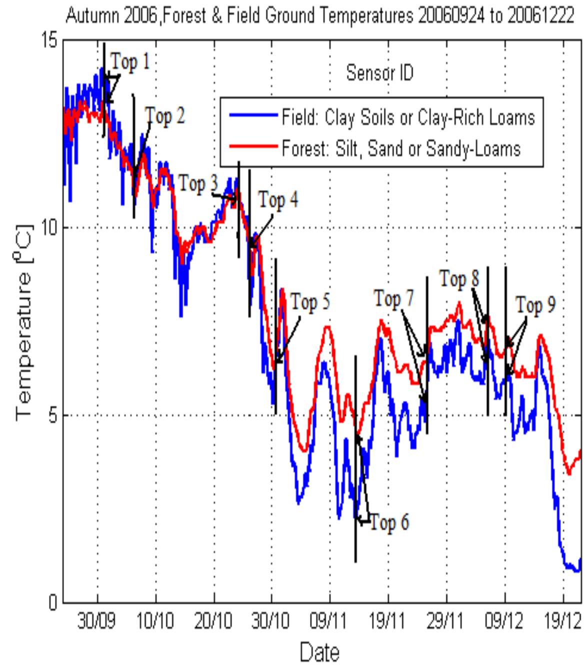


Figure. TAutumn06. Aquaflex forest & field ground Temperatures (ºC) 20060924-20061222

In table 6 we present the data for each precipitation top recorded.

	Precipitation (mm)	**Max. Temp Remning Stat (ºC)**	**Min. Temp Remning Stat (ºC)**	**Aver.Temp Remning. Stat (ºC)**	**Forest.Sensor at 12h (ºC)**	**Forest. Ground Temp At 12h (ºC)**	**Field. Ground Temp At 12h (ºC)**	**WVC. Forest (%)**	**WVC. Field (%)**
Top1	7,9	20,3	12,2	**15,0**	14,1	12,9	13,5	8	18
Top2	12,1	12,3	7,1	**10,7**	9,5	10,9	10,8	6	19
Top3	13,3	13,1	8,6	**10,1**	15,3	10,6	10,5	14	70
Top4	17,4	11,8	3,1	**9,1**	13,8	8,8	8,1	18	100
Top5	20,0	11,3	2,3	**7,2**	16,9	7,8	8	21	98
Top6	8,3	3,8	-2,8	**0,6**	2,9	4,5	2,1	14	88
Top7	6,3	11,8	7,0	**8,5**	-	7,3	6,5	13	76
Top8	9,2	8,3	6,8	**7,8**	-	7,4	6,6	18	99
Top9	11,8	10,6	6,1	**8,4**	-	6,9	6,1	18	96

Table 6. Precipitation at Remningstorp. Max, Min &Aver Temp at Remningstorp. TinyTag Sensor Temp. Forest & Field Ground Temp. Forest & Field Water Volume Content.

The ground temperatures around the Aquaflex sensors are very similar. However there are some degrees differences between the air temperatures recorded by the TinyTag at 12h; figure TinyAutumn06 and the temperatures recorded in the ground at the same hour; table 6.

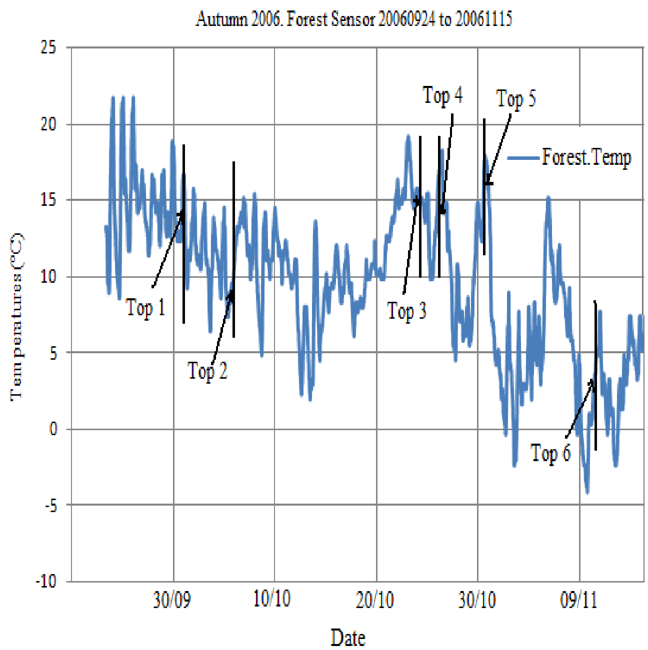


Figure TinyAutumn06. Temperature at Forest (ºC) 20060924-20060922

Top 6 and Top 7 were clearly registered by the Aquaflex sensor in the field ground, however it seemed to be lost by the Aquaflex sensor in the forest ground, figure Wautumn06. This sensor kept constant water volume content from Top 5 to Top 8. During one month, the forest ground kept values between 18% to 20% water volume content.

The causes of that constant water volume content in the forest could be the decreased rainfall from 20mm at Top 5 to 8,3mm at Top 6 and 6,3mm at Top 7. Also that the sensor in the forest is surrounded by soil that do not retain moisture for long time.

5.1.4 Winter 2007

Data collected from 20061222 to 20070321. The plots showed below, represent the volumetric water content measured by Aquaflex humidity sensors; Figure WWinter07. The precipitation at Remningstorp meteorological station; Figure PWinter07. The ground temperature measured by Aquaflex humidity sensors; Figure TWinter07 and maximum, minimum and average temperature at Remningstorp meteorological station; Figure MmAW07.

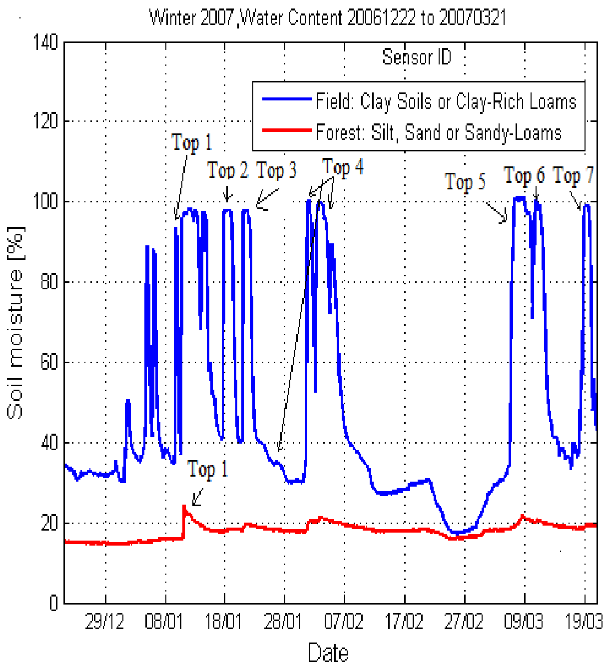


Figure. WWinter07.
Aquaflex-sensor.Water Content (%)
200601222-20070321

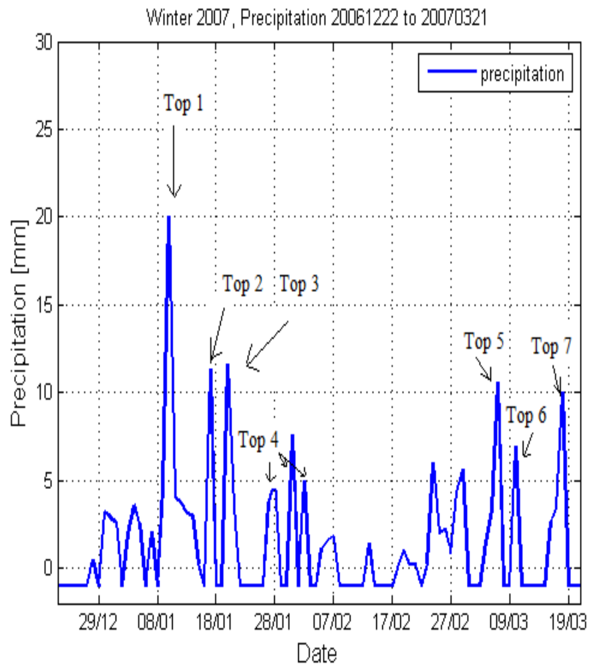


Figure. PWinter07.
SMHI data. Precipitation (mm)
20061222-20070321

7 precipitation tops were selected in figure PWinter07. These precipitation tops are; Top 1 on January 10th, Top 2 on January 17th, Top 3 on January 20th, Top 4 on January 27th, January 31st and February 2nd, Top 5 on Mars 6th, Top 6 on Mars 10th and Top 7 on Mars 18th.

The precipitation tops recorded by Remningstorp meteorological station were also registered by two Aquaflex sensors. Those tops are visible on the figure WWinter07. Top 1 was recorded on January 10th, Top 2 on January 18th, Top 3 on January 21st, Top 4 on January 27th, January 31st and February 2nd, Top 5 on Mars 6th , Top 6 on Mars 10th and Top 7 and Mars 19th.
However the Aquaflex sensor situated in the forest recorded only Top 1 and kept almost constant water volume content value afterwards.

The precipitation tops are also indicated on the temperature graph at Remningstorp meteorological station, figure MmAW07 and on the temperature figure at forest and field ground, recorded by Aquaflex sensor, figure Twinter07.

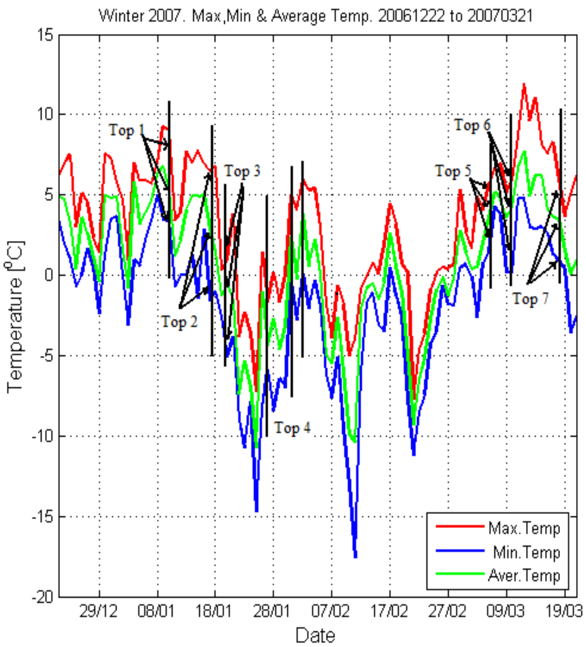


Figure. MmAW07. SMHI data. Max, Min & Average Temperatures (ºC) 20061222-20070321

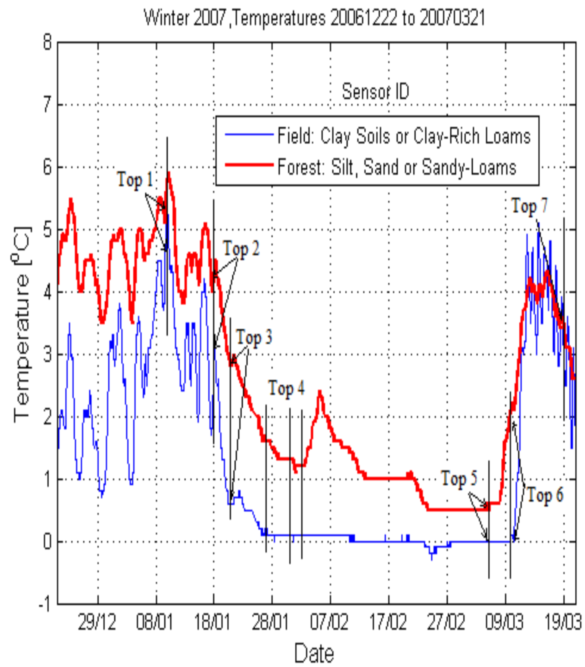


Figure. TWinter7. Aquaflex forest & field ground Temperatures (ºC) 20061222-20070321

In table 7 we present the data for each precipitation top recorded.

	Precipitation (mm)	Max. Temp Remning Stat (ºC)	Min. Temp Remning Stat (ºC)	Aver.Temp Remning. Stat (ºC)	Forest.Sensor at 12h (ºC)	Forest. Ground Temp At 12h (ºC)	Field. Ground Temp At 12h (ºC)	WVC. Forest (%)	WVC. Field (%)
Top1	20,0	9,1	3,4	**5,3**	-	5,7	4,3	25	94
Top2	11,3	6,5	-1,6	**2,9**	-	4,3	2,5	19	98
Top3	11,6	1,0	-5,1	**-0,5**	-	2,9	0,7	19	98
Top4	3,8 7,6 5,0	-1,7 5,0 6,0	-5,9 -0,4 0,1	**-4,4 2,4 3,8**	-	1,6 1,3 1,2	0,1 0,1 0,1	19 20 20	36 100 100
Top5	3,4	5,7	1,5	**3,7**	-	0,6	0,0	20	100
Top6	6.9	5,9	0,2	**4,2**	-	2,1	0,1	20	100
Top7	10,0	3,7	0,4	**1,5**	-	3,1	2,9	20	100

Table 7. Precipitation at Remningstorp. Max, Min &Aver Temp at Remningstorp. TinyTag Sensor Temp. Forest & Field Ground Temp. Forest & Field Water Volume Content.

One again the capacity of the clay soils or clay-rich loams to store water is observed. According to table 7 the water volume content at field ground, is 5 times higher than the water volume content at forest. The constant rain fall during the winter would do that the soil on the field, retain water and reach high water volume values. The forest sensor registered Top 1 however seemed to miss the other six tops.

5.1.5 Spring 2007

Data collected from 20070321 to 20070622. The plots showed below, represent the volumetric water content measured by Aquaflex humidity sensors located in the ground; Figure WSpring07. The precipitation at Remningstorp meteorological station; Figure PSpring07. The ground temperature measured by Aquaflex humidity sensors located in the ground; Figure TSpring07. Maximum, minimum and average temperature at Remningstorp meteorological station; Figure MmAS07 and air temperature measured by TinyTag sensor; Figure TinySpring07.

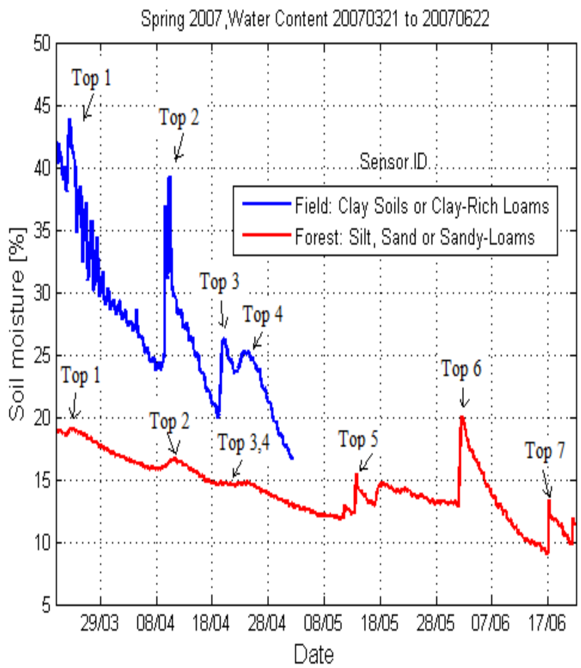


Figure. WSpring07.
Aquaflex-sensor.Water Content (%)
20070321-20070622

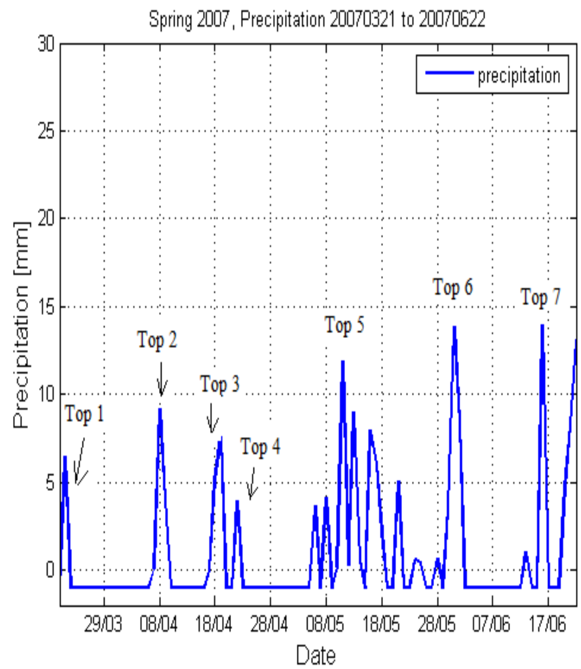


Figure. PSpring07.
SMHI data. Precipitation (mm)
20061222-20070321

The field sensor finished to work sometime in the summer 2007 and the last data that could be downloaded are from May 2th without any known reason. This is clearly appreciable on the figure WSpring07, where data from the mentioned date is missing. The last data recorded by the sensor, was data collected at Top 4. We believe that water inside the signal treatment device in the cable sensor could be the reason behind the sensor failed.

7 precipitation tops were selected in the figure PSpring07. These tops are; Top 1 on Mars 22nd, Top 2 on April 8th, Top 3 on April 19th, Top 4 on April 22nd , Top 5 on May 11th , Top 6 on May 31st and Top 7 on June 16th.

The precipitation tops recorded by Remningstorp meteorological station were also registered by two Aquaflex sensors. Those tops are visible on the figure WSpring07. Top 1 was recorded on Mars 22nd, Top 2 on April 10th, Top 3 on April 19th and Top 4 on April 22nd. From Top 5 only data for the sensor located in the forest are available. Top 5 was recorded by the forest sensor on May 14th, Top 6 on June 2nd, Top 7 on June 17th.

The seven precipitation tops are also indicated in the temperature figure of data from Remningstorp meteorological station, figure MmAS07 and on the temperature in the ground recorded by Aquaflex sensor, figure TSpring07.

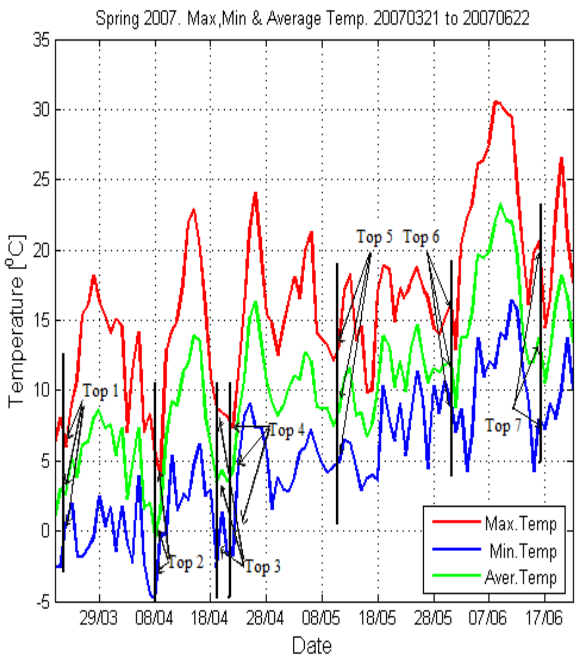


Figure. MmAS07. SMHI data. Max, Min & Average Temperatures (°C) 20070321-20070622

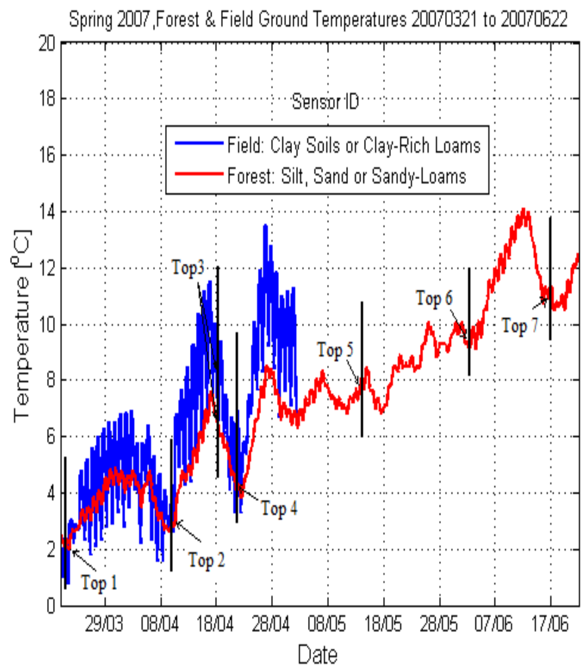


Figure. TSpring07. Aquaflex forest & field grou Temperatures (°C) 20070321-20070622

In table 8 data for each precipitation top are presented.

	Precipitation (mm)	Max. Temp Remning Stat (°C)	Min. Temp Remning Stat (°C)	Aver.Temp Remning. Stat (°C)	Forest.Sensor at 12h (°C)	Forest. Ground Temp At 12h (°C)	Field. Ground Temp At 12h (°C)	WVC. Forest (%)	WVC. Field (%)
Top1	6,5	8,1	-2,6	**3,0**	4,8	2,0	1,3	19	44
Top2	9,2	5,4	-4,9	**-0,4**	7,0	2,9	4,0	17	39
Top3	7,6	8,7	-2,6	**3,5**	7,3	5,6	6,6	15	26
Top4	3,9	7,3	-1,7	**4,2**	3,5	3,8	4,1	15	25
Top5	11,9	13,2	4,9	**8,5**	16,9	7,9	-	15,5	-
Top6	13,9	16,1	9,1	**12,0**	24,2	9,1	-	20	-
Top7	14,0	20,6	8,0	**13,8**	10,1	10,5	-	14	-

Table. 8. Precipitation at Remningstorp. Max, Min &Aver Temp at Remningstorp. TinyTag Sensor Temp. Forest & Field Ground Temp. Forest & Field Water Volume Content.

We compare the first 4 tops and see that the sensor placed in the field, show stronger variation on its water volume content than the sensor placed in the forest.
At Top 1 the field sensor recorded 44% water volume content and decreased to 24% just before Top 2, figure WSpring07. This decrease depends on lack of precipitations between Top 1 and Top 2, figure PSpring07, as well as an increase of the temperatures between Top 1 and Top 2,

figure MmAS07. A similar temperature increase is observed by the TinyTag sensor located in the forest, figure TinySpring07 and also from Top 1 to Top 2 at the Aquaflex sensors located in the field and in the forest, figure TSpring07.

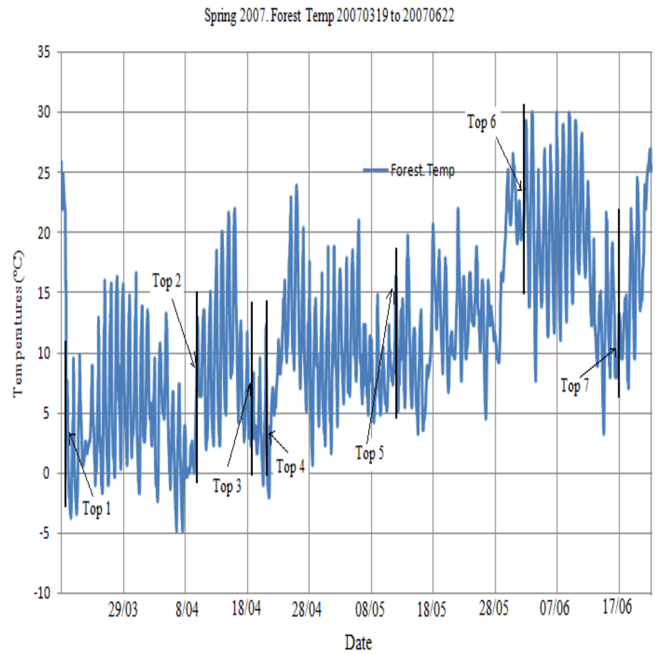


Figure TinySpring07. Temperature at Forest (ºC) 20070319-20070622

The water volume decreased 20% in the field ground and 3% in the forest ground; from 19% at Top 1 to 16% just before Top 2. Between Top 2 and Top 3 is again a decrease of the water volume content observed, in both the forest ground; from 39% soil moisture to 20% and the field ground from 17% soil moisture to 15%, figure WSpring07. This decrease depends on, lack of precipitations between Top 2 and Top 3, figure PSpring07, as well as an increase of the temperatures between Top 2 and Top 3, figure MmAS07. A similar temperature increase is observed by the TinyTag sensor located in the forest, figure TinySpring07 and also from Top 2 to Top 3 in the Aquaflex sensors. The forest ground temperature increased with 2,7ºC whereas the field ground increased with 2,6ºC.

Top 3 and Top 4 show constant water volume content values in both field and forest sensor. From 26% to 25% between Top 3 and Top 4 for field sensor, table 8 and 15% for both Top 3 and Top 4 for forest sensor, table 8.

We look at top 6 in the forest sensor and try to understand, why this top had the highest soil moisture, 20% and also try to understand what happened afterwards. During the second half of the spring, the precipitation is almost constant i.e. from May 11th at Top 5 to May 31st at Top 6; figure PSpring07. The soil retains much water volume due to the constant precipitation, decreasing only from 15,5% on Top 5 to 13,5% just before Top 6, figure WSpring07. Directly after top 6, the soil moisture decreased strongly from 20% to 10%; figure WSpring07. The precipitation after Top 6; figure PSpring07 stopped for ten days. On the other hand the temperatures recorded at Remningstorp increased significantly; figure MmAS07 and the maximum temperature reached 30ºC just some days after Top 6. The Aquaflex sensor in the forest location also recorded the increase of the temperature, from 9,1ºC at Top 6 to 14ºC just some days before Top 7 happened, figure TSpring07. The temperature increase and the lack of precipitation did that the soil moisture in the forest decreased strong after Top 6.

5.1.6 Summer 2007

Data collected from 20070622 to 20070924. The plots showed below, represent the volumetric water content measured by Aquaflex humidity sensors located in the forest; Figure WSummer07. The precipitation at Remningstorp meteorological station; Figure PSummer07. The ground temperature measured by Aquaflex humidity sensor located in the forest; Figure TSummer07. Maximum, minimum and average temperature at Remningstorp meteorological station; Figure MmAS07 and air temperature measured by TinyTag sensor, Figure TinySummer07.

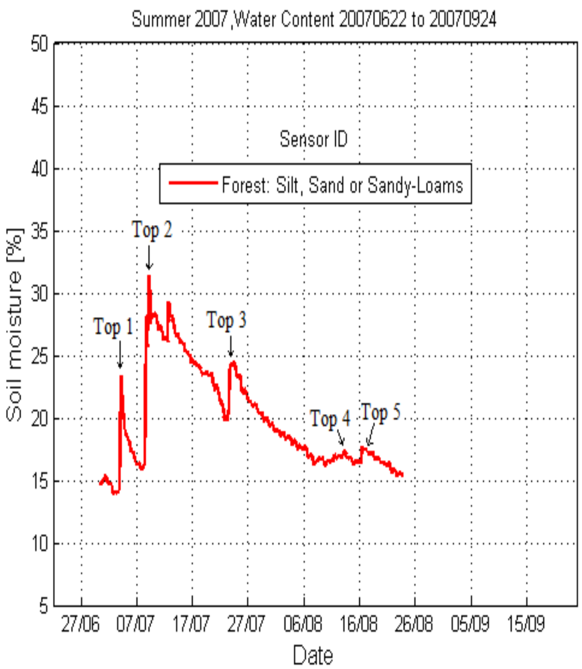


Figure. WSummer07.
Aquaflex-sensor.Water Content (%)
20070622-20070924

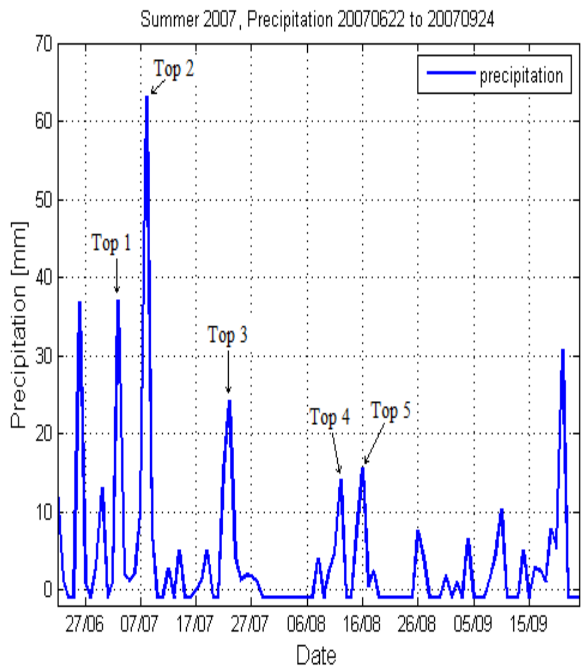


Figure. PSummer07.
SMHI data. Precipitation (mm)
20070622-20070924

As we can see in figure Wsummer07, the forest sensor missed data from date 20070621 at 22h to 20070630 at 9h and from 20070823 at15h to 20071027 at 16h. The reason for that could be that the sensor memory capacity was full and consequently the new recorded records were registered at the old data allocations.

5 precipitation tops were selected in figure PSummer07. These tops are; Top 1 on July 3rd, Top 2 on July 8th, Top 3 on July 23th, Top 4 on August 12th and Top 5 on August 16th.

The precipitation tops recorded by Remningstorp meteorological station were also registered by the Aquaflex sensor, situated in the forest. Those tops are visible on the figure WSummer07. Top 1 was recorded on July 4th, Top 2 on July 9th, Top 3 on July 24th, Top 4 on August 12th and Top 5 on August 16th.

The five precipitation tops are also indicated on the temperature figure with data from Remningstorp meteorological station, figure MmAS07 and on the temperature figure with data from forest ground, recorded by the Aquaflex sensor, figure TSummer07.

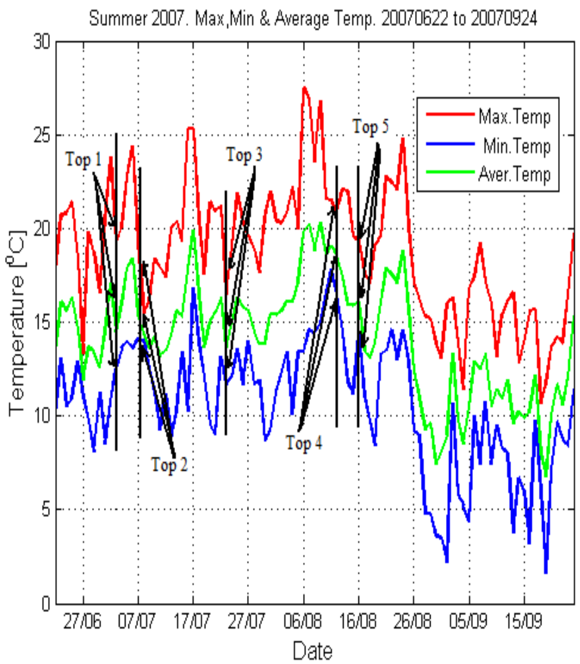


Figure. MmAS07. SMHI data. Max, Min & Average Temperatures (ºC) 20070622-20070924

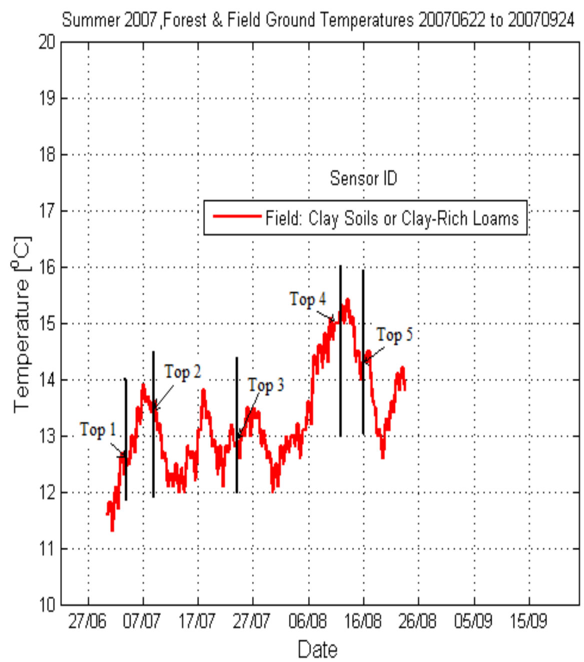


Figure. TSummer07. Aquaflex forest ground Temperatures (ºC) 20070622-20070924

Table 9 present the data for each precipitation top recorded.

	Precipitation (mm)	Max. Temp Remning Stat (ºC)	Min. Temp Remning Stat (ºC)	Aver.Temp Remning. Stat (ºC)	Forest.Sensor at 12h (ºC)	Forest. Ground Temp At 12h (ºC)	WVC. Forest (%)
Top1	37	19,2	12,5	**14,5**	20,9	12,5	23,5
Top2	63	15,5	14,0	**14,4**	22,8	13,1	31,5
Top3	24	16,5	11,7	**13,7**	15,0	12,6	24,5
Top4	14	20,9	16,5	**18,6**	18,1	15,0	17,0
Top5	15,5	19,3	14,3	**16,1**	14,7	14,3	17,5

Table 9. Precipitation at Remningstorp. Max, Min &Aver Temp at Remningstorp. TinyTag Sensor Temp. Forest Ground Temp. Forest Water Volume Content.

Between Top 1 and Top 2, we can observe that the water volume content decreased in the forest sensor from 23,5% to 16,0%; figure WSummer07. This decrease followed an increase of the temperatures, drying the water of the ground.

The temperature increase can be observed in both Remningstorp station records, figure MmAS07 and the Aquaflex sensor in the forest ground, figure TSummer07.

Similarly increasing temperatures were recorded by the TinyTag sensor in the forest, figure TinySummer07.

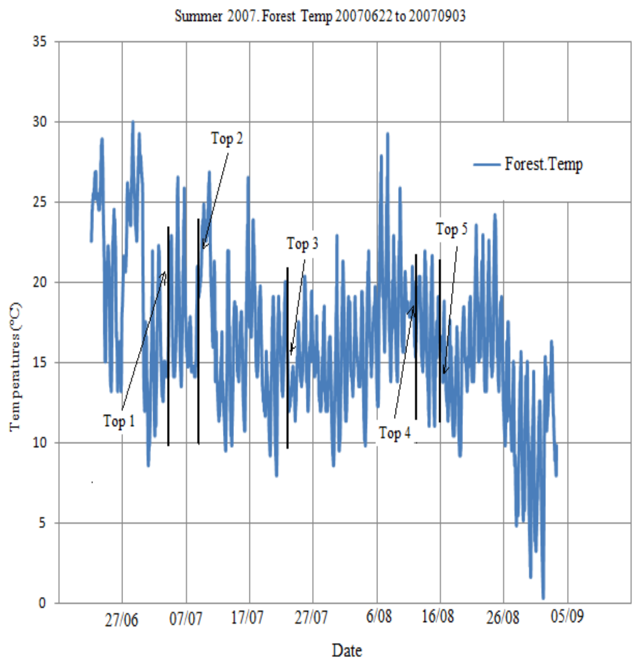


Figure TinySummer07. Temperature at Forest (ºC)
20070622-20070924

As can be seen in figure TinySummer07, no temperature data were available after September 3rd. This temperature sensor started to record data again on April 14th 2008.

The high precipitation at Top 2 made the water volume content increase from 16% to 31,5%, figure WSummer07.

Between Top 2 and Top 3, we again observe a decrease in soil moisture from 31,5% to 20%, just the day before Top 3; graph WSummer07. We also see that between those tops, 2 and 3, there is a small top which increased the water volume content from 27% to 29%. This small top was caused by the rainfall the days July 12th and July 14th; figure PSummer07.

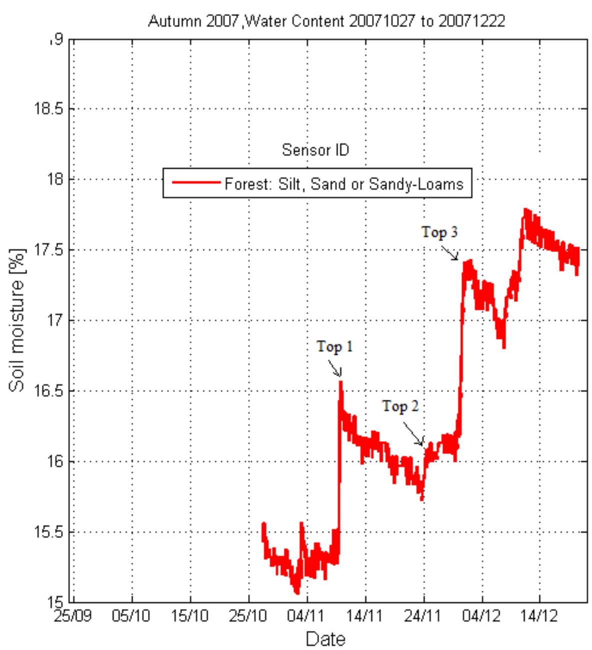
The falling water volume between Top 2 and Top 3 is caused by a raise in the temperatures between the same tops at Remningstorp station; figure MmAS07. The maximum temperature rose from 15,5ºC to 26ºC from July 8th to July 17th. The minimum temperature rose from 14ºC to 17ºC the same dates. Between Top 2 and Top 3 the TinyTag sensor in the forest, experimented 7,8ºC difference from Top 2 to Top 3, table 9.

Between top 3 and top 4, the water volume content decreased from 24,5% to 17%, however from August 6th to August 16th the water volume kept almost constant values. The decreasing water content is again related to an increase in temperatures. The average temperature rose from 15ºC to 20ºC from July 24th to August 6th. We observed a similar increase of the temperature for the Aquaflex forest sensor; figure TSummer07, in which the temperatures rose from 12, 6ºC to 15, 0ºC, between Top 3 and Top4, table 9.

5.1.7 Autumn 2007

Data collected from 20071027 to 20071222. The plots showed below, represent the volumetric water content measured by the Aquaflex humidity sensor placed in the forest; Figure WAutumn07. The precipitation at Remningstorp meteorological station; Figure PAutumn07. The ground temperature measured by Aquaflex humidity sensors placed in the forest; Figure TAutumn07 and the maximum, minimum and average temperature at Remningstorp meteorological station; Figure MmAA07.

As mentioned above, the forest sensor has not registered data from 20070823 at15h to 20071027 at 16h, and the TinyTag sensor didn't record any temperature data from 2007-09-04 to 2008-04-13 and therefore no air temperature data from forest during autumn 2007 is available.



Aquaflex-sensor. Water Content (%)
20071027-20071222

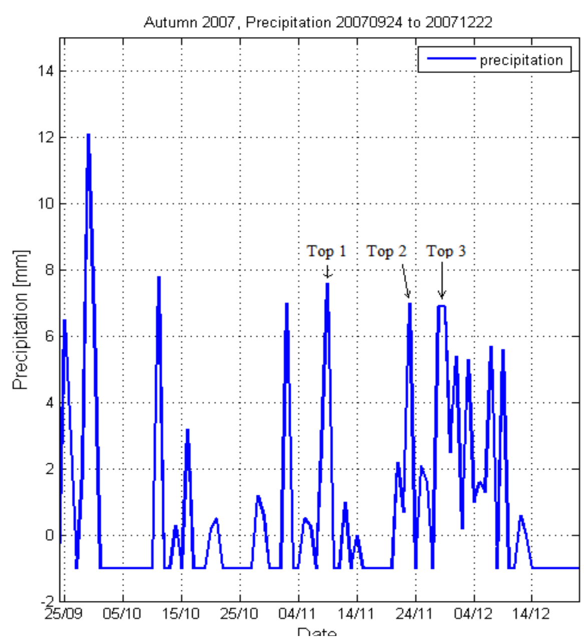


Figure. PAutumn07.
SMHI data. Precipitation (mm)
20070924-20071222

In figure PAutumn07, three precipitation tops are selected. Those tops are; Top 1 on November 9th, Top 2 on November 23rd and Top 3 on November 29th.

These precipitation tops recorded by Remningstorp meteorological station were also registered by the Aquaflex sensor situated in the forest. Those tops are visible in the figure WAutumn07. Top 1 was recorded on November 10th, Top 2 on November 24th and Top 3 on November 30th.

The three precipitation tops are also indicated in the temperature figure with data from Remningstorp meteorological station, figure MmAA07 and in the temperature figure with data from the forest ground, recorded by the Aquaflex sensor, graph TAutumn07.

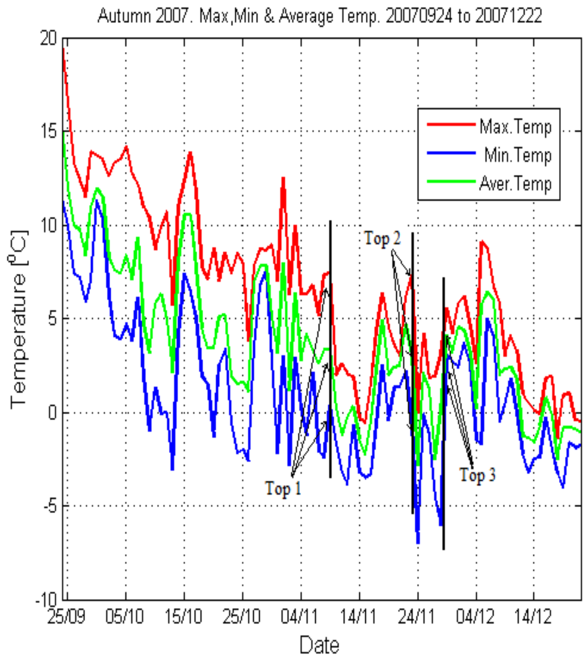


Figure. MmAA07. SMHI data. Max, Min & Average Temperatures (ºC) 20070924-20071222

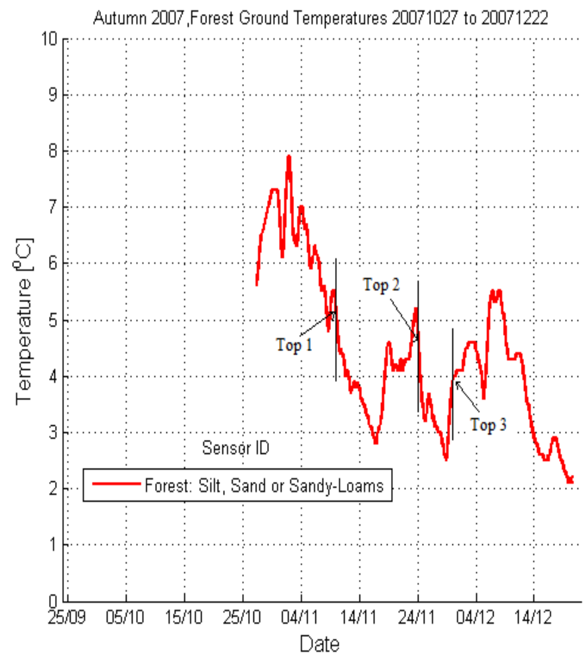


Figure. TAutumn07. Aquaflex forest ground Temperatures (ºC) 20070924-20071222

Table 10 present data for each precipitation top recorded. Temperatures and water volume content in the forest ground from the Aquaflex sensor are also included.

	Precipitation (mm)	Max. Temp Remning Stat (ºC)	Min. Temp Remning Stat (ºC)	Aver.Temp Remning. Stat (ºC)	Forest.Sensor at 12h (ºC)	Forest. Ground Temp At 12h (ºC)	WVC. Forest (%)
Top1	7,6	7,4	0,4	**3,3**	-	4,5	16,6
Top2	7,0	7,3	-0,6	**3,1**	-	3,9	16,1
Top3	6,9	5,6	3,0	**4,1**	-	4,0	17,4

Table 10. Precipitation at Remningstorp. Max, Min &Aver Temp at Remningstorp. TinyTag Sensor Temp. Forest Ground Temp. Forest Water Volume Content.

Between top 1 and top 2 the forest sensor experienced a decreasing in the water volume content of approximately 0, 5%, from 16, 6% to 16,1% table 10. This decreasing water volume content is not only caused by the lack of rain from November 14th to November 20th, figure PAutumn07 but also by the increase of the temperatures from November 14th to November 24th figure MmAA07. This is also observed in figure TAutumn07, Top 1 to Top 2 in which the temperature in the forest ground increased from 3ºC on November 17th to 5ºC on November 23rd .

At Top 2 Remningstorp recorded 16,1mm rain, table 10. Further 2mm rain on November 25th, therefore the water volume content experienced an increase from 24th to 29th November, figure WAutumn07.

After Top 3 was registered by Remningstorp meteorological station, the meteorological station registered rainfall constantly until December 8th. After Top 3, we can observe four tops with above 4mm rain. Those are on December 1 (5,4 mm), December 3 (5,3mm), December 7th (5,7mm), December 9th (5,6mm), and caused the water volume increased until December 11th.

A decreasing tendency on the temperatures is observed in both the temperatures recorded by the Remningstorp station and the temperatures recorded by the Aquaflex sensor in the forest. Figures MmAA07 and TAutumn07. At the beginning of autumn 07, the Remningstorp station recorded a maximum temperature of 20ºC and at the end of autumn the maximum temperature had decreased to 0ºC, figure MmAA07. Likewise, the first temperature record registered by the Aquaflex sensor in the forest ground was 5,6ºC and the last one 2,2ºC.

5.1.8 Winter & Spring 2008

During winter and spring 2008 recorded data are missing from 20071221 to 20080621. 20071220 only 15 records were registered; these are from 20071220 at 00:00:00 to 14:00:00. 20080414 only three measurements were taken at 15:32, 15:41 and 15:42. Day 20080622 registered 16 records from 08:00:00 to 23:00:00

5.1.9 Summer 2008

Data collected from 20080622 to 20080924. The plots showed below represent the volumetric water content measured by the Aquaflex humidity sensor placed in the forest; Figure WSummer08. The precipitation at Remningstorp meteorological station; Figure PSummer08. The ground temperature measured by Aquaflex humidity sensor placed in the forest; Figure TSummer08. The maximum, minimum and average temperature at Remningstorp meteorological station; Figure MmAS08 and air temperature measured by TinyTag sensor, Figure TinySummer08.

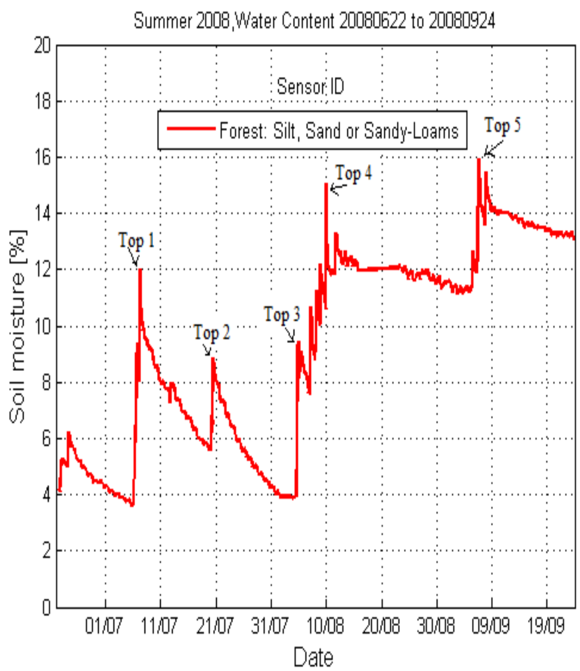


Figure. WSummer08.
Aquaflex-sensor.Water Content (%)
20080622-20080924

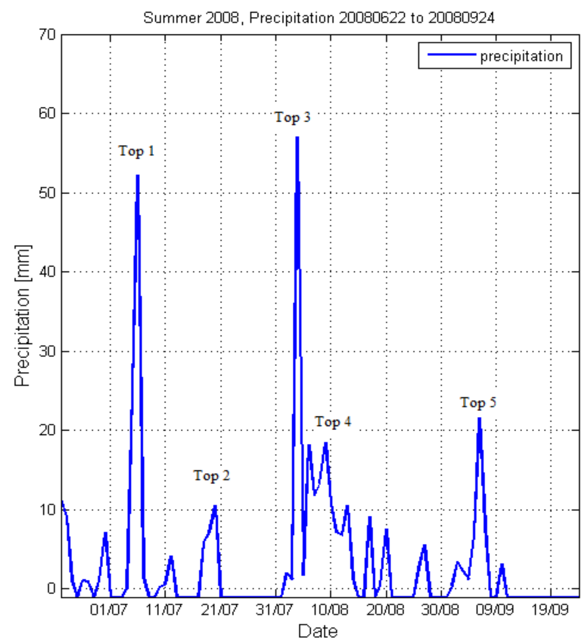


Figure. PSummer08.
SMHI data. Precipitation (mm)
20080622-20080924

Five precipitation tops are selected. These tops are; Top 1 on July 6th, Top 2 on July 20th, Top 3 on August 4th, Top 4 on August 9th and Top 5 on September 6th

The precipitation tops recorded by Remningstorp meteorological station were also registered by the Aquaflex sensor, situated in the forest. Those tops are visible in figure WSummer08. Top 1 was recorded on July 6th , Top 2 on July 20th, Top 3 on August 4th, Top 4 on August 10th and Top 5 on September 6th.

The five precipitation tops are also indicated in the temperature figure with data form Remningstorp meteorological station, figure MmAS08 and in the temperature in the forest ground, recorded by Aquaflex sensor, figure TSummer08.

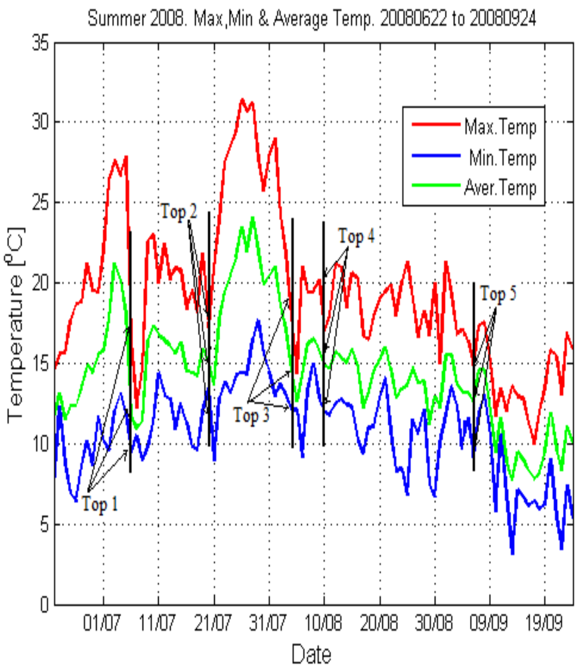


Figure. MmAS08. SMHI data. Max, Min & Average Temperatures (ºC) 20080622-20080924

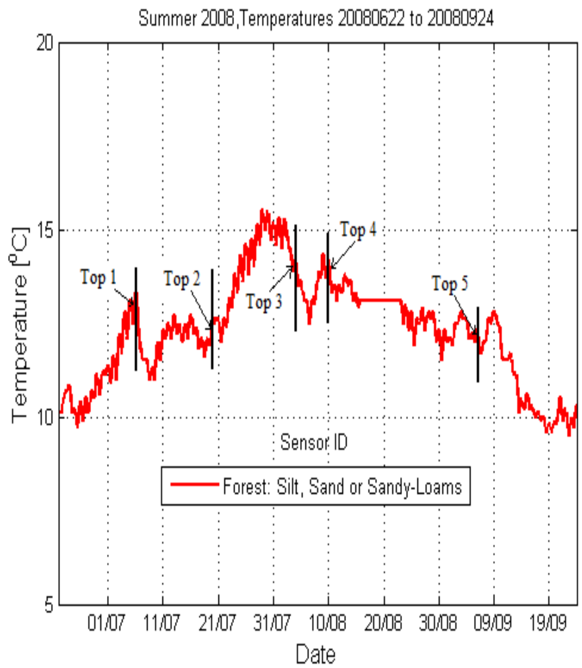


Figure.TSummer08. Aquaflex forest ground Temperatures (ºC) 20080622-20080924

Table 11 present data for each precipitation top.

	Precipitation (mm)	**Max. Temp Remning Stat (ºC)**	**Min. Temp Remning Stat (ºC)**	**Aver.Temp Remning. Stat (ºC)**	**Forest.Sensor at 12h (ºC)**	**Forest. Ground Temp At 12h (ºC)**	**WVC. Forest (%)**
Top1	52,2	16,4	9,5	**11,7**	9,5	12,3	12
Top2	10,6	17,2	13,5	**15,0**	14,4	12,6	9,0
Top3	57,0	18,0	12,2	**14,6**	15,0	13,5	9,6
Top4	18,5	20,2	12,8	**15,9**	18,8	13,3	15,0
Top5	21,6	14,9	9,2	**12,6**	11,3	11,6	16,0

Table 11. Precipitation at Remningstorp. Max, Min &Aver Temp at Remningstorp. TinyTag Sensor Temp. Forest Ground Temp. Forest Water Volume Content.

Due to precipitation Top 1, figure PSummer08 we see the water volume increase in the forest sensor from 4% to 12%, figure WSummer08. There were 14 days between Top 1 and Top 2 and during those days, only one day registered rainfall, figure PSummer08. The temperatures experience an increase, figure MmAS08. I.e. the average temperature registered by Remningstorp station increased with 3,3ºC from Top 1 to Top 2. The temperatures registered by the TinyTag sensor increased with 4,9ºC from Top 1 to Top 2, figure TinySummer08.

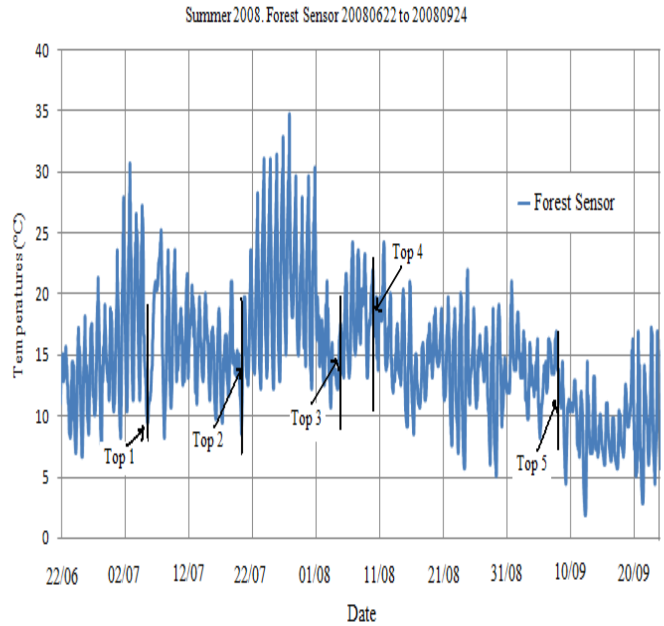


Figure TinySummer08: Temperature at Forest (ºC) 20070622-20070924

Consequently the water volume content was reduced to 6% just before Top 2.

In figure WSummer08 we see that the soil moisture decreased exponentially until the beginning of Top 3, due to the raise of the temperatures between top 2 and top 3, figure MmAS08. A similar increase is observed for the air temperature, figure TinySummer08 with temperatures also above 30ºC. Between Top 3 and Top 5, there were constant precipitation, figure PSummer08 and consequently the water volume in the forest increased until 16%.
From Top 4 to Top 5 the temperatures decreased slowly, graph MmAS08, graph TSummer08 and graph TinySummer08.

5.1.10 Autumn 2008

Data collected from 20080924 to 20081209. The plots showed below, represent the volumetric water content measured by Aquaflex humidity sensor placed in the forest; figure WAutumn08. The precipitation at Remningstorp meteorological station; figure PAutumn08. The ground temperature measured by Aquaflex humidity sensor placed in the forest; figure TAutumn08. The maximum, minimum and average temperature at Remningstorp meteorological station; figure MmAA08.

The forest sensor has not registered data from 20081206 at15:00:00 to 20090119 at 04:00:00. For that reason the plots cover the period until 20081209 and not until 20081222 as the plots before during autumn 2006 and autumn 2007. The TinyTag, has no temperature record from 20080929 5:48:00 to 20081210 11:34:00 and for that reason this temperature plot is not presented.

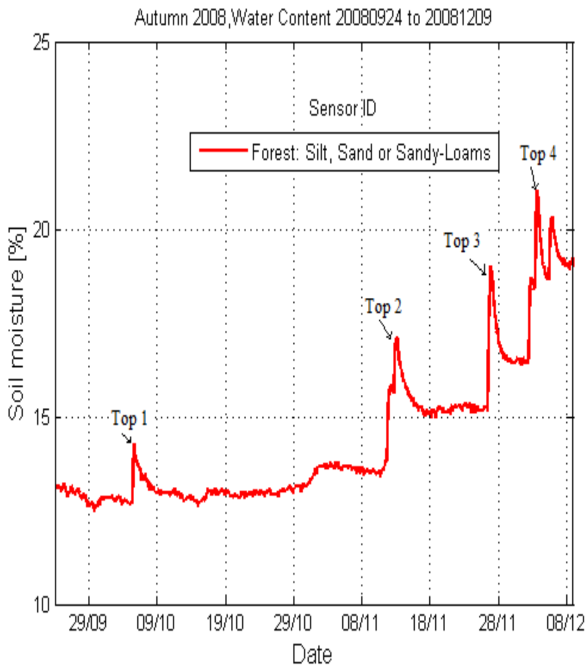


Figure WAutumn08.
Aquaflex-sensor.Water Content (%)
20080924-20081209

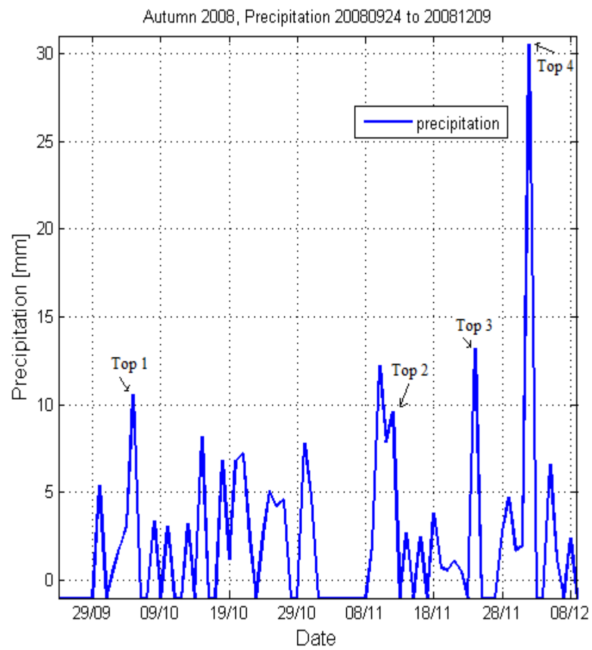


Figure PAutumn08.
SMHI data. Precipitation (mm)
20080924-20081209

Four precipitation tops are selected; Top 1 on October 5th, Top 2 on November 12th, Top 3 on November 24th and Top 4 on December 2nd.

The precipitation tops recorded by Remningstorp meteorological station were also registered by the Aquaflex sensors, situated in the forest. These tops are visible in figure WAutumn08. Top 1 was recorded on October 6th, Top 2 on November 12th, Top 3 on November 27th and Top 4 on December 4th.

The four precipitation tops are also indicated on the temperature plot for Remningstorp meteorological station, figure MmAA08 and also on the temperature figure for the forest ground, recorded by Aquaflex sensor, figure TAutumn08.

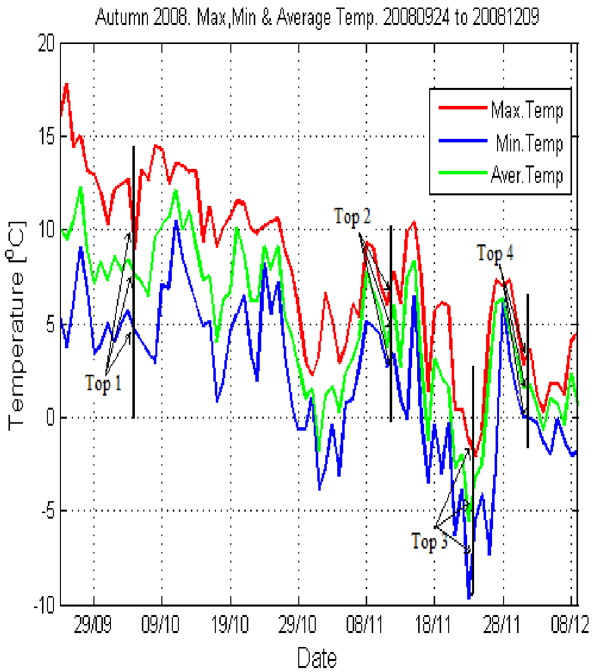


Figure MmAA08. SMHI data. Max, Min & Average Temperatures (ºC) 20080924-20081209

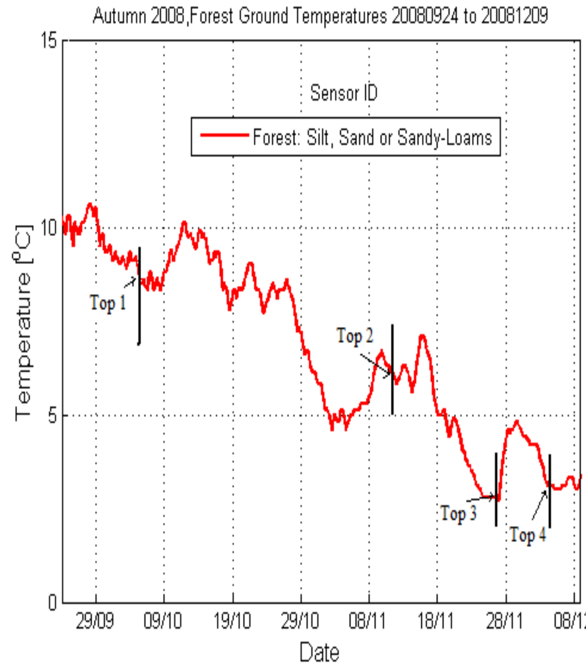


Figure TAutumn08. Aquaflex forest ground Temperatures (ºC) 20080924-20081209

Table 12 present the data for each precipitation top recorded.

	Precipitation (mm)	Max. Temp Remning Stat (ºC)	Min. Temp Remning Stat (ºC)	Aver.Temp Remning. Stat (ºC)	Forest.Sensor at 12h (ºC)	Forest. Ground Temp At 12h (ºC)	WVC. Forest (%)
Top1	10,6	9,0	4,6	**7,6**	-	8,3	14,5
Top2	9,6	7,8	3,4	**6,0**	-	6,0	17,0
Top3	13,2	-2,1	-5,5	**-3,2**	-	3,6	19,0
Top4	30,5	3,6	-0,7	**1,7**	-	3,1	21,5

Table 12. Precipitation at Remningstorp. Max, Min &Aver Temp at Remningstorp. TinyTag Sensor Temp. Forest Ground Temp. Forest Water Volume Content.

The average temperature at Remningstorp was around 10ºC at the beginning of autumn and at the end of autumn the temperature had decreased to almost 0ºC, figure MmAA08. Similarly the ground temperature in the forest was 10ºC at the beginning of autumn and at the end, the forest ground temperature had decreased to 3,1ºC, table 12.
The coldest temperatures ocurred the days between November 18th and November 28th, figure MmAA08, during those days even the maximum temperatures reached values below 0ºC.

In figure PAutumn08, can be observed between Top 1 and Top 2 and between Top 2 an Top 3 a number of small precipitations tops, some of them above 5mm precipitation. The water volume content between those tops is almost constant, figure WAutumn08. The maximum temperatures during those tops are above 10ºC (between Top 1 and Top 2, figure MmAA08), causing the water on the ground to dry fast. In the case of the ground temperature between Top 1 and Top 2 the temperature oscillated between 5ºC to 10ºC and from Top 2 to Top 3 between 7ºC to 3ºC. It is known that the soil in the forest (silt, sand or sandy loams soil) stay loose and allow moisture to penetrate easily, but do not retain it for long time. High or frequent precipitation is needed to increase the water volume in the forest.

5.1.11 Winter 2009

Data collected from 20090119 to 20090321. The plots showed below, represent the volumetric water content measured by the Aquaflex humidity sensor placed in the forest; Figure WWinter09. The precipitation at Remningstorp meteorological station; Figure PWinter09. The ground temperature measured by Aquaflex humidity sensor placed in the forest; Figure TWinter09. The maximum, minimum and average temperature at Remningstorp meteorological station; Figure MmAW09 and air temperature measured by TinyTag sensor, Figure TinyWinter09.

The forest sensor has not registered data from 20081206 at15:00:00 to 20090119 at 04:00:00. For that reason the figures, show values from the date 20090119 and not from December 22, as before during winter 2006 and winter 2007.

Figure WWinter09.
Aquaflex-sensor.Water Content (%)
20090119-20090321

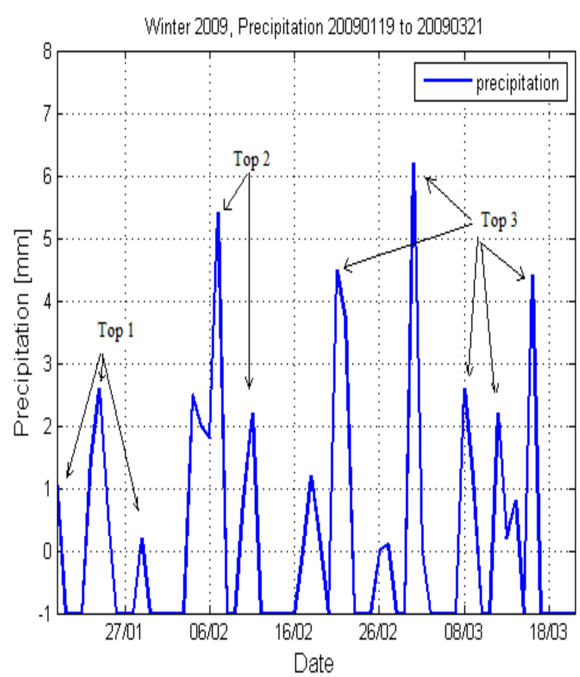


Figure PWinter09.
SMHI data. Precipitation (mm)
20090119-20090321

In figure PWinter09, three precipitation tops are selected. These tops are; Top 1 from January 19th to January 29th, Top 2 from February 7th to February 11th and Top 3 from February 21st to Mars 16th.

The precipitation tops recorded by Remningstorp meteorological station were also registered by the Aquaflex sensor. Those tops are visible in figure WWinter09. Top 1 was recorded from January 19th to February 1st, Top 2 from February 6th to February 12th and Top 3 from February 21st to Mars 18th.

The three precipitation tops are also indicated in the temperature figure from Remningstorp meteorological station, figure MmAW09 and also in the temperature figure from forest ground, recorded by the Aquaflex sensor, figure TWinter09.

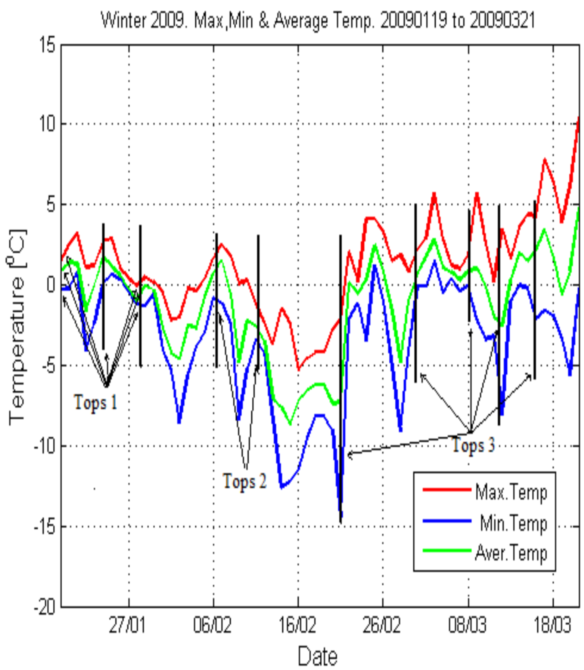


Figure. MmAW09. SMHI data. Max, Min & Average Temperatures (ºC) 20090119-20090321

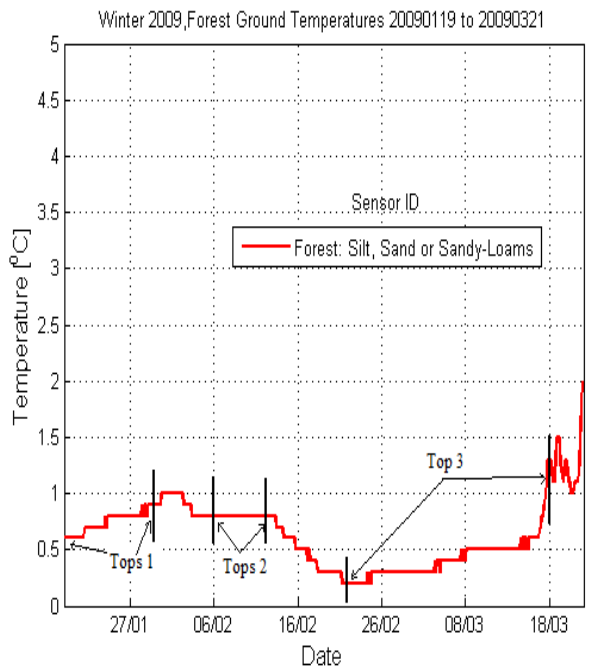


Figure.TWinter09. Aquaflex forest ground Temperatures (ºC) 20090119-20090321

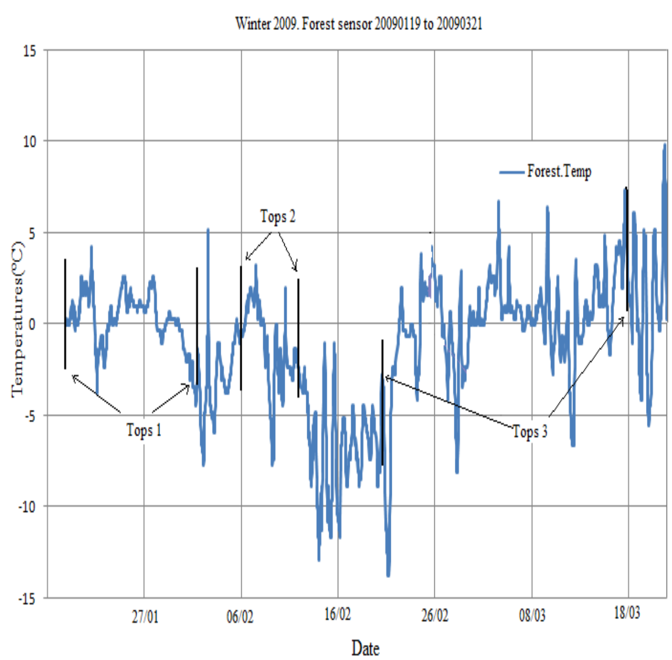
Table 13 presents data for each precipitation top recorded.

	Precipitation (mm)	Max. Temp Remning Stat (ºC)	Min. Temp Remning Stat (ºC)	Aver.Temp Remning. Stat (ºC)	Forest.Sensor at 12h (ºC)	Forest. Ground Temp At 12h (ºC)	WVC. Forest (%)
Top1	1,2	1,4	-0,3	**0,8**	0,9	0,6	17,0
	2,6	2,7	0,0	**1,8**	-	-	-
	0,2	0,5	-1,3	**0,0**	-1,4	1,0	17,5
Top2	5,4	2,5	-1,2	**1,5**	0,9	0,8	16,8
	2,2	-1,2	-3,4	**-2,6**	-3,1	0,8	17,0
Top3	4,5	-2,1	-14,4	**-7,3**	-3,4	0,2	13,5
	6,2	2,2	-0,1	**0,6**	-	-	-
	2,6	1,8	0,0	**0,9**	-	-	-
	2,2	3,5	-8,1	**-2,5**	-	-	-
	4,4	4,3	-2,1	**2,2**	4,8	1,1	17,0

Table 13. Precipitation at Remningstorp. Max, Min &Aver Temp at Remningstorp. TinyTag Sensor Temp. Forest Ground Temp. Forest Water Volume Content.

Between the precipitation at Top 2 and at Top 3, there is a significant decrease in water volume content. The soil in the forest doesn´t retain the water for a long time, which is a characteristic for silt, sand or sandy loams.

We also see a decrease in the temperatures from Top 2 to Top 3; table 13. However the temperature registered by the TinyTag sensor, figure TinyWinter09 only, registered -0,3ºC decrease, from top 2 to top 3; figure TinyWinter09.



Graph. TinyWinter09. Temperature at Forest (ºC) 20090119-20090321

Higher precipitation (above 5mm) would have been needed to avoid the water volume decrease from top 2 to top 3.

5.2 Analysis of Benareby Soil Moisture Data

Data collected from 20090316 to 20090525 at Benareby (Mölnlycke). The plots showed below, represent the volumetric water content and the ground temperature, measured by the new updated Aquaflex humidity sensor.

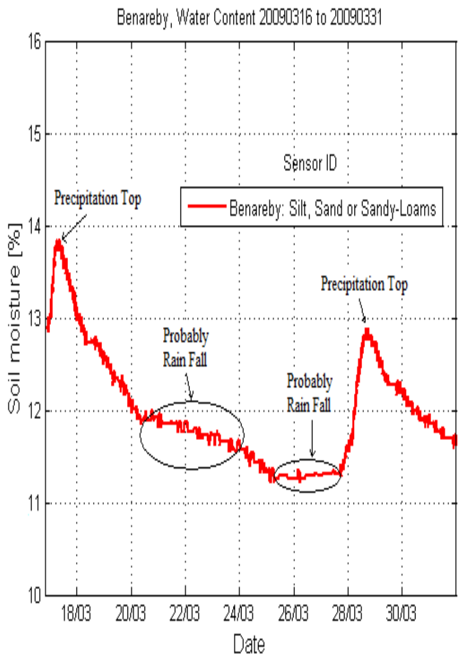


Figure Bwvc_1:
Aquaflex-sensor. Water Content (%)
20090316-20090331

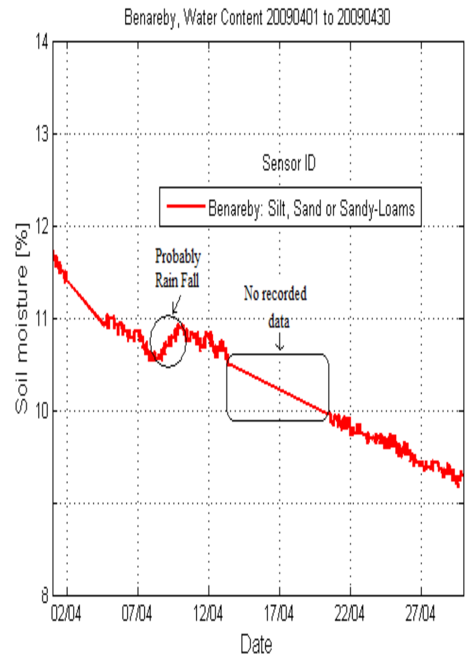


Figure Bwvc_2:
Aquaflex-sensor. Water Content (%)
20090401-20090430

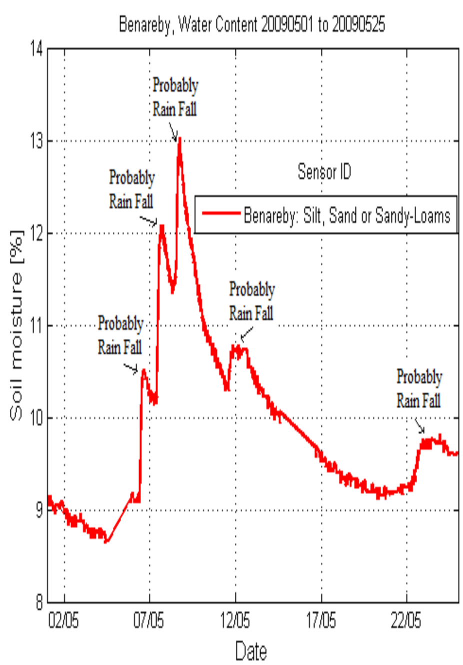


Figure Bwvc_3:
Aquaflex-sensor. Water Content (%)
20090501-20090525

Figure Bwvc_1 shows the water volume content from 20090316 to 20090331, and indicate two possible precipitation tops. According to the figure, it rained on Mars 17th (13,8% water volume) and Mars 28th (12,8%). Between those days the water volume in the area decreased, indicating that the precipitation in the area of Benareby was low. However we can deduce some probable rain fall in the periods from Mars 20th to Mars 24th and Mars 25th to Mars 26th. From Mars 20th to 24th it is observed that the water volume decreased less than the days before and during Mars 25th to 26th it is also observed that the water volume in the ground kept almost a constant value.

Figure Bwvc_2 shows the water volume content from 20090401 to 20090430, and displays a decrease of ground water volume, starting at 11,6% water volume on April 1st and finishing at 9,1% on April 30th. From April 13th to April 20th no data were recorded. A probable rain fall top can be observed during the 8th and 10th of April. The water volume in the ground increased from 10,5% to 10,9% during those days.

Figure Bwvc_3 shows the water volume content from 20090501 to 20090525, and reveal five possible precipitation tops. These tops occurred on, May 6th (10,5%water volume), May 7th (12,1%), May 8th (13,0%), May 12th (10,7%) and May 23th (9,8%).

According to the type of the soil in the area; Silt, Sand or Sandy-Loams, one of the characteristics is that the water penetrates easily but does not stay in the ground for a long time. We can deduce that the first rain fall happened on May 6th and was followed by daily rain fall until May 8th. Later the rain fall ended or decreased until May 12th when a new rainfall top is found. From May 12th the rain fall ended or decreased again until May 23rd when a new rainfall top occurred. A similar case was observed during the summer 08, figure WSsummer08, where the decrease in water volume content from top 2 to top 3 was caused by a decrease in the rain fall, figure PSummer08.

Figure Bt_1 shows the ground temperature from 20090316 to 20090331. During those days we see an increase of the temperatures from 1,4ºC to almost 4,0ºC, this temperature increase continues during April, starting at 4,0ºC on April 1st and finishing at 12,0ºC on April 31st, figure Bt_2. From April 13th to April 20th no data were recorded.
May started with a temperature of 12,5ºC on May 1st and decreased to 9,6ºC on May 9th. Later the ground temperature increased to 13ºC on May 25th, figure Bt_3.

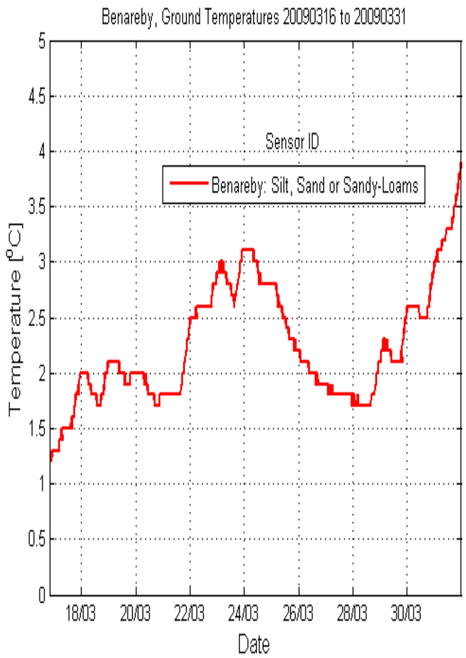


Figure Bt_1: Aquaflex forest ground Temperatures (ºC) 20090316-20090331

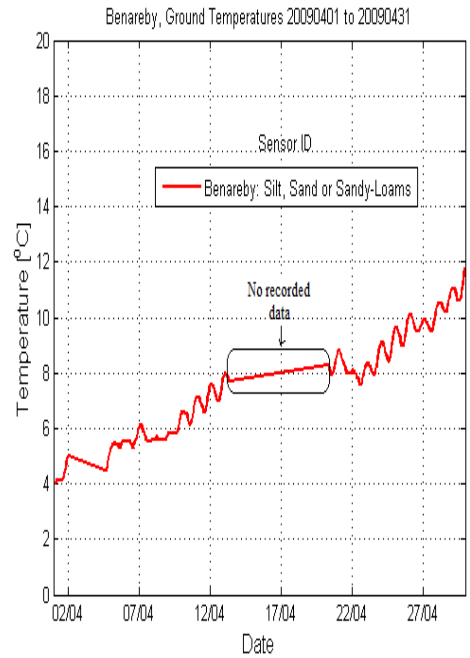


Figure Bt_2: Aquaflex forest ground Temperatures (ºC) 20090401-20090431

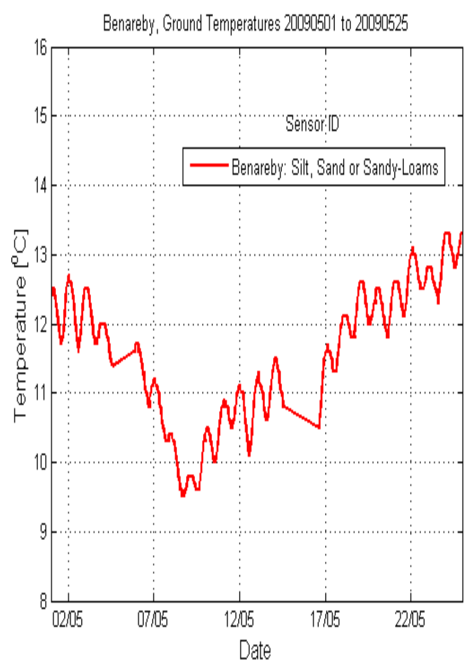


Figure Bt_3: Aquaflex forest ground Temperatures (ºC) 20090501-20090525

6 Discussion and Conclusions

The new Aquaflex system with remotely controlled soil moisture sensors has been installed and tested and the results analyzed. The soil moisture and temperature are recorded by using the same technology as the old Aquaflex humidity sensor used. This technology measures the dielectric constant of the soil with TDT process. However, there are important differences between these two systems. The new Aquaflex sensor is supplied with a lead acid rechargeable 12V battery, solar panel and two GPRS modems for remote access. According to manufacturers, the expected service life for the 12V battery is five years. After five years the percentage of capacity available is 40%. This is something to have in consideration for future Aquaflex sensors which would be installed at Remningstorp area during a longer time period.
The operating temperature range is; charge (-15ºC to 50ºC) and discharge (-20ºC to 60ºC) however no temperature at -20ºC or lower, has been registered at Remningstorp from April 2006 to Mars 2009.

The remote soil moisture access is an advantage compared to the older Aquaflex sensors in which the data downloading was done by connecting a computer to the sensor through a serial port cable and consequently a visit to the place where the sensor was located was required. Now the connection between the sensor and the modem at Chalmers will be done through the GPRS network, saving a lot of time.

Some difficulties were found during Aquaflex software installation on Windows Vista.
It is worth to mention that Aquaflex software version 4.13 has not been tested for Windows Vista by the supplier. Some of the functions of the Aquaflex software didn´t work at all, or didn´t work as expected. E.g. the graphs couldn´t be showed because the Aquaflex software couldn´t read the data saved in the Microsoft´s Access database. Instead the graphs were plotted in Matlab. The sample interval couldn´t be changed in Microsoft Access, so the original sample interval (10 minutes) was used in the graphs. This sample interval reduced the time to save data to only 9 days. One hour sample interval would instead provide approximately two months data.
Some problems were also experienced trying to install the modem´s driver on Windows Vista. The modem is supplied with an installation CD, Windows Vista didn´t recognize the drivers on the CD, however no problems occurred when the drivers were installed on a computer with Windows XP. However, the driver for Windows Vista can be downloaded from the following homepage.

http://www.multitech.com/SUPPORT/Families/MultiModemGPRS/drivers.asp

For these reasons it is not recommended to use a computer with Windows Vista as operating system until the Aquaflex supplier has developed and tested a new software adapted to Vista. A computer with Windows XP will also work.

The communication between the two modems has been tested from 16th Mars 2009 to 25th May 2009 and some difficulties were experienced. In the beginning the communication between the modems was not enabled, this problem was caused by troubles in the sim card placed in the modem located in the Aquaflex electric box. After an update of the sim card by Telia, the sim card worked as expected and the communication was excellent until the beginning on June. On that date the communication between the modems ended unexpectedly and no data could be recorded, even though the two sim cards worked properly according to Telia.

The white connector where the solar panel wires are connected to each other, is a simple one made of plastic for home applications, see figure 26 in Appendix A. It is recommended to fill the holes where the wires are connected with silicone to avoid water to come in or replace the white connector with a better one, i.e. range IP44.

The new Aquaflex humidity sensor provided accurate water volume content and ground temperature records from 16th Mars 2009 to 25th May 2009, however due to the mentioned troubles on Windows Vista computers and troubles in the communication between the modems, I will recommend to wait and not buy the Aquaflex sensor until the supplier has tested the entirely system in Windows Vista. Of those problems the failure in the communication is the most serious. The graphs can be plotted in Matlab without the Aquaflex software, but if the communication fails, there is no remote access to the records and the data will be lost after a time period, unless they can be downloaded on site.

7 Future Work

Three more Aquaflex remotely controlled soil moisture sensors could be ordered and they would consequently be installed at Remningstorp. Each sensor should be installed in different locations and therefore an analysis of the soil type where the sensor would be placed is recommended to guarantee the accuracy of the measurements.

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Appendix A

<u>Installing the sensor program on a PC with Windows XP</u>

sensor.exe is executable file with help us to establish the communication between the modem at Chalmers and the modem on the Aquaflex sensor.

sensor.mdb is a Microsoft Access database file in which the data collected is recorded.

Plug the USB-stick for the Multitech GSM into a USB port on the Windows PC.
Copy the two files sensor.exe and sensor.mdb from the medium you got it, to the desktop on your computer.
Using **Start→Control Panel→Administrative Tools→Data Sources (ODBC)** and open the dialog box "**ODBC Data Source Administrator**".
Select the tab pane "**System DSN**". Press **Add** button.

Select "**Microsoft Access Driven(*.mdb)**". Press the **Finish** button.
In the "**Data Source Name**" filed type **SENSOR.** Press the **Select** button.
Find **sensor.mdb** under **"C:\Documents and Settings\<username>\Dekstop".**
Press **OK** (Leave System Database: None selected).
Press **OK** again.

If data is to be entered into an Aquaflex database the Aquaflex database should be configured as follow:

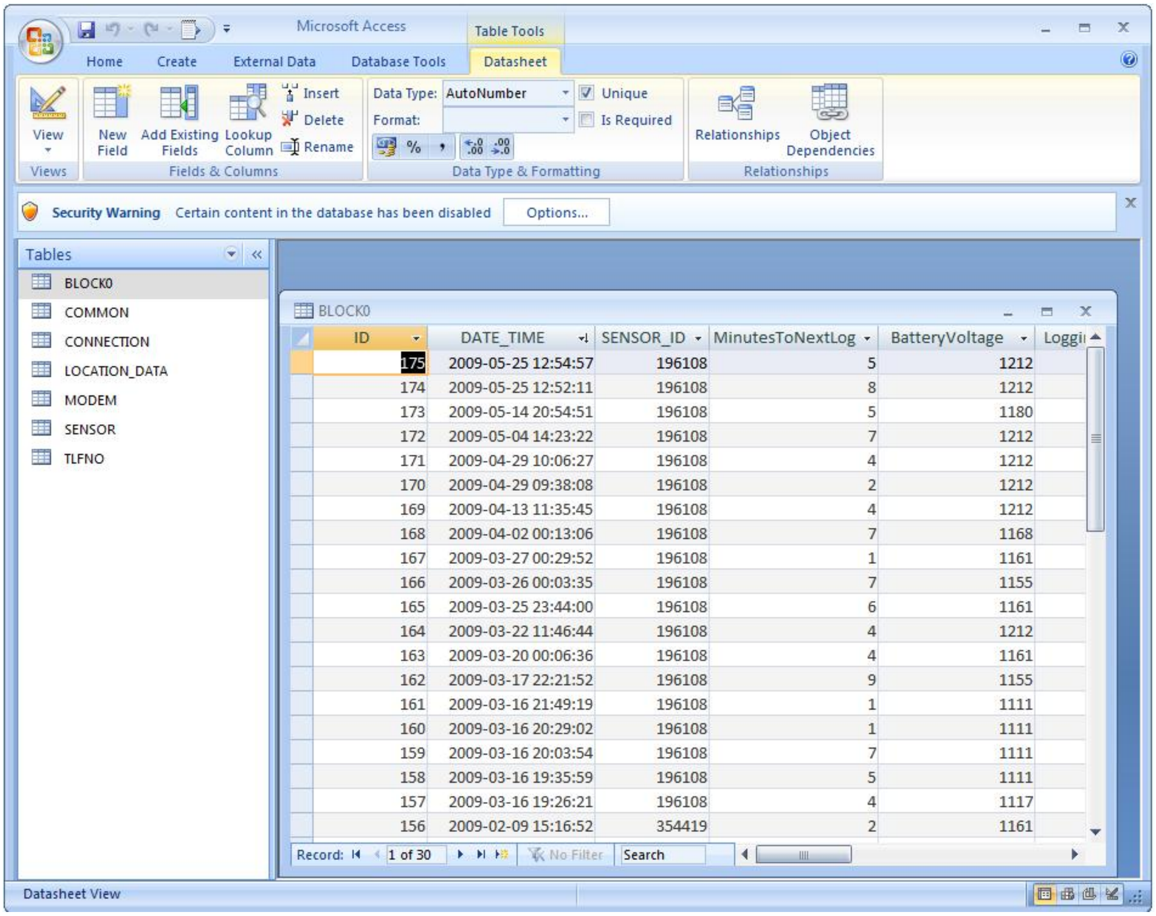
Press **Add** button. Select "**Microsoft Access Driver(*.mdb)**". Press the **Finish** button. In the "**Data Source Name**" field type **AQUAFLEX.**
Press the **Select** button. Select "**List files of type**"="**All files(*.*)**". Find the Aquaflex database to be used. The default name is "**C:\ProgramFiles\Aquaflex\Data\Database.aqd**".
Press **OK** (Leave System Database: None Selected).
Press **OK** again

Test the installation by clicking on the **sensor.exe** icon on the desktop. A black DOS box should open and display status messages white the program calls the telephone numbers enabled in **sensor.mdb.**

Sensor.mdb is an Access database and it can be read using the usual tools, Microsoft Access, Microsoft Excel or similar. In this thesis work I used Microsoft Access as the usual tool. Microsoft Access has the following tables (Windows Vista).

- *Block*

This table contains information about the date and time for the successful calls, the sensor identification number, the remaining time until the next call, battery voltage, the time interval for each call and number of records saved, figure 20.

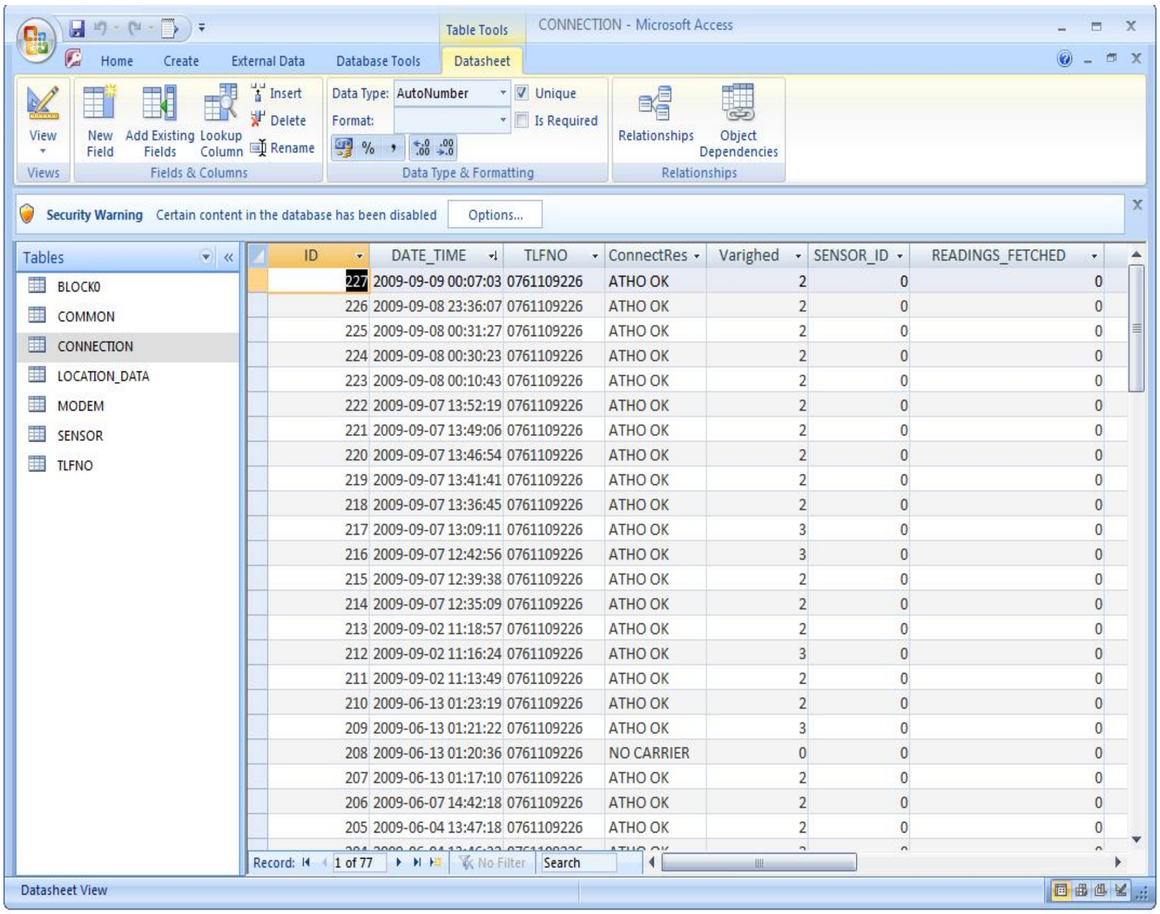


ID	DATE_TIME	SENSOR_ID	MinutesToNextLog	BatteryVoltage	Loggi
175	2009-05-25 12:54:57	196108	5	1212	
174	2009-05-25 12:52:11	196108	8	1212	
173	2009-05-14 20:54:51	196108	5	1180	
172	2009-05-04 14:23:22	196108	7	1212	
171	2009-04-29 10:06:27	196108	4	1212	
170	2009-04-29 09:38:08	196108	2	1212	
169	2009-04-13 11:35:45	196108	4	1212	
168	2009-04-02 00:13:06	196108	7	1168	
167	2009-03-27 00:29:52	196108	1	1161	
166	2009-03-26 00:03:35	196108	7	1155	
165	2009-03-25 23:44:00	196108	6	1161	
164	2009-03-22 11:46:44	196108	4	1212	
163	2009-03-20 00:06:36	196108	4	1161	
162	2009-03-17 22:21:52	196108	9	1155	
161	2009-03-16 21:49:19	196108	1	1111	
160	2009-03-16 20:29:02	196108	1	1111	
159	2009-03-16 20:03:54	196108	7	1111	
158	2009-03-16 19:35:59	196108	5	1111	
157	2009-03-16 19:26:21	196108	4	1117	
156	2009-02-09 15:16:52	354419	2	1161	

Figure 20.
Microsoft´s Access block table. Windows Vista.

- *<u>Connection</u>*

The Connection table provides us with information about the number of connections, the date and time for the last connection, the telephone number we are calling to, the time spent for each connection (varighed), the sensor identification number and the number of readings, figure 21.



ID	DATE_TIME	TLFNO	ConnectRes	Varighed	SENSOR_ID	READINGS_FETCHED
227	2009-09-09 00:07:03	0761109226	ATHO OK	2	0	0
226	2009-09-08 23:36:07	0761109226	ATHO OK	2	0	0
225	2009-09-08 00:31:27	0761109226	ATHO OK	2	0	0
224	2009-09-08 00:30:23	0761109226	ATHO OK	2	0	0
223	2009-09-08 00:10:43	0761109226	ATHO OK	2	0	0
222	2009-09-07 13:52:19	0761109226	ATHO OK	2	0	0
221	2009-09-07 13:49:06	0761109226	ATHO OK	2	0	0
220	2009-09-07 13:46:54	0761109226	ATHO OK	2	0	0
219	2009-09-07 13:41:41	0761109226	ATHO OK	2	0	0
218	2009-09-07 13:36:45	0761109226	ATHO OK	2	0	0
217	2009-09-07 13:09:11	0761109226	ATHO OK	3	0	0
216	2009-09-07 12:42:56	0761109226	ATHO OK	3	0	0
215	2009-09-07 12:39:38	0761109226	ATHO OK	2	0	0
214	2009-09-07 12:35:09	0761109226	ATHO OK	2	0	0
213	2009-09-02 11:18:57	0761109226	ATHO OK	2	0	0
212	2009-09-02 11:16:24	0761109226	ATHO OK	3	0	0
211	2009-09-02 11:13:49	0761109226	ATHO OK	2	0	0
210	2009-06-13 01:23:19	0761109226	ATHO OK	2	0	0
209	2009-06-13 01:21:22	0761109226	ATHO OK	3	0	0
208	2009-06-13 01:20:36	0761109226	NO CARRIER	0	0	0
207	2009-06-13 01:17:10	0761109226	ATHO OK	2	0	0
206	2009-06-07 14:42:18	0761109226	ATHO OK	2	0	0
205	2009-06-04 13:47:18	0761109226	ATHO OK	2	0	0

Figure 21.
Microsoft´s Access Connection table. Windows Vista.

- *Location data*

The location data table provides us with information about the date and time for the last connection, the sensor identification number, the real part of the dielectric permittivity (Moisture_raw), the imaginary part of the dielectric permittivity (Conductivity), the ground temperature (ºC) and the ground water volume content (%), figure 22.

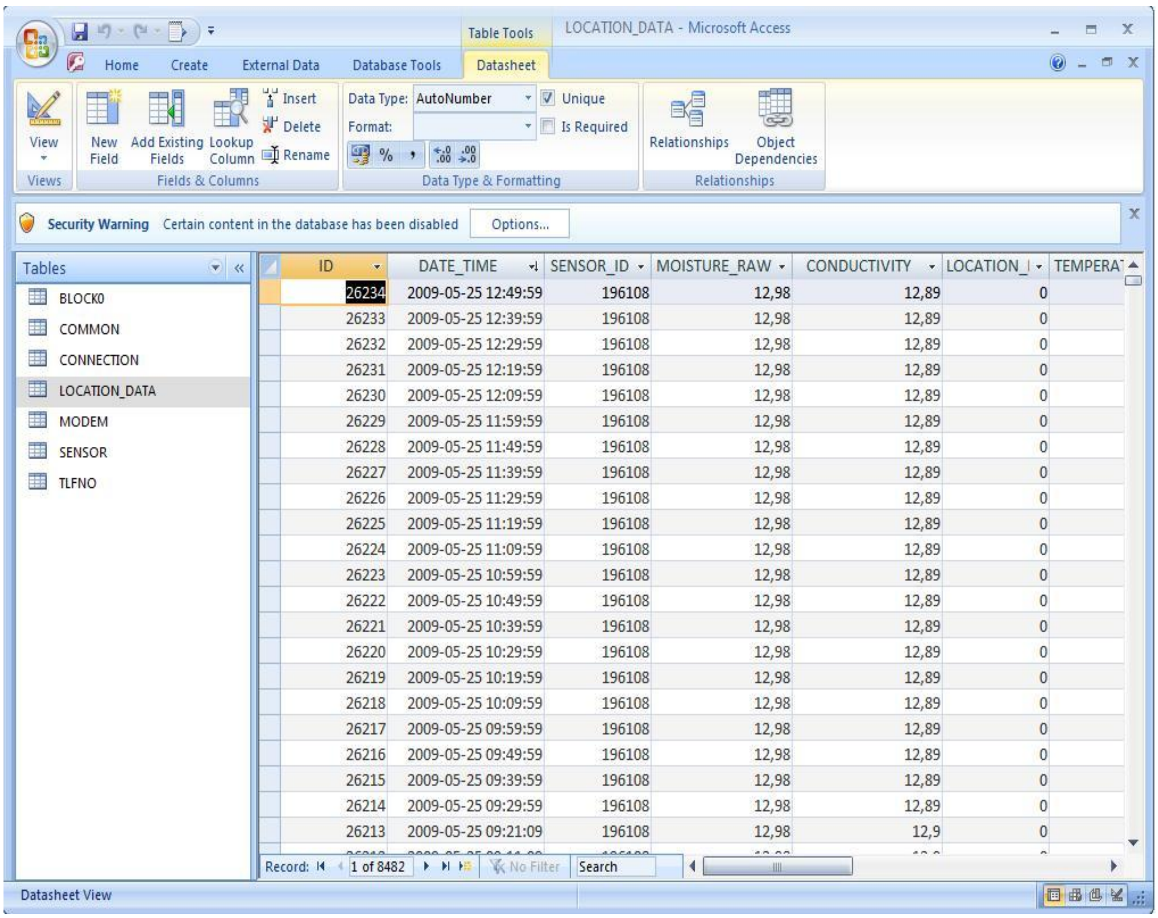


Figure 22.
Microsoft´s Access Location_data table. Windows Vista.

- *Modem*

The modem table provides the following information: the number and the name of the modem, the COM port on the computer where the connection is done from. The boxes Enable, USB, Variable COM and GSM have to be marked, figure 23.

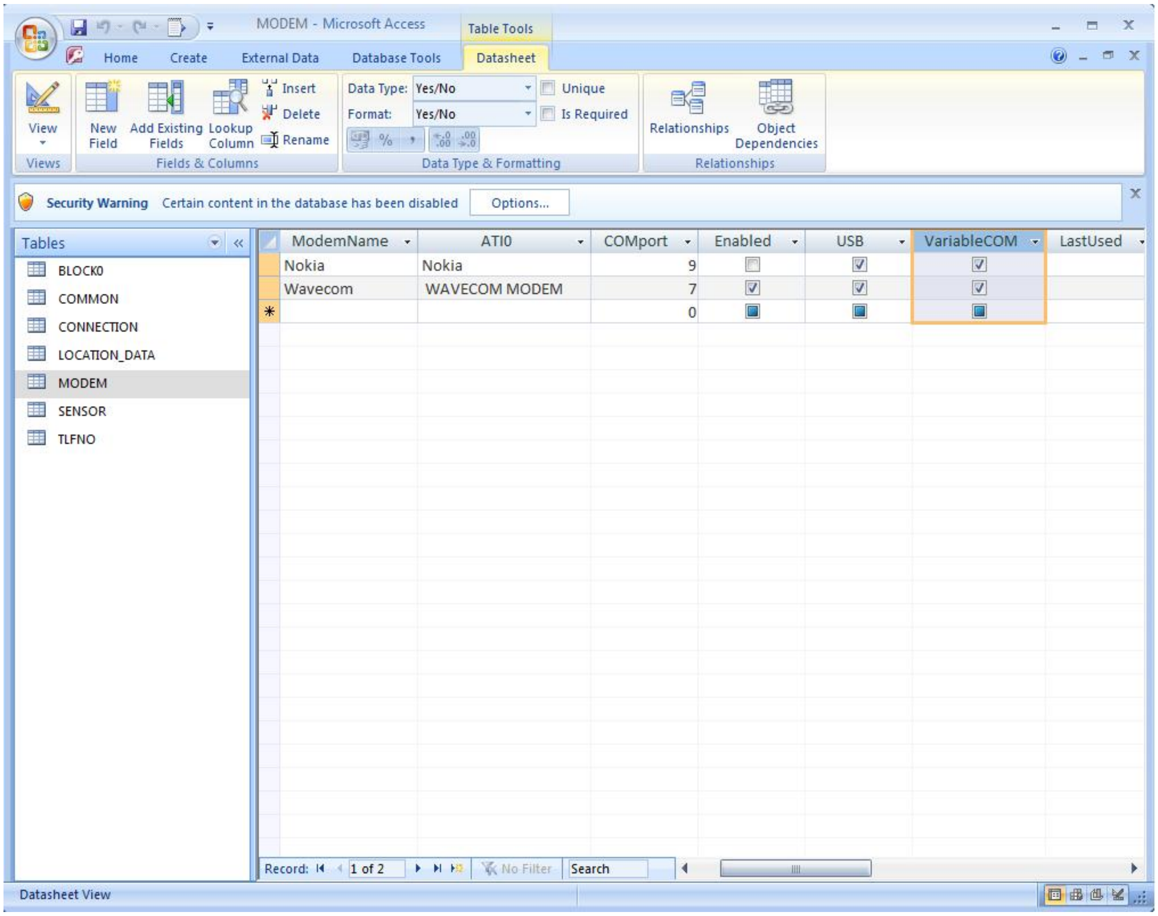


Figure 23.
Microsoft´s Access Modem table. Windows Vista.

- *Sensor*

The sensor table provides the following information: the sensor identification number, the date and time for the last reading, the telephone number we called to and the time interval for each call, figure 24.

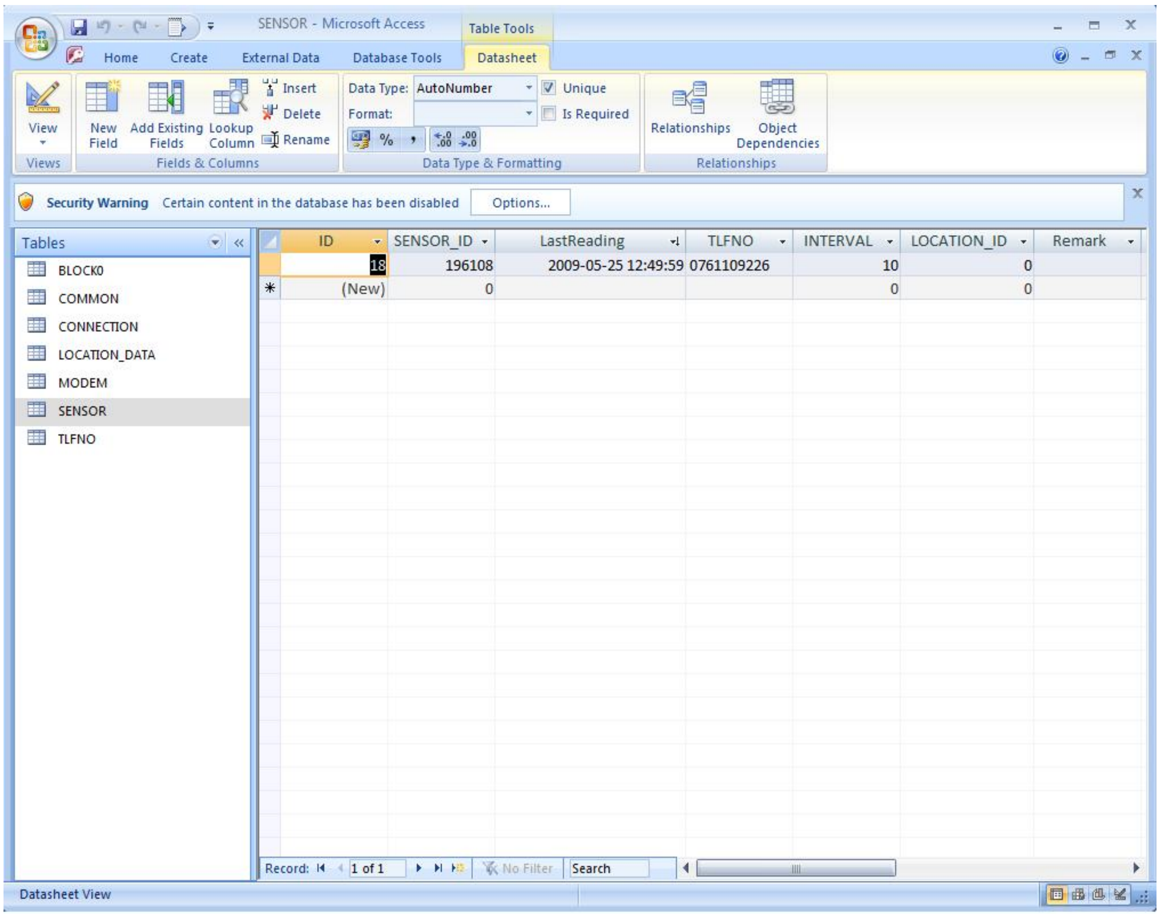


Figure 24.
Microsoft´s Access Sensor table. Windows Vista.

- *Tlfno*

The Tlfno table provides us with the following information. The telephone number we are calling to, the date and time for the last successful call, the date and time for the last failed call and the time interval for each call. The box Enabled has to be marked.

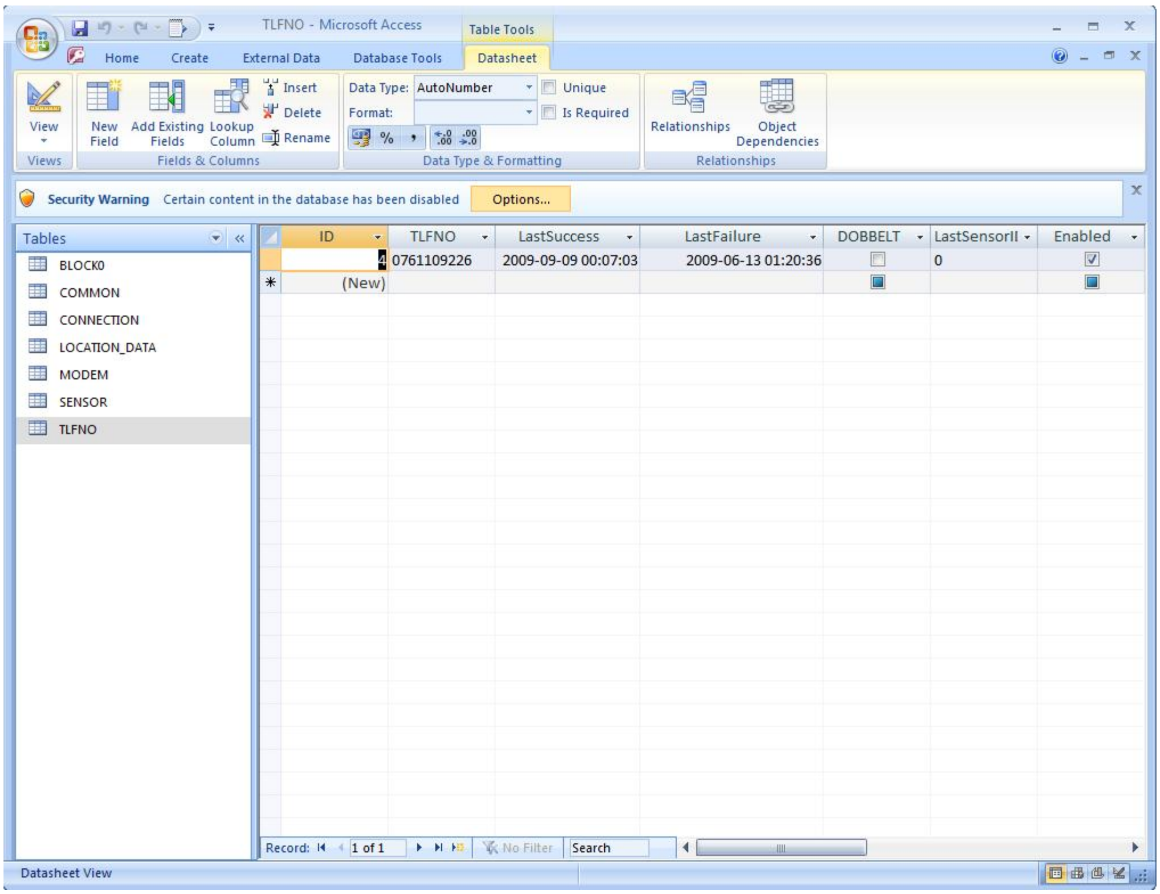


Figure 25.
Microsoft´s Access Tlfno table. Windows Vista.

Connections of the new Aquaflex humidity sensor.

The solar panel wire should be connected to the Aquaflex´s electric box solar panel wire as the picture 26 shows. The blue cable (0) connected to the black cable and the brown (phase) to the red/black. If the connections are done correctly, a red light should shine on the charging regulator.

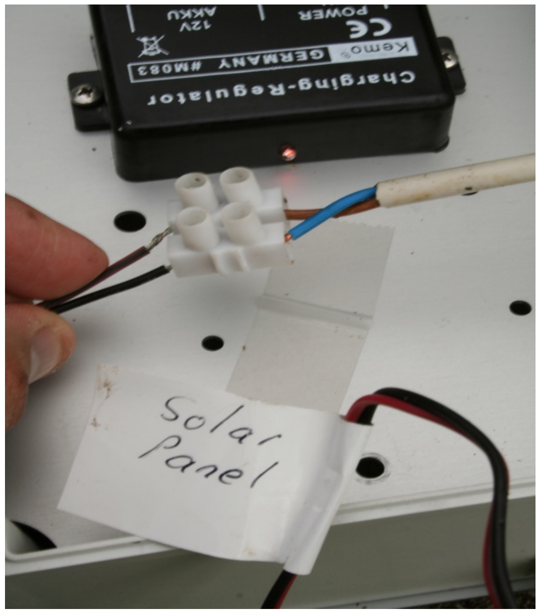


Figure 26.
Aquaflex´s Solar panel wires connection.

The battery should be connected to the Aquaflex´s electric box battery wire as the picture 27 and 28 show. The red wire to the red marked connection on the battery and the black wire to the black connection on the battery.

Figure 27.
Aquaflex´s Battery wires connection.

Figure 28.
Aquaflex´s Battery connection.

In the figures 29 and 30 we can see the Aquaflex´s modem and the SIM card. The SIM card can be difficult to put inside the modem. The card should be introduced parallel to the horizontal line. Any angle on the SIM card would do that the SIM card miss the slot and disappear into the modem box.

Figure 29.
Aquaflex´s electric box.

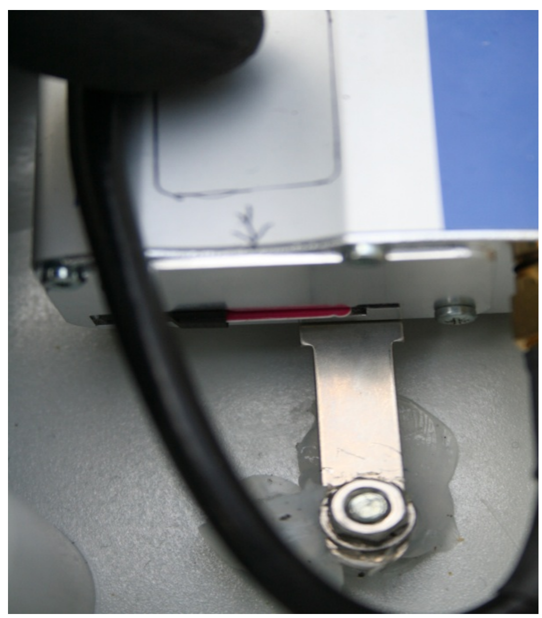


Figure 30.
Aquaflex´s modem and sim card.

You should feel friction when passing the SIM card in. To lock the SIM card, push the black lock sideways towards the SIM card.

Appendix B.

Ärende Roberto Montes Cañizares	
Borrhål Benareby	**Provnr** 1

Glödningförlust	Delprov 1	Delprov 2	**Vattenkvot**	(gram)
a Massa hos porslingdegel, g	32,87	32,87	Skål nr	1
b Massa hos degel + torr jord, g	46,96	46,96	Fuktigt prov + skål	27,9
c Massa hos degel + bränd jord, g	45,41	45,41	Torkat prov + skål	21,0
			Vatten $m_w =$	7,0
			Skål	1,1
			Torkat prov $m_s =$	19,9
			Vattenkvot (%) $w =$	35

Beräkning	Delprov 1	Delprov 2
d Massa hos torkad jord, g b -a	14,09	14,09
e Massförlust vid bränning, b – c	1,55	1,55
f Glödgningsförlust, % (b - c /b - a) * 100	11,00071	11,00071
g Medelvärde för delproven,%(f1 + f2) / 2	11,0	

Ärende Roberto Montes Cañizares	
Borrhål Field	**Provnr** 2

Glödningförlust	Delprov 1	Delprov 2	**Vattenkvot**	(gram)
a Massa hos porslingdegel, g	44,77	44,77	Skål nr	3
b Massa hos degel + torr jord, g	60,57	60,57	Fuktigt prov + skål	52,0
c Massa hos degel + bränd jord, g	59,69	59,69	Torkat prov + skål	38,6
			Vatten $m_w =$	13,5
			Skål	1,1
			Torkat prov $m_s =$	37,5
			Vattenkvot (%) $w =$	36

Beräkning	Delprov 1	Delprov 2
d Massa hos torkad jord, g b -a	15,8	15,8
e Massförlust vid bränning, b – c	0,88	0,88
f Glödgningsförlust, % (b - c /b - a) *100	5,56962	5,56962
g Medelvärde för delproven,%(f1 + f2) /2	5,6	

Ärende Roberto Montes Cañizares	
Borrhål Forest	**Provnr** 3

Glödningförlust	Delprov 1	Delprov 2
a Massa hos porslingdegel, g	44,01	44,01
b Massa hos degel + torr jord, g	62,83	62,83
c Massa hos degel + bränd jord, g	61,77	61,77

Vattenkvot		(gram)
Skål nr		5
Fuktigt prov + skål		34,2
Torkat prov + skål		27,2
Vatten	m_w =	7,0
Skål		1,1
Torkat prov	m_s =	26,1
Vattenkvot (%)	*w* =	27

Beräkning

		Delprov 1	Delprov 2
d Massa hos torkad jord, g	b -a	18,82	18,82
e Massförlust vid bränning,	b – c	1,06	1,06
f Glödgningsförlust, %	(b - c /b - a) *100	5,632306	5,632306
g Medelvärde för delproven,%	(f1 + f2) /2	5,6	

Appendix C.

Specifications

Batteries	8 x AA-size Alkaline cells (type E91 or equivalent)
Battery life	6 months minimum under normal conditions.
Measurement interval	Selectable from 10 minutes to 6 hours
Memory capacity	1300 measurements (e.g. two months of logging at hourly intervals)
Operating Temperature	-10 to 40°C (14 to 104°F)
Soil Moisture Measurement	
Range	0 to 60% volumetric moisture content
Precision / Repeatability	± 0.5% volumetric moisture content
Accuracy	± 2% volumetric moisture content
Soil Temperature Measurement	The temperature is measured at the body of the sensor, not along the moisture-sensing cable.
Range	-10 to 50°C (14 to 122°F)
Accuracy	± 0.5°C (0.9°F)
Voltage Supply Required	+8 to +24V DC.
Current Consumption	0.2mA normal. 200mA peak for 60 milliseconds while a reading is being taken. 35mA when connected to a PC or Palm handheld.

Options

The following options are available:

- A dual AQUAFLEX Logging Sensor, where a second Sensor tape is connected to the Battery Box
- Cellular Telemetry to allow remote communication over the GSM Cellular network

Appendix D.

$\nabla \times \boldsymbol{E} = -\mu \frac{\partial \boldsymbol{H}}{\partial t}$ [a1]

$\nabla \times \boldsymbol{H} = \varepsilon \frac{\partial \boldsymbol{E}}{\partial t} + \sigma \boldsymbol{E}$ [a2]

$\nabla \cdot \varepsilon \boldsymbol{E} = 0$ [a3]

$\nabla \cdot \mu \boldsymbol{H} = 0$ [a4]

$\boldsymbol{D} = \varepsilon \boldsymbol{E}$	Electric flux density [C/m^2]	[a5]
$\boldsymbol{B} = \mu \boldsymbol{H}$	Magnetic flux density [$Wb/m^2(Tesla)$**]**	[a6]
$\boldsymbol{J} = \sigma \boldsymbol{E}$	Volume current density [A/m^2] σ indicates the conductivity (S/m).	[a7]

Appendix E.

Fresnel's equations describe the reflection and transmission of electromagnetic waves at an interface. They give the reflection and transmission coefficients for waves parallel and perpendicular to the plane of incidence.

Coefficients of reflection and transmission when **E** is parallel to the plane of incidence.

$$R_p = \frac{E_{pr}}{E_{p0}} = \frac{n_1 cos\theta_2 - n_2 cos\theta_1}{n_1 cos\theta_2 + n_2 cos\theta_1} = -\frac{\tan(\theta_1 - \theta_2)}{\tan(\theta_1 + \theta_2)} \qquad [b1]$$

$$T_p = \frac{E_{pt}}{E_{p0}} = \frac{2n_1 cos\theta_1}{n_1 cos\theta_2 + n_2 cos\theta_1} = \frac{2\cos\theta_1 \sin\theta_2}{\sin(\theta_1 + \theta_2)\cos(\theta_1 - \theta_2)} \qquad [b2]$$

Coefficients of reflection and transmission when **E** is perpendicular to the plane of incidence.

$$R_\perp = \frac{n_1 cos\theta_1 - n_2 cos\theta_2}{n_1 cos\theta_1 + n_2 cos\theta_2} = -\frac{\sin(\theta_1 - \theta_2)}{\sin(\theta_1 + \theta_2)} \qquad [b3]$$

$$T_\perp = \frac{2n_1 cos\theta_1}{n_1 cos\theta_1 + n_2 cos\theta_2} = \frac{2\cos\theta_1 \sin\theta_2}{\sin(\theta_1 + \theta_2)} \qquad [b4]$$