Soil moisture sensor sensitivity

A research on the performance of different soil moisture sensors in different soil textures

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a Royal Eijkelkamp Company

Hogeschool VHL
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Colophon

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Acknowledgments

When I look back at my four and a half month employment at the Royal Eijkelkamp company as an intern I feel pleased. I'm very happy and grateful for the opportunities that I have had during my internship. What I liked most about this research is that I was able to perform the full research myself; research setup, data gathering and data analysing were all included.

I have learned a lot about soil moisture in the unsaturated zone. Yet, I have also learned how much more there is to learn about hydrology. I feel triggered to expand my education with a master degree at the Wageningen University. I plan to start with this new education as soon as possible.

The start of my internship back in February unfortunately also turned out to be the start of some very turbulent and unfortunate events in my personal live. Without going into too much detail, I'd really like to thank my colleagues from Eijkelkamp for the understanding they showed for this.

I would really like to thank **all employees of Royal Eijkelkamp** for giving me an unforgettable time in their company and for following up to my queries. Above all I would like to thank **Chesron Tetelepta** for his input in my project approach and **Cor Verbruggen** for his input relating to the contents of my research.

At last I would like to thank **Hogeschool VHL** with **Dan Assendorp** in particular for their understanding of my personal situation.

Summary

Royal Eijkelkamp is an international organisation which produces and retails different kinds of products for soil and water research. Different soil moisture sensors that use varying measuring techniques are included in their line of products. This research aims to clarify what sensor can best be advised for a client in what situation.

For this research measurements have been conducted with the different sensors in a sandy, clayey and loamy soil. Soil samples were taken to determine the actual soil moisture content. These contents have been compared to determine the accuracy of the sensors in the different soils.

According to the coefficient of determination the measurements in the sandy and clayey soil are rather reliable. However, the measurements in the loamy soil were not conducted in a range wide enough to consider the outcome reliable. The accuracy described in the specifications of the sensors is also not very reliable. It turns out that on average only around 30% of the measurements conducted comply with the given accuracy.

The root mean squared error shows that the ML3 and SM300 sensor give the most reliable output in a sandy soil, whereas the WET sensor is most accurate in the clayey soil. However, for the best advice, also price, durability, soil disturbance, temperature and salinity range should be taken into consideration.

Contents

1 Preface

1.1 Background
Royal Eijkelkamp Earth Sampling Group is an international organisation which produces different kinds of equipment used for environmental, soil and water research. Since its establishment in 1911 as a blacksmith, Eijkelkamp has become a group of companies that develops and delivers products for soil science worldwide. Among others, Eijkelkamp produces and trades in different kinds of soil moisture sensors. To better inform the client about their sensors, Eijkelkamp wants to conduct a research on the different values the measurements give for the different sensors. The project will be conducted in the Eijkelkamp Academy, a department aimed for students to conduct their research on innovative projects. (Eijkelkamp, 2013)

Global warming and climate change occasionally come with extreme weather. Floods, hurricanes, landslides and drought occur more often. Floods and hurricanes for example are clearly visible phenomena's while drought is less visible. Against expectations, drought damage is occasionally much more severe and harder to restore. Drought can be visible in rain, soil moisture and surface water. (Tetelepta)

The agricultural sector has to cope with the effects of drought. These effects are lower yields and bad development of a crop. A plant needs a sufficient amount of water to grow and develop properly. Nowadays, irrigation is a common method. The amount of water that has to be irrigated is decided by visual aspects of the plant and the knowledge the farmer has of the soil. To increase the farmers yield to a maximum, measuring and controlling the soil moisture is of great help. Soil moisture sensors tell much about the condition of the plant. Measuring soil moisture is not a problem, but there is a wide range of sensors available of which it is not clear in which terrains they are most reliable. (Tetelepta)

1.2 Problem definition
To be able to inform clients in a more proper way about their products, Eijkelkamp wants to have a research executed to give insight in the functioning of the sensors. To inform clients, Eijkelkamp wants to know which sensor can best be advised for which soil type under which circumstances. This research focuses mainly on the soil texture, but also salinity, temperature, organic content and active clay content play an important role in the variability of a sensors accuracy. Soil texture can more or less be determined by choosing for sandy, silty and clayey soils. Therefore research locations will be chosen in variable soils. The errors caused by deviations in measurement value due to the above named factors will be assumed by the producers specifications. Therefore mainly the effect of changing soil textures on the performance of the sensors will be tested. An important output for the research is a flowchart for the sales department. This flowchart should help the staff of this department to give the best advice to the client.

In other words, the main question Eijkelkamp wants to answer is:
'What are the differences between the soil moisture sensors sold by Eijkelkamp and which give the most realistic value for soil moisture in changing soil textures?'

The sub-questions that will help answering the main question are:

- *What are the differences between the sensors sold by Eijkelkamp and what are their technical specifications?*
- *Which three locations can best be measured to examine the reliability of the different sensors?*
- *What are the differences between the measured values and the values determined with Kopecky rings for moisture content in the different soils?*

1.3 Goal

The goal of this research is to find how to more properly advise Eijkelkamps clients when they want to buy soil moisture sensors. The advice should be based to their needs and the soil properties and circumstances they have in their measuring area.

1.4 Scope and limitations

This research aims only on the changing in soil texture since this factor has the biggest influence on the actual value in soil moisture.

The amount of soil moisture intervals measured is limited by the Kopecky rings taken. Taking these samples and analysing them takes most time by far. Taking a measurement with a sensor only requires a few seconds.

1.5 Bookmark

In chapter one an introduction on the topic will be given. Chapter two describes the methodology used in this research. In chapter three the different soils examined are elaborated followed by the explanation of the sensors in chapter four. In chapter five the results are defined and in the sixth chapter conclusions are drawn.

1.6 Audience

This report has been written for the employees of Royal Eijkelkamp and its clients. Besides, this report has been written for the teachers and students at Hogeschool VHL.

2 Methodology

This research can be summarized in four stages. First there was an orientating desk study; secondly there was a testing period in the field and in the laboratory. In the third stage the results of this testing period were processed. In the final stage conclusions and recommendations were drawn. In this chapter the different stages will be elaborated.

2.1 Stage 1; Orientating desk study

To get a better understanding of the different sensors this research started with a desk study in the Royal Eijkelkamp office. The manuals of the different sensors have been studied to get a good understanding of the way the different sensors work and what their possibilities are. All specifications of the sensors will be included in the appendix. The result of this desk study can be found in chapter four.
Beside the sensors that needed analysing, also different locations had to be found. Because this research had a limited span of time before completion, only three locations with three different soil types were selected. The locations that have been chosen can be found in chapter three.

2.2 Stage 2; Field research

The field research consists of a few parts. Part one is the measuring with the sensors, part two is taking samples of the soil and part three is a laboratory research.

In the first step all sensors, except the PlantCare logger and the Watermark sensor, were used 10 to 15 times for a measurement in the field. The PlantCare logger and the Watermark sensor had to be installed a few days prior to measuring. The exact reason for this can be found in chapter three.

All sensors together gave 80 readings for each soil moisture interval on average. Multiplied by the three different textures and the 19 different soil moisture intervals that have been measured, 1500 readings have been done in total. Since the sensors all measure a soil variable that is later on related to soil moisture content, these values cannot be exact. Therefore soil samples have to be taken with a ring sampling kit, i.e. Kopecky rings. Kopecky rings are 100cc cylinders that are used to take undisturbed soil samples. A few rings are shown in figure 1 as an example. (Eijkelkamp Agrisearch Equipment, 2012)

Figure 1 Kopecky rings (Eijkelkamp)

The sampling rings were attached to a ring holder and pushed into the ground. When the ring had been pushed deep enough to fill the entire ring, the ring was removed from the soil. Excess soil at the ends of the ring was sewed off so the volume of sampled soil is exactly 100cc. A cap was placed on both sides of the ring to secure the soil for transport.

In the laboratory the caps were loosened and a gauze was attached to the bottom of the sample so the soil could not fall out. The sample was scaled with a precision of a thousandth of a gram so the weight of the soil, moisture, ring and gauze were known.

After weighing, the soil was moisturized to 100%. To do so the samples were positioned in a container with shallow water. In a timespan of a few days the water level was raised to the top of the rings. If the water level had been raised to fast, air would have been trapped in the soil sample making the sample scaling incorrect.

After the soil was completely saturated the samples were weighted again. The new value for weight consisted of the soil, the weight of the water with all pores filled, the ring and the gauze.

Following the saturated weighing, the samples were put in the oven for at least 24 hours straight. Thanks to the 105°C in the oven all the water had evaporated for the final scaling of the soil. In this case, only the weight of the soil, gauze and ring was measured. When these weightings were done the soil was thrown and the ring and gauze were weighted at last. With all measured values combined, the bulk density[1], gravimetric moisture content[2] (GWC) and the volumetric moisture content[3] (VWC) were determined. This data was analysed in stage 3.

Sensors were also calibrated specifically to the ground that was examined. To do so, the voltage measured in the field and the voltage in an air-dried sample was required. With a couple of formulas that are given in the user manuals of the different sensors, a linearization table was created to make the sensors much more accurate.

2.3 Stage 3: Data Analysis

All the collected data is analysed in Microsoft Excel 2010. After all the measured data had been implemented in excel, the first step was to determine all the soil moisture values of the Kopecky rings. These were aligned with the data measured by the sensors. These two values plotted gave a good image of the distribution of measurements compared to the real moisture values. A calculation of the statistical term R squared[4] did give a clear view of the linear distribution of these values.

The next step was to determine the average of each sensor at each moisture interval. When the average of the measurement varies from the actual soil moisture content, the sensors calibration is not proper.

In the specifications of the sensors the accuracy of the sensors is given. To put this to the test, it was calculated what percentage of the measurements taken corresponded with this given accuracy.

Finally the Root Mean Squared Error (RMSE) was calculated. This measure displays the difference between actual values and sample values. The RMSE looks a lot like the better known standard deviation. The difference is that the standard deviation is based on the difference between a value and an average whilst the RMSE compares a value and a

1 Weight of a unit volume of a loose material. (Business Dictionary)
2 Weight of water in sample divided by the weight of the dry sample. (University of Washington)
3 Weight of water in sample divided by the volume of the sample. (University of Washington)
4 R squared, coefficient of determination, or R^2, is a statistical term that indicates how well data fits in a statistical model. R^2 is a value between -1 and 1 where R^2=-1 indicates a perfect negative fit for the data and R^2=1 indicates a perfect positive fit. A value of R^2=0 indicates that the data does not fit the statistical model. (Ott & Longnecker, 2009)

determined value. With this method, one value for each sensor can be determined concerning reliability. This value can also be determined per soil moisture interval. (Ott & Longnecker, 2009)

2.4 Stage 4: Conclusion and Recommendations

In this final stage conclusions will be drawn by looking at the processed data critically. The best sensors for each texture type will be elected and will be used as recommendation. Factors as salinity and temperature range will be assumed from the specifications of each sensor.

At last a flowchart will be made for the sales department, showing the recommendation that fits the clients wishes best. The flowchart van be found in appendix 4.

3 Locations

The Wageningen University and Research, i.e. the WUR, made one of their testing locations for different researches on irrigation available for this research. The Willem Genet-tunnel (figure 2) covers a sandy and a clayey soil that are being used for all different kinds of agricultural research. To be exact, these soils are named by the WUR as a cover sand and a river clay (figure3).

Figure 2 Willem Genettunnel with a sandy soil at the left side and a clayey soil on the right. Source: (Wilde)

Although the soils are not the natural soils that occur in this location, the soils were located here by the WUR a long time ago. Therefore the soil properties as compaction and structure come close to natural occurring soil properties. Because of this, the clayey and sandy soils in the Willem Genettunnel are considered suitable for this researches purposes.

Another big advantage of these soils is that they have been examined much more precise than will be possible with the tools and funds available for this research. Granular properties and pF-curves[5] are made available by the WUR and are attached in appendix 2.

Figure 3 Sandy soil measurement area (left) and clayey soil measurement area (right). Source: (Wilde)

[5] Curve that plots VMC on the x-axis and suction power (pF) on the y-axis.

The location with a loamy soil is located on the Nijmeegse Stuwwal near Berg en Dal. It is a push moraine formed some 130.000 years ago. The risen area is covered with a loamy layer as shown in figure 4. This drill description was made on the exact same spot as the measurements for this research are taken. The location is shown in figure 5.

Since the exact texture data of this soil is not known, these have been determined in the lab in accordance with the procedure described in the practical regulations used by Hogeschool VHL. (Internationale Agrarische Hogeschool Larenstein, 1991). The clay-, silt- and sand content were determined and the granularity was examined. Also the organic matter content was determined. All actions were carried out in triplex. Results of this part of the research can be reviewed in appendix 2.

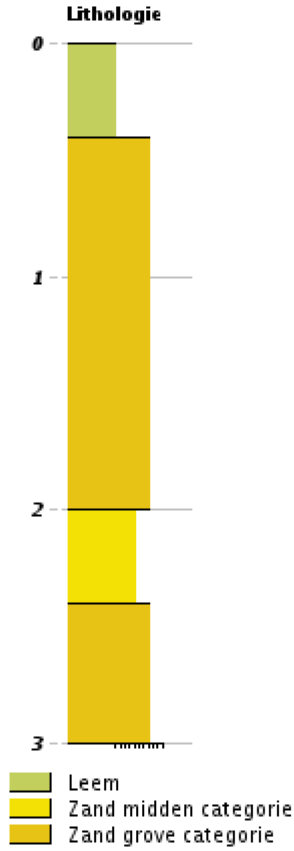

Figure 4 Drilling description measurement location loam. Source: (DINOloket)

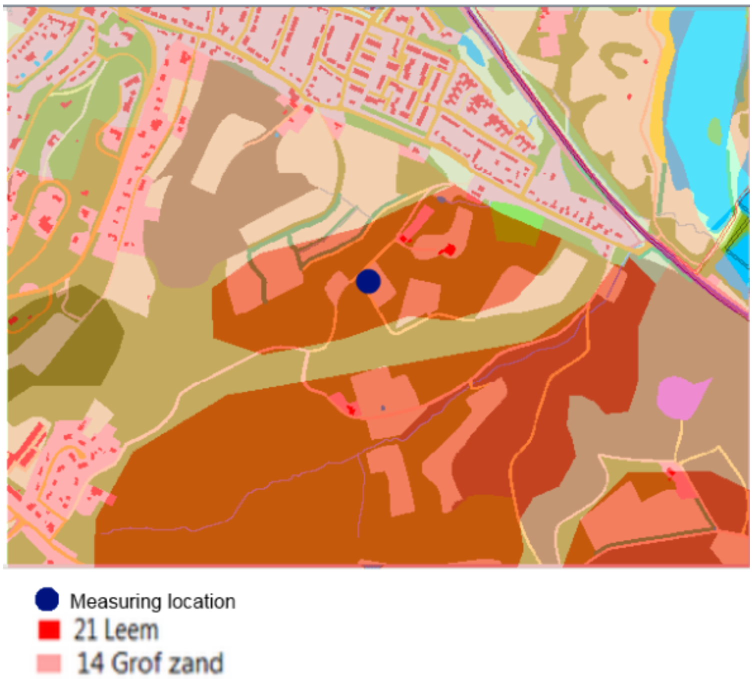

Figure 5 Measuring location near Berg en Dal. Source: (Wageningen UR)

3.1 Soil determination according to the Stiboka methodology

The soils in this research have been named following the Stiboka methodology. This choice was made because the granular data that was already available for the sandy and clayey soil was based on 53μ as boundary between clay fraction and silt fraction. The more common NEN 5104 uses 63μ as the boundary. Another important difference between the Stiboka and NEN 5104 methodology is that the Stiboka takes the sedimentary environment into account if known. (Nederlandse Vereniging van Leveranciers van Bouwgrondstoffen)
For the correct name to be designated to the soil, the clay, silt and sand content have to be determined. These can be plotted in a soil texture triangle. The clay is a fluviatile[6] deposition

[6] Deposition / sedimentation by water

and therefore the texture triangle of the non-aeolian[7] soils is used. This triangle can be reviewed in figure 6.

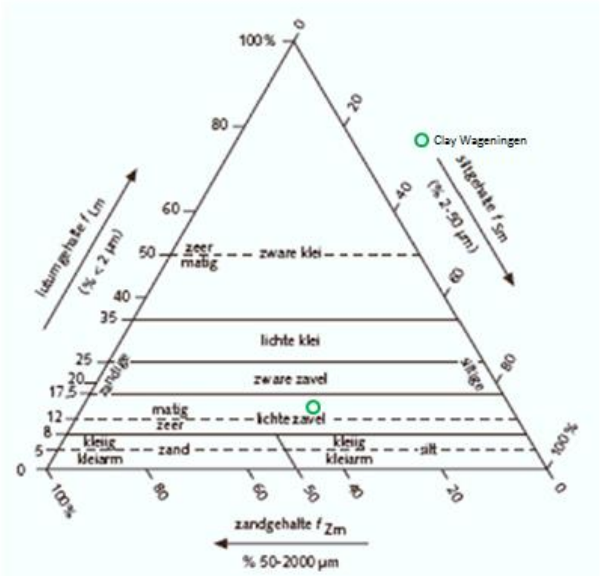

Figure 6 Stiboka soil texture triangle for non-aeolian soils with the clayey soil indicated. Source: (Nederlandse Vereniging van Leveranciers van Bouwgrondstoffen)

The soil that was assumed a clayey soil turns out to be a 'matig lichte zavel', which is best, translated as a very silty clay.

The sand and loam have been deposited by the wind. They are therefore considered an aeolian deposition. Thus, the texture diagram for an aeolian soils is used. This triangle can be found in figure 7.

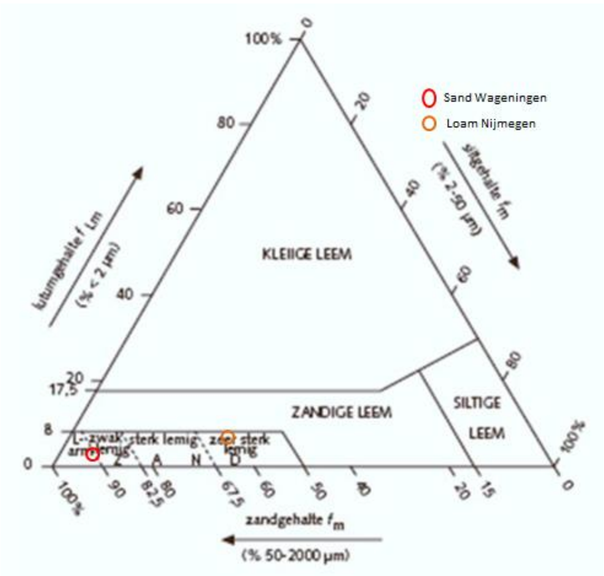

Figure 7 Stiboka soil texture triangle for non-aeolian soils with the sandy and loamy soil indicated. Source: (Nederlandse Vereniging van Leveranciers van Bouwgrondstoffen)

The sandy soil can be named as a sandy soil with low loam content. The loamy soil is a very loamy sand according to the stiboka methodology. These variations between the named and actual determined soil name can be caused by variations of the soil in the field or by usage of another determination method.

[7] Deposition / sedimentation by wind.

4 Sensor techniques and their differences

In this research multiple different sensor types are used, namely: SM300, WET, ML2x, ML3, Trime-Pico32, e^+ soil MCT, PlantCare Minilogger and the Watermark. These sensors all measure soil moisture in an indirect manner. That means that they don't measure the water directly, but they measure another property of the soil that is related to soil moisture content.
Because the measurements are indirect, errors do occur in soil moisture values. Characteristics as salt content, organic content, temperature, bulk density, texture, and clay activity influence the behaviour of the indirect measurement. The range of influence of these factors differs for each sensor and each technique. In this chapter the different techniques that are used for the sensors and the differences between those sensors will be elaborated. (Campbell, 2014)

4.1 Dielectric sensors

The most common measuring method that is used for determining soil moisture is a measurement of the dielectric constant of the soil. In short, the dielectric constant of the soil is its capacity to store charge. (Campbell, 2014)
When the dielectric constant is measured, an electromagnetic field is applied to the soil. The soil, and especially the water in the soil, can store part of this energy. This behaviour is caused by the dipole moment of molecules, dielectric relaxation and dissipation. These factors will not be further explained in this report. (Castiglione, 2014)
The relation between dielectric constant and soil moisture is considered as a proper way to determine soil moisture content because the dielectric constant of the soil is mainly determined by the presence of water. Water is best able to store charge. The dielectric constants of different components of the soil are shown in figure 8. Since the characteristics of soil, except for water and air content, do not vary much over time, it is mainly the air and water component in the soil that determines the change of the soils dielectric constant. Especially when the other components of the soil have been determined precisely, quite exact approximation of the soil moisture content can be determined.

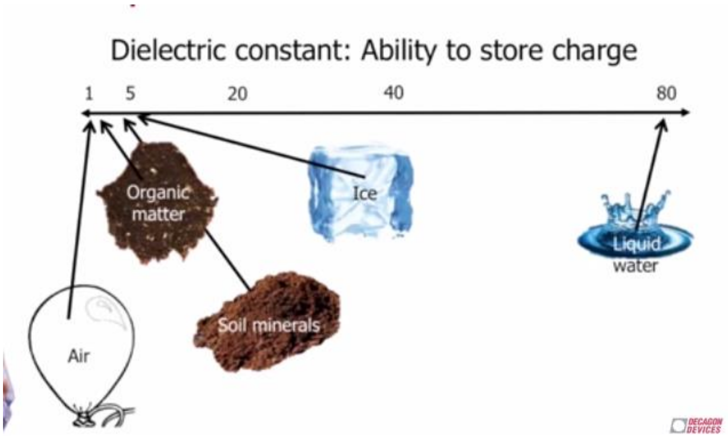

Figure 8 Dielectric constants of soil components. Source: (Campbell, 2014)

There are two different techniques that use the dielectric properties of the soil to measure soil moistures. These are Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FDR). (Eijkelkamp Agrisearch Equipment, 2012)

4.1.1 Time domain reflectometry

A soil moisture sensor that uses the time domain reflectometry (TDM) technique, consist of mainly four parts. These are a pulse generator, a cable, a probe and a sampling oscilloscope. When a measurement is started, the pulse generator creates an electrical pulse and sends it through the cable to the probe. In the probe the pulse is reflected back into the cable. The sampling oscilloscope reads this reflection as shown in figure 9. (Castiglione, 2014)

As mentioned before soil is a dielectric material that tends to store charge. Besides that, it was mentioned that the more moist a soil is, the higher the dielectric constant is.

The electrical pulse will partly be reflected at the connection between cable and sensor because of resistance there. This reflection is visible in the peak in figure 9. The remaining energy in the pulse travels down into the sensors rods. The dielectric material (soil) surrounding the rods will store part of this energy creating an electrical field. Because the energy is stored in the soil temporary, the pulse will need a longer time to flow to the end of the rod. When the pulse reaches the end of the rod, it is reflected. This reflection is visible in figure 9 too.

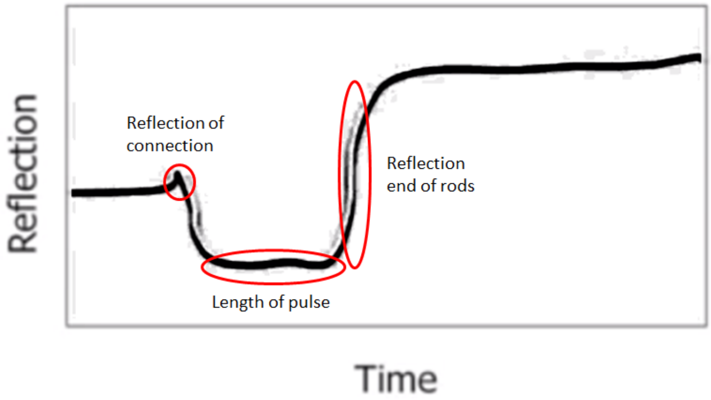

Figure 9 TDR oscilloscope reading. Source: (Castiglione, 2014)

When the moisture content of the soil increases, the storage capacity of energy of the soil also increases. Thus, more energy will be stored and it will take longer before the pulse is reflected at the end of the rod.

To sum up, if the time between reflection at the connection of the sensor and at the end of the rod gets longer, the soil is more moist. (Castiglione, 2014)

In figure 10 readings of different moisture levels are shown. In this graph the distance is on the x-axis. This is in fact in this case the same as time, since the length of the reflected pulse is equal to the time it takes to be reflected. On the y-axis the reflection coefficient is shown. This parameter describes how much of an electromagnetic wave is reflected.

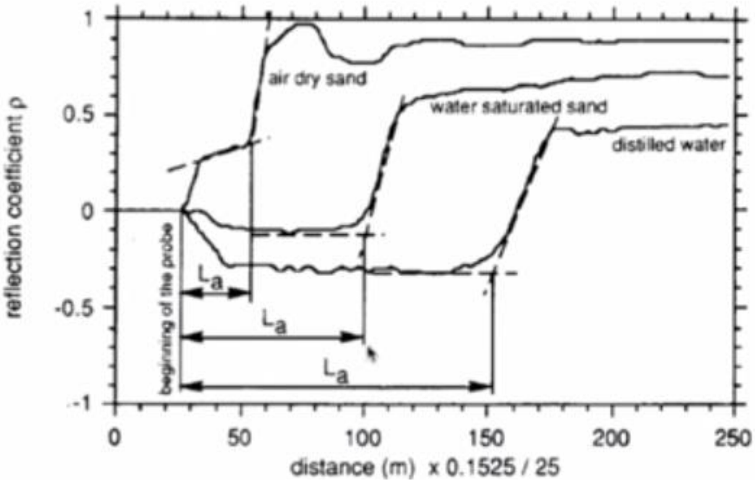

Figure 10 TDR readings at different moisture intervals. Source: (Castiglione, 2014)

It is well visible that if there is more moisture in a sample, it takes longer for that pulse to be reflected. In other words, the length of the pulse gets longer with increasing moisture content. Of course, the TDR doesn't only come with advantages. Although it can make really accurate measurements, a soil moisture sensor equipped with the TDR technique is quite expensive. This is also due to the fact that each individual sensor has to be connected to a pulse generator and a sampling oscilloscope by cable. Therefore a network of sensors requires extensive cabling. Besides that, it requires a significant battery capacity to run. TDR can also not be used in very salty soils (i.e. >2-3 dS/m). The electrical conductivity is too high then, causing the reflection to not return at all. The TDR technique is used by the SM300 sensor, the WET sensor, ThetaProbe ML2x and ML3 and the Trime-Pico.

4.1.1.1 Delta-T SM300

The SM300 is the smallest dielectric sensor available at Eijkelkamp. It is a white cased sensor with an IP68 connection plug and is compatible with the GP1, DL6, DL2e and HH2. The sensor has two small measuring rods that cause minimum disturbance in the soil.

It measures with 2.5% accuracy with a range from 0 %to 50% VWC and 0^0C to 60^oC. The SM300 also houses a soil temperature sensor. The full list of specifications can be found in appendix 1. (Delta-T Devices Ltd, 2014)

4.1.1.2 Delta-T WET-2-sensor

The WET-2 Sensor is a sensor with 3 rods. It is a thin sensor and therefore quite easy to burry. The sensor can measure water content, temperature and electrical conductivity. It can measure VWC ranging from 0% to 100% with an accuracy of 3%. The sensor operates from 0^oC to 50^oC. The sensor can be connected to the HH2 meter and the GP1 Data Logger. The full list of specification can be found in appendix 1. (User Manual for the WET Sensor type WET-2, 2007)

4.1.1.3 ThetaProbe ML2x

The ThetaProbe ML2x is not sold by Eijkelkamp anymore. It is the precursor of the ThetaProbe ML3 which will be described in the next paragraph.

The ML2x is a sensor with 4 rods. It can measure the full range of VWC from 0% to 100%. The accuracy of the sensor is 1% with a temperature form 0^oC to 40^0C and 2% with a temperature ranging from 40^0C to 70^0C. The ML2x can be connected to the HH2 meter and the DL2 and DL3000 logger. All specifications can be found in the Appendix. (Delta-T Devices Ltd, 1999)

4.1.1.4 ThetaProbe ML3

The ThetaProbe ML3 is, as said before, the successor of the ML2x. The sensor also has 4 rods and the same soil moisture measuring accuracy as its precursor. In the ML3 a temperature sensor is added. The sensor in compatible with the GP2, GP1, DL6, DL2e and the HH2 meter. (Delta-T Devices Ltd, 2013)

4.1.1.5 IMKO Trime-PICO32

The Trime-PICO32 is a sensor from IMKO GmbH. It measures soil moisture ranging from 0% to 100%. The accuracy of the sensor is 1% from 0-40% VWC and 2% 40-70% VWC. The Trime-PICO sensor can measure from a soil temperature of -15^0C to 50^OC. The sensor can, among others, be read with a HD2 meter and a Bluetooth device. For the full list of specifications see appendix 1. (IMKO micromoduletechnik GmbH, 2012)

4.1.2 Frequency domain reflectometry

The FDR sensor, also called a capacitance sensor, looks like a capacitor. A typical capacitor is used in all kinds of electronics. A capacitor exists of two magnetic plates parallel to one another. One of those has a positive charge, the other a negative charge. In between, a dielectric material is placed. When voltage is applied to the plates, an electromagnetic field is created. In this field some energy can be stored. The amount of energy that can be stored is dependent on the dielectric constant. That means that if a constant amount of charge is applied, it takes longer to charge to the maximum for a system with more water. (Castiglione, 2014)

This charging time is what a frequency domain sensor measures. Unfortunately this is very much affected by the electrical conductivity of the soil. When the applied charge is lost, it takes longer for the sensor to fully charge the soil. The FDR sensors are cheaper than the TDR sensors because it requires but a simple readout device. The FDR sensors show the best resolution to changes in water content of any method. It can detect changes of 0.001%. The e^+ soil MCT sensor uses the FDR technique. (Royal Eijkelkamp, 2005)

4.1.2.1 e^+ soil MCT sensor

The MCT sensor is the only soil moisture sensor that is developed and produced by Eijkelkamp. The other sensors are only distributed by Eijkelkamp. MCT stands for Moisture, Conductivity and Temperature, and thus these are the parameters the sensor measures. The sensor is a data logger, which means it is designed to measure it one place with a constant interval of time. The sensor can store up to 20.000 readings. It measures VWC with an accuracy of 2.5% with a temperature ranging from 0^0C to 50^0C. The sensor can be read with a readout unit, an optical unit or a cable. The device can also be connected to an e-SENSE system that sends the data per SMS to the internet. (Royal Eijkelkamp, 2005)

4.2 PlantCare Mini-Logger

The Plantcare Mini-Logger has a patented measuring technique. The measuring occurs in a specially developed felt material that is housed in the yellow casing as shown in figure 11. The felt is able to act as an interface between the soil moisture and the sensor. The sensor is briefly heated and the cooling-down time is measured. This cooling down time varies due to the amount of moisture in the felt and therefore the moisture level in the soil. Therefore the sensor provides a reliable statement off the soils moisture content. (PlantCare)

Figure 11 PlantCare Mini-Logger. Source: (PlantCare)

The Mini-Logger device has to be configured before installing. To do so, the Plantcare configuration program is required. This can be downloaded from www.plantcare.ch . In this program the logger can be programmed with a few simple steps. For soil calibration, three parameters, alpha, n and K, have to be inserted in the van Genuchten equation[8]. These values have been determined for 6 standard soils that differ in soil texture. The corresponding soil can be chosen from the texture triangle shown in figure 12. In this figure also the textures examined in this research are visible. For soil specific calibration, the standard soil closest to the measured soil have been chosen. In other words, the sand soil is calibrated with the parameters of standard soil 1, the loam soil with standard soil 3 and the clay soil with standard soil 4.

[8] A hydrological model that predicts the pF curve. (Soil Science Society of China, 2010)

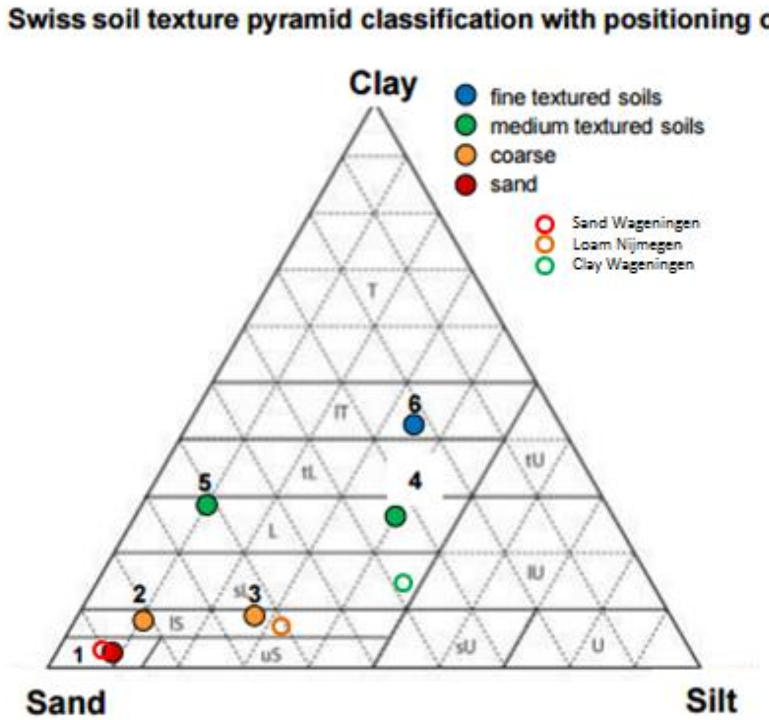

Figure 12 Texture pyramid for soil specific calibration of the Plantcare Mini-Logger

4.3 Watermark Tensiometer

The Watermark tensiometer does not measure volumetric water content like the other sensors do, but it measures the soil water tension, or matric potential. Just like the PlantCare sensor the Watermark has some kind of felt that equilibrates in moisture content with the surrounding soil. The moisture that is in the felt acts as an electrical conductor. The more moist the felt is, the better it conducts electricity and the littler the resistance is. A reading device that is compatible with the Watermark sensor measures this resistance and converts it to centibars (cb). The tension can be converted to volumetric water content with a pF-curve. (Hendriks, 2010)

5 Results

In this chapter the results will be elaborated. First of all the results of the accuracy of the sensors will be shown, sorted by soil type. After that other outcomes of the research will be elaborated as well.

5.1 Accuracy

In this paragraph the results of the field tests are described. The different graphs that present the data are attached in appendix 3. To increase readability these graphs are not included in this chapter.

5.1.1 Coefficient of determination

In figure 21, 23 and 25 all measurements taken in this research are shown in respectively a sandy, clayey and loamy soil with a standard calibration. This graph shows the distribution of soil moisture intervals and the variation in single measurements very well. It is clear that the accuracy of a single measurement between the sensors vary over 20% at the same soil moisture content.

With the values of actual and measured water content plotted on the x-axis and y-axis respectively, a perfectly accurate sensor would show a linear trend line where Y is equal to X (Y=X). X and Y show the same variable after all. This situation is what a soil specific calibration aims for. In figures 22, 24 and 26 it is visible that the trend lines approximate more to the described Y=X situation.

With these trend lines the statistical term R^2 for these linear models can be determined. The R^2 doesn't change when the soil is calibrated specifically. Explanation for that can be found in the definition of R^2 and in literature. (Ott & Longnecker, 2009) The R^2 values for the different sensors and soils can be found in table 1.

Sensor	Sand	Clay	Loam
MCT	0,7343	0,8943	0,0376
TrimePico	0,6846	0,5574	0,6057
SM300	0,8139	0,8808	0,4849
ML2x	0,7663	0,8772	0,3555
ML3	0,8095	0,8790	0,2263
WET	0,7754	0,8978	0,5159

Table 1 R^2 for the different soils with the different sensors

The R^2 values show the reliability of the measurements when fitted in this linear model. The low values for the Trime-Pico can be explained by the fewer moisture intervals covered by the sensor. Another explanation is that the measurements of the Trime-Pico have a higher standard deviation rather than the other sensors.

The measurements in the loam soil are not considered reliable for a linear relationship according to the R^2 term. This is caused by the small range of soil moisture intervals measured.

5.1.2 Average

Because figures 21 to 26 show too much data to create a proper visualisation, the averages of the measured soil moisture have been calculated for each sensor in each soil moisture interval. These results are shown in figure 27, 28 and 29.

Figure 27 shows a rather large deviation between the actual and measured moisture content around 10 and 12% actual moisture content in the sandy soil. This deviation cannot yet be explained. It is rather remarkable that the sensors al show the same abnormality on the Y-axis. Yet again, the gravimetric determination of soil moisture is a reliable process. Especially when al determinations are carried out in triplex as is the case in this research. What causes the variation between the sensors and the gravimetric determination is therefore not evident. Further research would be necessary to give a clearer view of the performance of the sensors around this soil moisture content.

It is visible in figure 27a that, except for the MCT, all sensors give a rather good average for the measured soil moisture in the sandy soil. Figure 27b shows that the average measurement value of the MCT sensor comes much closer when the sensor is calibrated soil specifically. The accuracy of the MCT improves most when calibrated specifically.

In figure 28 the average measurement values for the clay soil are presented. The sensors in the clay soil show a comparable abnormality around an actual soil moisture content of 12% as was measured in the sandy soil. Again, the MCT shows the best improvement when calibrated specifically to the soil (figure 28b).

The measurements in the loamy soil, figure 29, show different average measured values at 33,5% actual moisture content. Since this deviation is quite small, around 1 or 2%, this could well be explained by small deviations in the field or temperature differences.

5.1.3 Accuracy according to specifications

The average of the measured values doesn't provide the possibility to give any conclusions on the accuracy of a single measurement. The accuracy of a sensor is described in the specifications of each sensor. These values are shown in table 2. In the table the percentages of measurements in this research that are within this accuracy range are also given.

	accuracy according to specifications	**Percentage of measurements in range**		
		Sand	Clay	Loam
MCT	2,5%	34,2%	33,8%	49,1%
TrimePico	2,0%	24,6%	25,9%	79,4%
SM300	2,5%	60,6%	48,1%	48,4%
ML2x	1,0%	26,5%	20,6%	30,8%
ML3	1,0%	33,3%	17,9%	16,0%
WET	3,0%	71,6%	67,4%	26,9%

Table 2 Measurements within accuracies range

The outcome of table (2) clearly shows that the accuracy named in the specifications can hardly be depended upon. For both of the Thetaprobes only 20 to 30% of the measurements turn out to be within the given 1% accuracy. The WET sensors performance comes closest to the promised accuracy in the sandy and clayey. This is because the sensor has the lowest claimed precision.

Next in line is the SM300. This sensors claimed precision is a little higher than the WET sensors precision, and therefore fewer measurement values end in this range. The MCT should have the same precision as the SM300, but the results show it can't make up to this promise. Only 30 to 35% of the measurements have this claimed accuracy of 2.5%.

The Thetaprobes promise a very high precision of 1%. In the field this accuracy would not be very useful because of the spatial variations in the soil. Only around 15 to 30% of the infield measurements have an accuracy of 1%.

5.1.4 Root Mean Squared Error at different moisture intervals

The RMSE can be determined for each soil moisture interval as well as for the full range of intervals. In figure 30, 31 and 32 the RMSE of respectively the sandy, clayey and loamy soil are shown. The higher the RMSE, the more the sensors output differs from the actual soil moisture content.

According to literature, about 68% of all measurements drawn from a normal distribution are within one standard deviation away from the mean. (Ott & Longnecker, 2009) The same can be concluded from a RMSE. When for example the result of the RMSE gives a 5 at a moisture interval of 20%, it can be concluded that 68% of all measured values are within the range of 15 to 25%.

In figure 30 the same abnormalities are visible as discussed in paragraph 5.1.2. Furthermore, it is hard to conclude anything about the accuracy of a single sensor in a certain moisture content based on this output. There are too few intervals measured to give a reliable conclusion on which sensor is best at a certain moisture content. Besides, the SM300, ML2x, WET and ML3 show quite an equal pattern in measurements.

From figure 30 it can be concluded that MCT sensor and Trime-Pico show a rather large RMSE over the full range of soil moisture intervals in the sandy soil. That concerns both the standard calibration as well as the soil specific calibration

From figure 31 it can be concluded that in a clayey soil the MCT sensor is not useful when not calibrated soil specifically. The Trime-Pico performance worsens when the sensor is calibrated soil specifically in this case. This is due to the fact that a 2 point calibration had been performed. The values in between show a larger RMSE on that account.

The Trime-Pico shows a very low RMSE in the loamy soil with both calibrations. Unfortunately this might be caused by the fewer moisture intervals that have been measured. One of the sensor rods had been broken.

5.1.5 Root Mean Squared Error in measured range

As mentioned in chapter 2.3, the RMSE can also be calculated over the full range of measurements. This gives a rather clear view of the accuracy of the sensor. The results for the sandy soil are shown in figure 13.

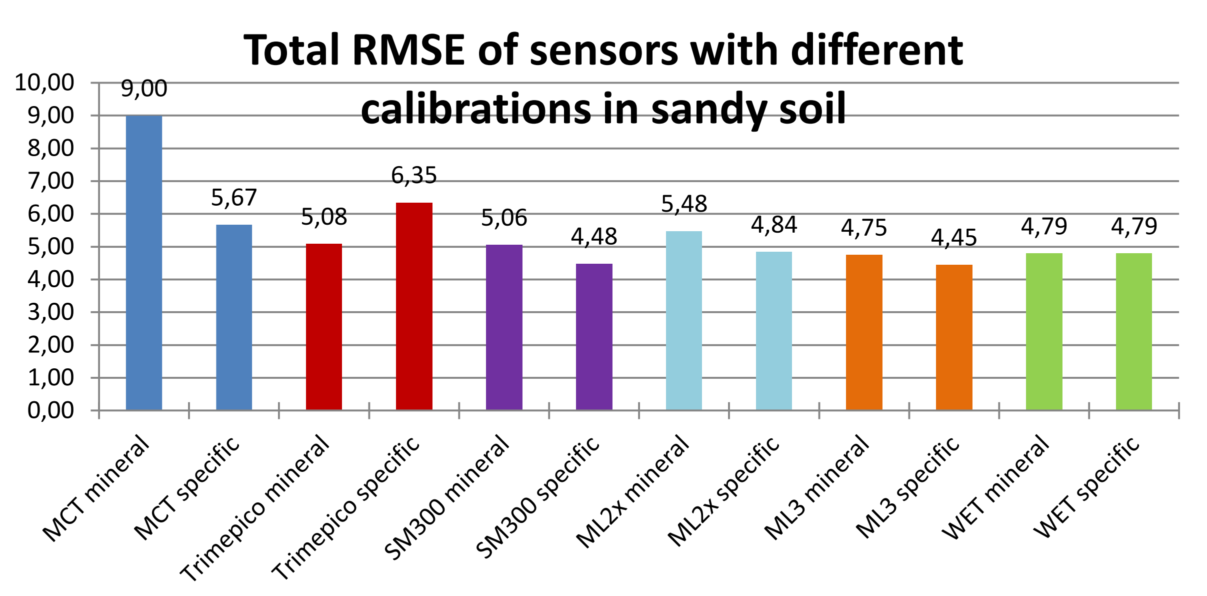

Figure 13 RMSE of the sensors in sandy soil with standard calibration and soil specific calibration

Figure 13 proves that the ML3 or WET sensor can best be used if measurements are being performed in a sandy soil without the possibility to calibrate the soil specifically. When soil specific calibration is possible, the SM300 or the ML3 would give the best results in a sandy soil.

Usage of the MCT in a sandy soil without soil specific calibration should be prevented. It does not appear to give any reliable results.

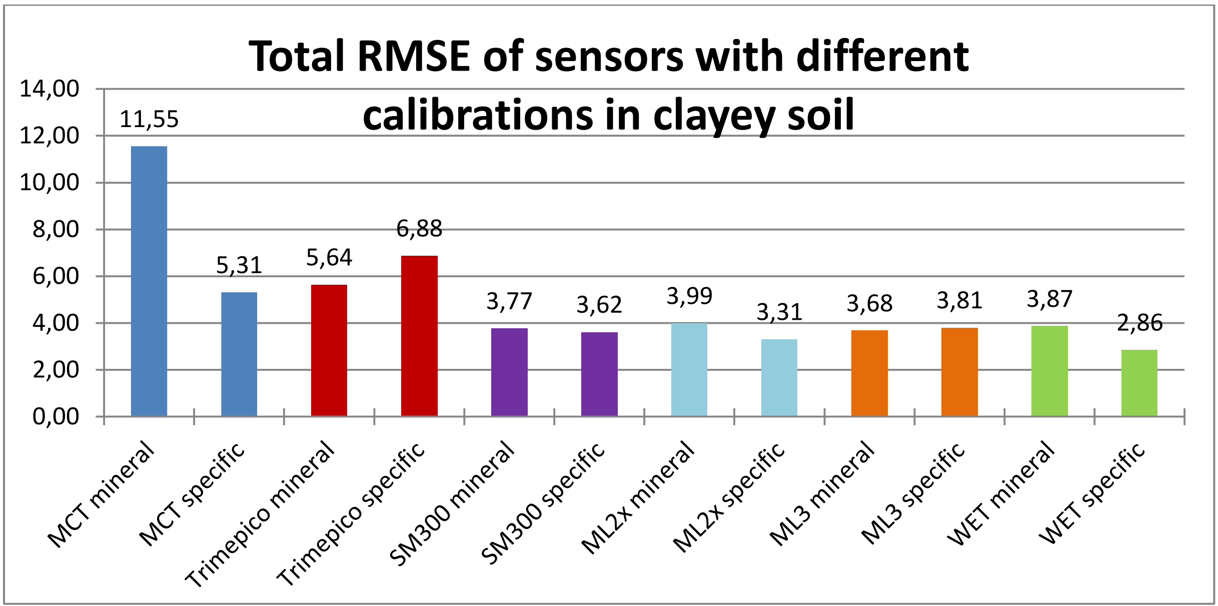

Figure 14 RMSE of the sensors in clayey soil with standard calibration and soil specific calibration

According to figure 14, the SM300, ML2x, ML3 and WET sensor all give rather precise measurement output in a clayey soil. The MCT should again not be used when soil specific calibration is not possible. When soil specific calibration is possible, a wet sensor would be the best option concerning accuracy.

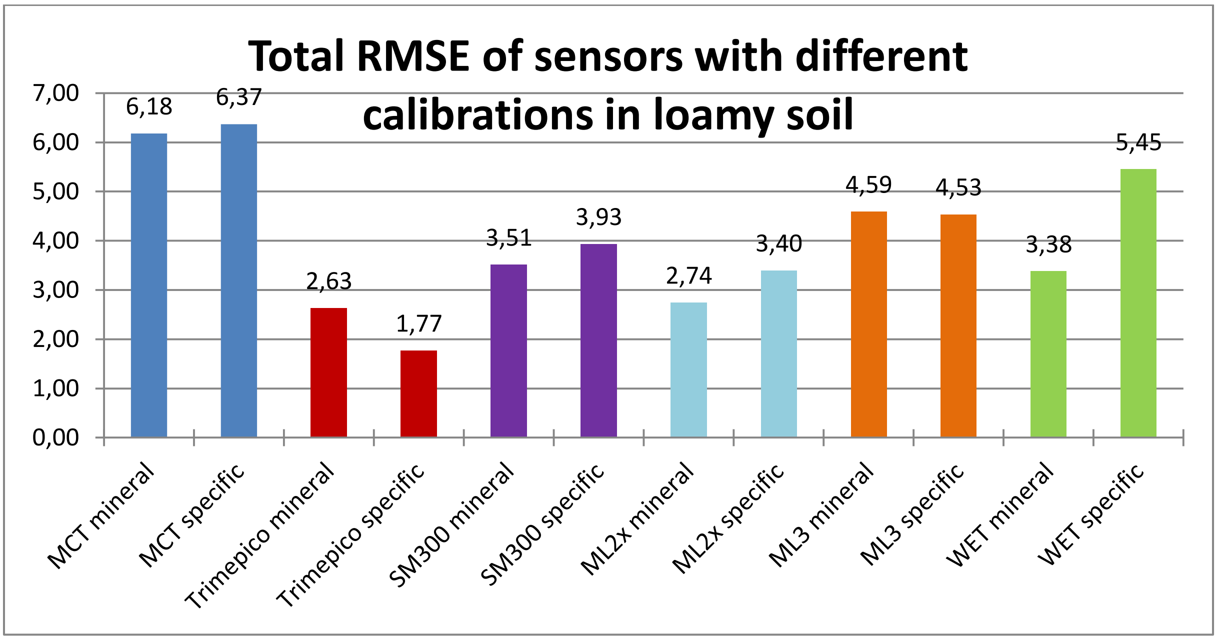

Figure 15 RMSE of the sensors in loamy soil with standard calibration and soil specific calibration

The output of the measurements in the loamy soil as shown in figure 15 is less clear. The soil specific calibrations have not been as successful as in the sandy and clayey soil. The SM300, ML2x, ML3 and WET sensor have been calibrated for the range from 0% moisture to 38.5%. It seems like these calibrations don't comply quite well with the output in the range between 30 and 35% moisture. The Trime-Pico is calibrated for a soil moisture interval of 33,5% to 38.5%. That explains the very low RMSE and it would thus not be fair to compare these outputs. The MCT is calibrated in the same way as the Trime-Pico is, but the standard deviation between the measurements of the MCT is very high. Therefore also the RMSE is very high.

5.2 Plantcare Mini-logger

The Plantcare sensor turned out to no show volumetric water content after all. The sensor shows a relative moisture content which is not related to VWC nor suction power. (Schmidt, 2015) It is thus not possible to compare the loggers output with any of the other sensors.
The sensor gives an indication of soil moisture, which can be used for irrigation purposes when one has learned to interpret the sensors output with a certain soil. It will be presented in the flowchart as a sensor that gives an indication of soil moisture.

5.3 Watermark sensor

The Watermark sensor is a tension meter that measures the suction power of the soil. This cannot be linearly related to moisture content, since this relation is dependent on the history of wetting and drying. At the same water content, the suction is much higher in a drying soil rather than in a wetting soil. This phenomenon is called hysteresis and an example is shown in figure 16. Due to this fact, suction can hardly be related to soil moisture content and the precision of the other tested sensors. Therefore these results are elaborated separately in this chapter. (Hendriks, 2010)

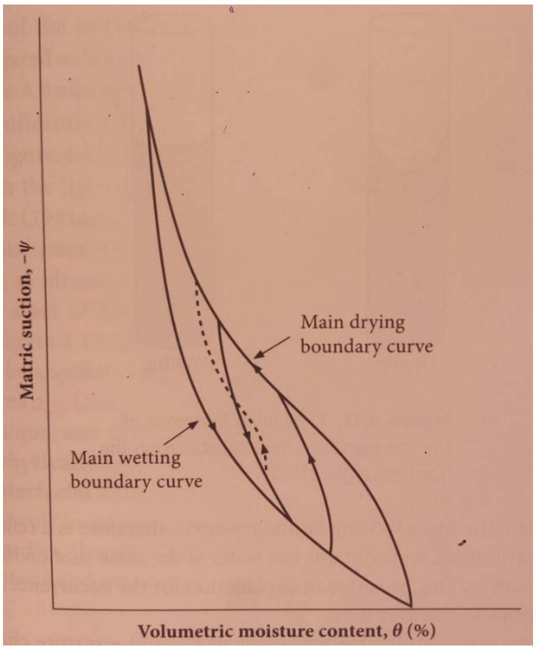

Figure 16 Hysteresis in soil moisture characteristics. Source: (Hendriks, 2010)

In figure 17, 18 and 19 on the next page the outcomes of the Watermark in the 3 different soils are shown. The pF curves of the sandy and clayey soil have been determined in the laboratory by the WUR. The pF-curve of the loamy soil has been assumed on the Genuchten equation with variables predicted by the 'Bundesanstalt für Geowissenschaften und Rohstoffe'. (Wageningen UR) (BGR). The variables of the Genuchten equation used in this research are the variables used by Plantcare and the American Society of Agricultural Engineers (ASAE). (PlantCare) (American Society of Agricultural Engineers, 1982) Their values can be found in table 3.

Soil type	Saturated water content	Residual water content	alpha	n
Sand	0,37165	0,02	0,013	2,834
Clay	0,41629	0,035	0,013	2,956
Loam	0,41165	0,015	0,014	2,812

Table 3 Variables for Genuchten Model. Source: (PlantCare) (American Society of Agricultural Engineers, 1982)

The Watermark output looks much like the outcome of the Genuchten equation. The pF is around 2 for most of the measurements (figure 17). This could well be explained since all water that is held (suction) below pF 2 tends to infiltrate. (Hendriks, 2010) Since the soil had dried completely at the start of this research, it is likely that the suction of the soil was around 2 pF.

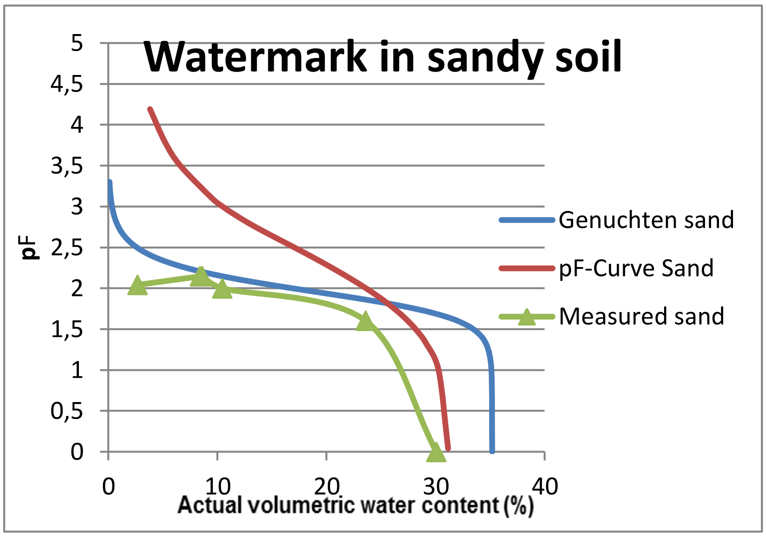

Figure 17 Watermark in sandy soil combined with pF-curve and Genuchten retention curve.

The pF around 30% saturation could be right either, since the pF at saturation ranges from 0 to approximately 1.5 according to the pF curve and the Genuchten equation.
According to this research, the Watermark sensor seems to work rather good in a sandy soil.

The clayey soil's ranges up to 2.8 pF as seen in figure 18. This would be contrasting with the 2 pF as named above, if other factors did not affect suction power. The suns radiation increases soil temperature causing a higher possible suction. Therefore, the results of the Watermark in the clayey soil do not seem unlikely.

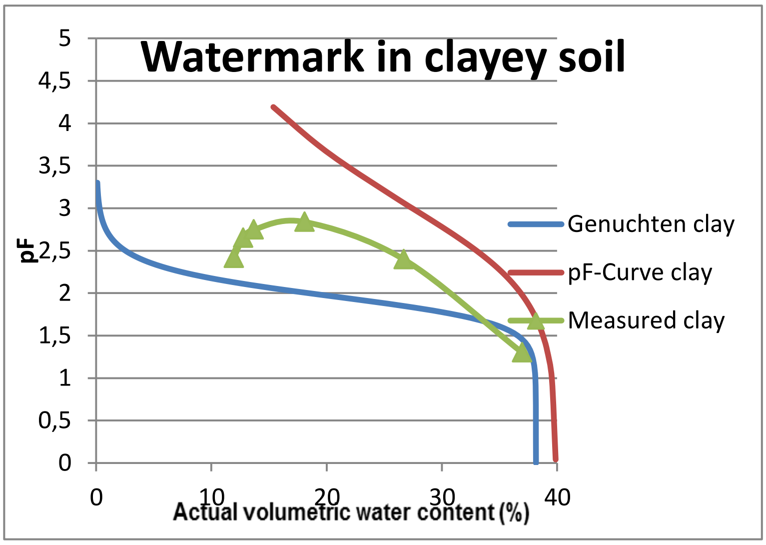

Figure 18 Watermark in clayey soil combined with pF-curve and Genuchten retention curve.

Unfortunately this research does not cover enough soil moisture intervals in the loamy soil to give any result for the performance of the Watermark in the loamy soil. As seen in figure 19, the readings of the Watermark nearly vary in pF nor moisture content.

For a better result on the Watermark sensor, a more laboratory controlled research seems necessary. In the laboratory the drying and wetting history can be influenced creating a much clearer and reliable view on the sensors performance. In a pF sandbox the suction power can be influenced directly.

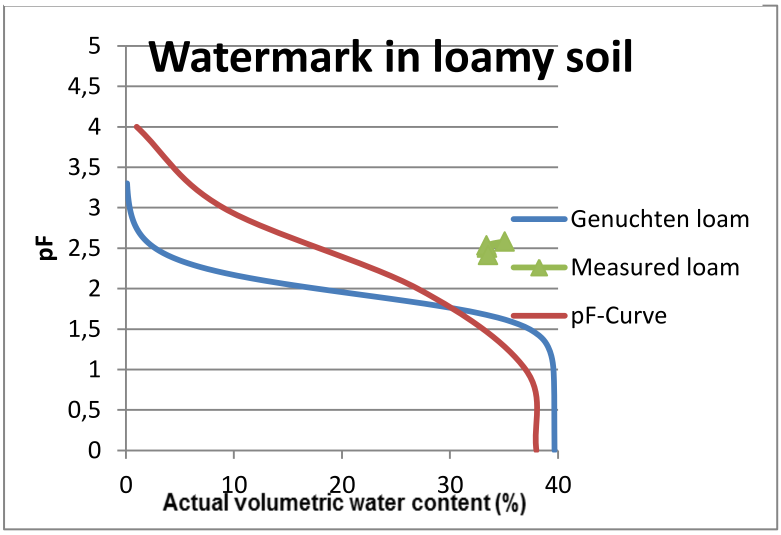

Figure 19 Watermark in loamy soil combined with pF-curve and Genuchten retention curve.

5.4 Price

The price of a product always plays an important part when considering to buy a product. The sensors Eijkelkamp sells come in different price ranges. In table 4 the different sales prices of the different products are shown. The ThetaProbe ML2x is not shown in this table since it is not sold by Eijkelkamp anymore.

Article description	Article number	Price in euros (€)
HH2 meter	14.26.02	620
ThetaProbe ML3	06.15.50	505
SM300	14.24.07	366
WET-2 sensor	19.33.03	1115
Watermark reader	14.27.01	341
Watermark Sensor	14.27.05	42
Plantcare mini-logger	19.50.01	460
MCT logger	11.41.11	1210
MCT control	11.31.92	729
Trime-PICO32	14.65.03	605
HD2 meter	14.65.21	1330

Table 4 Prices of the sensors and related products. Source: (Eijkelkamp)

5.5 Durability

In this research not all sensors turned out to be suitable for in situ use. Because the sensors are pushed in the soil over and over again, the rods need to be quite durable. In this research especially the rods of the Trime-Pico turned out to break easily. Besides that, when the rods are positioned skew this can cause an error in the measurement.

Next to the Trime-Pico, also the MCT sensors rods didn't seem to be very durable. Although they didn't break, they were easily bended causing a significant deviation in the measured value. However, the MCT sensor is developed as a logger, and therefore it wouldn't be used much as a in situ device. Maintenance is recommended yearly when installed permanently. This includes a battery replacement. (Royal Eijkelkamp, 2008)

The SM300 rods can easily bended when not used thoughtful. The thin rods can easily be bended and therefore they can easily be destroyed when pushing it too hard onto a rock. When the sensor is used with caution, the SM300 can be very durable.

The Thetaprobes and the WET sensor did not show any sign of disruption in this research and are therefore considered most durable.

For the Plantcare sensor a yearly replacement of the felt is recommended. Besides that, depending on measuring interval, and other properties, the battery needs replacement yearly too. (PlantCare)

The Watermark sensor does not need maintenance when installed permanently. It has to be cleaned when removed from the soil. The reading device needs a new battery each growing season.

5.6 Soil disturbance

During this research a tremendous variation in soil disturbance was noticed with the different sensors. As can be expected, especially the clayey soil is very sensitive to soil disruption. The clay conglomerates easily when dried. This chunk of soil gets stuck in the sensors rods. When plants are stuck in this chuck, they might be destroyed when taking the measurement. Therefore, it is important to take the soil disturbance into account when choosing a sensor.

As seen in the figure 20, the ML3 takes a lot of soil with it after taking a single measurement. The ML2 has this same disadvantage, since it has the same rods.

Also the wet sensor was very disturbing to some soils, but far less rather than the ML3 did. The Trime-Pico32 and the e^+ soil moisture sensor cause some soil disruption when used for in situ measurement. The SM300 nearly caused no disruption in the soil thanks to its thin measuring rods.

Figure 20 The Thetaprobe with a chunk of clay after a measurement

5.7 Temperature

According to the specifications all the sensors, except for the ML2x and the Watermark, have a thermometer built in the device. The Plantcare sensor measures temperature with an accuracy of 0.3^{0}C. The MCT, SM300 and ML3 measure temperature with an accuracy of 0.5^{0}C. The Trime-Pico and the WET sensor have the lowest accuracy of 1.5^{0}C.

5.8 Salinity range

Only the dielectric sensors are affected by salt content. Thus, Plantcare and Watermark are unaffected by salt content. The ML2x has the highest operating range regarding salinity. The WET sensor cannot be used in salty soils. All operating ranges are shown in table 5.

Sensor type	Lower boundary	Upper boundary	Unit
MCT	0	500	mS/m
SM300	50	1000	mS/m
ML2x	0	2000	mS/m
WET	0	300	mS/m
ML3	50	500	mS/m
Trime-Pico	0	1000	mS/m
Plantcare	N/A	N/A	
Watermark	N/A	N/A	

Table 5 Operating range in saline soils

6 Conclusion

Royal Eijkelkamp sells soil moisture sensors that measure soil moisture with different techniques. The most used technique is Time Domain Reflectometry, but also Frequency Domain Reflectometry, heat pulse and tensiometers are for sale. Their specifications differ in accuracy, price, durability, soil disturbance, temperature range and salinity range.

For the most reliable results the examined soils have to differ in texture as much as possible. Therefore a sandy, clayey and loamy soil have been selected for this research. The sandy and clayey soil in the Willem Gennettunnel in Wageningen were considered the best locations for these soil types. The best loamy soil was selected on the Nijmeegse Stuwwal in Berg en Dal.

The values measured with the sensors and the actual soil moisture contents that have been determined with the Kopecky rings, match rather well. With exception of a few measurements around the 12% water content in the sandy and clayey soil, a good linear fit was found for all sensors included in the research. Is has to be noted though, that the accuracy of all sensors is not as good as claimed by the producers.

It can be concluded that the ML3 and SM300 gives the best accuracy in a sandy soil. The WET sensor is most accurate in a clayey soil. The results for the loamy soil are not reliable enough to give a proper conclusion. Besides the accuracy, also other specifications and the clients requirements should be taken into account when consulting.

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8 List of tables and figures

9 Appendix 1: Technical specifications of sensors

Technical Specification e+ soil MCT

General:	
Length	: Type dependent (from 220 mm to 1125 mm excl. electrodes)
Working length	: Type dependent (10, 25, 50, 75 and 100 cm)
Diameter	: 22 mm
Measuring electrodes	: 2 electrodes. Dimensions: 68 x 3 mm. Distance between them: 15 mm
Weight	: Type dependent (± 300 g to 1163 g)
Temperature working range	: -20...80 °C
Relative humidity range	: 0...100%
Housing	: Stainless steel 316L
e+ SOIL MCT data logger:	
Storage capacity	: 3 x 20.000 measurements
Measurement interval time	: 10 ...60 sec. 1...60 minutes 1...24 hours
Data logging method	: Fixed interval time
Clock accuracy	: 1 sec. per day
Alarm level (adjustable)	: low and/or high alarm in the whole measuring range of all parameters
Battery status indication	: 0...100%
e+ SOIL MCT sensor:	
Measuring frequency	: 20 MHz
Measuring volume (saturation)	: ≥ 1000 ml (500 ml 98% accuracy)
Soil moisture measuring range	: 0...100% volumetric
Soil moisture accuracy	: +/- 2.5% of the measurement value (mineral soil types, 0...50 °C)
Soil moisture resolution	: 0.01%
Conductivity measuring range	: 0...5 mS/cm
Conductivity accuracy	: +/- 5% of the measurement value (0...50 °C, 0...2 mS/cm)
Conductivity resolution	: 0.01 mS/cm
Temperature measuring range	: 0...80 °C
Temperature accuracy	: +/- 0.5 °C
Temperature resolution	: 0.01 °C
Power:	
Battery	: 3.6V (AA) lithium battery 2.3 Ah
Lifespan of battery	: 1 year (typ. for 1 hour sample speed and 0...50 °C)
Communication:	
Via	: e-SENSE SMS-modem, Optical connector (IR) Readout unit, DRC-cable (5...200m), IrDa readout unit remote (1...2 m)

(Royal Eijkelkamp, 2005)

Accuracy (in % volumetric water content):			
conductivity range:	0..6dS/m	6..20dS/m	>20dS/m
Moisture range 0..40%:	±1%	±2%	with material specific calibration
Moisture range 40..70%:	±2%	±3%	
Repeating accuracy:	±0.2%	±0.3%	
Temperature caused drift of electronics (full range):	±0.3%		
Soil temperature measuring range:	-15°C...50°C		
Soil temperature measuring accuracy:	±1,5°C absolute; ±0,5°C relative		
Measurement volume:	0,25L ≙ 110x50mm diameter		
Operating Temperature:	-15°C...50°C (extended temperature range on request)		
Calibration:	Calibration for a wide range of standard soil types (in accordance with Topp (equation))		
	standard calibration for most soils, customizable material specific calibration, storage of up to 15 user defined calibration curves, calibration of dialectric permittivity is possible		
Probe body:	waterproof sealed PVC (IP68)		
Size:	155 x Ø32mm		
Rod lenght:	standard: 110mm		
Rod diameter:	3,5mm		
Interfaces:	IMP-BUS RS485 Analogue output: 2x 0..1V, 0(4)..20mA[1] 0..100% vol. water content -40..+70°C soil temperature		
Option 1 (RS485 & analogue):	1,5m cable with 7-pin female connector		
Option 2 (IMP-BUS):	5m cable with 4-pin female connector		
Option 3 (all interfaces):	5m cable with end splices (all interfaces) Optional available for cable extension: E-BOX (cable extension box) [1]Optional available for cable extension and current output: C-BOX (0..1V to 0(4)..20 mA converter box)		

(IMKO micromoduletechnik GmbH, 2012)

	SM300	***Notes***
Soil Moisture Content		
Accuracy	$0.025m^3.m^{-3}$ (2.5%)	*Note [1]*
Measurement range	Full accuracy over 0 to $0.5m^3.m^{-3}$	*Measures full range up to $1.0m^3.m^{-3}$ with reduced accuracy*
Salinity range	50 to $1000mS.m^{-1}$	*Salinity errors < $0.035m^3.m^{-3}$ from 0 to $0.4m^3.m^{-3}$*
Temperature range	Full accuracy over 0 to 60°C	*Moisture content readings in frozen soil are not meaningful*
Output	0 to 1.0V differential	*Corresponding to ~ 0 to $0.6m^3.m^{-3}$ nominal*
Sample volume	~55 x 70mm diameter	*Sample volume extends to ~1 litre, but is weighted towards soil immediately surrounding the rods*
Soil Temperature	*SM300 must be fully buried for the sensor to accurately measure the temperature of the soil*	
Accuracy	0.5C	*Excludes cable length errors, see User Manual for details [2]*
Measurement range	Full accuracy over 0 to 40°C	
Output	Resistance 5.8 to 28kΩ	*10k precision thermistor*
Power requirement	5 to 14V, ~18mA for 1s	
Environmental	IP68	*-20 to +60C operating range*
Dimensions	143 x 40mm diameter	*See drawing below*
Weight	0.1kg	*Excluding cables*
Sensor calibration	Sensors are fully interchangeable	*Individual sensor calibrations not required*
Logger / Meter compatibility	GP1, DL6, DL2e and HH2	*HH2 does not record or display the soil temperature*

[1] Accuracy figures are quoted at an expanded uncertainty coverage level of k=2 and calculated using standard Monte Carlo techniques.

[2] Maximum cable lengths: 100m for GP1 and DL6 data loggers, 100m for DL2e water content measurement, 25m for DL2e temperature.

(Delta-T Devices Ltd, 2014)

Technical Specifications	Theta Probe ML2x	
Type No.	ML2x	
Measurement parameter	Volumetric soil moisture content, θ_V ($m^3.m^{-3}$ or %vol.).	
Range	Accuracy figures apply from 0.05 to 0.6 $m^3.m^{-3}$, Full range is from 0.0 to 1.0 $m^3.m^{-3}$	
Accuracy	±0.01 $m^3.m^{-3}$, 0 to 40°C, ±0.02 $m^3.m^{-3}$, 40 to 70°C,	after calibration to a specific soil type
subject to soil salinity errors, see below	±0.05 $m^3.m^{-3}$, 0 to 70°C	using the supplied soil calibration, in all 'normal' soils,
Soil salinity errors	0.0 to 250 $mS.m^{-1}$, < -0.0001 $m^3.m^{-3}$ change per $mS.m^{-1}$, 250 to 2000 $mS.m^{-1}$, no significant change.	
Soil sampling volume	>95% influence within cylinder of 4.0cm diam., 6cm long, (approx 75 cm^3), surrounding central rod.	
Environment	Will withstand burial in wide ranging soil types or water for long periods without malfunction or corrosion (IP68 to 5m)	
Stabilization time	1 to 5 sec. from power-up, depending on accuracy required.	
Response time	Less than 0.5 sec. to 99% of change.	
Duty cycle	100 % (Continuous operation possible).	
Interface	Input requirements: 5-15V DC unregulated. Current consumption: 19mA typical, 23mA max. Output signal: approx. 0-1V DC for 0-0.5m^3m^{-3}	
Case material	PVC	
Rod material	Stainless steel	
Cable length	Standard: 5m. Maximum length: 100m	
Weight	350 gm approx. with 5m cable.	

. (Umweltanalytische Producte GmbH, 1999)

Specifications W.E.T. sensor

Probe Output		**Range**	**Accuracy**	**Units**	**Notes**
Serial data for:	Permittivity, ε'	1 to 80	± 2.5	(none)	0 to 40°C, 0.1 to 0.55 $m^3.m^{-3}$ soil moisture content
	Bulk electrical conductivity, EC_b	0 to 300	± 10	$mS.m^{-1}$	
	Temperature, °C	-5 to 50	± 1.5	°C	after equilibration (~20s)
Which is used to calculate:	Water Content, θ	0.2 to 0.8 0 to 0.55 0 to 0.55	± 0.04 *[1]* ± 0.05 ± 0.03	$m^3.m^{-3}$	with WET-CL calibrations with supplied soil calibrations after soil-specific calibration
	Electrical conductivity of pore water, EC_p	see graph in following section			
Frequency	20 MHz				
Calibration	Individual sensor calibrations supplied (3.5" FDD)				
Environment	Probe sealed to IP67, 25-way D-connector sealed to IP65, 9-way D-connector sealed to IP44 Operating temperature 0 to 40°C				
Power	Typically 40mA during 2.5s measurement cycle, WET-2 (all versions) 5 to 9 VDC				
Dimensions	**Probes**: 68 long x 3mm diameter, (Centre rod 60mm) **Housing**: 55 x 45 x 12mm.				
Sampling vol.	~500 ml				
Weight	75g.				

[1] Water Content accuracy specifications apply at 20°C.

(Ltd, Delta-T Devices, 2007)

Specifications ML3

Volumetric water content	
Accuracy	±1% vol over 0 to 50% vol and 0-40°C using soil specific calibrations
Measurement range	0 to 100% vol with reduced accuracy[6]
Salinity error (see p.27)	≤3.5%vol over 50 to 500 mS.m^{-1} and 0-50% vol
Output Signal	0-1V differential ≈ 0 to 60% vol nominal
Output compatible with	GP1, GP2, DL6, DL2e, HH2
Temperature	*ML3 must be fully buried to accurately measure soil temperature*
Sensor accuracy	±0.5°C over 0-40°C *not including logger or cabling error*
Output	Resistance[7]: 5.8kΩ to 28kΩ
Output compatible with	GP1, GP2, DL6[8], DL2e, HH2
Cabling error contribution (to temperature readings)	Negligible for GP1, GP2 & DL6 (any cable length) Negligible for DL2e (with 5m cable)[9]
Maximum cable length	100m (GP1, GP2 & DL6 data loggers) 100m (DL2e: water content measurement) 25m (DL2e: temperature measurement)
Power requirement	5-14VDC, 18mA for 0.5 to 1s
Operating range	-20 to +60°C
Environment	IP68
Sample volume	>95% influence within 40mm dia. cylinder 60mm long (approx. 75 cm^3) around central rod.
Dimensions/weight	170.5 mm x 39.8 mm dia./138 gm (without cable)

(Delta-T Devices Ltd, 2013)

PlantCare Mini-Logger	Description
Measuring principle	MHP: Micro-Heat-Pulse measurement of soil moisture and soil temperature
Operating temperature	-20° C to +50° C
Measuring range	▪ Moisture: 0 -100% at 0° - 37°C soil temperature ▪ Temperature: -20 - +50°C
Reading accuracy	▪ Moisture: Relative %: 1% / hPa: 1hPa ▪ Temperature: 0.1 °C
Measuring accuracy	▪ Moisture: +/- 3% ▪ Temperature: +/- 0.3°C
Frost resistant	Yes
Type of soil	All
Weight	130 gr.
Power supply	2 AA 1.5V mono-cells
Battery life	Approx. 1 year depending on measuring cycle **and frequency of data readout**
Logging capacity	approx. 12.000 records
Data-Export	Export cable and USB stick
Programming	Via configuration file on USB stick
Possible settings	▪ Device name ▪ Start-time for first measurement ▪ Measuring cycle time: 10 – 360 min ▪ Moisture output in relative % or hPa ▪ Date and time ▪ Data erase
Data analysing	PlantCare DataViewer software (included)
Sealing electronics and sensor	IP67
Maintenance	None
Accessories	Sensor tip with felt / Data upload/download cable with 2 USB Sticks

(PlantCare)

Watermark Technical Specifications

Maximum measuring depth	> 100 cm
Measuring accuracy	± 5%
Measuring range	0...2000 hPa
Reading accuracy	0.5%
Registration type	logging
Volume of material needed	30 ml

(Eijkelkamp)

10 Appendix 2: Granular data soils

Onderzoek
Granulair
Zandgrond Nieuwlanden

Postbus 115
6860 AC Oosterbeek
Meer informatie:
T: 0900-2352544
F: 026-3346409
E: klantenservice@blgg.nl
I: www.blgg.nl

Uw klantnummer: 2211378

Unifarm De Haaff
Vollegrond
Bornsestg 48
6708 PE WAGENINGEN

Onderzoek	Onderzoek-/ordernr: 168303/002148428	Datum monstername: 19-03-2008	Datum verslag: 10-04-2008	Subsidieverlener: Blgg Kortingsregeling, Postbus 115 6860 AC OOSTERBEEK
	Nieuwlanden Tunnel			
Monster	Grondsoort: Dekzand		Monster genomen door: Derden	Contactpersoon monstername: Herman Dorresteijn: 0652002114

Resultaat		**Eenheid**	**Methode**	**Resultaat**	**Streef-niveau**	**Waardering**
weergegeven in droge grond	Zuurgraad (pH)		$CaCl_2$ *	6,4		
	Organische stof	%	Gloeiverlies	2,9		
	Koolzure kalk	% $CaCO_3$	Scheibler	0,2		

		Eenheid	**Resultaat**	**0 10 20 30 40**
weergegegen in % van de minerale delen.	0-2 μ	%	2,9	
	2-16 μ	%	1,8	
	16-50 μ	%	5,3	
	50-105 μ	%	14,7	
	105-150 μ	%	21,2	
	150-210 μ	%	22,3	
	210-300 μ	%	17,1	
	300-420 μ	%	7,8	
	420-600 μ	%	3,4	
	600-2000 μ	%	3,5	
	M50 Mediaan	μ	174	
	D60/D10	Verhoudingsgetal	3,8	

Eijkelkamp Academy
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Hogeschool VHL
University of Applied Sciences

Blgg

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Uw klantnummer: 2211378

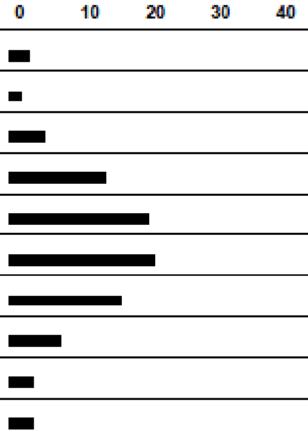
Unifarm De Haaff
Vollegrond
Bornsestg 48
6708 PE WAGENINGEN

Onderzoek	Onderzoek-/ordernr: 168303/002148428 Nieuwlanden Tunnel	Datum monstername: 19-03-2008	Datum verslag: 10-04-2008	Subsidieverlener: Blgg Kortingsregeling, Postbus 115 6860 AC OOSTERBEEK

Monster	Grondsoort: Dekzand	Monster genomen door: Derden	Contactpersoon monstername: Herman Dorresteijn: 0652002114

Resultaat		**Eenheid**	**Methode**	**Resultaat**	**Streef-niveau**	**Waardering**
weergegeven in droge grond	Zuurgraad (pH)		$CaCl_2$ *	6,4		
	Organische stof	%	Gloeiverlies	2,9		
	Koolzure kalk	% $CaCO_3$	Scheibler	0,2		

		Eenheid	**Resultaat**
weergegegen in % van de minerale delen.	0-2 μ	%	2,9
	2-16 μ	%	1,8
	16-50 μ	%	5,3
	50-105 μ	%	14,7
	105-150 μ	%	21,2
	150-210 μ	%	22,3
	210-300 μ	%	17,1
	300-420 μ	%	7,8
	420-600 μ	%	3,4
	600-2000 μ	%	3,5
	M50 Mediaan	μ	174
	D60/D10	Verhoudingsgetal	3,8



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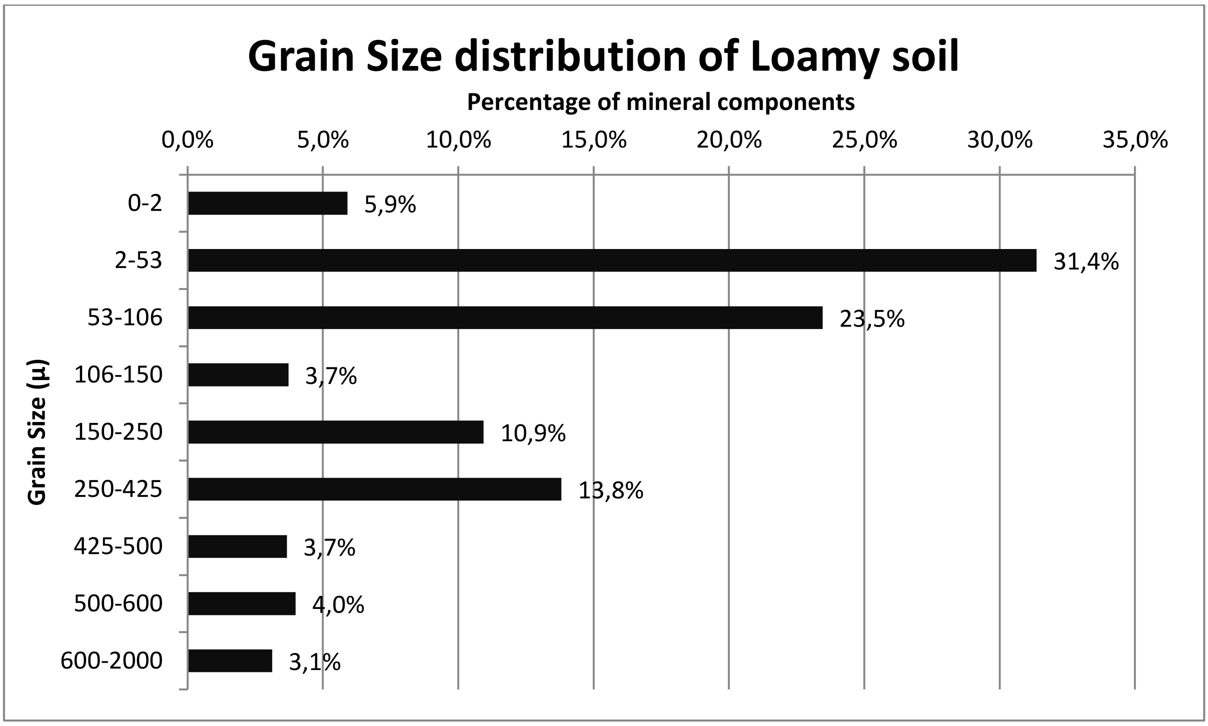
Granular research Loam soil Berg en Dal

Soil type	**Loam**
Organic matter determined by loss on ignition	**3.9%**
Carbonate of lime	**N/A**



11 Appendix 3: Output figures

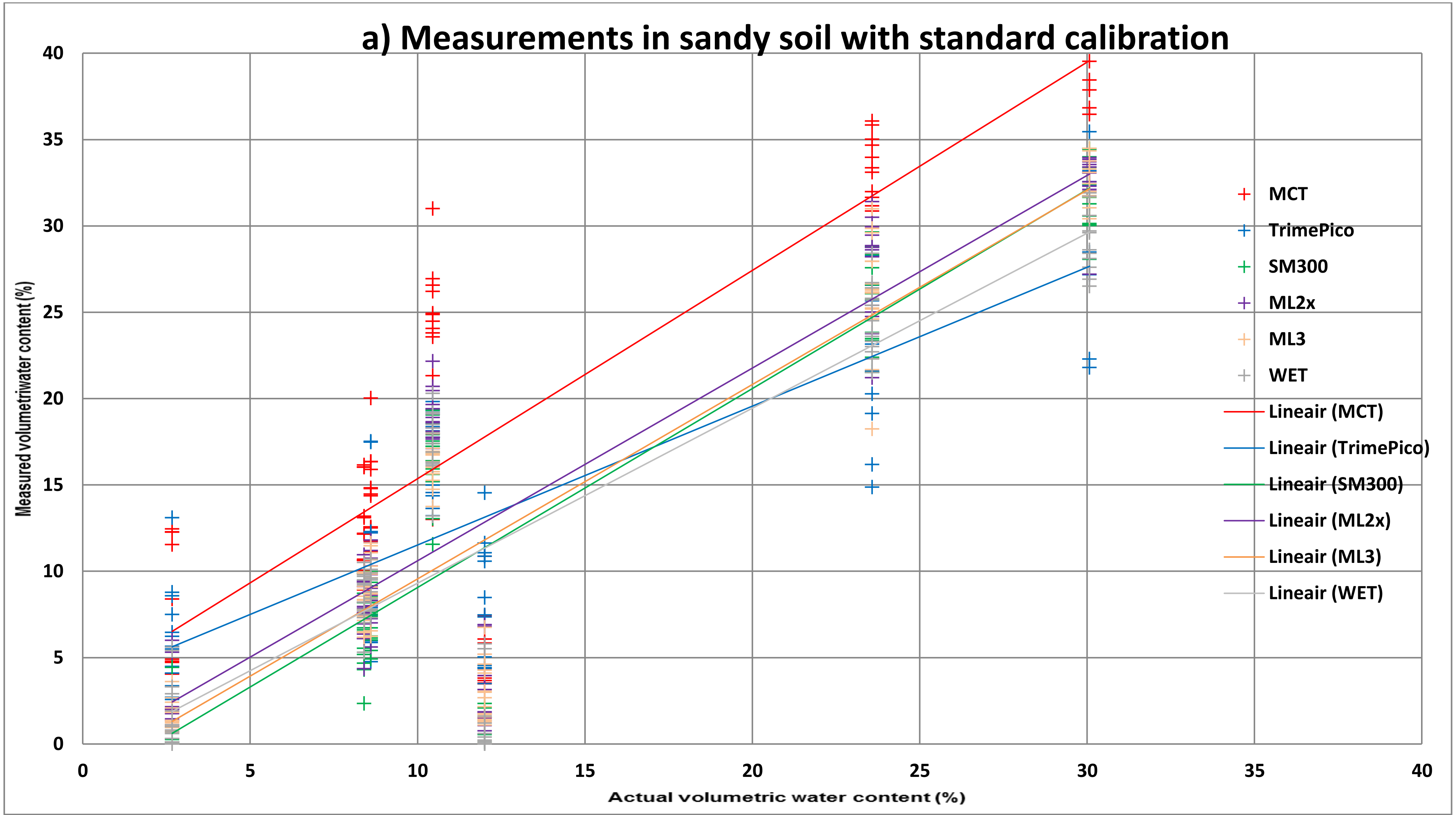


Figure 21 Measurements in sandy soil with standard calibration

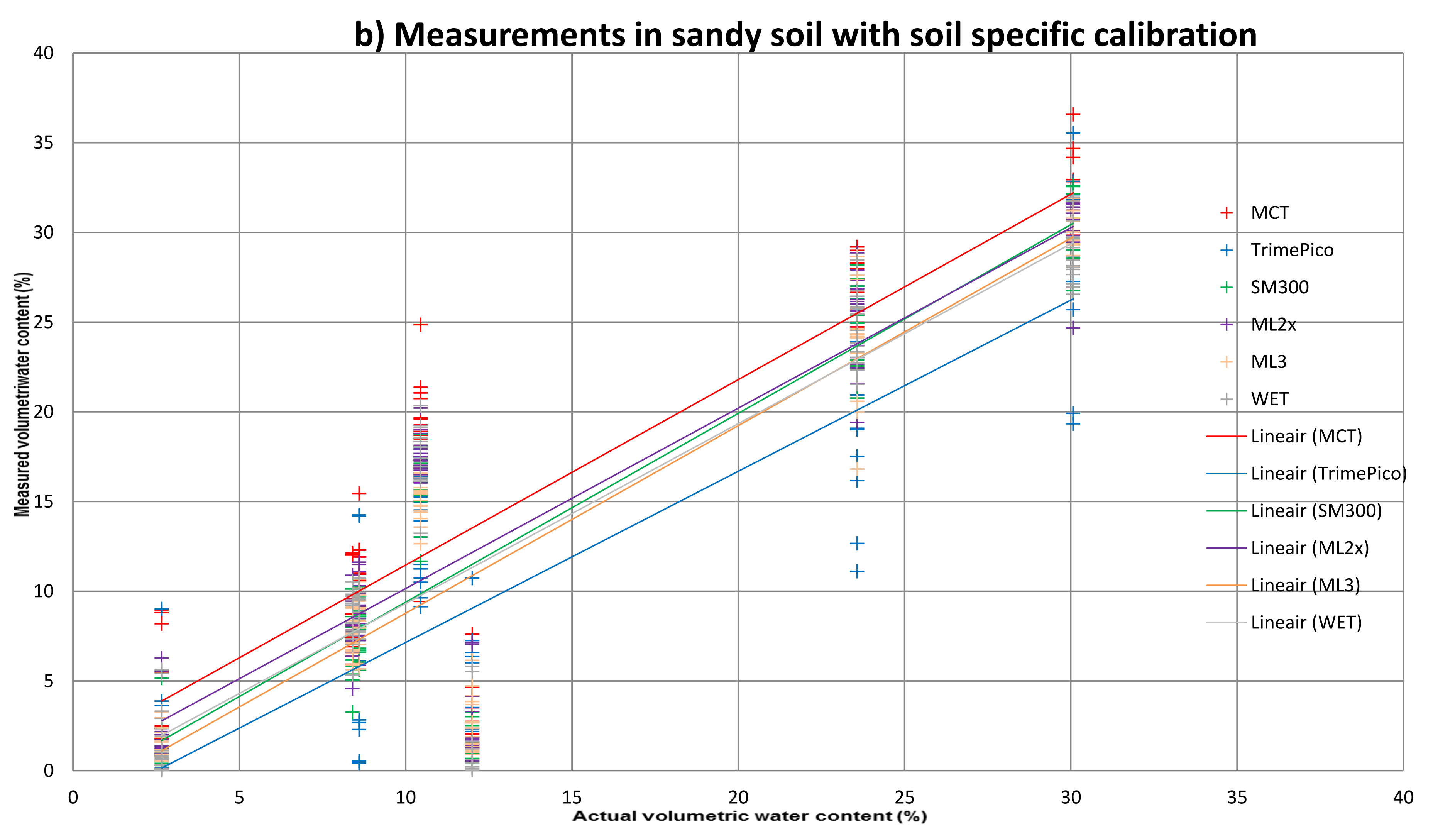


Figure 22 Measurements in sandy soil with soil specific calibration

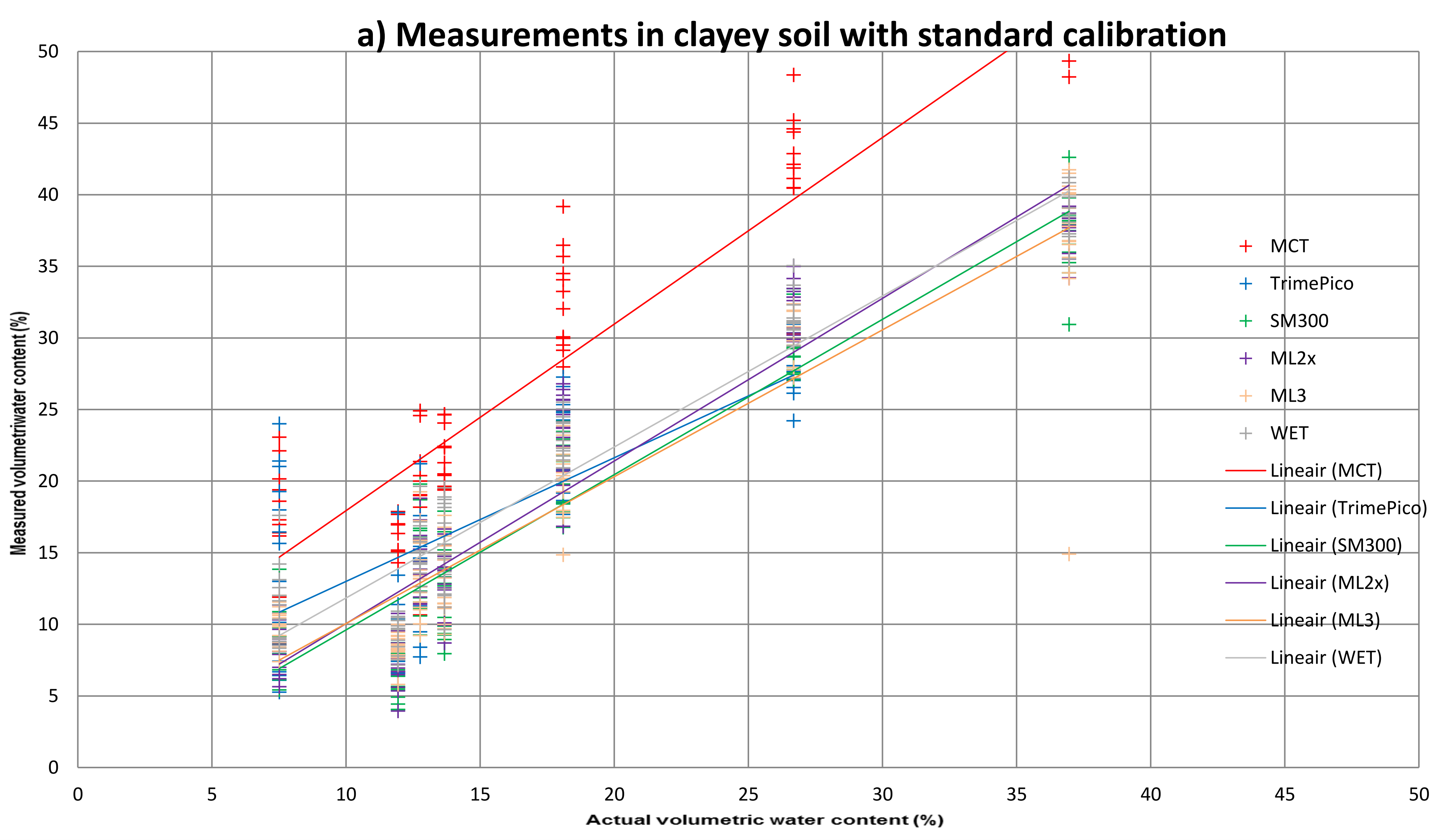


Figure 23 Measurements in clayey soil with standard calibration

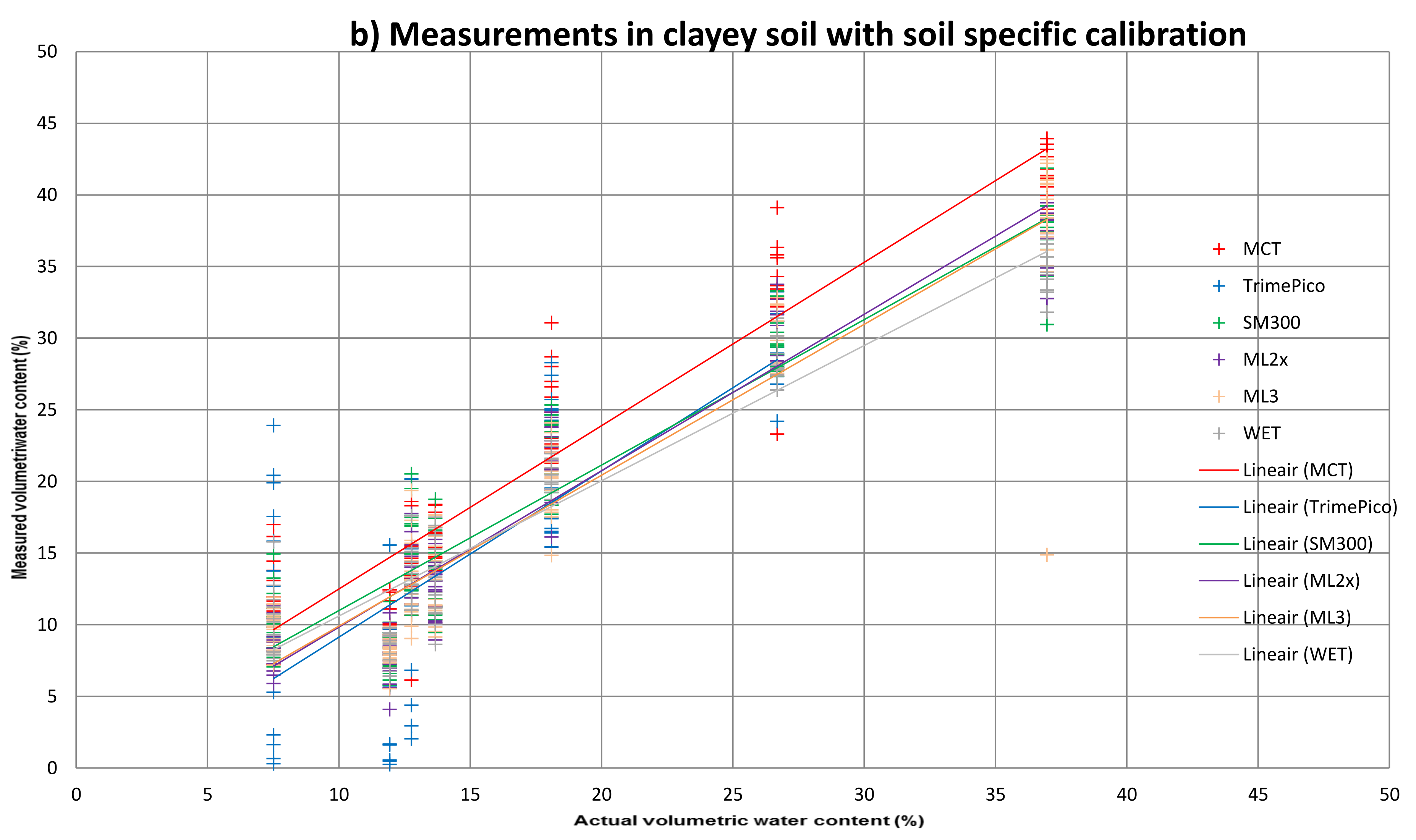


Figure 24 Measurements in clayey soil with soil specific calibration

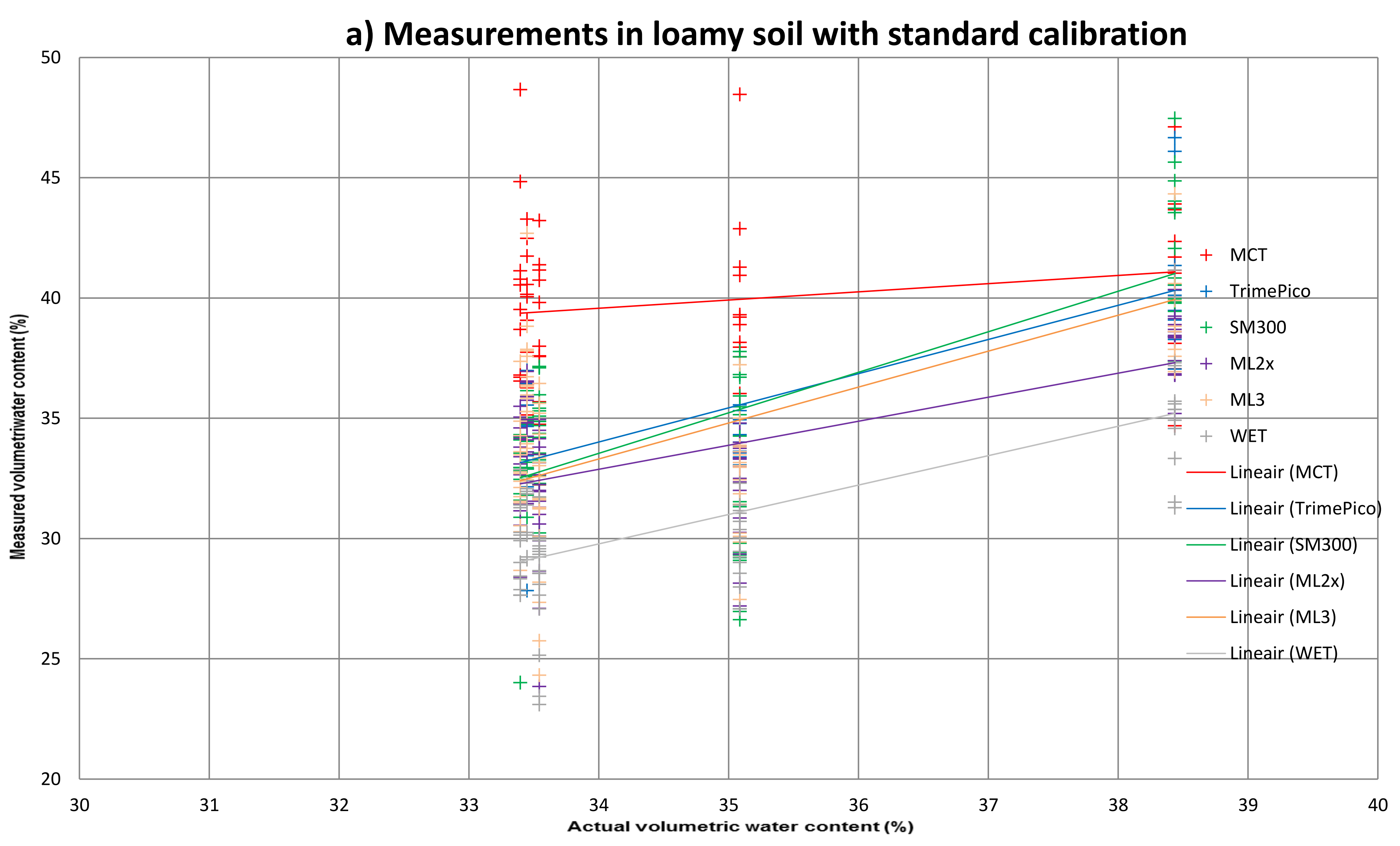


Figure 25 Measurements in loamy soil with standard calibration

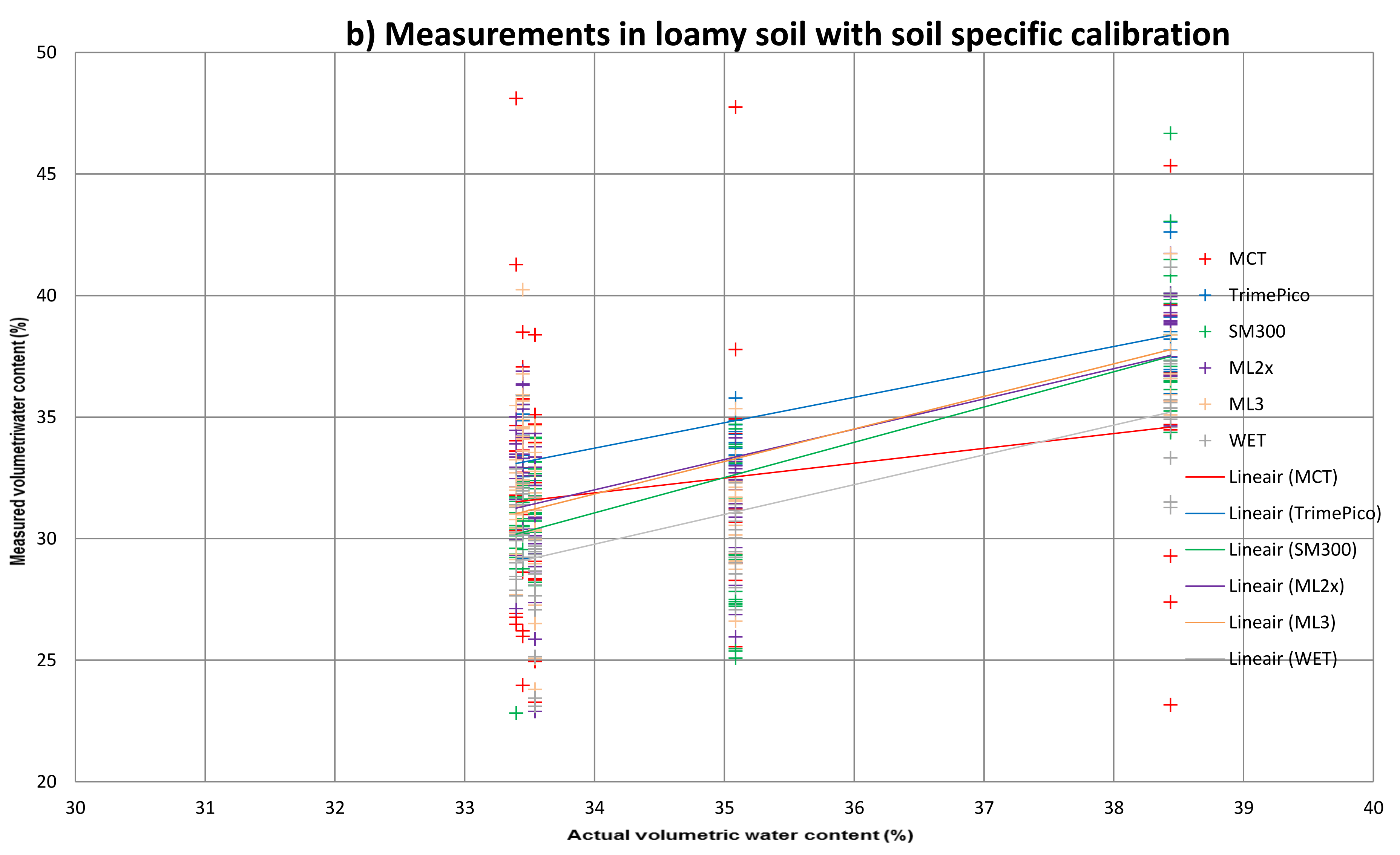


Figure 26 Measurements in loamy soil with soil specific calibration

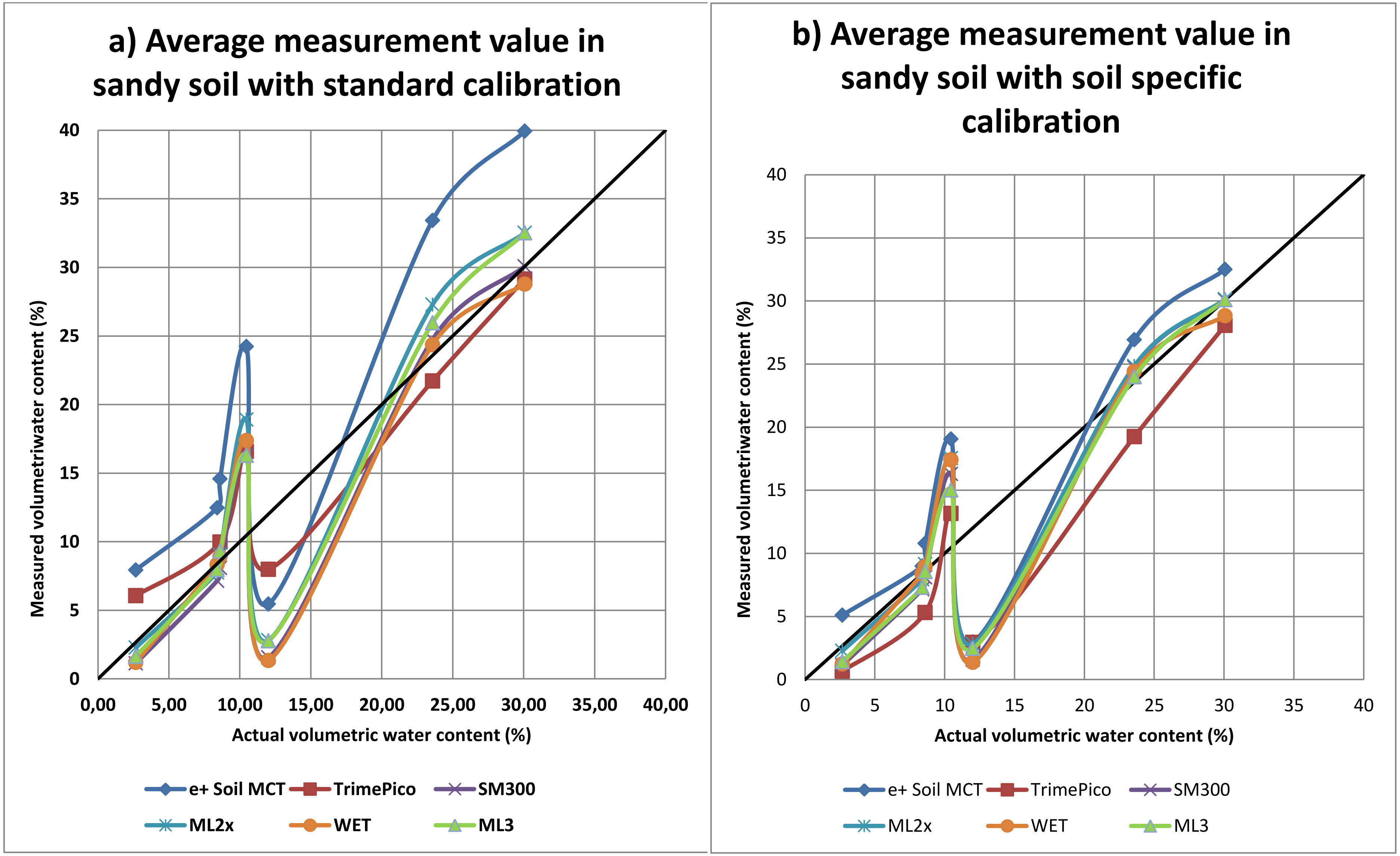


Figure 27 Average measurement value in sandy soil with standard calibration (a) and soil specific calibration (b)

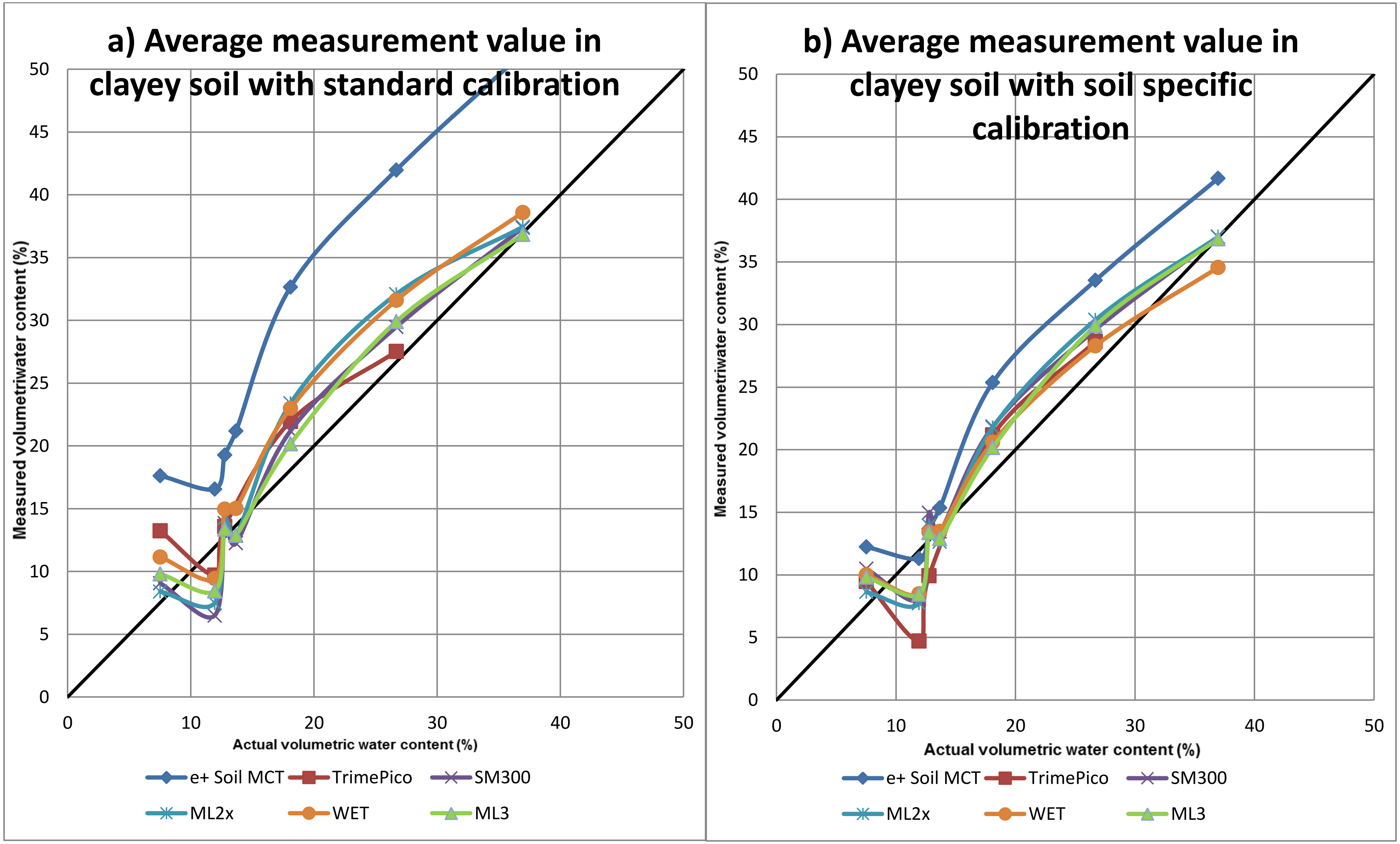


Figure 28 Average measurement value in clayey soil with standard calibration (a) and soil specific calibration (b)

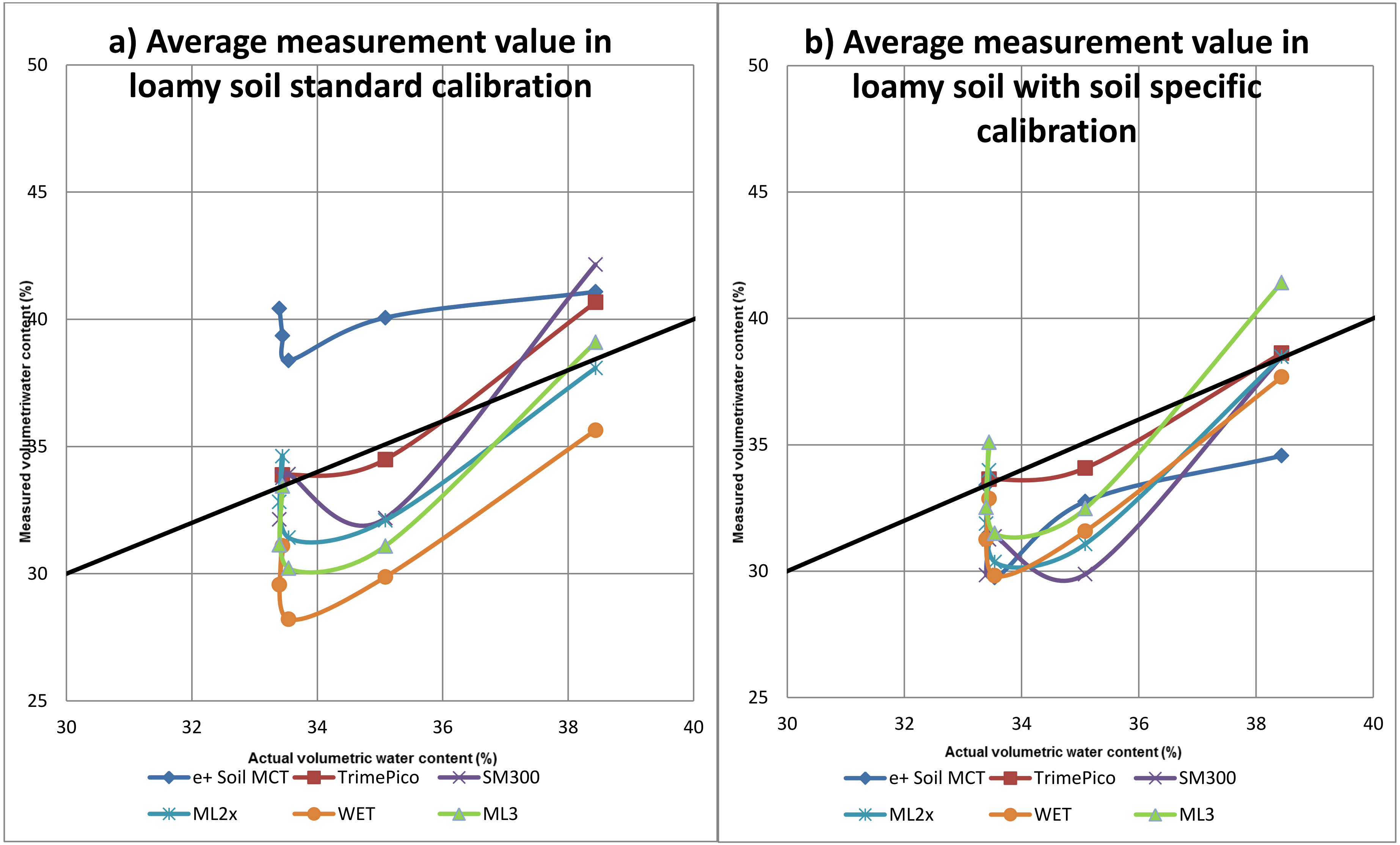


Figure 29Average measurement value in loamy soil with standard calibration (a) and soil specific calibration (b)

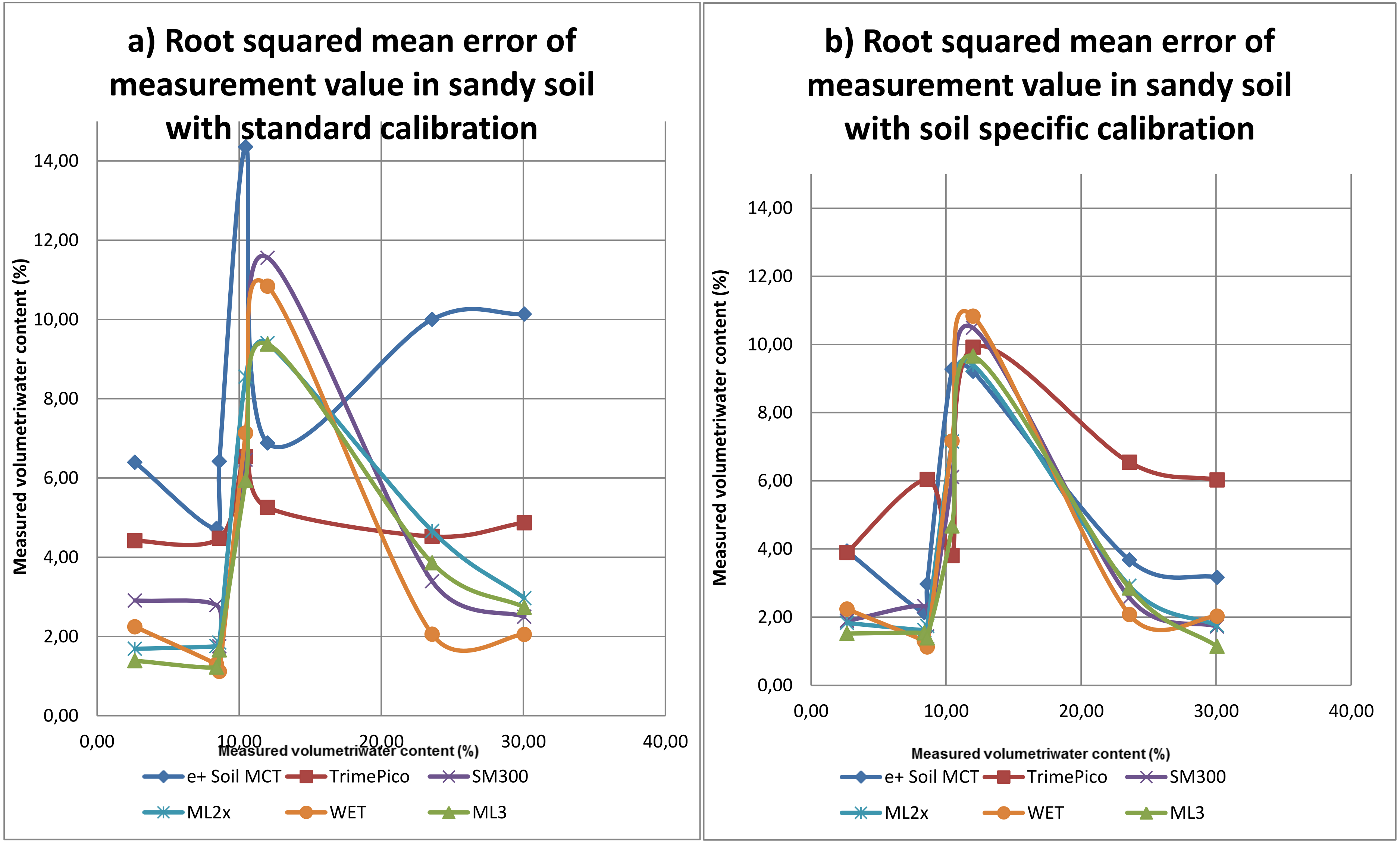
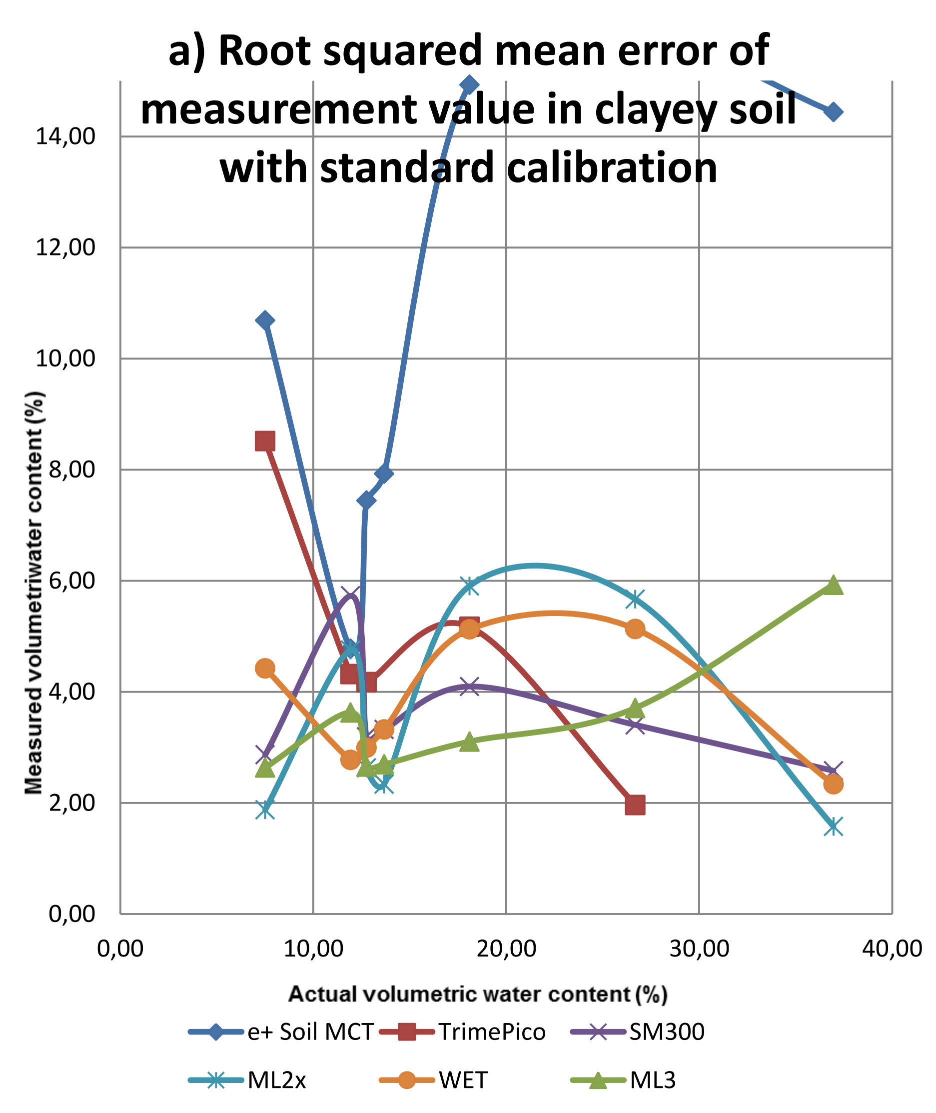


Figure 30 Root squared mean error of measurement value in sandy soil with standard calibration (a) and soil specific calibration (b)



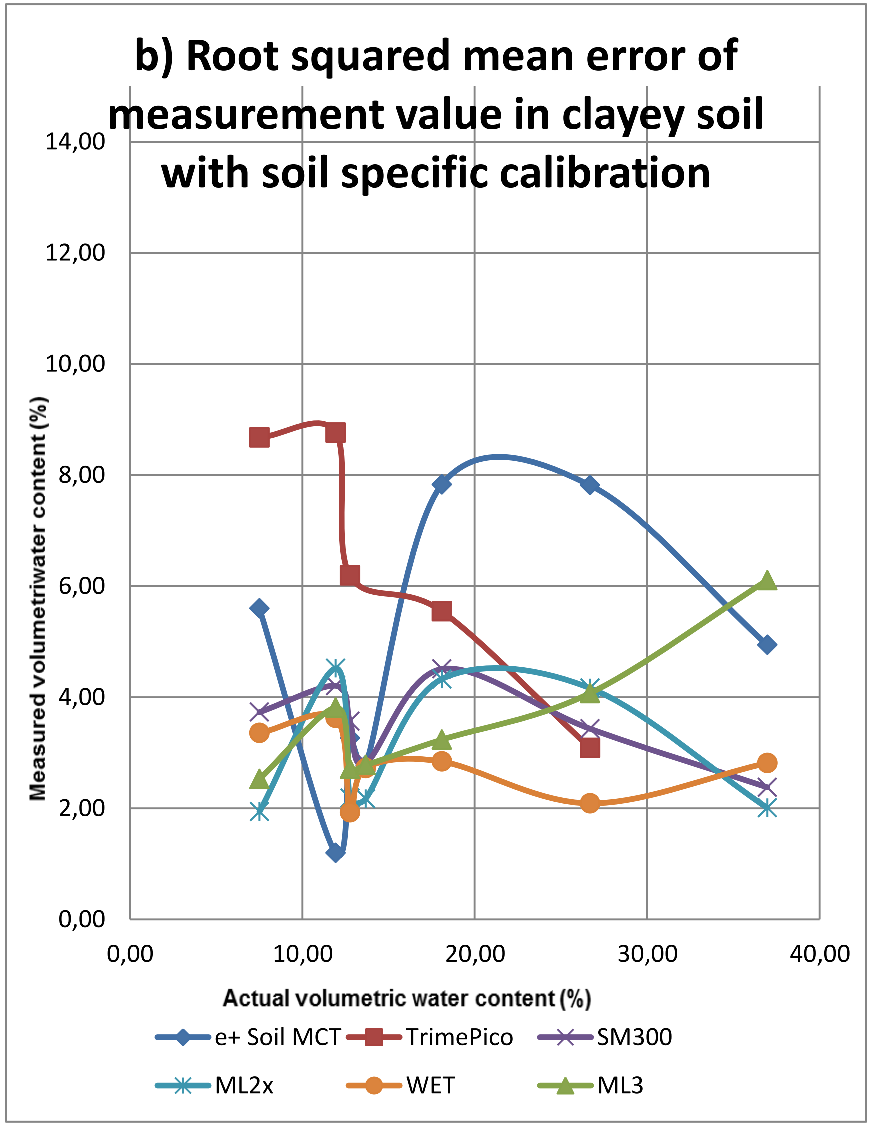


Figure 31 Root squared mean error of measurement value in clayey soil with standard calibration (a) and soil specific calibration (b)

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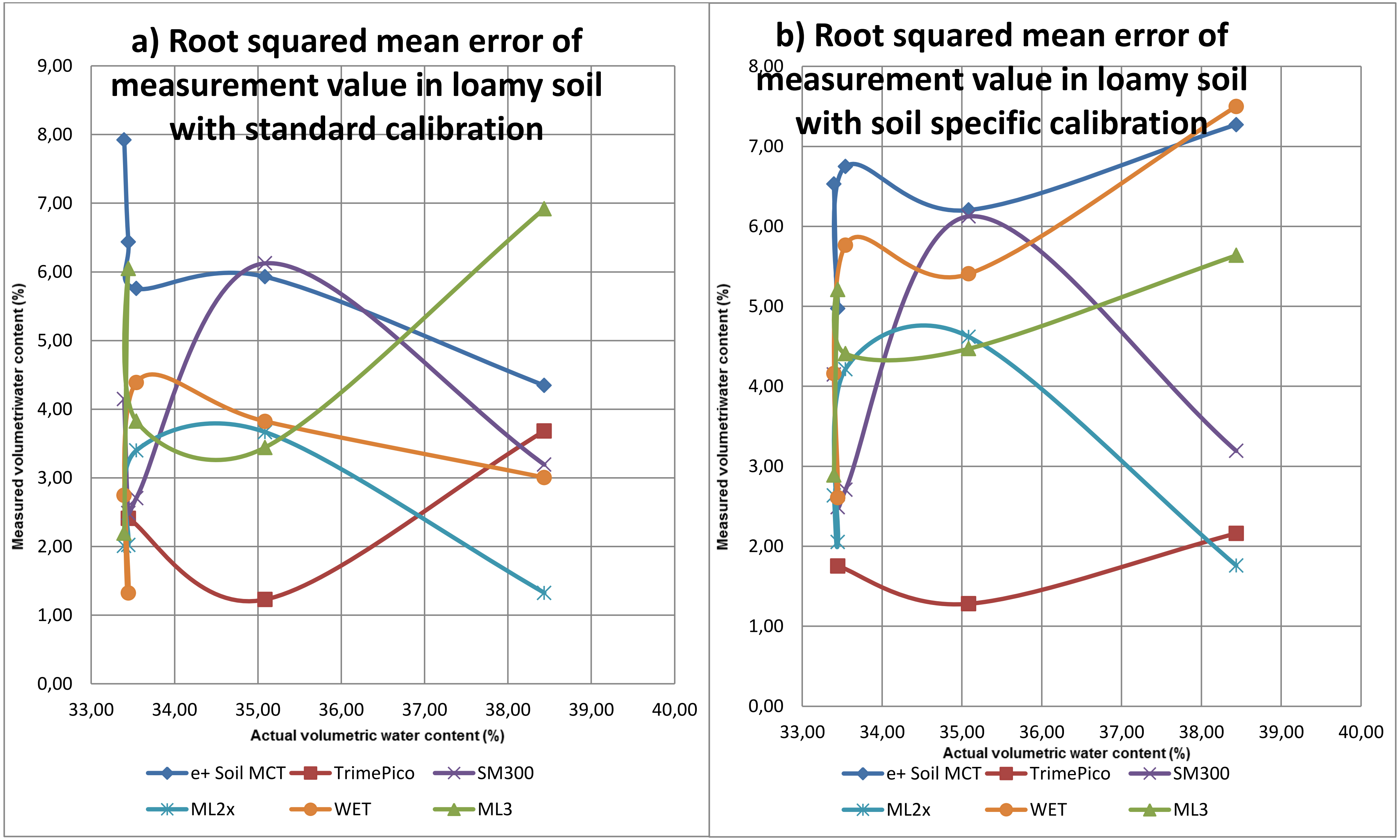

Figure 32 Root squared mean error of measurement value in loamy soil with standard calibration (a) and soil specific calibration (b)