UNIVERSITY OF TWENTE / DELTARES

# Soil moisture simulations on a regional level

## The ability of groundwater model MIPWA to replicate soil moisture observations in Twente

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# Abstract

The groundwater model MIPWA simulates the groundwater levels in the North-Eastern part of the Netherlands. For this purpose MIPWA utilizes the unsaturated zone model MetaSWAP. The simulations of this unsaturated zone model have only been verified (van Walsum & Veldhuizen, 2011), no calibration or validation has been performed. Research by Mehrjardi (2015) and Schuurman et al. (2011) suggested that the simulated soil moisture content by MetaSWAP can be improved. The objective of this research is to evaluate and potentially improve the ability of MIPWA to simulate the soil moisture by comparing the simulations of MIPWA to field measurements. This research compares the MIPWA model results to measurement of the ITC soil moisture monitoring network.

At 20 observation sites the soil moisture content has been measured at various depths by the ITC soil moisture network. From these measurements, characteristics have been derived which the model should replicate. The measurement data has been explored to identify potential errors, which have been removed during the measurement data preparation.

The measurements showed that the measured porosity differs from the expected porosity based on soil type. At 9 observation sites porosities have been measured deviate significantly from the soil type based porosity. This is partly due to disturbances in the soil, as the recorded soil moisture content could not have been recorded in the undisturbed soil at 4 observation sites.

The soil moisture content over time has a similar pattern to the evapotranspiration and precipitation deficit. As a result the soil moisture content in the spring and summer lower than the rest of the year. The correlation between meteorological condition and the soil moisture content furthermore showed different behaviour in different layers in the soil. The probes near the surface are more sensitive to precipitation than deeper located probes, while the deeper located probes are more similar to the trend of evapotranspiration and precipitation deficit. As a result the probes near the surface measure large variance in soil moisture content, which dampens with increasing depth.

Two classifications of the observation sites have been made. The first classification divides the observations sites based on the groundwater level. Observation sites with a groundwater table close to the surface have higher soil moisture content than the sites with a deep groundwater table. This difference in soil moisture content in visible throughout the year, expect during dry period. The second classification is based on soil type. Two soil types are dominant on the surface of Twente, loamy sandy soils and sandy soils. At the surface the sandy soils contain less moisture than the loamy sandy soil, as was expected based on the soil properties.

The MIPWA model simulation period has been extended from 2001 to 2012 by extending the meteorological dataset of the model. This allows the model to be compared to the measurements between 2010 and 2012. The comparison shows that the model is able to simulate the dynamics of soil moisture content in the root zone. The model is able to explain on average 71% of the variance in the soil moisture content in the root zone, but the model does systematically underestimate the soil moisture content.

The individual observation sites that perform best are sites with similar measured and simulated porosity, a groundwater table far underneath the surface and have a loamy sandy soil type. In general, observation sites with a similar measured and simulated porosity are able to explain more of the model variance and are able to simulate the soil moisture content with a smaller root mean square error. The smaller error is also present for observation sites with a groundwater table located further away from

the surface. The loamy sandy soils are in general better simulating soil moisture dynamics than sandy soils. The other observation sites are quite able to replicate the soil moisture content in the root zone, however can be improved.

The observation sites which required improvement are observation sites with a groundwater table close to the surface. The soil moisture stress at these sites is not well simulated as Schuurman et al. (2011) already indicated. The lack of soil moisture stress increases evapotranspiration rates. This decreases the groundwater level in regions with a high groundwater table. The capillary rise has been limit, which allowed the model to simulate the soil moisture stress better and increase the groundwater tables. To improve the soil moisture simulations the modelled porosity has been increased to better match the observed soil moisture content. This significantly reduced the root mean square error of the modelled soil moisture content. The combination of the measures proved successful in improving both soil moisture dynamics and absolute value.

# Contents

# 1 Introduction

## 1.1 Background

The soil moisture content in the unsaturated zone contains only 0.15% of the global fresh water, however the interaction with plants, atmosphere, open water and aquifers makes the unsaturated zone important for the availability of water (Freeze & Cherry, 1979). The soil moisture content directly affects the growth of plants and crops; therefore the agricultural sector is dependent on the water availability in the unsaturated zone. The flow of water through the unsaturated zone determines the recharge of aquifers, thereby influencing the extraction rates of drinking water companies and industrial companies. Due to climate change, droughts and flood are expected to occur more frequently, while the domestic water demand is increasing (Berendrecht, et al., 2007). Therefore water is becoming a more scarce resource and planning is required to fulfil the water demand of all parties.

To gain insight into the water availability policy makers rely on models. In these models the unsaturated zone is incorporated in various methods and complexity. For the agricultural sector, damages to crops can be determined using a simple groundwater model to determine the groundwater level (van Bakel, 2002) , these models require only a simplified model of the unsaturated zone. These simplified models give no insight in the moisture content near the roots of the plants and therefore cannot determine whether a plant experiences stress due to lack of soil moisture. The unsaturated zone has been modelled in groundwater models to determine the water availability for plants (van Walsum & Veldhuizen, 2011). These models give an more precise indication of the water availability for plant and can be used in plant growth models to determine economic damage to farmers (Peerboom, 1990) .

Moreover unsaturated zone models can also be utilized to optimize water management (Peerboom, 1990), since the unsaturated zone models describe the interaction between unsaturated zone and saturated zone in great detail. The Soil Water Atmosphere and Plant model (SWAP) divides the unsaturated and saturated zone in thin layers to model the flow of water in between the layers. This detailed description of the unsaturated zone requires limited computational time for a single grid cell. However operational water management models cover a large area with a high spatial resolution. Implementing SWAP into operational water management models would result in large computational times; therefore restrict the amount of scenarios and measures that can be evaluated by policy makers or water managers.

Therefore a simplified model for the unsaturated zone, MetaSWAP, was developed (Schaap & Dik, 2007). MetaSWAP is based on SWAP, however with a smaller amount of layers in the unsaturated zone. This simplification of the SWAP model reduces the computational time (van Walsum & Groenendijk, 2006; van Walsum & van der Bolt, 2013), while the verification showed the model was able to replicate the model results of SWAP. For this reason MetaSWAP has been coupled to the saturated zone model iMODFLOW in the project 'Development of a Methodology for Interactive Planning for Water Management' (MIPWA) (van Walsum & Groenendijk, 2006; Lange, et al., 2014), to give policy makers insight in the water availability in the North eastern part of the Netherlands.

The main focus of MIPWA is to simulate the groundwater dynamics; therefore MIPWA has been calibrated for the groundwater level in the North-Eastern part of the Netherlands. However the unsaturated zone model has only been verified, no calibration or validation has been performed on the unsaturated zone model. The verification confirmed that the model was able to replicate the model results from the complex unsaturated zone model. Large scale soil moisture measurements are limited and therefore are rarely used for calibrating and validating hydrological models.

The use of remote sensing techniques has led to more soil moisture data becoming available, as these remote sensed techniques require calibration. For this purpose in Twente the ITC soil moisture and soil temperature monitoring network has been installed. However soil moisture measurements are only representative for a small area, while hydrological models and remote sensing techniques cover a large region. The measurements can be used for calibration of the soil moisture content at the measurement locations. Mehrjardi (2015) concluded that National Hydrological Instrument (NHI) has difficulties to replicate the soil moisture content in winter and might have difficulties to replicate the interaction between saturated and unsaturated zone. Since this interaction is modelled by MetaSWAP in the NHI, the MetaSWAP needs to be compared to field measurements. Schuurman et al. (2011) concluded based on remote sensing that the soil moisture stress, the lack of soil moisture, in summer is underestimated by MetaSWAP.

Similar problems with the simulation of the soil moisture content are expected in MIPWA. This study will focus on the soil moisture simulation of MetaSWAP as implemented in MIPWA, as well as the interaction between the unsaturated zone model MetaSWAP and the groundwater model iMODFLOW. Before the model can be compared to measurements, the measurements first have to be analysed. Based on this analysis the ability of the model can be determined. Based on the study, improvements to MetaSWAP and MIPWA will be suggested. The effect of these improvements is evaluated for the soil moisture content, as well as for the simulation of the groundwater level by iMODFLOW.

## 1.2 Research objective and Research questions

The simulation of the unsaturated zone influences the simulation of the groundwater level in MIPWA, therefore the functioning of the unsaturated zone model MetaSWAP is important for MIPWA. The calibration of MIPWA has mainly focussed on the saturated zone, while the unsaturated zone has only been verified (van Walsum & Veldhuizen, 2011). The aim of this project is to determine the ability of MIPWA to simulating the soil moisture content in the unsaturated zone. This is done by fulfilling the following research objective of the research is:

> *To evaluate and potentially improve the ability of MIPWA to simulate the soil moisture by comparing the simulations of MIPWA to data from the ITC soil moisture monitoring network in Twente.*

The extent of the research is limited by the available data, only soil moisture data from the ITC soil moisture network will be utilized during this research. The field measurements cover the region Twente in the Netherlands. The field measurement data only describes the water content in the upper section of the unsaturated zone; therefore the research will focus on the comparison between the field measurements and models in the upper section of the root zone. With these restrictions taken into account, the following research question will be answered.

1. Which characteristics can be derived from the soil moisture data of the ITC soil moisture monitoring network in Twente?

2. What are the differences between the results of the model simulations of MIPWA and the field data of the ITC soil moisture monitoring network?

3. Can the ability of MIPWA to simulate soil moisture content possibly be improved and what is the effect of these improvements on the simulation of the groundwater level?

## 1.3 Report outline

The report can be divided into 7 parts divided over different 10 chapters. In the first chapter the background of the research and the objective of the research are explained. Chapter 2 describes the data and model used in the research. This chapter contains a brief description of the study area, the MIPWA model and the measurement data. The methodology used to answer the first two research questions is described in chapter. This chapter has two distinct sections. The first section focusses on the measurements, while the second mainly focusses on the model analysis.

The results are discussed in chapters 4, 5 and 6. Each chapter focusses on different research question. In the fourth chapter the field measurements are analysed. Based on this analysis the model performance is evaluated in the fifth chapter. In the sixth improvements are suggested based on the conclusions of chapters 4 and 5. In the last three chapters the results are discussed, conclusions are made and recommendations for further research are done. This is done is chapters 7,8 and 9 respectively.

# 2 Model and Data

The research is focussed on the region of Twente. to describe the region various data sources have been used as well as the groundwater model MIPWA model. In this chapter first a brief overview of the region of Twente is given. Secondly, a comprehensive summary of the MIPWA model is given, with particular focus on the unsaturated zone model MetaSWAP. Finally the soil moisture measurements are discussed.

## 2.1 Study area

The study focusses on the region of Twente, the region is located in the Eastern part of the Netherlands, on the border with Germany. The region is characterized by large agricultural areas, concentrated nature areas and several cities and small villages. Figure 2.1 shows that most of the area was used for agricultural purposes in 2010. The agricultural area consists mostly out of grass fields, as well as corn fields.

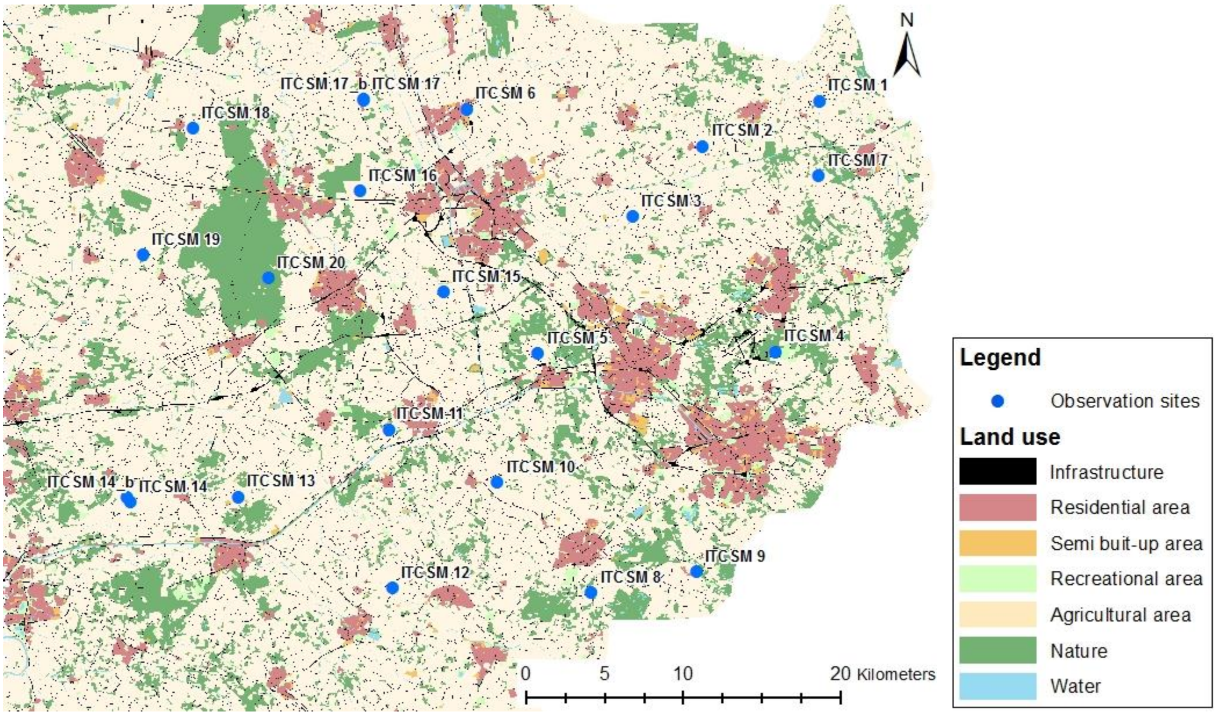

**Figure 2.1: Land use in Twente in 2010 (based on 'Bestand Bodemgebruik' (CBS)), in blue the measurement sites are located**

The climate in the Netherlands is an temperate climate according to the Koeppen classification system (Dente, et al., 2011). Precipitation is spread equally over the year (Dente, et al., 2012; Jacobs, et al., 2010), the average precipitation is 760 mm a year. The potential evapotranspiration in the Netherlands has a seasonal trend with the highest evaporation measured in July and August, the yearly potential evapotranspiration is 525 mm. Over an entire year there is more precipitation than evapotranspiration, Due to the uneven distribution of evapotranspiration, drought can occur in the summer. To mitigate the drought in summer, water is pumped from ground and surface water for agricultural purposes.

The geohydrology of Twente is defined by multiple layers of aquifers and aquitards, due to layers of permeable sand and impervious maritime clay. At the surface the soil predominantly consists out of sand, with thin loam deposits in the stream valleys (Hendriks, et al., 2010). A detailed description of the geohydrological structure of the region is given by Kuijper et al (2012).

## 2.2 MIPWA

The project 'Development of a Methodology for Interactive Planning for Water Management' (MIPWA) was started to evaluate the effects of policy measures and climate change on the water availability in the North-Eastern part of the Netherlands. Before MIPWA was implemented, different models were used by policy makers. However parties were in disagreement of the model assumptions and the output of these models. MIPWA was developed to create consensus over the model output among policy makers in the North of the Netherlands (Schaap & Dik, 2007; Berendrecht, et al., 2007). MIPWA provides policy makers a tool with a high spatial resolution of 25 by 25 meter at a temporal resolution of 1 day for their decisions, as well as a database with the effects of measures on different areas.

MIPWA can be divided into two coupled models, an unsaturated zone model, MetaSWAP, and a saturated zone, MODFLOW. In Figure 2.2 the domain of the two coupled models is shown, it shows that both models simulate the processes between the subsoil and the groundwater storage. The purpose of MODFLOW is to simulate the groundwater water flow in horizontal and vertical direction. MetaSWAP focusses on the simulation of the interaction between soil water atmosphere and plant. The model therefore simulated only in vertical direction, however repeats this calculation for each cell.

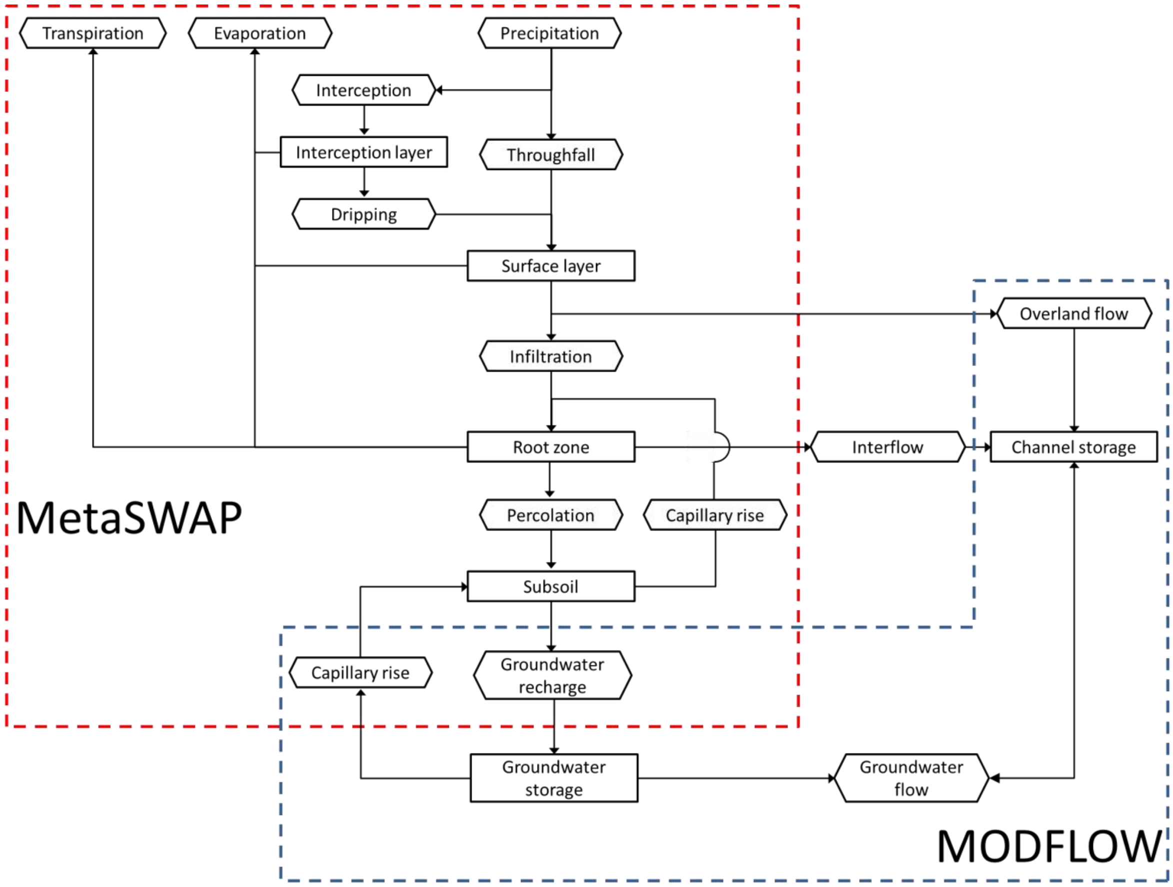


**Figure 2.2: Modelled processes by MetaSWAP and MODFLOW in hydrological cycle (modified after Walsum et al. (2010). Storage bodies are displayed as rectangles, while the processes between storage bodies are displayed as hexagons.**

The unsaturated zone model therefore lacks the interflow, the horizontal flow in the unsaturated zone. More complex models are able to replicate this process and model in greater detail processes in the subsoil and root zone (van Walsum & Groenendijk, 2006). However these models require extensive computer time, which makes it difficult to model on a catchment level. Models as MODFLOW and MIKE-SHE have a simplified top layer (van Walsum & Groenendijk, 2006), which reduces the computer time. However the results of these simplified top layers show deviations compared to the complex models. MetaSWAP is able to achieve similar results as the complex models, at comparable calculation times as the simplified models.

MODFLOW determines the groundwater flow based on a quasi-three-dimensional model, simplifying the geology of the North-Eastern part of the Netherlands into 7 vertical layers. For each of the 7 layers, the groundwater level is determined on a horizontal grid of 25 by 25 meters. The groundwater flow within and between these layers is determined by Darcy's law. The driving forces of Darcy's law are groundwater level difference, porosity and hydraulic conductivity. MODFLOW is considered to be a highly efficient and accurate model for the groundwater (Zhu, et al., 2011). Detailed descriptions of MODFLOW are given by Harbaugh (2005) and Vermeulen et al (2016) respectively.

### 2.2.1 Simulation of the unsaturated zone

MetaSWAP is a one-dimensional model and therefore only calculation vertical flows in the unsaturated zone. However by dividing the region into vertical columns representing an area of 25 by 25 meters, spatial differences in the unsaturated zone are realized. Each vertical column can be divided into four layers, the interception layer, the surface layer, the root zone and the subsoil. In Figure 2.3 the different layers are visualized.

***Interception layer***

The interception layer is formed by the leaves of the vegetation; these can retain an amount of precipitation. Water in retained by the leaves will either be evaporated or is transported to the surface layer through dripping. The evaporation in the interception storage can only occur when water is stored in the layer storage. The storage capacity is determined by the vegetation type; however the storage is relatively small. When the storage capacity is exceeded the water is released directly to the surface layer. The water remaining is mostly evaporated from this storage body; the remaining water is released to the surface layer through the process of dripping.

***Surface layer***

The surface layer is located just above the unsaturated zone, on top of the earth surface. The main source of water of the surface is precipitation that falls through the vegetation or that could not be stored in the canopy. Dripping from the leaves in the interception storage and sprinkling are additional source of water. A final source of water is overland flow, although not active in MetaSWAP. Instead, overland flow is modelled by the iMODFLOW overland flow package. All water on the surface layer can infiltrate, unless it is limited by the root zone or the maximum infiltration. The remaining water is stored in the surface layer, referred to as ponding storage, and is subjected to evapotranspiration.

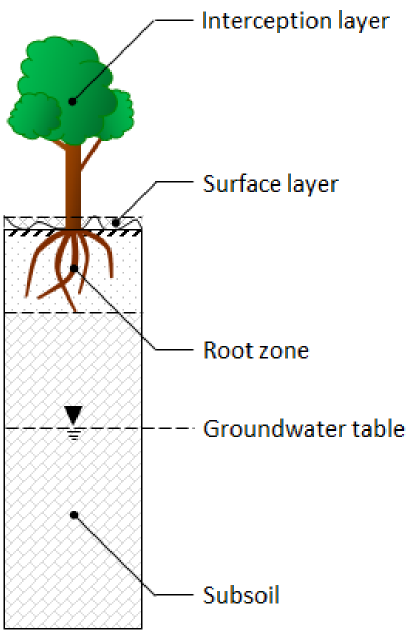


**Figure 2.3: Schematization of the different layers in MetaSWAP**

***Root zone***
The top layer of the unsaturated zone is the root zone. The root zone is defined as the layer of soil from which plants can extract water. The thickness of the root zone depends on the vegetation type and soil type (Snepvangers & Berendrecht, 2007). Changes in the moisture content of the root zone are caused by infiltration, bare soil evaporation, transpiration, capillary rise and percolation.

The amount of water that can enter the root zone from the surface is determined based on three conditions. The condition which leads to the lowest infiltration rate will be used to determine the actual infiltration.

- The infiltration rate cannot exceed the available amount of water in the surface layer.
- The infiltration rate cannot exceed the soil type based maximum infiltration rate
- The infiltration rate cannot cause the total volume to root zone to surpass the storage capacity of the root zone.

In MIPWA the first condition is often the limiting condition. This condition depends on the amount of precipitation that reaches the surface layer, which is often lower than the infiltration capacity of maximum infiltration rate of 1 meter a day.

For every vegetation type a fraction of the soil is not covered by vegetation, however evaporation still occurs at these areas. This evaporation is simulated by the bare soil evaporation in MetaSWAP, which is dependent on four components.

- Soil coverage
- Reference evapotranspiration
- Precipitation deficit
- Crop factor of bare soil

As mentioned, the bare soil evaporation only occurs in areas without coverage of vegetation. The soil coverage fraction indicates the amount of area covered by vegetation; the remaining area is subjected to the bare soil evaporation. The amount of evaporation is determined by the reference evapotranspiration and the crop factor. However during dry periods, the top layer of the soil starts to form a crust, thereby reducing the evaporation. In MIPWA crusting occurs after a precipitation deficit of 3 mm, quickly reducing the potential evaporation from the bare soil. The bare soil evaporation is a relatively small component of the total evapotranspiration, with the exception of the soil type bare soil.

Transpiration determines the amount of moisture extracted at the roots of the plant. The growth of plants is not simulated during this research, although this is an option of MIPWA. This reduces complexity and reduces factors the transpiration is dependent on. The actual transpiration is dependent on four factors.

- Crop factor of the vegetation type
- Reference evapotranspiration
- Fraction interception evaporation active
- Soil moisture content of the root zone

The combination of crop factor and evapotranspiration determines the potential water use of the plant. This potential water use is based on the plant growth model within MIPWA and has validated with the SWAP model results. Two factors can reduce the amount of transpiration from the crops. In case the interception storage is filled with water, water is first taken from the leaves instead of from the roots. A second limiting factor is soil moisture stress, excessive water or lack of water can limit the transpiration. The transpiration is limited when the soil moisture content exceeds a critical threshold. Based on these limiting factors the actual transpiration from the root zone is calculated.

The final flux that is determined is the combination of capillary rise and percolation. The flux between the subsoil and root zone is actually not calculated but based on 2 look-up tables (van Walsum & Groenendijk, 2006). Based on the moisture content and groundwater table a pressure head can be determined from a look-up table similar to Figure 2.4. Afterwards the pressure head can be used to find the corresponding capillary rise and percolation in a look-up table as shown in Figure 2.5. The relation within the look-up tables is based on simulation of SWAP. The moisture content, capillary rise and percolation are calculated for a variety of groundwater levels and pressure heads for each soil type. This resulted in the relations shown in Figure 2.4 and Figure 2.5 .

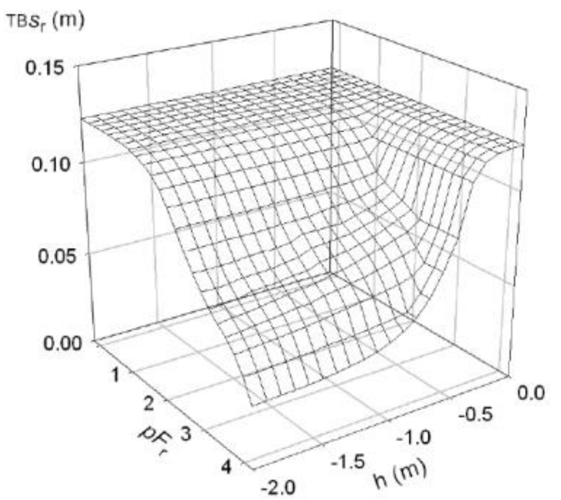


**Figure 2.4: The total storage in the root zone ($TBs_r$) as a function of the pressure head in the root zone (pF) and the ground water elevation (h) for a loamy sand soil (van Walsum & Groenendijk, 2006)**

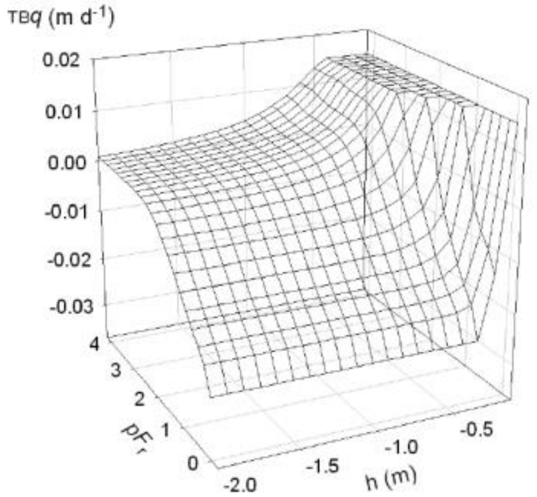


**Figure 2.5: The flux between subsoil and root zone (TBq) as a function of the pressure head in the root zone (pF) and the ground water elevation (h) for a loamy sand soil (van Walsum & Groenendijk, 2006)**

**Subsoil**

The section of soil underneath the root zone is referred to as the subsoil. Figure 2.3 showed that the groundwater table is located within the subsoil, thereby the subsoil consists of both the unsaturated and saturated zone. The change of moisture content in the subsoil is dependent on the groundwater flow and the combination of capillary rise and percolation. The later water flow is determined by the root zone.

The groundwater flow is outside the domain of MetaSWAP and is part of the calculations performed by MODFLOW. Remarkably, MetaSWAP and MODFLOW do not pass the actual groundwater flow. MetaSWAP calculates the groundwater flow based on the groundwater level change. The coupling of the models is described in detail by van Walsum, et al (2010).

### 2.2.2 Model set-up

The database of MIPWA contains the groundwater level and soil moisture of the entire study area, however the period MIPWA covers is limited. The simulations of MIPWA cover the period 1989 until 2002; while the soil moisture measurements have been performed from 2008. Therefore the model has been to be extended from 2001 to 2012. Main purpose of this extension is to simulate the soil moisture content at the observation sites during the study period. Important for the simulation of the soil moisture content are the boundary conditions and especially the groundwater level at the measurement locations.

To simulate the groundwater level the model is run on two scales; regional and local. The regional model covers the extent of Figure 2.6 at a resolution of 250 by 250 meters. The regional model covers a region of 4500km$^2$. The purpose of the regional model is to determine the groundwater level on the boundaries of the local models. The local models simulate the groundwater level and soil moisture content on a finer resolution of 25 by 25 meters, however this fine model only covers an area of 5km by 5km. The local models are defined as such that the measurement locations are located at the centre of the model, as shown in Figure 2.6.

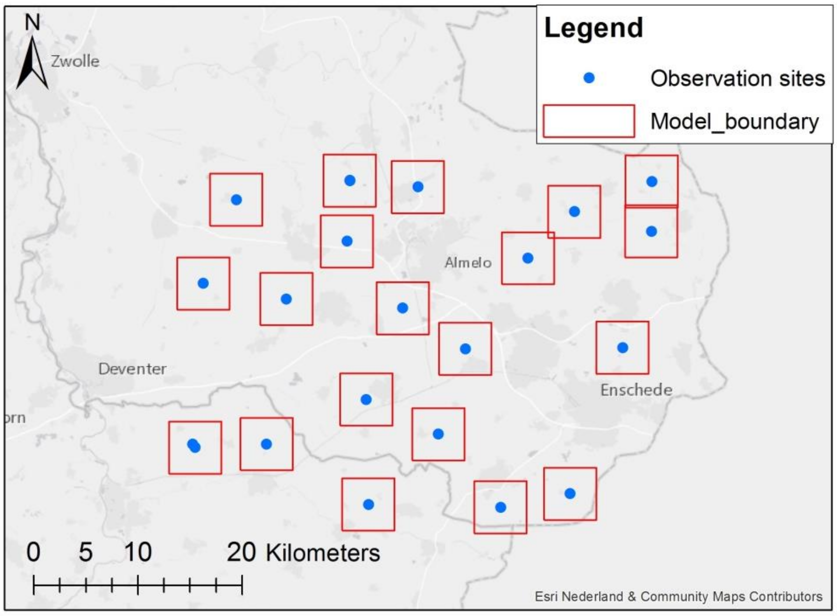


**Figure 2.6: Model boundaries of the**

The input data for the model is derived from the MIPWA model described by Berendrecht, et al. (2007). The only adaptation of the model by Berendrecht, et al. (2007) is the extension of the simulation period and meteorological data.

### 2.2.3 Meteorological data

Precipitation and reference evapotranspiration are used as input for the simulation of MIPWA. This meteorological data is gathered by the Royal Netherlands meteorological Institute (KNMI). The precipitation in the Netherlands is recorded on a daily interval by precipitation stations; additional hourly precipitation data is available from the weather stations. In total 325 precipitation stations are present in the Netherlands; Figure 2.7 shows that 19 are located in vicinity of the study area. The precipitation stations are used for the simulation of precipitation in MIPWA. The weather stations at Hupsel, Heino and Twenthe also record the daily potential evapotranspiration, which is interpolated to determine the potential evapotranspiration at each observation site.

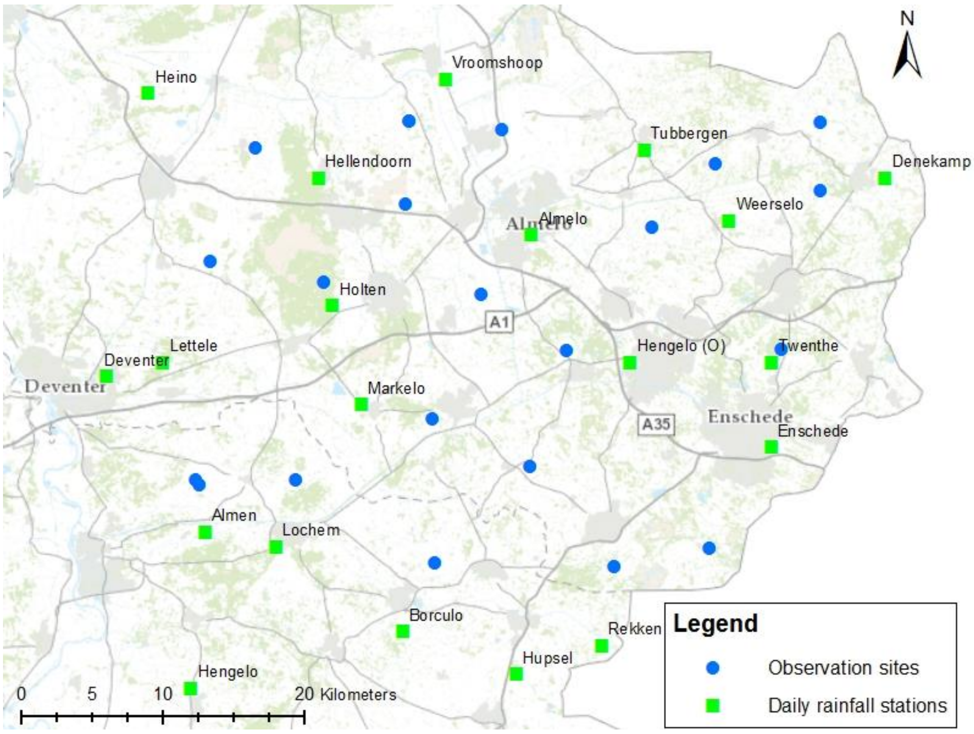


**Figure 2.7: Location of daily rainfall stations in the region of Twente**

## 2.3 Soil moisture measurements

The soil moisture content in Twente is measured at 20 locations by the Geo-Information Science and Earth Observation Faculty of the University of Twente (ITC). These so called observation sites are spread over the region to give a spatial image of the soil moisture content, the network is intended for validating satellite based soil moisture products. These products often measure the soil moisture content up to 5 cm depth. At most observation sites measurements are available for larger depths as well. All sensors measure the soil moisture content at 5 cm and 10 cm depth. In addition to these depths, some monitoring sites have been equipped with sensors at 20 cm and 40 cm depth. During 2009 the soil moisture content at 20 cm depth was measured by 12 monitoring sites. Only 4 sensors recorded the soil moisture content at 40 cm depth. In 2015 this has increased to 16 monitoring sites and 13 monitoring sites respectively.

The probes measure the soil moisture content and soil moisture temperature every minute. Initially, the network stored the average soil moisture content at an interval 10 minutes, registering the time of the measurement in Central European Time (UT + 1). From 2009 the recording interval has been set to 15 minutes (Dente, et al., 2011). The high temporal resolution is able to give insight in the development of the soil moisture content since 2008. The soil moisture measurements are not continuously available due to malfunctioning of the equipment. An overview of the available soil moisture data is given in Appendix A, The overview shows that there is no data available in 2011 for observation sites 16 and 17. In the period 2010- 2012 only observation sites 5, 8 and 19 measure the soil moisture content at all depths.

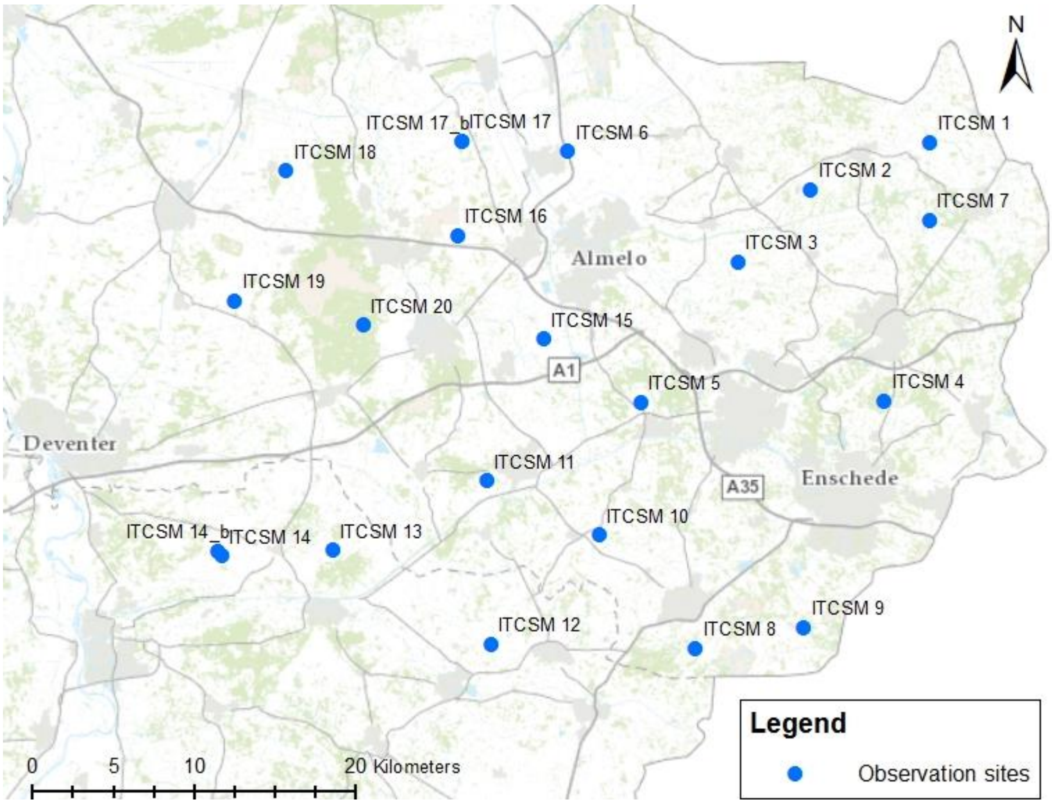


**Figure 2.8: Locations of the observation sites of the soil moisture Network (based on Dente et al. (2012))**

# 3 Methodology

The research questions require the use of multiple techniques to derive information from the data. The process of converting data into information is described in chapter. This chapter is divided into two sections. The first section focusses on the field measurement, the data preparation and actual analyses are described in the first section. The second section focusses on the model performance, for this the different analyses of the field measurements are used. The relation between the different subsections of this chapter is shown in Figure 3.1.

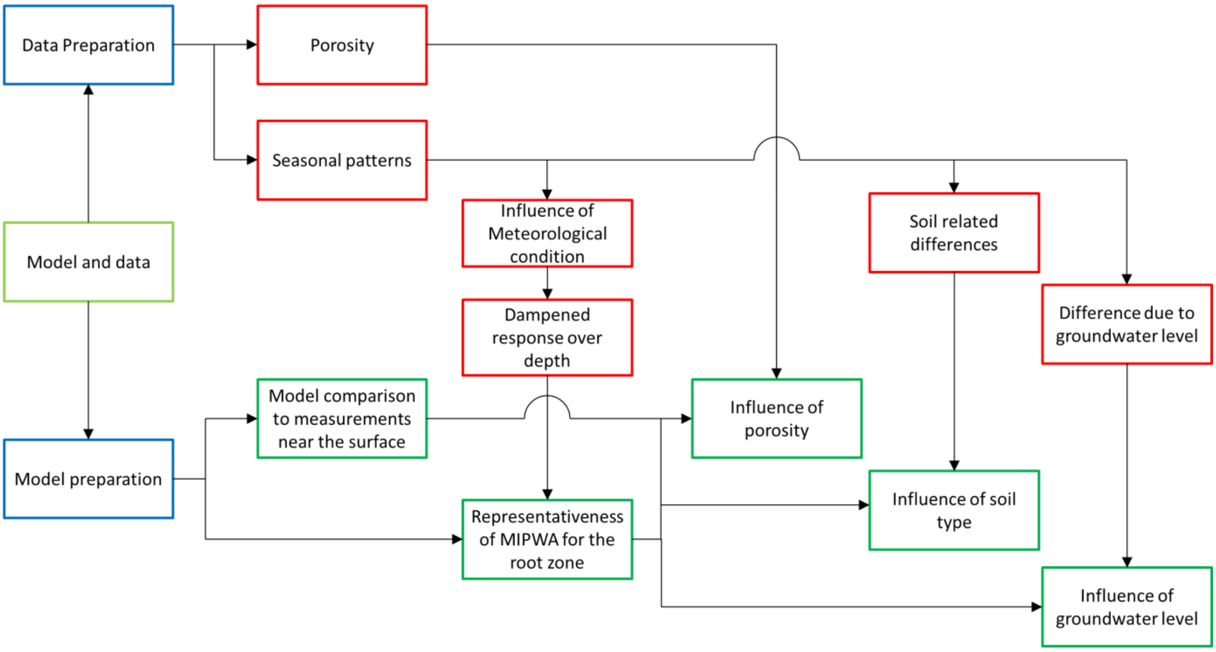


**Figure 3.1: Schematic overview of subsection of methodology and the relation between the individual subsections. Red marked sections are related to the field data analysis, green marked section are related to the model evaluation.**

## 3.1 Field data analysis

The field measurements of the soil moisture network in Twente have been used in previous studies, however these studies mainly focus on the upscaling of the field data to a regional level. For the spatial upscaling, the measured soil moisture content at 5 cm depth has been used (Brink, 2014; Wu, 2010; Mehrjardi, 2015). However the soil moisture content is measured at multiple depths at most observation sites. Since MIPWA describes the entire root zone, the field measurements at all depths have to be included in the comparison with MIPWA. Before field measurements can be compared to the model results the field data has to be prepared and analysed.

### 3.1.1 Measurement data preparation

The soil moisture content is measured by the ECH2O-TE/EC-TM probes; these have been calibrated by Dente et al (2011). Except for the calibration, the data set is the unprocessed data from the probes. Therefore, the first step of the analysis is to identify potential errors in the data set.

A common observation in the winter period is the sudden drop in the soil moisture content due to freezing of the soil moisture. When the water in the soil freezes, the dielectric permittivity decreases proportional to unfrozen soil moisture content (Watanabe & Wake, 2009) (Nagare, et al., 2011). Thereby the probes, which use the dielectric permittivity, only record a fraction of the total moisture content (Quinton, et al., 2005; Nagare, et al., 2012). This causes the soil moisture content drops rapidly when the soil temperature is slightly below zero degrees. When the soil thaws the soil moisture content is restored to similar values as before the freezing of the soil.

This behaviour is also visible in Twente, as the red marked area in Figure 3.2 shows. The temperature during this period is however slightly above zero degrees Celsius. The probes likely overestimate the soil temperature due to the measurement inaccuracies of 1 degree Celsius (Decagon Devices Inc., 2008). Because of this inaccuracy all periods with soil temperatures below 2 degrees Celsius are marked as potential unreliable. Manual assessment of these periods is used to ensure only periods with the sudden drops are removed from the dataset.

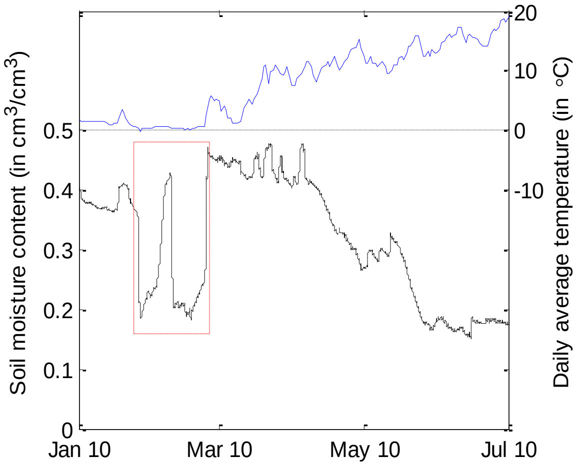


**Figure 3.2: Soil moisture content at observation site 1 before removal of two frost periods in February 2010. Average temperature (blue) is compared to the soil moisture content (black) at 5 cm depth**

Another frequent observation is sudden short jumps in the soil moisture measurements, without responses of the shallow layers or deeper layers. The recorded soil moisture content increases or decreases rapidly followed by a quick recovery to the initial value within the time span of less than30 minutes. The behaviour is happens only at sensor; in the deeper or shallower layers this behaviour is not visible before or after these events. Since the influence the temporal upscaling of the soil moisture measurement, these measurements are regarded as errors.

Furthermore an error is observed at observation site 6 in March 2011, affecting all measurements after this month. The soil moisture content is increasing in three steps at observation site 6 in March 2011, as can be seen in Figure 3.3. The increase is unexpected since the precipitation amount in this period is limited and nearby observation sites show a decrease of the soil moisture. The increase of soil moisture affects also the measurements in the remaining months of 2011. The reason for the higher probe measurements is unknown, however the increase appear to be systematically. As a result of this the measurements before and after March 2011 are incomparable.  Since the dataset before March 2011 has a larger length, the data starting from March 2011 is considered incorrect and removed from the dataset.

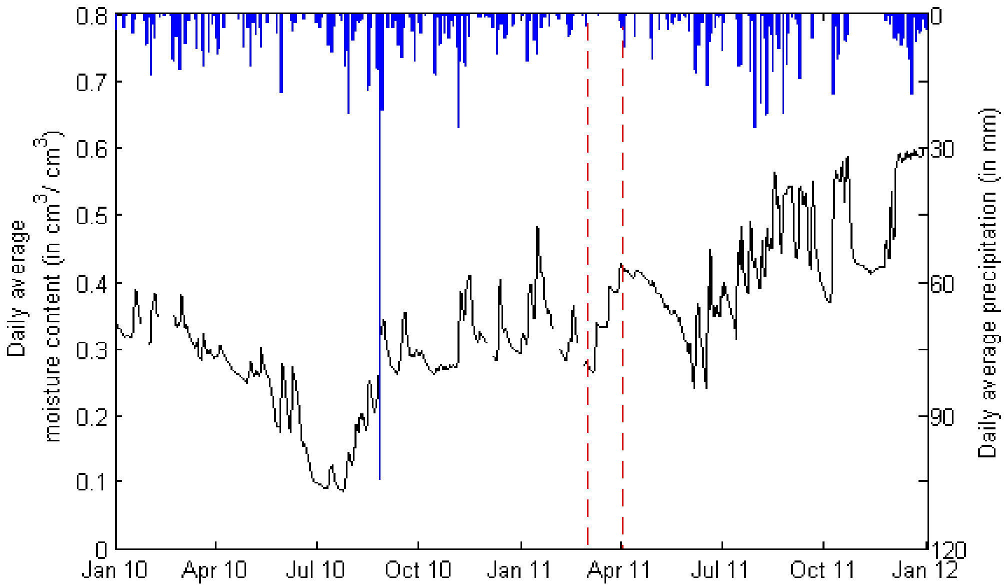


**Figure 3.3: Soil moisture content (black) at 5 cm depth measured at observation site 6 between 2010 and 2012, plotted against precipitation (blue)**

Finally some observation sites record very high soil moisture contents for a relatively short period, these peaks could be potential errors. These peaks in soil moisture content are shown in Figure 3.4 for observation site 12; however also occur at sites 4, 15, 18 and 19. Remarkable about these peaks is that they coincide with the high water levels in the nearby stream at observation site 12. The peaks in measured soil moisture content are likely caused by macro pores. Macro pores are only filled when the groundwater level is above the pores, causing a sudden increase and decrease of soil moisture content.

However it is unlikely for the groundwater table to reach the probes, especially the probe at 5 cm depth. Therefore it is likely there is an elevated groundwater table, known as perched water table, is present. The perched water tables are caused by impermeable layers near the surface. The soil above the impermeable layer can become saturated, creating an elevated groundwater level. This can cause the macro pores to become filled. Since perched water tables and macro pores are incorporated in the model, the model should be able to replicate this process. Therefore the peaks in soil moisture content are not removed from the measurement data.

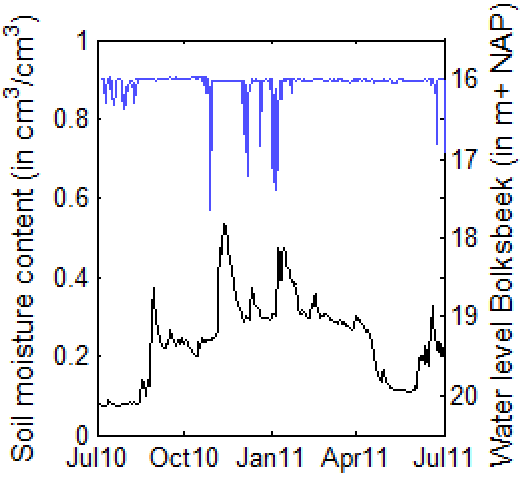


**Figure 3.4: Observed soil moisture content (black) at different depths at observation site 12 and water level (blue) in the Bolksbeek at weir located 4 km upstream from observation site**

### 3.1.2 Porosity

After data preparation the soil moisture measurements are compared to theoretical porosity of the soil type at the observation sites. In theory, the maximum observed soil moisture content cannot exceed the porosity of the soil, since all pores are filled whenever the soil moisture content is equal to the porosity (Freeze & Cherry, 1979). The measurements are expected to be equal or below the porosity based on the soil type.

For each observation site a soil type classification is available. The BOFEK classification distinguishes 72 separate classes based on physical properties of the soil (Wösten, et al., 2013). Each class describes the different layers of the soil up to a meter of depth and therefore provides detailed information on the root zone. In combination with the Staringsreeks (Wösten, et al., 2001), as presented in appendix C, the porosity of the root zone can be determined.

For each observation site the porosity in the root zone compared to the observed soil moisture content. Observation sites that over- or underestimate the porosity are identified and the magnitude of the deviation is determined. The uncertainty in the Staringsreeks and a confidence interval of 95% are used to determine whether the magnitude of the deviation is significant.

Underestimations of the porosity can be explained by multiple reasons. The soil moisture content might not have been close to saturation, therefore explaining the too low values. Alternatively the probes can systematically underestimate the soil moisture content. This option is explored by comparing the measurement to the permanent wilting point. The soil moisture content associated with the permanent wilting point is not reached in the Netherlands. The permanent wilting point is determined by applying a negative pressure head of 16000 cm to the soil. Van de Akker (2001) stated that in a grass covered soil the negative pressure head can reach up to 8000 cm, but only locally near the surface. Therefore it is expected that the measurements are always higher than the permanent wilting point. The wilting points have been listed in appendix B.

Overestimations of the porosity can be caused by an incorrect soil type for the observation site, however also by an overestimation of the soil moisture content by the probes. The volume of the pores in the soil needs to be equal to the maximum measured soil moisture content. This is examined by comparing the measurements to the porosity based on the bulk density. Samples of the soil taken at the observation have been used to determine the bulk density. The calculation of the bulk density based porosity is explained in detail in appendix C. The comparison determines the physical possibility of the measured soil moisture content.

### 3.1.3 Seasonal patterns in soil moisture content

The soil moisture content throughout the year varies, the focus of this section is to identify differences in between seasons. For a quantitative analysis, the year has been divided into four equal periods, corresponding to the seasons of the year. These are referred to as quartile 1 (Q1), quartile 2 (Q2), quartile 3 (Q3) and quartile 4 (Q4). Each quartile represents a period of 3 months of the year, starting on the first on January. The mean soil moisture content in each season is determined and compared to the other seasons. The mean soil moisture content is determined using equation (1). The mean captures the larger seasonal trend throughout the year. Within a season the soil moisture content also varies, this variation is quantified using the using the mean absolute difference (MAD) in equation (2).

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{1}$$

$$Mean\ absolute\ difference\ (MAD) = \frac{1}{n}\sum_{i=1}^{n} |X_i - \bar{X}| \tag{2}$$

Where $X_i$ is the value of variable X at time step i, $\bar{X}$ is the average of all $X_i$ and n is the number of values in variable X. For the purpose of this research $X$ is equal to the soil moisture content $\theta$ in $cm^3/cm^3$ at a specific depth during a specific period within the study period. Therefore the mean $\bar{X}$ is the mean soil moisture content in $cm^3/cm^3$ and the mean absolute difference is in $cm^3/cm^3$.

The seasonal pattern is dependent on the observation site and on the installation depth. To demonstrate the seasonal variation of soil moisture in the region, the results from all observation sites are averaged. Wu et al (2002) showed that the seasonal pattern has the largest amplitude close to the earth surface, therefore the probe measurements at 5 cm depth are used to determine the seasonal variance.

### 3.1.4 Influence of meteorological conditions

The evapotranspiration and precipitation have a large influence on the season behaviour of the soil moisture content. The purpose of this section is to determine the relation between soil moisture content and the meteorological conditions, specifically precipitation and evapotranspiration.

***Precipitation***

The relation between precipitation and soil moisture is quite strong; Pan et al. (2003) showed that the precipitation amount could predict the daily soil moisture content in summer. Sampaio et al. (2014) concluded that the soil moisture content at depths between 10 cm and 50 cm reacted with a delay of 3 to 4 hours to the precipitation. The reaction of the soil moisture content zone is almost simultaneous throughout the root zone. However both researches have been performed on dry soils in a semi-arid climate, causing a direct reaction to the precipitation. Therefore has to be determined whether the relation is valid for the temperate climate of the Netherlands. This is done by comparing the change of soil moisture content to the amount of precipitation in an hour. The comparison is done with the coefficient of correlation ($r^2$) in equation (3).

$$r = \frac{\sum_{i=t_1}^{t_2}([X_i - \bar{X}][Y_{i+l} - \bar{Y}])}{\sqrt{\sum_{i=t_1}^{t_2}(X_i - \bar{X})^2} * \sqrt{\sum_{i=t_1}^{t_2}(Y_{i+l} - \bar{Y})^2}} \quad (3)$$

Where $X_i$ is the value of variable X at time step i, $Y_i$ is the value of variable Y at time step i, $t_1$ is first time in the study period, $t_2$ is the last time in the study period and l is the lag time. To determine delayed response of change in soil moisture content on precipitation, variable X is equal to the change in soil moisture content in $cm^3\ cm^{-3}$, variable Y is equal to the hourly precipitation amount in mm and the lag time l is in hours.

The comparison is only done for observation site 4, since this station is located nearby weather station Twente. The other observation sites are located further from the weather stations. This distance can cause precipitation events to occur on a different moment than at the observation site. This causes a delayed or early response of the soil moisture, which distorts the correlation between the two components.

***Evapotranspiration***

The seasonal pattern of evapotranspiration is more evident in the soil moisture than the precipitation (Wu, et al., 2002), especially since the precipitation is spread equally over the year in the Netherlands (Jacobs, et al., 2010). The similarity of soil moisture content and reference evaporation is demonstrated in Figure 3.5. The correlation between these variables is investigated using equation (3). Where variable X is equal to the daily average soil moisture content in $cm^3\ cm^{-3}$, variable Y is equal to the daily potential evapotranspiration and the lag time l is in days.

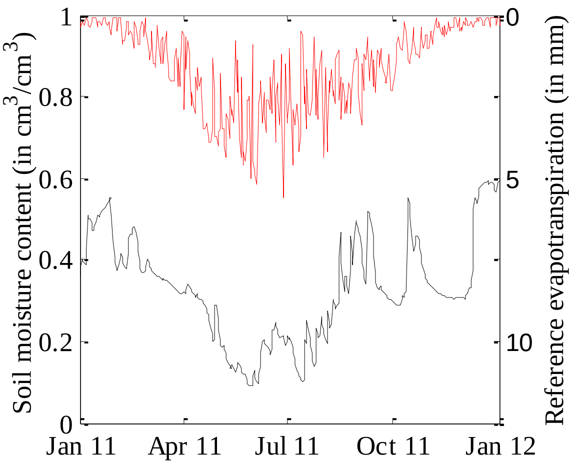


**Figure 3.5: Soil moisture content and reference evapotranspiration at observation site 4**

***Precipitation deficit***

The combination of evapotranspiration and precipitation can be used to calculate the precipitation deficit. The precipitation deficit can be used as an indication of the soil moisture content deficit (Rickard, 1960), thereby the soil moisture content. The precipitation deficit can be calculated using equation (4).

$$D_i = Max(D_{i-1} + ET_{ref,\ i} - P_i\ , 0) \quad (4)$$

Where $D_i$ is equal to the precipitation deficit in mm at time step i, $ET_{ref}$ is the reference evapotranspiration in mm at time step i and $P_i$ is equal to the precipitation amount in mm at time step i. This precipitation deficit is similar to the water balance of the root zone, however lacks capillary rise and percolation. Therefore is expected to have large similarities with the measured soil moisture content.

The precipitation deficit is compared on daily interval to the average soil moisture content. The strength of the relation between the precipitation deficit and the average soil moisture content is evaluated using the coefficient of correlation of equation (3) . Where variable X is equal to the daily average soil moisture content in $\mathrm{cm}^3\ \mathrm{cm}^{-3}$, variable Y is equal to the precipitation deficit and the lag time l is in days.

### 3.1.5 Dampened response over depth

The soil moisture content in the unsaturated zone can be determined by the water retention curve of the soil. The water retention curve relates the negative pressure head to the soil moisture content, this relation is shown in Figure 3.6. In a situation without evapotranspiration, groundwater level change or precipitation, the negative pressure head is related to the distance from the groundwater level. In this steady state, the soil moisture content profile is identical to the water retention curve.

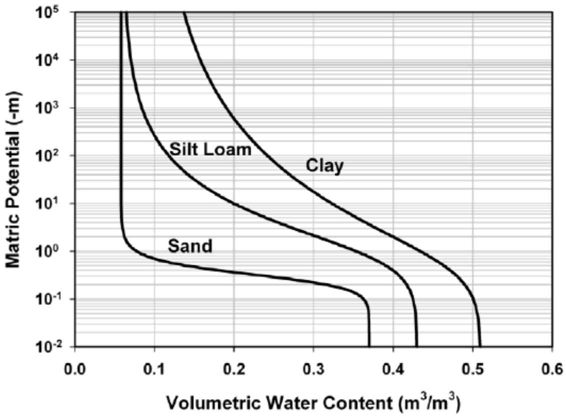


**Figure 3.6: Examples of soil water retention curves for different soils, from Tuller and Or (2003)**

In case of disturbances of the steady state situation, the negative pressure head is not related to the groundwater table. Effects of the disturbance are spread slowly throughout the unsaturated zone by processes similar to diffusion and advection. Since evaporation and precipitation occur at the earth surface; the soil moisture content in the top layer of the soil varies more over time. The effect on the deeper layers of precipitation and evaporation is dampened and delayed due to the diffusion and like process (Wu, et al., 2002).

The dampening effect of depth is examined at observation sites 5, 8 and 19, since these sites have measurements at 5 cm depth, 10 cm depth, 20 cm depth and 40 cm depth. The presence of dampening is determined by calculating the variance of the soil moisture, similar to the seasonal trend. Equation (1) is used to examine the variation between seasons, while equation (2) is used to determine the variation within a season at each individual depth.

### 3.1.6 Soil related differences

Two soil classifications are available for the observation sites; the local classification at the observation sites by Dente et al. (2011) and the BOFEK classification of the Netherlands. Samples of the soil have been taken at each observation site and have been classified by Dente et al. From this classification can be concluded that the soil moisture content is measured in 2 soil types, loamy sand and sand.

**Table 3.1: Soil classification at observation sites according to Dente et al. (2011).**

| | Observation site | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
| **Loamy sand** | | | ✓ | ✓ | ✓ | | ✓ | | | | ✓ | | | ✓ | | | | ✓ | | |
| **Sand** | | ✓ | | | | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ |
| **Other** | ✓ | | | | | | | | | | | | | | | | | | | |

The BOFEK classification by Wösten et al. (2013) identifies two soil types similar to the classification of Dente et al., these are fine to medium sand with loam and fine to medium sand with limited loam. The classification fine to medium sand with loam is similar to the loamy sand classification by Dente et al. (2011) and fine to medium sand with limited loam is similar to the sand classification.

**Table 3.2: Soil classification at observation sites according to Wösten et al. (2013). Astrix indicates that similar classification are used.**

| | Observation site | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
| **Loamy sand*** | | ✓ | | | ✓ | | | | | ✓ | | | | ✓ | | | | ✓ | ✓ | |
| **Sand*** | | | | | | ✓ | | ✓ | ✓ | | | | ✓ | | ✓ | ✓ | ✓ | | | ✓ |
| **Other** | ✓ | | ✓ | ✓ | | | ✓ | | | | ✓ | ✓ | | | | | | | | |

The classification by Dente et al. (2011) and the BOFEK classification are shown in Table 3.1 and Table 3.2 respectively. The average soil moisture content of each soil type is determined. For the comparison of the soil types the mean of the season are determined for the study period. The classification that shows the best difference between the classes will be compared to the model results in the comparison between model and observations.

### 3.1.7 Differences due to groundwater level

The groundwater table has a large influence on the negative pressure head, thereby in the soil moisture content near the surface. In regions with a groundwater table close to the surface the negative pressure heads are lower than in regions with a large distance between groundwater tables. Higher soil moisture content would be expected due to the lower pressure.

The observations sites are divided into two categories, deep and shallow groundwater table. The sites are grouped into the two categories is made based on the average highest groundwater table (GHG). Observation sites with an average highest groundwater table of 40 cm or less below the surface are considered as sites with a shallow groundwater table. Observation sites that have an average highest groundwater table deeper than this threshold are considered as sites with a deep groundwater table. The average highest groundwater is determined based on Dente et al. (2011) and verified with the groundwater level from MIPWA. Differences are observed at observation sites 4, 15 and 16 between MIPWA and the classification by Dente et al. (2011). De Vries, et al. (2003) stated that the classification method utilized by Dente et al. needs to be actualized, thereby MIPWA is preferred for the classification in Table 3.3.

**Table 3.3: Groundwater table classification of observation site.**

| | Observation site | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
| **Deep** | ✓ | ✓ | | ✓ | ✓ | | | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | | | ✓ |
| **Shallow** | | | ✓ | | | ✓ | ✓ | | | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | ✓ | |

The influence of the groundwater table is utilizing the variance of the soil moisture. Equation (1) is used to examine the variation between seasons at the surface for each class. These classes are compared to each other to identify differences.

## 3.2 Comparison of the model and field data

### 3.2.1 Model preparation

Before any comparison between the model and the observation sites can be done, the model output needs to be prepared. The measurements at the observation sites and the simulations of MIPWA measure different quantities represent different depths and have a different spatial, temporal resolution. Therefore the measurements of the observation sites are not directly comparable to the simulations of MIPWA. In the following sections the individual steps to prepare the model data of MIPWA are discussed.

***Definitions differences***

MIPWA and the probes define the soil moisture content using different definitions, for the comparison only one definition of soil moisture content can be used. The sensor measures the soil moisture content at different depths, expressed in $m^3\ m^{-3}$. The output of MIPWA contains the total volume of water in the root zone, expressed in $mm$. The total volume of water can be converted to soil moisture content by equation (5).

$$\theta = \frac{V_w}{d * A} \qquad (5)$$

Where $\theta$ is the soil moisture content of the root zone in $m\,m^{-1}$, $V_w$ is the total volume of water in the root zone in $m^3$, $d$ thickness of the root zone and A the area of the grid cell in MIPWA. The root zone thickness is dependent on the vegetation type and soil type, ranging from 15 cm for grass to 100 cm for forest, while the soil moisture content is measured on fixed depths at the observation sites. It should be noted that this soil moisture content is representative for the entire root zone. The probes measurements are only representative for the installation depth of the probes

***Temporal differences***

MIPWA determines the soil moisture volume on a daily basis, while the soil moisture content at the observation sites is measured on averaged over 15 minutes. The comparison of the model and measurements requires equal time interval. The measurement results are therefore temporally downscaled to the measurement interval of MIPWA. Two methods for downscaling have been considered.

The first method groups the measurements in groups of hours. The coefficient of Correlation equation (3) is used to determine which hour is strongest related to the model. Where variable X is equal to the modelled soil moisture content in $\mathrm{cm}^3\ \mathrm{cm}^{-3}$, variable Y is equal to the observed soil moisture content in $\mathrm{cm}^3\ \mathrm{cm}^{-3}$. The correlation increases over the day until 17:00 CET, after which the correlation slowly decreases. The maximum correlation is found between 16:00 and 16:59 CET, with a coefficient of correlation of 0.60. Alternatively the daily average can be used, which is done with the second method. The daily average resulted in a coefficient of correlation of 0.61. Since the daily average soil moisture content has the highest correlation and is therefore used for all subsequent analysis.

***Spatial differences***

Soil moisture content is variable in space and therefore the probe measurement might not be representative for an area of 25 by 25 meters, the grid cell size of MIPWA. Wu (2010) indicated that the correlation length of the soil moisture content in Twente is smaller than 250 meters. Western et al.

(1998) showed that the correlation length of the soil moisture content varied between 35 and 60 meters depending on soil type and season. From these correlation lengths can be concluded that measurements within the grid cell are likely correlated. Therefore the soil moisture content within a grid cell is expected to be similar to the measured soil moisture content.

However this does not imply that the measurements are directly comparable to the simulations of MIPWA. The simulation of the soil moisture content requires the conditions in the model to be similar to the conditions in the field. In MIPWA, three input parameters can be distinguished; these influence the soil moisture content directly. The three parameters are soil type, land use and the presence of drainage.

In case the situation in the field deviates from the modelled situation, corrections have to be applied. A comparison for all observation sites has been conducted, which is described in Appendix B. As a result, three observation sites are not compared to the grid cell corresponding with the coordinates of the observation site. This is mainly done due to a difference in land use. For these sites replacements sites selected up to 75 meters. The alternative sites exceed the correlation distance found by Western et al. (1998) for soil moisture content, therefore the measurements might be incomparable to the model. The selected sites have comparable groundwater level and land height. Due to the similar boundary condition difference should be limited.

***Groundwater level validation***

The groundwater level is important for the simulation of the soil moisture content. The unsaturated zone model is quasi steady-state; the simulated soil moisture content depends on the groundwater level. Therefore the simulation of the groundwater level is important for the simulation of the unsaturated zone. At 15 locations the groundwater level of MIPWA is compared to measurement. Overall can be concluded that MIPWA simulates the groundwater level lower than has been measured. The average underestimation of the groundwater level is 40 cm. However at 3 locations the difference is more than 1 meter, as can be seen in Figure 3.7. This underestimation can cause lower soil moisture contents to be simulated by the model.

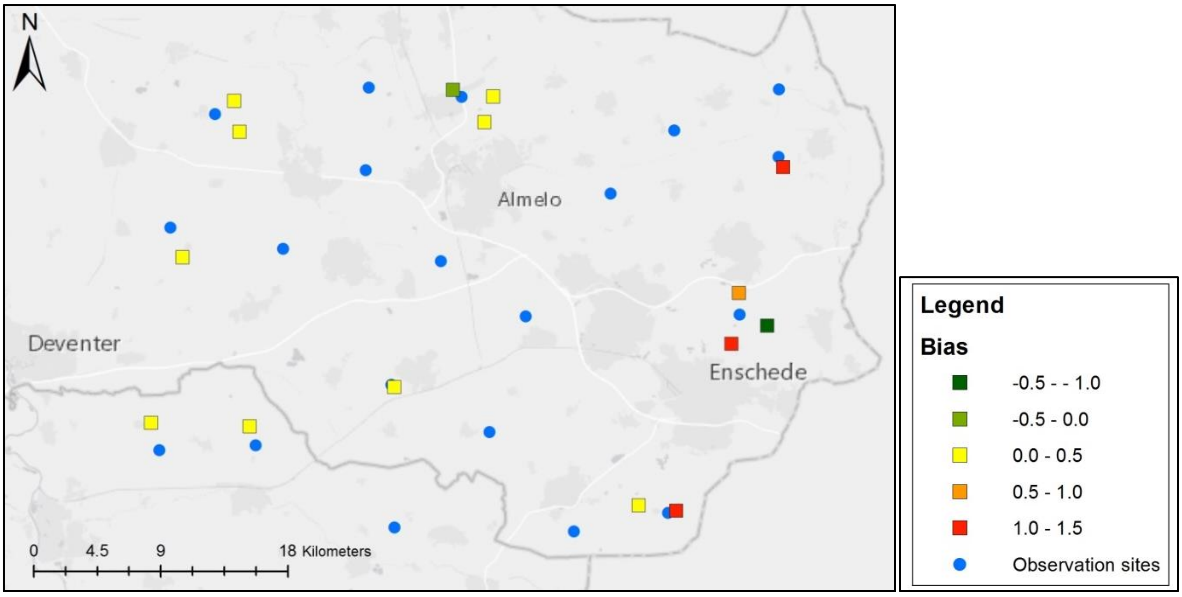


**Figure 3.7: Underestimation of the groundwater level in meters**

### 3.2.2 Representativeness of MIPWA for the root zone

MIPWA determines for each time the total volume of moisture in the root zone, however the probes at the observation sites are only representative for the depth they are located in. The probes measure the soil moisture content between the installation depth until 5 cm underneath the installation depth (Cobos, 2015). With this measuring range the sensors are unable to capture the entire soil moisture in the root zone, since the distance between probes is up to 20 cm. To determine the soil moisture content in the root zone 3 assumptions are made:

- The probe measurement at 5 cm depth is representative for the soil moisture content between the earth surface and the probe at 5 cm depth
- The soil moisture between two probes is linearly related
- The deepest probe measurement is representative for the soil moisture content of 10 cm below the installation.

Utilizing the first two assumptions the soil moisture content in the root zone can be determined for only 3 observation sites. Only observation sites 5, 8 and 19 have probes placed inside and outside the root zone. The third assumption enables the soil moisture content to be determined for 6 additional observation sites. This final assumption allows the soil moisture content to be determined at sites 1, 10, 11, 12, 14 and 18.

The ability of the model to simulate soil moisture content is examined by calculation the coefficient of correlation, the root mean square, the Nash-Sutcliffe coefficient and the bias for each observation site. The coefficient of correlation, equation (6), quantifies whether observed soil moisture content is linearly related to the simulated soil moisture. A high score on the coefficient of correlation indicates that observed soil moisture content is related to the simulated soil moisture and that changes in observed soil moisture are replicated by the model.

The other coefficients give insight in the ability of the model to determine the absolute value. The root mean squared error, equation (7) quantifies the difference between the model and the observed soil moisture content. The Nash-Sutcliffe coefficient, equation (8), compares the error in absolute error to the error of the mean. The root mean square error can be caused by a systematic deviation between the model and the observation, this systematic deviation is captured by the bias, equation (9).

$$\mathrm{r} = \frac{\sum([\mathrm{X_i} - \overline{\mathrm{X}}]\,[\mathrm{Y_i} - \overline{\mathrm{Y}}])}{\sqrt{\sum(\mathrm{X_i} - \overline{\mathrm{X}})^2} * \sqrt{\sum(\mathrm{Y_i} - \overline{\mathrm{Y}})^2}} \tag{6}$$

$$RMSE = \sqrt{\frac{\sum(X - Y)^2}{n}} \tag{7}$$

$$NS = 1 - \frac{\sum(X_{observed} - X_{modelled})^2}{\sum(X_{observed} - \bar{X}_{observed})^2} \tag{8}$$

$$Bias = \bar{X} - \bar{Y} \tag{9}$$

In this section variable X is equal to the measured soil moisture content in the root zone in $\mathrm{cm}^3\ \mathrm{cm}^{-3}$, variable Y is equal to the modelled soil moisture in the root zone in $\mathrm{cm}^3\ \mathrm{cm}^{-3}$.

### 3.2.3 Comparison of the model with all observation sites

Most observation sites measure only a small part of the root; however the other observation sites still contain valuable information on the model performance. The soil moisture content is measured at all observation sites at a depth of 5 cm, while the model simulates the soil moisture content of the entire root zone. Since the measurement at 5 cm depth is close to the surface, it is expected to have a larger variance than the entire root zone. However, the probe does measure the soil moisture content in the root zone. Therefore the dynamics of the measurement at 5 cm, as measured by the coefficient of correlation, should be similar to the entire root zone. Therefore the correlation is determined between the measurements at 5 cm depth and the modelled soil moisture content of the root zone for all observation sites.

### 3.2.4 Influence of porosity

The porosity for each site is different from the expected porosity; however some sites have significant differences of porosity and observed soil moisture content. The observation sites are divided into two categories. The first category contains sites with a similar measured porosity as the porosity in MIPWA. The second category contains the observation sites with discrepancy between measured and modelled porosity. These classes are applied to results of individual observation sites to identify differences.

### 3.2.5 Influence of groundwater

The differences due to groundwater level in the model are investigated in this section, the model should be able to show difference between observation sites with a deep groundwater level and sites with a shallow groundwater level. Seasonal patterns from the observations are compared to the seasonal patterns of the model. The modelling results are compared to the observed soil moisture content visually and using the coefficient of correlation.

### 3.2.6 Influence of soil type

Besides differences in groundwater level, the model has to be able to replicate the observed differences in soil moisture content for the two soil types identified. In the parameterization of the soil database the differences in soil type should be included; this is evaluated by comparing the correlation between the measurements of the soil moisture content and the model simulations.

# 4 Soil moisture observations

The first section of the results describes the field measurements and the properties that have been derived from the measurements. The measurements have been filtered for errors, which is described in the methodology. The data is used to derive properties the model has to fulfil; these are described in the following sections.

## 4.1 Observed porosity at 5 cm depth

The observed maximum soil moisture content is used to represent the observed porosity and compared to the BOFEK based porosity. This measured porosity deviates from the BOFEK based porosity, as demonstrated in Figure 4.1. Deviations from the BOFEK based porosity are however expected, as the soil type porosity has a large uncertainty. In Appendix C the deviations are compared to the uncertainty, 9 sites are proven to have a significant deviation from the BOFEK based porosity.

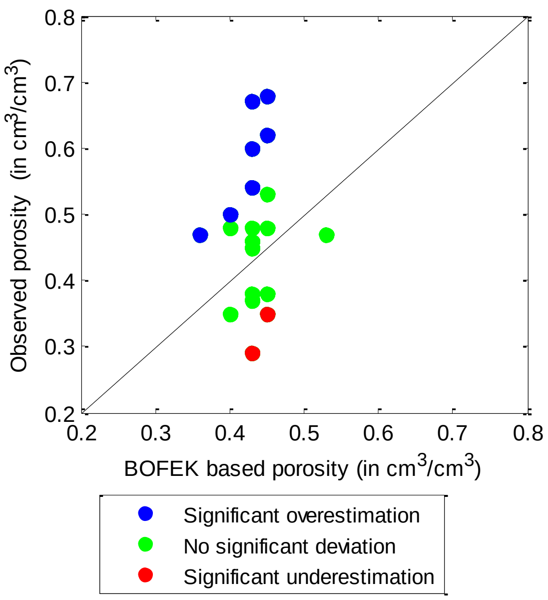


**Figure 4.1: BOFEK based porosity compared to the maximum soil moisture content for each observation site.**

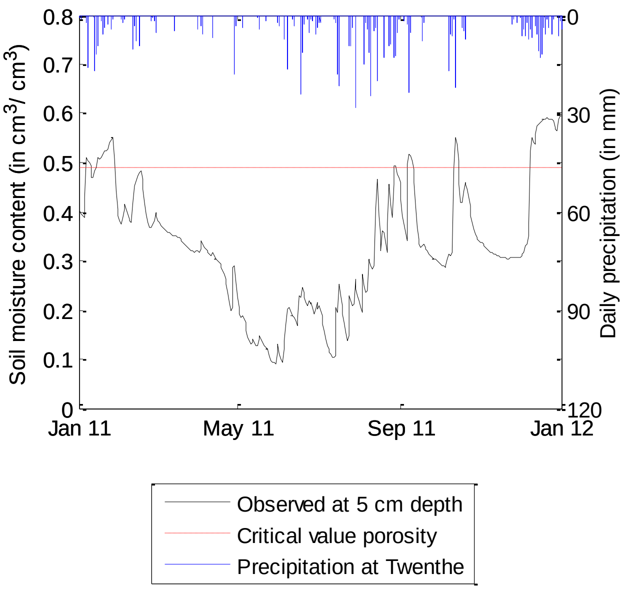


**Figure 4.2: Measurements compared to the critical porosity based on 95% confidence limits at observation site 4.**

A group of observation sites that exceed the soil type porosity have similar behaviour. The probes likely measure large pores in the soil that are filled by heavy precipitation and are emptied quickly afterwards. This occurs multiple times during fall and winter, indicating that the measured value is indeed likely to be the measured porosity instead of an outlier. The development of the soil moisture content of observation site 4 is shown in Figure 4.2, this behaviour is shown as well by observation sites 12, 15, 18 and 19. At these sites the porosity is also determined based on the bulk density. The results of the analysis in Appendix C show that the observed soil moisture content could not have been measured in an undisturbed sample of the soil. The soil around the probes has likely been disturbed and created large pores nearby the probes. Due to the large pores in the soil too high soil moisture content can be measured.

The observation sites that are under the soil type based porosity seem to underestimate the soil moisture content. The probes measure soil moisture content lower than the permanent wilting point; it is unlikely that the soil is this dry. More likely is that the probe has a negative systematic deviation or that the calibration is not suitable for low soil moisture contents. The observation stations that measure this low are sites 2 and 17.

## 4.2 Seasonal patterns

During the year the soil moisture content shows a strong seasonal trend, as shown in Figure 4.3. In 2010 the average soil moisture content in the first quartile and last quartile the amount of moisture in the soil is high compared to the rest of the year. From the end of March the soil moisture shows a decreasing trend until the end of June. From July the amount of water in the unsaturated zone starts to increase until September.

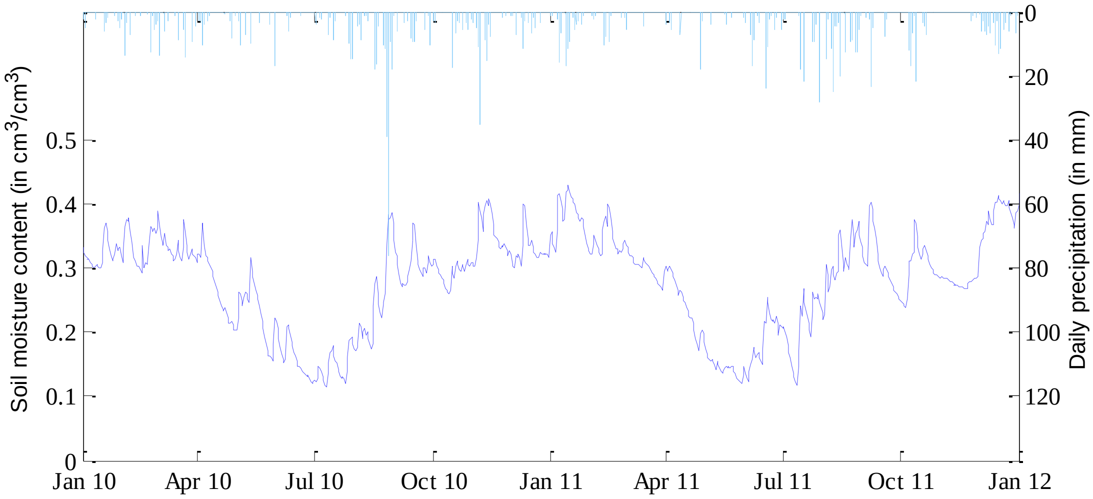


**Figure 4.3: Soil moisture content at 5 cm depth, averaged over all observation sites (dark blue) and precipitation at Twenthe (light blue)**

The seasonal trend in 2011 is slightly different compared to 2010 due to a dry spring and a wet summer in 2011. In 2011 the decrease of soil moisture content starts at the beginning of March and ends in august. This trend is disrupted by a wet period in the beginning of July. Furthermore September and November are relatively dry month for the year; the soil moisture content therefore steadily decreases in these months.

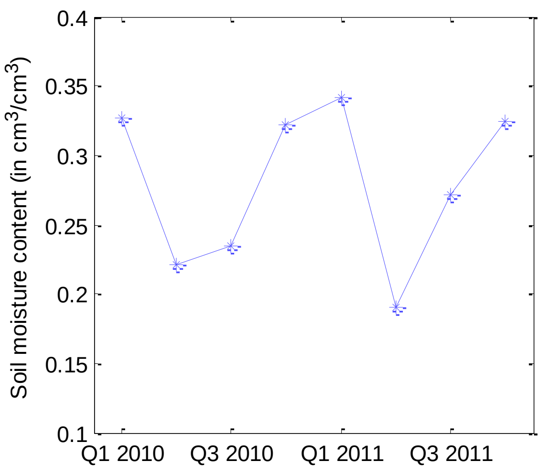


**Figure 4.4: Seasonal average soil moisture content at 5 cm depth, averaged over all observation sites**

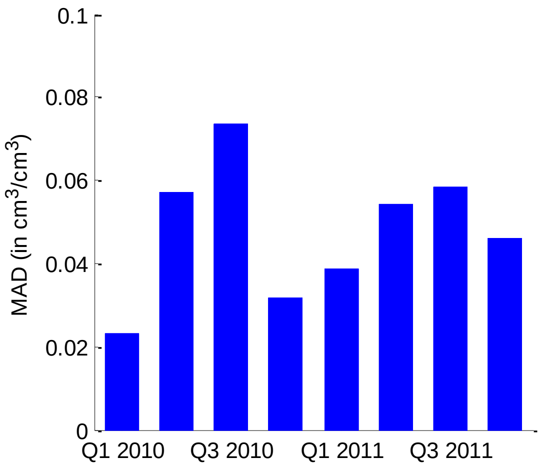


**Figure 4.5: Mean absolute deviation of soil moisture content at 5 cm depth, averaged over all observation sites**

The seasonal trend is also visible in the average soil moisture content in each quartiles, as shown in Figure 4.4. The soil moisture content in the second and third quartile of 2010 is remarkably lower than in winter. During these months the transpiration can be reduced due to soil moisture stress. The lower average soil moisture content allows also for a larger variance in soil moisture content, as demonstrated by Figure 4.5. Therefore the variance is higher during the summer than in winter. The larger variance in 2010 is likely due to a stronger reaction to precipitation events.

## 4.3 Influence of meteorological conditions

The precipitation and evapotranspiration directly influence the soil moisture content; the strength of this relation is examined in this section. This is only done for observation site 4 due to the availability of meteorological data.

On an hourly interval the change of soil moisture content is strongly related to the amount of precipitation. This is demonstrated by the coefficient of correlation in Figure 4.6 the correlation shows that the change in soil moisture content coincides with the precipitation amount at observation site 4. In 2010 the soil moisture content reacts delayed to the precipitation, with a lag time of 2 hours. In 2011 the reaction of the soil moisture is within an hour of the precipitation. The difference between 2010 and 2011 could be caused by the change in land use. In 2010 corn was cultivated on the field while in 2011 the land only covered by grass. In both years, the soil moisture content in the entire root zone reacts in a relatively short period of time to the precipitation. On the daily interval of MIPWA the soil moisture content will react instantly to precipitation.

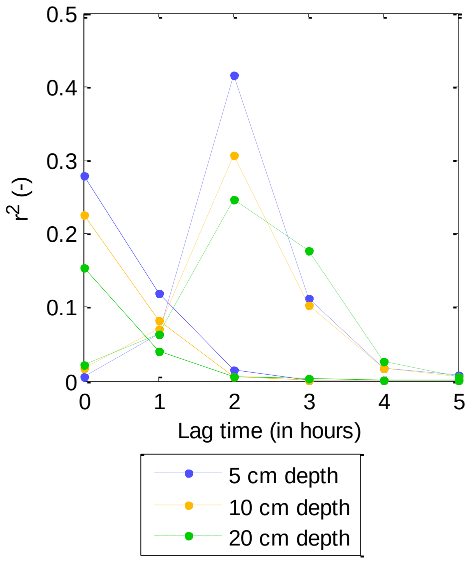


**Figure 4.6: Cross correlation of precipitation and change in soil moisture content at observation site 4 in 2010 (dashed) and 2011 (solid).**

While the precipitation can predict the change in soil moisture content reasonably, the seasonal trend of the soil moisture content can be predicted by the reference evapotranspiration. The variance in the soil moisture content can be explained up to 55% by the evapotranspiration, as shown in Figure 4.7. The correlation in 2010 is remarkably stronger than in 2011, indicating that the reference evapotranspiration has a larger influence on the soil moisture content in 2010. The transpiration by the vegetation in 2010 appears to be more affected by soil moisture stress than in 2011. Therefore the actual evapotranspiration in 2010 is lower than the reference evapotranspiration, reducing the correlation presented in Figure 4.7.

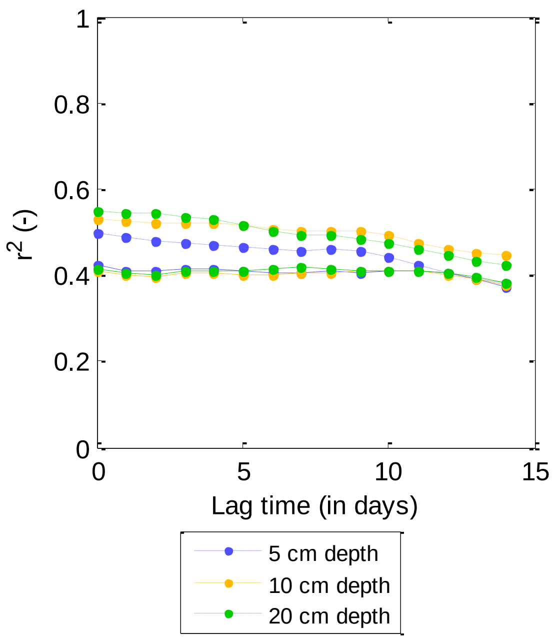


**Figure 4.7: Cross correlation of precipitation and change in soil moisture content at observation site 4 in 2010 (dashed) and 2011 (solid).**

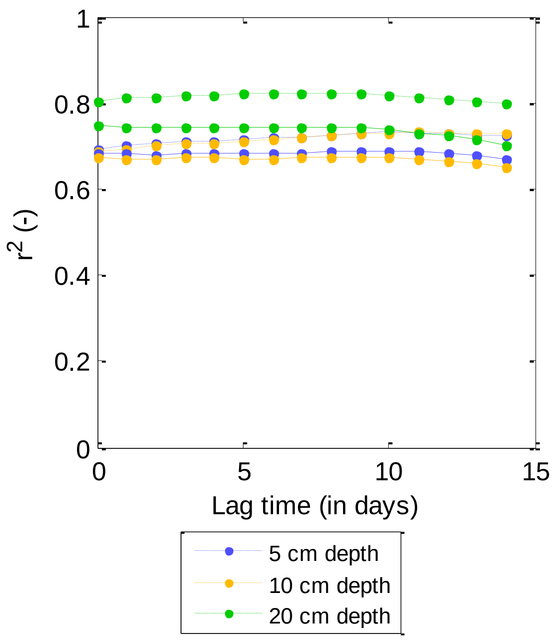


**Figure 4.8: Cross correlation of evapotranspiration and soil moisture content at observation site 4 in 2010 (dashed) and 2011 (solid).**

The precipitation deficit is able to predict up to 80% of the variance in the soil moisture content. The precipitation deficit is a good predictor of the soil moisture content at observation site 4. The precipitation deficit shows in Figure 4.8 that correlation increases with depth for both years. This is due to the uptake of water by vegetation. Water is absorbed from the entire root zone, however during dry periods the available water in near the surface is lower than deeper layers. Therefore the vegetation cannot drain water from the surface layer and the relation between evapotranspiration and soil moisture content is weaker.

## 4.4 Dampened response over depth

The precipitation and evapotranspiration are affected differently by depth, influencing the measured soil moisture content. Although the probes are located close to the surface, the dampening effect of depth is visible in the probe measurements. The difference in soil moisture between depths is shown in Figure 4.9.

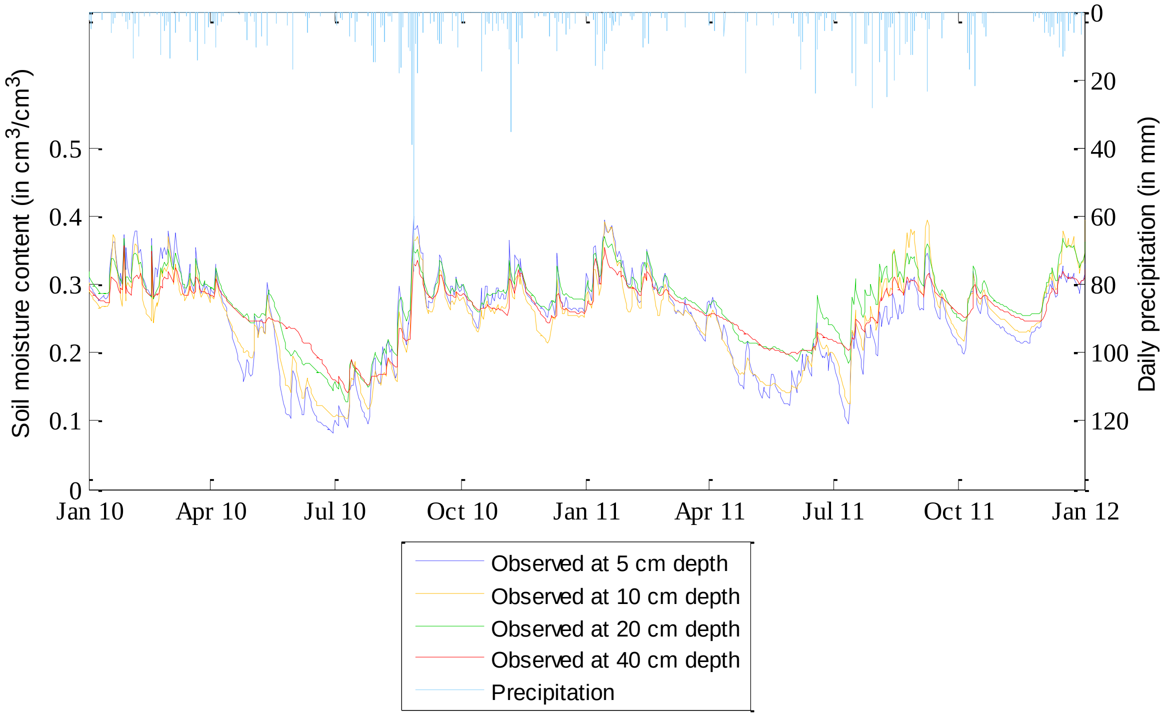


**Figure 4.9: Average soil moisture content of observations sites 5, 8 and 19 over time at the different measurement depths.**

The measurements near the surface are higher in winter than the measurements at 40 cm depth, while in summer the measurements near the surface are lower. The deviation from the annual mean is largest for the measurements at 5 cm depth and decreases with depth as shown in Figure 4.10. In 2010 the soil moisture content at 40 cm depth is reacts delayed to the soil moisture content at 5 cm depth.

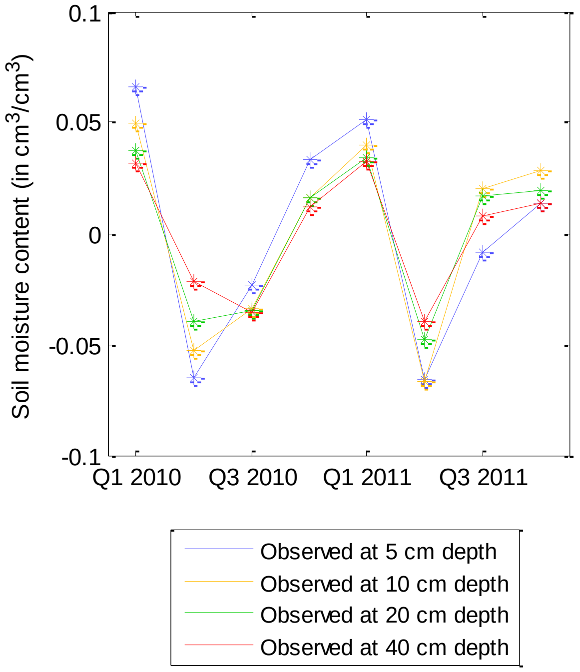


**Figure 4.10: Differences between seasonal mean and mean soil moisture content between 2010 and 2012. Average differences are shown of observation sites 5, 8 and 19.**

The dampening effect of depth is also observed the mean absolute in each quartile, as shown in Figure 4.11. In the first 3 quartiles of 2010 the variation in soil moisture content decreases with depth. In the fourth quartile the variation at 40 cm is slightly higher than the variation at 20 cm. The dampening effect is less evident in 2011, as the variation measured at 5 cm becomes smaller over the most variation can be observed at 10 cm depth in quartile 3 and 4. This difference is solely caused by observation site 19. The response to precipitation at this site is smaller than in the year before; while the measurements at 10 cm respond similar to precipitation events as in 2010.

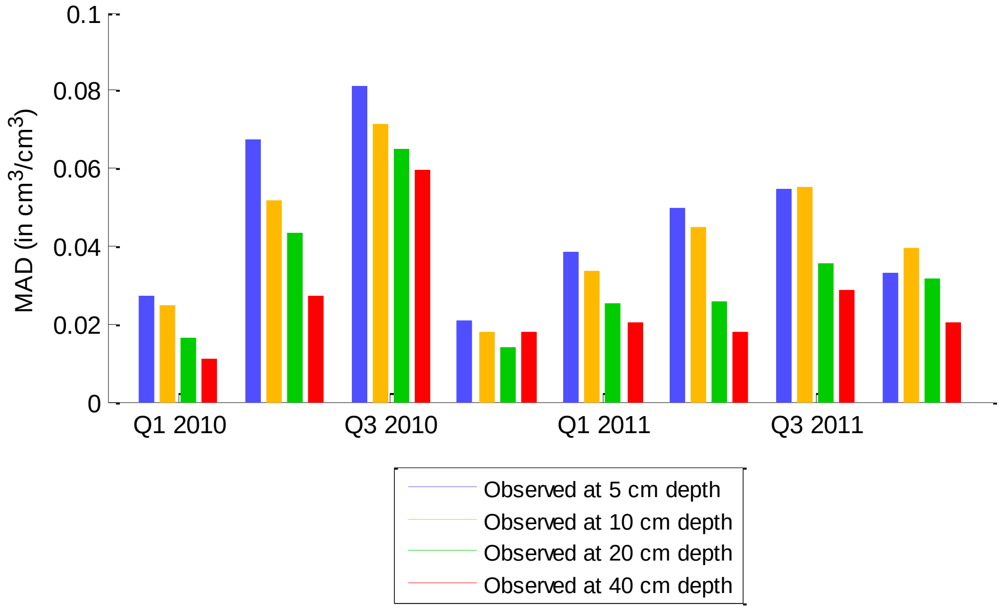


**Figure 4.11: Mean absolute deviation (MAD) of the soil moisture content at the different measuring depths. Average mean absolute deviation of observation sites 5, 8 and 19 is displayed.**

## 4.5 Influence of soil type on the observation

The soil moisture content at observation sites with loamy soils is systematically higher than moisture content at observation sites with sandy soils. This difference is present in both the classifications of Dente et al (2011) and Wösten et al. (2013). However, differences can be observed between the two classifications. Figure 4.12 and Figure 4.13 both show higher soil moisture content throughout the year. The difference between the two soil types become smaller during summer. The differences between soil types are slightly larger for the classifications by Wösten et al. (2013), although this is partly caused due to a smaller amount of observation sites with similar classifications.

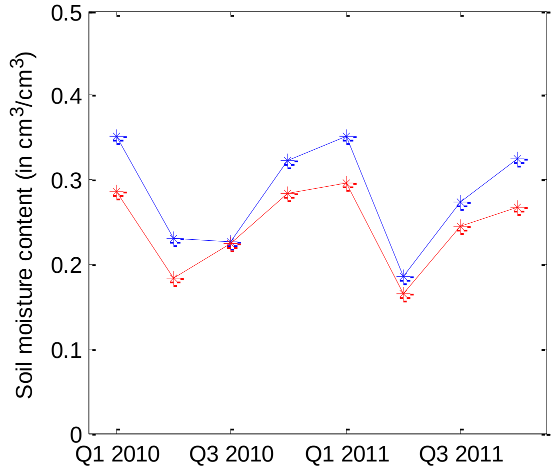


**Figure 4.12: Difference in seasonal pattern of soil moisture content of loamy sand (red) and sand (blue) by classification of Dente et al (2011)**

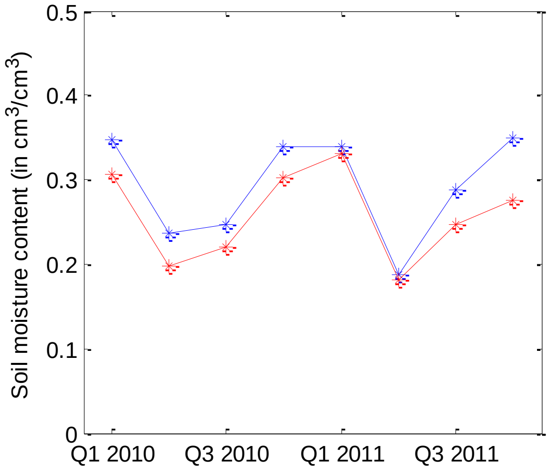


**Figure 4.13: Difference in seasonal pattern of soil moisture content of loamy sand (red) and sand (blue) by classification of Wösten et al. (2013)**

## 4.6 Effect of groundwater level

The influence of the groundwater level is visible at the observation sites, as Figure 4.14 shows a difference in soil moisture content between shallow and deep groundwater tables. Observation sites with a groundwater level deep under the surface have a large unsaturated zone, these sites are able to store large quantities in the unsaturated zone without increasing the moisture content at the surface. This is reflected in the quick decrease of soil moisture content after precipitation. At these sites water is percolated to deeper layers of the unsaturated zone.

Observation sites with a shallow groundwater level have only a limited unsaturated zone and therefore are unable to store large amounts of water. The precipitation cannot be stored in deeper layers as the sites with a deep groundwater level. During summer the small unsaturated zone has a positive effect on the soil moisture content, as capillary rise transports water more easily to the surface. As a result the soil moisture content at sites with a shallow groundwater table is higher in spring. The capillary rise is lower at sites with a deep groundwater level, as the pressure head is higher at these sites. This difference can be observed in spring of 2010.

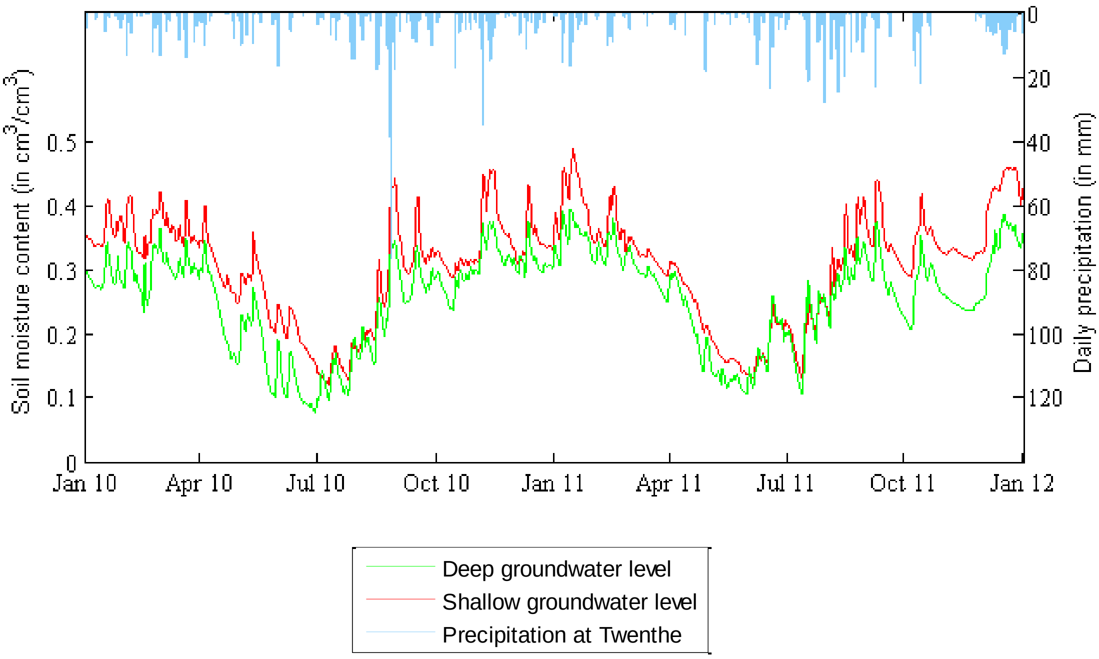


**Figure 4.14: Soil moisture content over time at 5 cm depth for observation sites with a deep groundwater level and observation sites with a shallow groundwater level.**

Throughout the year the soil moisture content at the sites with a groundwater level near the surface contain more moisture than the sites that have the groundwater level further away from the surface. This is reflected in the seasonal mean soil moisture content in Figure 4.15. In the third quartile of 2011 the difference between the soil moisture content is relatively small, since both soils have dried out.

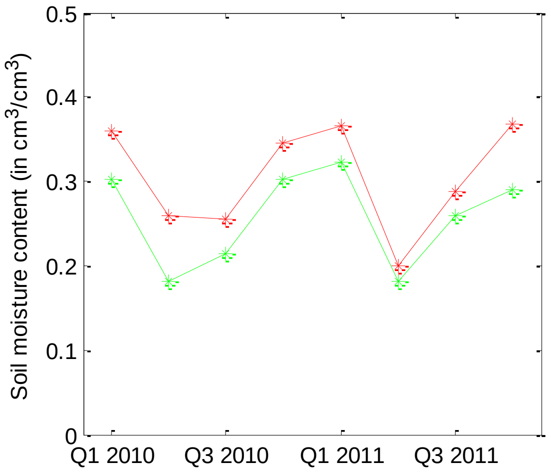


**Figure 4.15: Average soil moisture content of observations sites with a deep (green) and a shallow groundwater level (red).**

## 4.7 Characteristics in the measurement data

The measured porosity shows many differences with the porosity expected on the observation site. On average the measured soil moisture content is higher than would be expected from the soil type. However, the measured porosity lies within the variance expected from the soil type at most observation sites. At 7 observation sites recorded soil moisture content could not have been recorded in the undisturbed soil at the observation site, as the measured porosity is higher than the bulk density based porosity. The soil at these sites is likely disturbed, resulting in macro pores to be present in the soil. However this is only present at the observation site, not in the entire soil. The measurements might not be representative for the soil, as the measured soil moisture content exceeds the bulk density based porosity. Since the measurements might not be representative for the soil, the measurements cannot be replicated using parameters for the soil type. Therefore small differences between the model and observations are expected.

The soil moisture content follows a similar pattern to the evapotranspiration and precipitation deficit. As a result the soil moisture content in the second and third quartile is lower than the first and fourth quartiles. The correlation between meteorological condition and the soil moisture content furthermore showed differences in behaviour of different layers in the soil. The probes near the surface are more sensitive to precipitation than deeper located probes. The deeper probes are similar to the trend of evapotranspiration and precipitation deficit. As a result the probes near the surface measure large variance, which dampens over the length of the root zone. This indicates that the surface measurements are not always representative for the entire root zone, although the measurements are part of the root zone.

At the observation sites the effect of the groundwater level and soil type is clearly visible. Observation sites with the classification sand are drier than the observation sites with loamy sand classification. This is valid for the classifications of both Dente et al (2011) and Wösten et al. (2013). Therefore model, which is based on the classification by Wösten et al. (2013), should give comparable results with the in-situ classification of the soil by Dente et al (2011). The observation sites with a groundwater level far beneath the surface are drier throughout the year. Observation sites with a groundwater level near the surface contain more moisture, especially during spring. This difference between soil type and groundwater level should be able to be simulated by MIPWA.

# 5 Ability of MIPWA to replicate soil moisture content

The results of the unsaturated zone model of MIPWA are compared to the field measurements at individual observation sites. The results presented in this section are average results over all observation sites or groups of observation sites. Results of individual observations sites are only presented as examples.

## 5.1 Representativeness of MIPWA for the root zone

The comparison between the measurements and the model simulation in Figure 5.1 shows that MIPWA is able to replicate the dynamics quite well. The model is able to explain 71% of the variance in the measurements, however it should be noted that this is only based on 9 observation sites. Figure 5.1 furthermore shows that the soil moisture content is underestimated throughout the year, but especially during the winter. This results in an average bias up to 0.11 in the first quartile of 2010. The underestimation has a large influence on the model performance, Nash-Sutcliffe coefficient is -1.26. This indicates that the mean soil moisture content is a better predictor of the soil moisture content than the model simulation. The average root mean square error is 0.10, this indicates a large differences in absolute value of the soil moisture content.

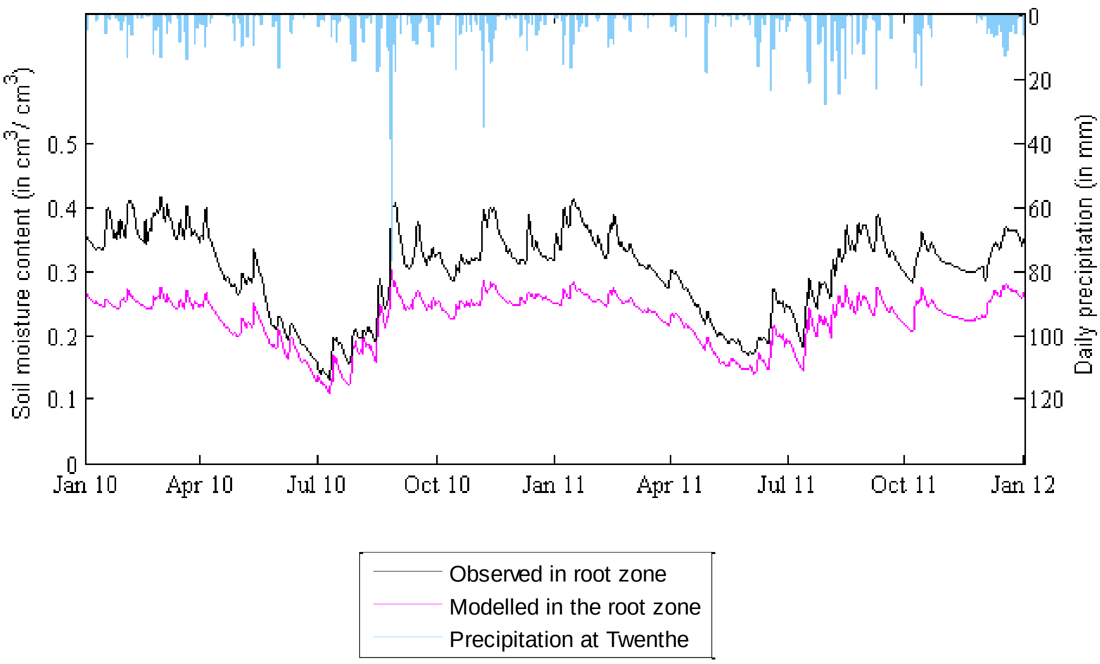


**Figure 5.1: Observed and modelled soil moisture content over time in the root zone at observation sites 1, 5, 8, 10, 11, 12, 14, 18 and 19.**

The model can simulate the difference in soil moisture content between the seasons. The modelled differences between the seasons are similar to the measurements, as can be seen in Figure 5.2. However, the absolute difference between the seasons is slightly smaller. The model is limited by the modelled porosity, which restricts the differences between seasons that can be achieved.

The variance within the season is slightly smaller than in the measurements, as can be seen in Figure 5.3. Especially during winter the variance is significantly underestimated, this indicates that the modelled percolation rate is limited during winter. During summer the variance is mainly limited due to the smaller difference between summer and winter.

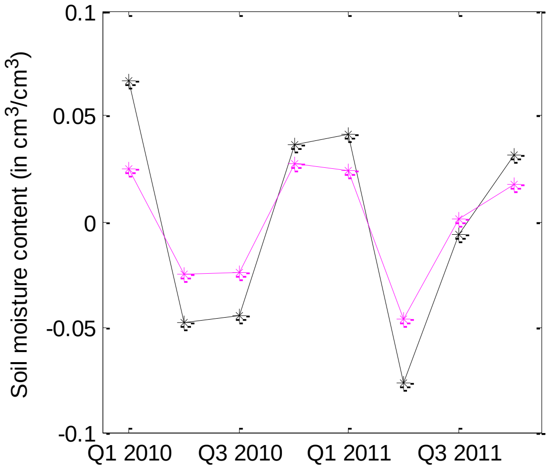


**Figure 5.2 Differences between seasonal mean and mean soil moisture content of modelled (magenta) and observed (black) soil moisture content in the root zone. Average differences are shown of observation sites 1, 5, 8, 10, 11, 12, 14, 18 and 19.**

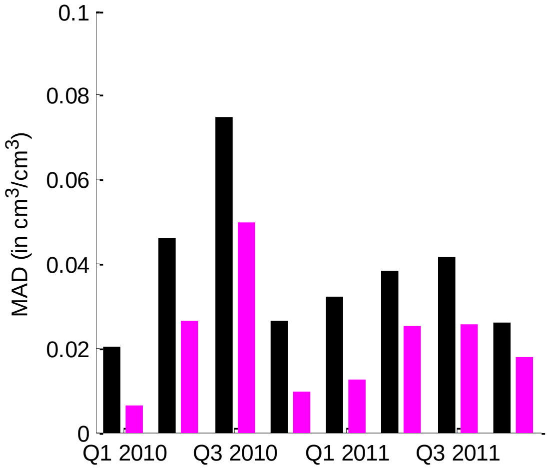


**Figure 5.3: Variance within season for the average observed (black) and average modelled (magenta) soil moisture content of observation sites 1, 5, 8, 10, 11, 12, 14, 18 and 19.**

The model performance at individual observation sites can best be demonstrated by comparing the modelled soil moisture content directly to the measurements. Figure 5.4 shows that there is a linear relation between the soil moisture content in MIPWA and the observed soil moisture content at observation site 5. This indicates that the modelled dynamics are quite similar to the observed dynamics, which results in the coefficient of correlation ($r^2$) of 0.86 at observation site 5. The difference between the model and the measurements is quantified utilizing the root mean square error. These 2 parameters are used to show the ability of the model to replicate the soil moisture content at individual sites.

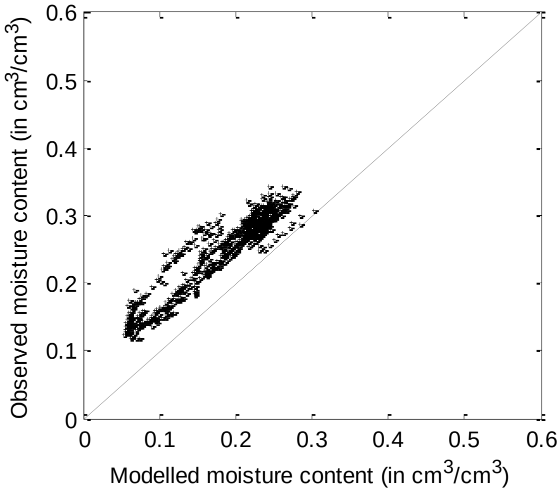


**Figure 5.4: Modelled soil moisture content compared to observed soil moisture content in the root zone at observation site 5.**

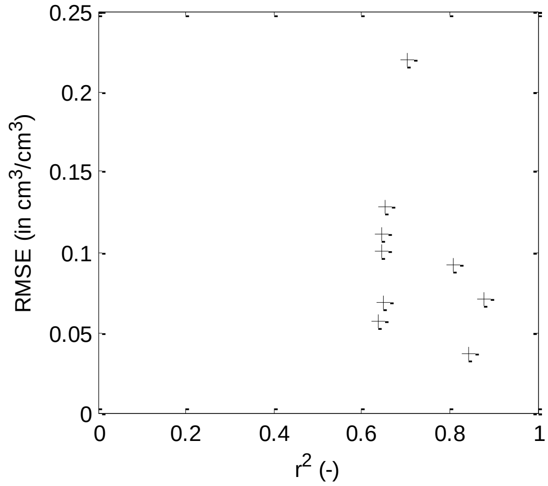


**Figure 5.5: Root mean square error (RMSE) plotted compared to coefficient of correlation ($r^2$) based on comparison measured soil moisture content in the root zone and modelled soil moisture content in the root zone.**

The model shows a good ability to simulate the soil moisture content in the root zone at individual observation sites, as can be seen in Figure 5.5. The root mean square error however indicates that large difference between the model and the measurements are present. Difference between the observation sites are investigated further by evaluating the influence of porosity, groundwater level and soil type.

## 5.2 Model comparison with measurements at 5 and 10 cm depth for all observation sites

The measurements for the entire root zone are limited to less than half the observation sites. The measurements at the remaining observation sites contain valuable information of the model performance as well. Therefore the model simulation is compared to the measurements at these depths.

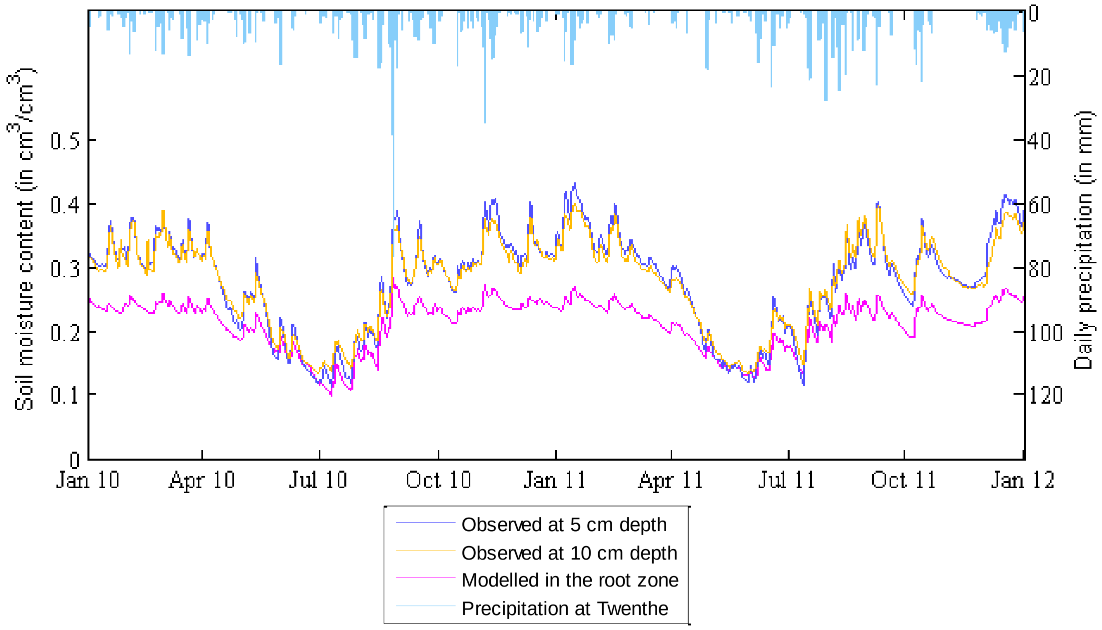


**Figure 5.6: Observed soil moisture content at 5 and 10 cm depth compared to the modelled soil moisture content**

As the probes at 5 cm depth and 10 cm depth are part of the root zone, they give similar results as the comparison with the root zone in the previous section. The model has similar dynamics as the probes at 5 cm depth and 10 cm depth, but also shows a difference in absolute value. The largest difference is in the variance within a season, as the previous chapter showed depth has a dampening effect on the variation within a season. The variation within a season therefore is not always similar to the modelled variation within the season as Figure 5.7 demonstrates, however the yearly pattern of variance is similar.

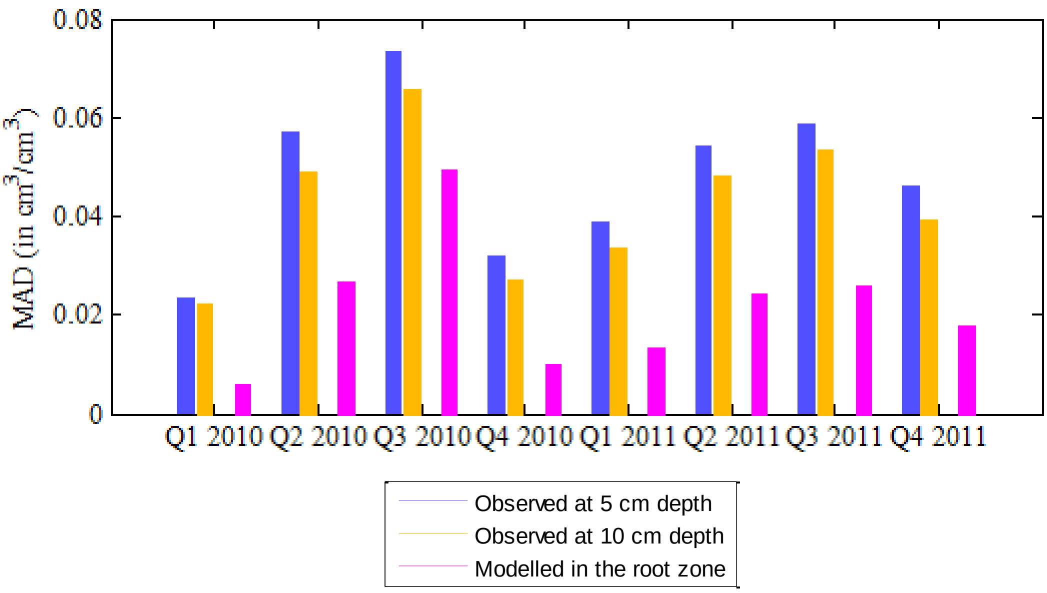


**Figure 5.7: Variance within season for the average observed and average modelled soil moisture content of all observation sites**

The conclusions based on measurements near the surface can be misleading. From Figure 5.8 can be concluded that the model is able to replicate the dynamics of the 5 cm depth quite well, which is confirmed by the coefficient of correlation ($r^2$) of 0.62. The measurements of the entire root zone in Figure 5.9 show that the model has difficulties with simulating high soil moisture contents observed in the field. This different interpretation is caused by dampening effect of depth. The dampening is smaller for the measurements at 5 cm depth and 10 cm depth than for the entire root zone.

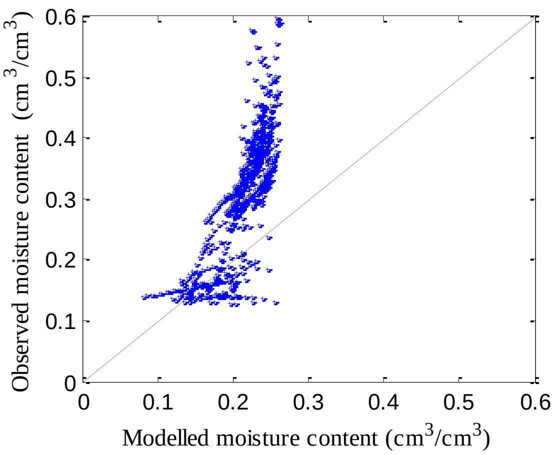


**Figure 5.8: Modelled soil moisture content compared to the observed soil moisture content by the probe at 5 cm depth at observation site 19 during 2010 – 2012**

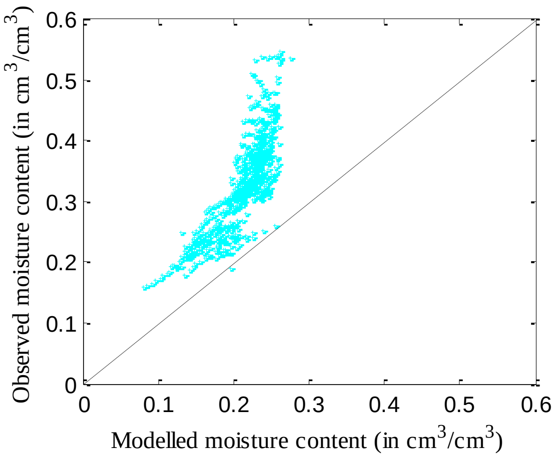


**Figure 5.9: Modelled soil moisture content compared to the observed soil moisture content in the root zone at observation site 19 during 2010 – 2012**

Figure 5.10 shows the performance of individual sites for both the measurements at 5 cm depth and the 10 cm depth. These measurements will be used to evaluate the model performance in support of the root zone measurements.

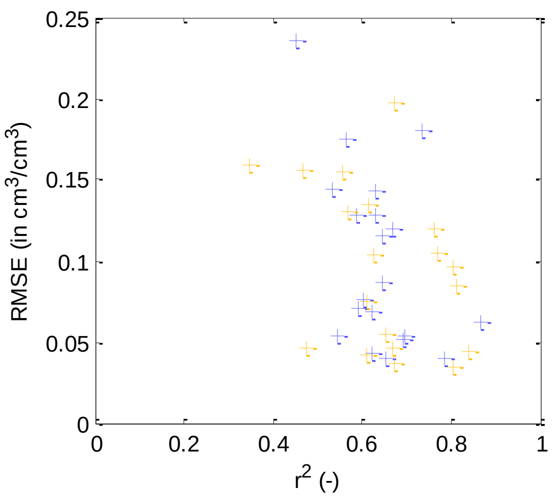


**Figure 5.10: Root mean square error (RMSE) compared to the coefficient of correlation ($r^2$) for the modelled and the observed soil moisture content at 5 cm (blue) and 10 cm depth (orange)**

## 5.3 Influence of the porosity

Differences between the measured soil moisture content and the soil type based porosity do not have consequences for the comparison to the model, as long as the model has a comparable porosity to the measured soil moisture content. However the porosity of the model is actually lower than the porosity of the BOFEK classification, this difference results in a bigger difference between model and measurements.

The difference between the porosity in MIPWA and the observed maximum soil moisture content is shown in Figure 5.11; the figure shows that the porosity of MIPWA is remarkably lower than the maximum observed soil moisture content. At some observation sites the difference between measured soil moisture content is 2 times larger than the porosity in MIPWA; the model will have difficulties reproducing the measured soil moisture content at these stations. Observation sites 2, 5, 11 and 17 have a similar porosity in MIPWA as the maximum observed soil moisture content, therefore the results are more comparable to the measured soil moisture content.

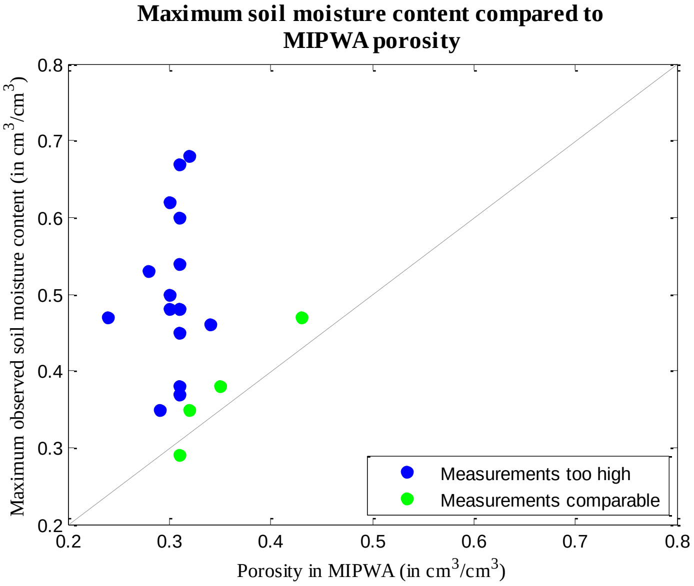


**Figure 5.11: Maximum observed soil moisture content compared to the porosity in MIPWA**

The effect of the porosity is best demonstrated by comparing the NS coefficients of individual observation sites. Sites with similar values for the maximum soil moisture content and porosity show better scores than sites with incomparable values. Observation site 10 and 11 demonstrate this difference clearly, the porosity at observation site 11 is close to the maximum observed soil moisture content, at observation site 10 the difference between the two is almost a factor two. The NS coefficients of these sites are 0.73 and -3.11 respectively. When the porosity is similar to the maximum observed soil moisture content the NS score is higher, due to the lack of bias.

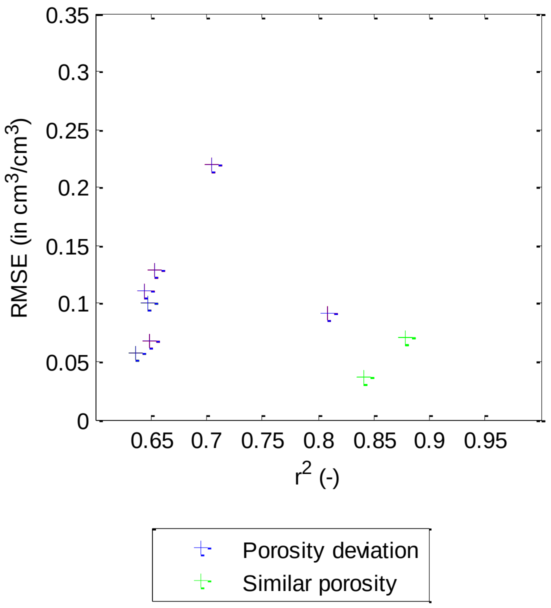


**Figure 5.12: Root mean square error (RMSE) and coefficient of correlation ($r^2$) of individual sites correlation for the modelled soil moisture content and the observed soil moisture content. Different classes based on comparable measured and modelled porosity (2 sites) and incomparable porosity (7 sites).**

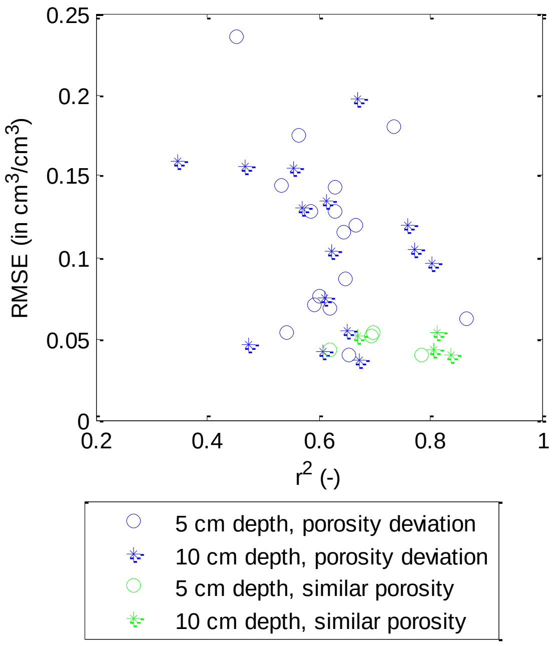


**Figure 5.13: Root mean square error (RMSE) compared to the coefficient of correlation ($r^2$) for the modelled and the observed soil moisture content at 5 cm and 10 cm depth. Different classes based on comparable measured and modelled porosity (4 sites) and incomparable porosity (16 sites).**

The root means square error is consistently lower for the observation sites with a comparable measured and modelled porosity in the root zone, as 5.12 shows. The same is valid for the measurements at 5 cm depth and 10 cm depth. The lower error is due to the underestimation of the soil moisture content, which creates a systematic error. The coefficient of correlation is higher for these sites, especially for the comparison between the measurements in the root zone and the model. Therefore the ability of the model to simulate the soil moisture content is better when the porosity in the model is equal to the observed porosity.

The difference between measurements and porosity is not limited to the observation sites, because the porosity of MIPWA is based on soil type. Since the observation sites are representative of the soil in Twente, the porosity in the entire region is underestimated. This lower porosity is a side effect of the calibration of the model, which has only been performed to improve the simulation of the groundwater level. The porosity was a parameter subjected to calibration and has been altered (Hoogewoud, et al., 2013). The consequence of the calibration is that MIPWA will underestimate the soil moisture content in the entire region; not only at the observation sites. This is demonstrated by Figure 5.14, most of the region has porosity between 0.23 and 0.34. The expected range of sandy soils is 0.36 until 0.43 based on the Staringreeks in Appendix C.

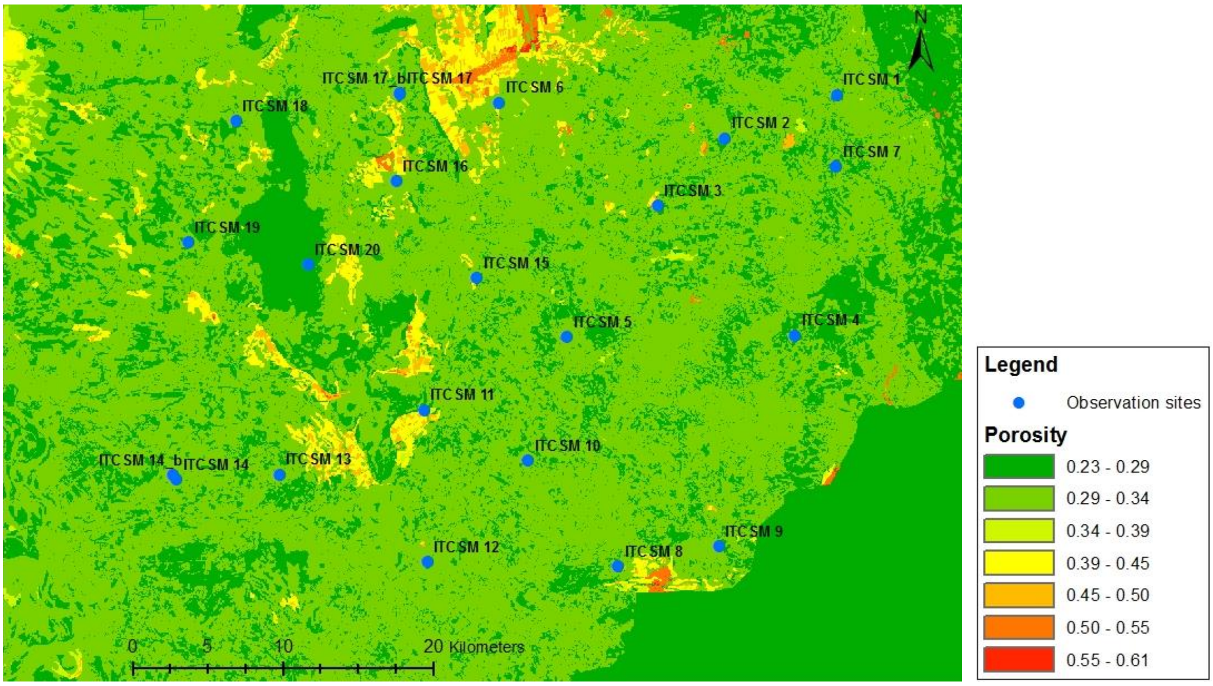


**Figure 5.14: The porosity in Twente as implemented in MIPWA**

## 5.4 Influence of groundwater level on the modelled soil moisture content

The model is able to simulate a difference between areas with a deep groundwater level and a shallow groundwater. Similar to the observed soil moisture content, the areas with a shallow groundwater level contain more moisture in the root zone than the areas with the groundwater level deep under the surface. The dynamics are similar as well for both groups of observation sites; however in absolute value a clear difference in performance can be observed for the observation sites.

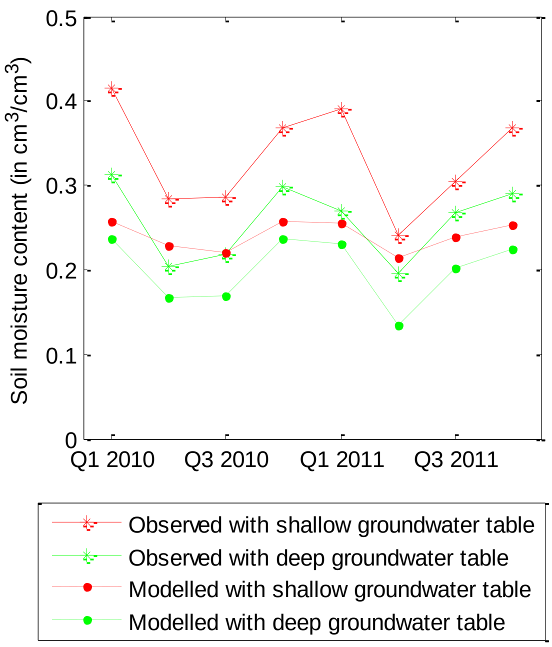


**Figure 5.15: Soil moisture content modelled and observed soil moisture content in the root zone. Observation sites are divided into sites with shallow groundwater level (5 sites) and sites with deep ground water level 4 (sites).**

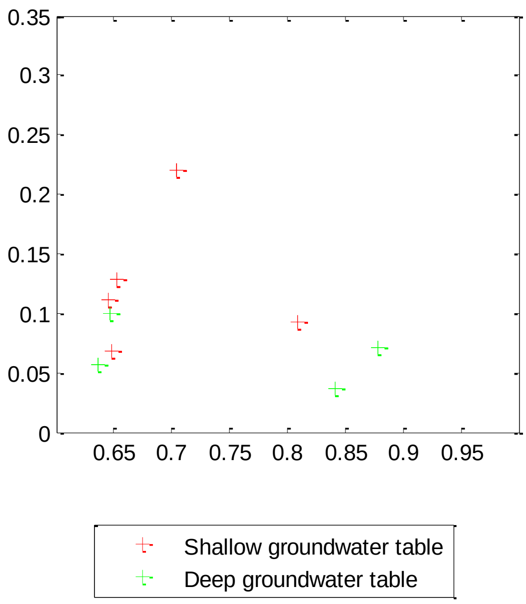


**Figure 5.16: Root mean square error compared to the coefficient of correlation for the modelled and the observed soil moisture content in the root zone. Observation sites are divided into sites with shallow groundwater level (5 sites) and sites with deep ground water level (4 sites).**

Figure 5.15 shows that the observations sites with deep groundwater level are able to replicate the difference between summer and winter quite well. The sites with a shallow groundwater level also show a difference between winter and summer, however less evident as would be expected from the observations. As a result, the observation sites with deep groundwater level have better dynamics than observation sites with a shallow groundwater level. This is only valid for the average of both classes; individual observation sites can have different performance as can be seen in Figure 5.16 and Figure 5.17. In general, sites with a deep groundwater level have a lower root mean square error for the root zone, 5cm and 10 cm measurements. This is likely due to the lower soil moisture content; similar to the better performance of sites similar measured and observed porosity. The high correlation of the observation site with shallow groundwater level is due to the linear scaling of the modelled soil moisture.

Figure 5.18 shows a linear relation between the modelled and observed soil moisture content, however the difference in absolute value is poorly replicated by the model. The difference is better replicated by the sites with a deep groundwater level, although the better performance of these sites can also be due to the better matching porosity.

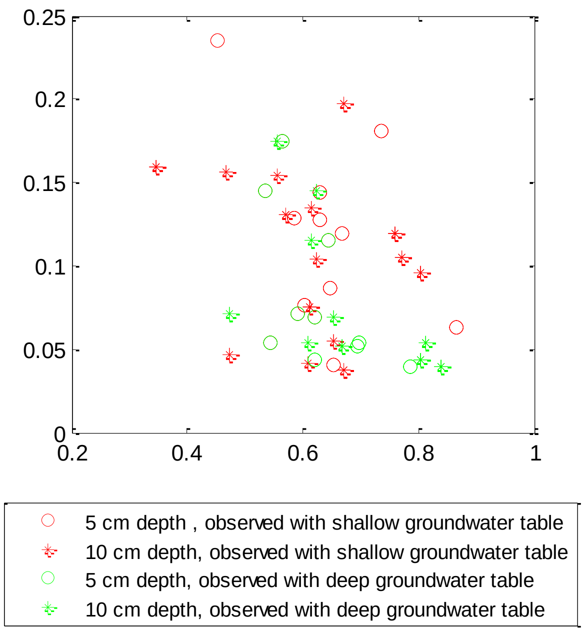


Figure 5.17: Root mean square error compared to the coefficient of correlation for the modelled and the observed soil moisture content at 5 cm and 10 cm depth. Different classes based on loamy sandy soils (10 sites) and sandy soils (10 sites).

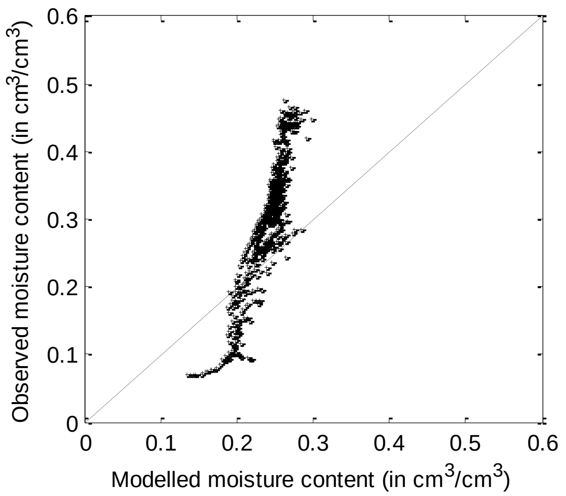


Figure 5.18: Modelled soil moisture content compared to the observed soil moisture content in the root zone at observation site 18 during 2010 – 2012

The lack of seasonal differences indicates that evapotranspiration is compensated by capillary rise. Observation sites with a shallow groundwater level should have a large capillary rise, although the measurements indicate that the model exaggerates the capillary rise. As a result, the evapotranspiration is compensated by the capillary rise during spring and summer. This causes a limited difference in soil moisture content between the seasons. Figure 5.19 shows that evapotranspiration from the root zone is compensated by a flow of water from the subsoil. The colours indicate that the water originates mainly from the saturated zone. The groundwater level is therefore influenced directly by the evapotranspiration at these observation sites. Since the soil moisture content in the root zone is kept stable, the potential evapotranspiration is always reached. This increases the variability of the groundwater level further at observation sites with a shallow groundwater level.

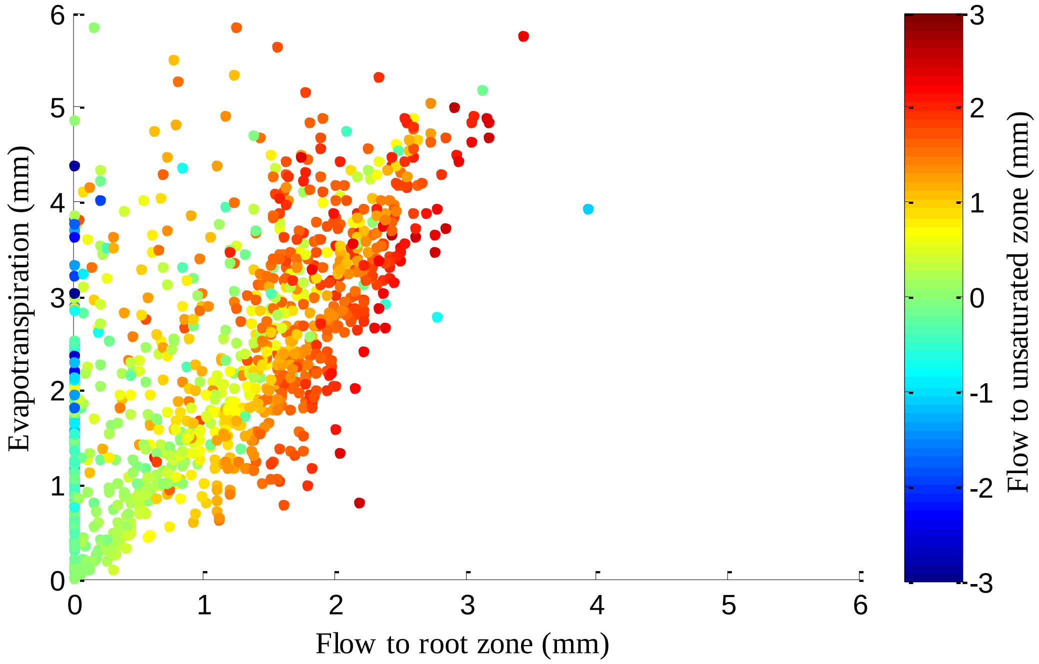


**Figure 5.19: Modelled actual evapotranspiration, flow to root zone and flow from saturated zone between 2010 and 2012 at observation site 3**

## 5.5 Influence of soil type

The soil type has a large influence on the performance of the model. The model is able to simulate the same difference in soil moisture content as the field measurement analysis. The loamy sandy soil contains more moisture content than sandy soils, as can be seen in Figure 5.20. The field measurement analysis focussed on the surface layer; however this figure shows that this difference is actually not present in the measurements of the root zone. Over the entire root zone, more moisture is observed in the sandy layers than in the loamy soils. The Staringsreeks in appendix C indicates that in the deeper layers of the subsoil this would be expected, however not in the root zone. As a result a large error is made by the model by simulating higher moisture content for loamy sandy soils.

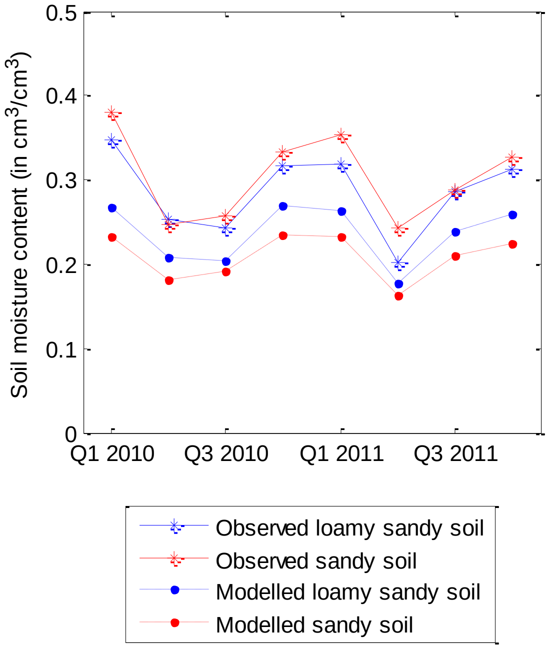


**Figure 5.20: Seasonal average soil moisture content of the root zone, observation sites are divided into classes loamy sandy soil (4 sites) and sandy soil (4 sites).**

This error is reflected in both the correlation and the root means square error of the model and the measurements of the root zone. The root means square error of the sandy soils can therefore reach up to 0.22 $cm^3$/ $cm^3$, as can be seen in Figure 5.21. The coefficient of correlation indicates that the model can explain 66% of the variance, therefore is still capable to replicate the dynamics reasonably. The dynamics are even better replicated by loamy sandy soils, as on average 79% of the variance can be explained. The observation site with a low correlation, site 14, has a low correlation due to an incomplete dataset, as can be seen in appendix A. When ignoring this observation site, the dynamics of the loamy sandy soils is well simulated by the model. This better dynamics is also visible in the 5 cm depth and 10 cm depth.

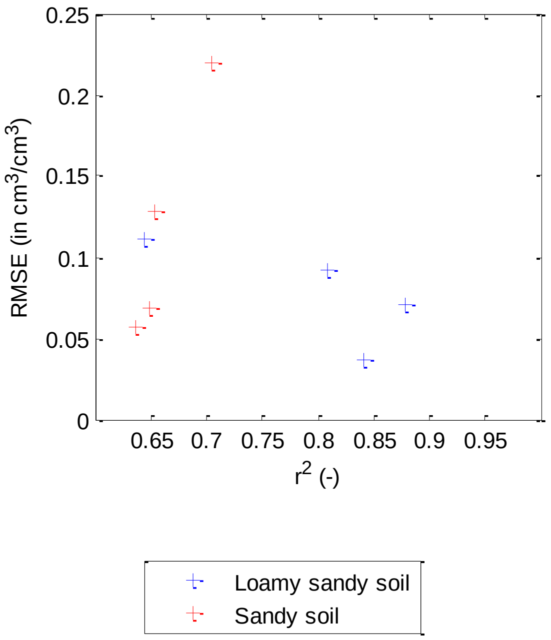


**Figure 5.21: Root mean square error compared to the coefficient of correlation for the modelled and the observed soil moisture content in the root zone. Observation sites are divided into sites with loamy sandy soils (4 sites) and sites with sandy soils (4 sites).**

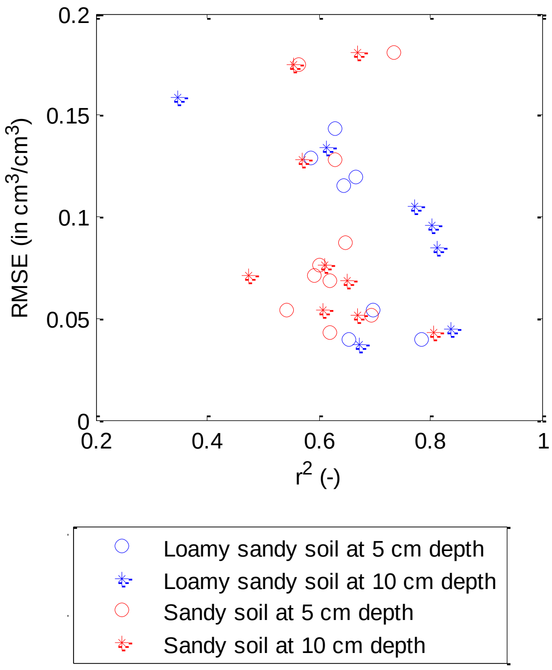


**Figure 5.22: Root mean square error compared to the coefficient of correlation for the modelled and the observed soil moisture content at 5 cm and 10 cm depth. Different classes based on loamy sandy soils (7 sites) and sandy soils (12 sites).**

The difference between sandy soil and loamy sandy soil is also demonstrated by comparing the simulation of soil moisture content to the measured soil moisture content. In Figure 5.23 the observed and modelled soil moisture content is shown of a loamy sandy soil. The model is able to follow the dynamics of the observations well, mainly during dry periods small, deviations are present. This is also present in observation site 18, as shown in Figure 5.18. The observed and modelled soil moisture content of a sandy soil has deviations throughout the year, as can be seen in Figure 5.24. This results in a lower correlation for these sites. Observation site 19, showed in Figure 5.9, has difficulties with simulating high soil moisture contents.

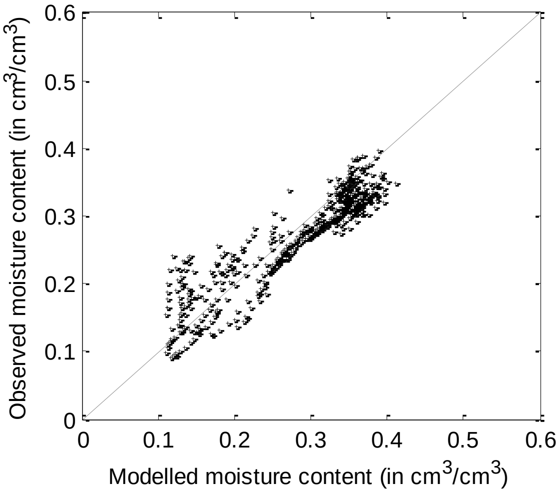


**Figure 5.23: Modelled soil moisture content compared to the observed soil moisture content in the root zone at observation site 11 during 2010 – 2012**

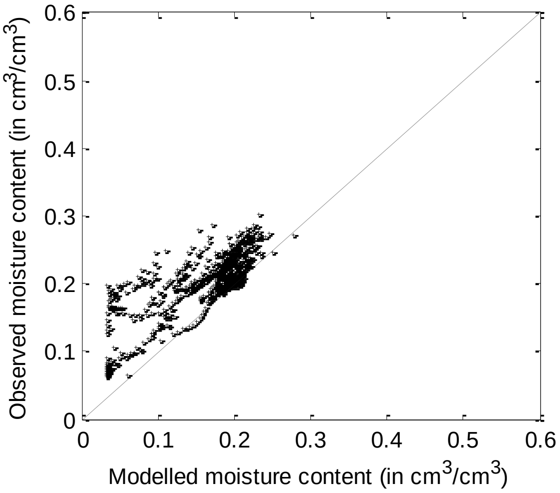


**Figure 5.24: Modelled soil moisture content compared to the observed soil moisture content in the root zone at observation site 8 during 2010 – 2012**

## 5.6 Performance of MIPWA in simulation soil moisture content

The model is able to simulate the dynamics of soil moisture content in the root zone. The model is able to explain on average 71% of the variance in the soil moisture content in the root zone, however large differences between the observations sites are present. Also in the simulation of the absolute value, large differences are observed. On average, the model underestimates the soil moisture content. Although small difference were expected based on the soil moisture observations, at specific observation sites the simulated soil moisture content is half of the observed soil moisture content. This difference results in a large root mean square error for the entire model.

The observation sites that perform best are sites with similar measured and simulated porosity, a groundwater table far underneath the surface and with a loamy sandy soil type. Observation sites with a similar measured and simulated porosity are able to explain more of the model variance and are able to simulate the soil moisture content with a smaller root mean square error. The smaller error is also present for observation sites with a groundwater table located further away from the surface. The loamy sandy soils are in general better simulating soil moisture dynamics than sandy soils. The other observation sites are quite able to replicate the soil moisture content in the root zone, especially for a model with the focus on simulating groundwater level.

The observation sites with a groundwater table close to the surface have an error which does affect the simulation of the groundwater level. The model is unable to replicate the difference in seasons, which has been observed in the field measurements. The soil moisture content in summer is therefore stable and no soil moisture stress occurs. Thereby the potential evapotranspiration is reached more often than the measurements imply. This is due to the modelled capillary rise, as the evapotranspiration is compensated by the capillary rise. As a result, the variability of the groundwater level increases and the groundwater recharge decreases at locations with a groundwater table close to the surface.

# 6 Improvements to MIPWA

The comparison between observations and modelled soil moisture content has indicated that the model has difficulties replicate the soil moisture content. In this chapter several possible improvements are suggested for MIPWA and MetaSWAP. Some of the improvements have been implemented and the effects on the soil moisture content are listed. The improvements not only affect the soil moisture content, also the evapotranspiration, water availability for plants, available water storage, recharge and groundwater level are affected. Especially the effect on the recharge and groundwater level is important for MIPWA, as the performance of the model has been evaluated based on these criteria.

The effect of the measures is evaluated at an observation site with a loamy sand soil with a shallow groundwater table. The observation sites with a loamy sandy soil have high root mean squared errors due to underestimation of the soil moisture content by the model. The sites with a shallow groundwater lack the seasonal trend present in the measurements. These properties are present at observation site 19. As a result, the modelled soil moisture content has limited seasonal differences, as shown in Figure 6.1. This situation is referred to as the baseline in the effect of measures on simulation of MIPWA.

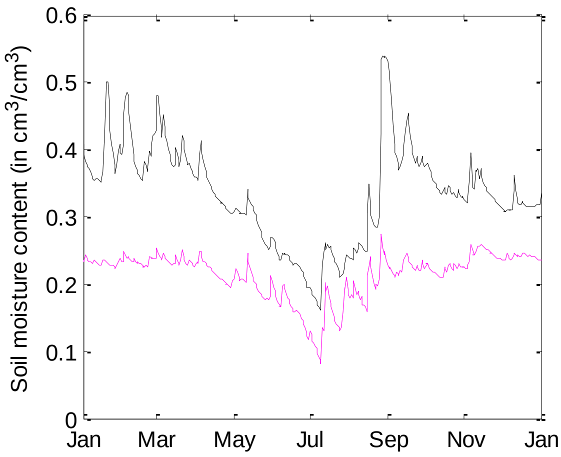


**Figure 6.1: Observed (black) and modelled (magenta) soil moisture content at observation site 19 in 2010**

## 6.1 Porosity changes

The influence of the porosity was visible in the results; the observation sites with a comparable maximum observed soil moisture content and porosity in MIPWA were able to reproduce both dynamics and absolute value of the soil moisture content quite well. Therefore the porosity at an observation site with poor absolute values is modified to investigate the effects of increasing the soil moisture content on different elements. The porosity in MIPWA at observation site 19 is approximately 50% lower than has been observed; therefore the porosity has been increased for the whole region with the factor 1.5. It should be noted that this factor is only appropriate for this observation site, not all soil types as has been implemented.

## 6.2 Capillary rise reduction

The sites with a groundwater level close to the surface were able to replicate the dynamics of the soil moisture content quite well; however the absolute value of the observed soil moisture content could not be replicated. This was visible in the lack of differences in the mean soil moisture content of different quartiles.

The cause of this problem is a strong capillary rise from the saturated zone to the unsaturated zone, which reduces the change in soil moisture content. This dampening effect of the shallow groundwater level was expected, however is stronger than intended. The best way to reduce the capillary rise in the model is to modify the relation between the capillary rise, groundwater level and soil moisture in the root zone. To reduce the capillary rise two options are explored, the reduction of hydraulic conductivity and capillary rise prevention at threshold groundwater level.

The first option would decrease the amount of moisture that can be transported, increasing the gap between evapotranspiration and groundwater flow. This option is implemented by a reduction of the hydraulic conductivity of 90% for all soil types. The second option limits the capillary rise by implementing the perched water table concept. This concept prevents capillary rise whenever a threshold groundwater level has been achieved. The threshold implemented for the whole region is 1 meter below the surface, at this threshold no capillary rise to the surface is expected.

## 6.3 Effect of measures on simulation of MIPWA

The improvements have a large effect of the simulated soil moisture content, but also on the other processes that are simulated. In this section these effects are discussed for the individual improvements as well as a combination of the most promising improvements.

The absolute value of the soil moisture is most affected by the increase of porosity. Throughout the year the soil moisture content is increased significantly as can be seen in Figure 6.2. This causes a strong decrease of the root mean square error in Table 6.1. Further increases of the porosity could decrease the root mean square error in winter, however would increase the error in summer. As a result of the higher porosity the simulation of the dynamics decreases slightly according to the coefficient of correlation, but overall the model and measurements are more similar. The increase of porosity decreases the average groundwater table, as can be seen in Figure 6.6. The groundwater table is already underestimated in this region; therefore this change has a negative effect on the groundwater model. The change in groundwater level is due to changes in regional groundwater flow, as the recharge and evapotranspiration in Table 6.2 are unchanged.

**Table 6.1: Root means square error and coefficient of correlation for the original model (baseline) and improvements in 2010**

| | $R^2$ (-) | RMSE ($cm^3/cm^3$) |
|---|---|---|
| **Baseline** | 0.62 | 0.131 |
| **Porosity increased** | 0.59 | 0.053 |
| **Threshold capillary rise** | 0.65 | 0.142 |
| **Conductivity decreased** | 0.68 | 0.127 |
| **Combination of measures** | 0.71 | 0.046 |

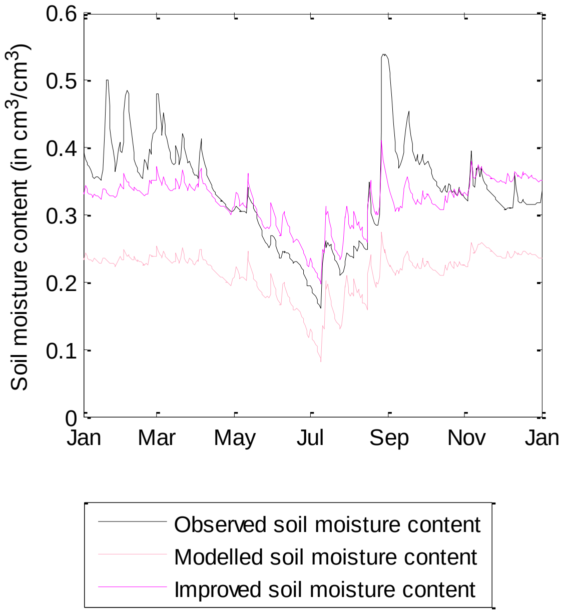


**Figure 6.2: Effect of increase of porosity on the soil moisture content at observation site 19 in 2010.**

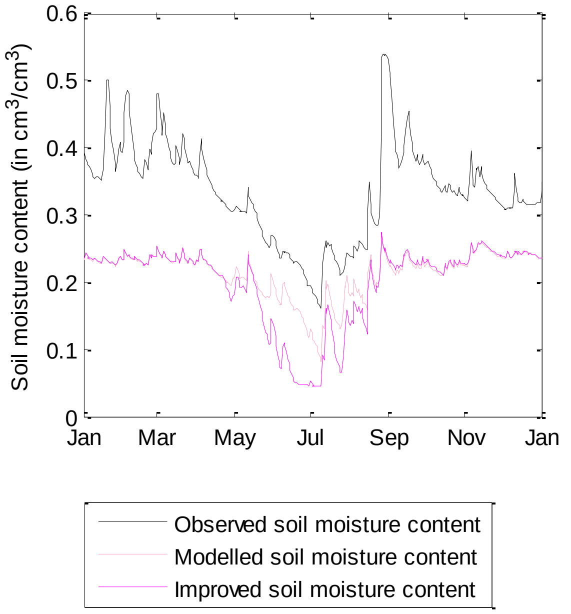


**Figure 6.3: Effect of reduction of capillary rise beyond groundwater level threshold on the soil moisture content at observation site 19 in 2010.**

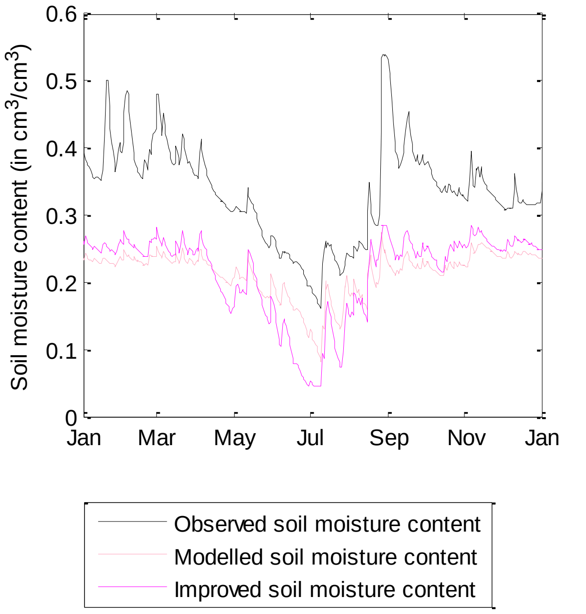


**Figure 6.4 Effect of decrease of hydraulic conductivity on the soil moisture content at observation site 19 in 2010.**

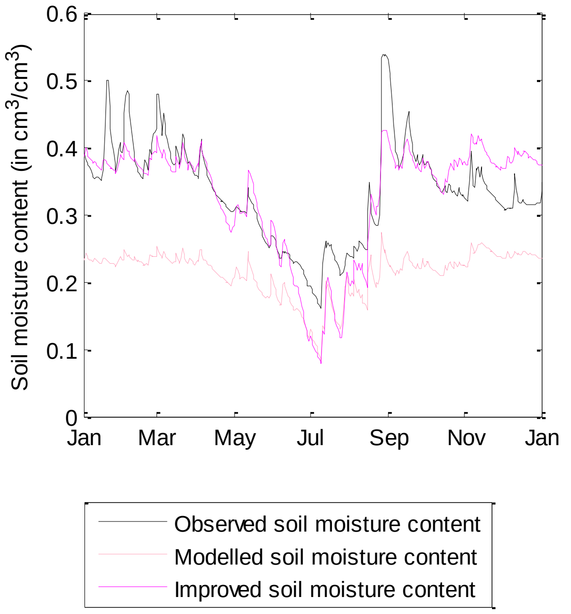


**Figure 6.5: Effect of combination of decrease of hydraulic conductivity and increase of porosity on the soil moisture content at observation site 19 in 2010.**

The dynamics benefit from capillary rise reduction, as can be seen in Figure 6.3 and Figure 6.4. Table 6.1 shows s shows small differences between the two methods for capillary rise reduction. The groundwater level based capillary rise reduction is effective in limiting the negative groundwater recharge. As a result the evapotranspiration at this observation site is lower in summer and the groundwater recharge is higher. The reduction of hydraulic conductivity affects the soil moisture content both in summer and in winter. In winter higher moisture content is required to reach similar groundwater recharge. In summer the percolation can be neglected, Table 6.2 shows that the groundwater recharge is limited in the second quartile due to this improvement. The groundwater level is increased by both improvements, as can be seen in Figure 6.6. The groundwater level based threshold increases the groundwater level over the entire year, mostly in summer. The decreased hydraulic conductivity has similar the variability of the groundwater level as the baseline situation, with higher peaks in winter.

**Table 6.2: Actual Evapotranspiration and groundwater recharge for the original model (baseline) and improvements in the different quartiles of 2010**

| | Actual Evapotranspiration (mm) | | | | | Groundwater Recharge (mm) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Q1 | Q2 | Q3 | Q4 | Total | Q1 | Q2 | Q3 | Q4 | Total |
| **Baseline** | 57 | 235 | 237 | 44 | 573 | 107 | -67 | 90 | 133 | 263 |
| **Porosity increased** | 57 | 235 | 238 | 44 | 574 | 104 | -63 | 99 | 127 | 267 |
| **Threshold capillary rise** | 57 | 195 | 213 | 44 | 510 | 107 | -6 | 93 | 134 | 329 |
| **Conductivity decreased** | 57 | 210 | 212 | 44 | 523 | 109 | -17 | 67 | 130 | 288 |
| **Combination of measures** | 57 | 229 | 221 | 44 | 551 | 119 | -10 | 50 | 128 | 287 |

The improvements capillary rise reduction and porosity increase are combined to attempt to replicate the observed soil moisture content in the root zone. Figure 6.5: Effect of combination of decrease of hydraulic conductivity and increase of porosity on the soil moisture content at observation site 19 Figure 6.5 and Table 6.1 show that the moisture content is quite similar to the observed soil moisture content. The capillary rise reduction might be slight overestimated, as the soil moisture content in summer is too low and too high in December. The groundwater level variability is reduced due to the combination of these measures, however not as strong as the porosity.

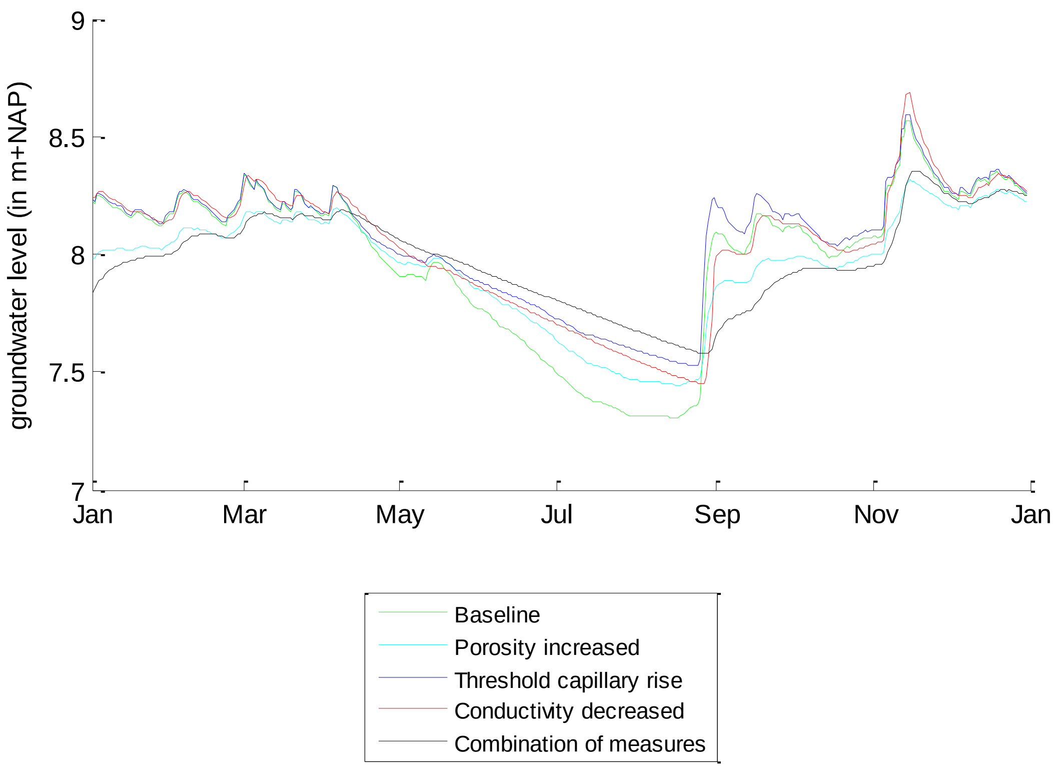


**Figure 6.6: Effect on groundwater level for each improvement in 2010**

## 6.4 Further improvements

In the process of implementing improvements listed above, several other options for improvement have been encountered. These measures have not been implemented in MIPWA, nonetheless are mentioned in this paragraph.

### *Coupling MetaSWAP and iMODFLOW*

The coupling between groundwater model IMODFLOW and unsaturated zone MetaSWAP is important for the calculation of the groundwater level in MIPWA. In the current implementation of MetaSWAP into iMODFLOW, the saturated zone model is given a variable specific yield. The specific yield is a soil property and therefore should not be variable in time.

The variable specific yield can have effect on the groundwater model that should be further investigated. The first is the effect on the water balance of the saturated zone. In theory amount of water in the saturated zone is related to the groundwater level, utilizing a fixed specific yield this relation is present. The relation in MIPWA is shown in Figure 6.7. The figure shows that more water is stored in the saturated zone over time. This relation can be corrected utilizing post-processing by adding a factor to the change in storage and the capillary rise term. This factor consists out of the difference between porosity and calculated specific yield, multiplied by the change in groundwater level. This factor should be implemented during the calculations, as it can influence the model results.

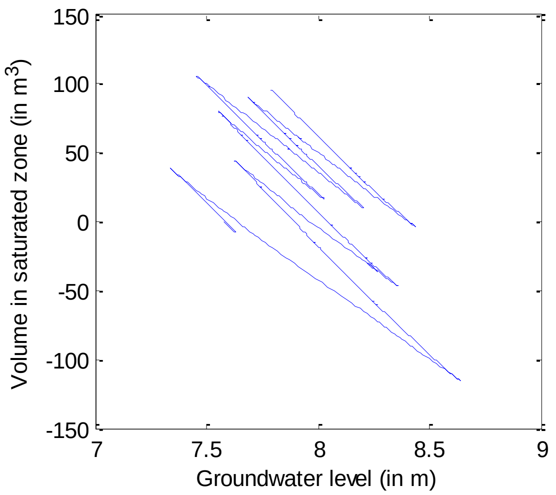


**Figure 6.7: Relation between groundwater volume and groundwater level. The groundwater volume = 0 at first time step of the simulation at groundwater level 7.58 m.**

### *Vegetation growth*

The vegetation in MIPWA plays an important role for the evapotranspiration, especially the start of the growth season. The start of the growth season is fixed for a single crop type; however in the region the crops can be planted at a different period. Within MIPWA it is possible simulation of plant growth, which will prove to yield a better indication of the growth season. This improvement is expected to increase the evapotranspiration in the spring period, especially in 2011.

### *Precipitation*

The exact soil moisture content for each observation site will be difficult to model, since the exact amount of precipitation in the region is unknown. The spatial distribution of precipitation has a large influence on the soil moisture content, as precipitation events can occur locally or have a different intensity spatially. These differences cannot be implemented in MIPWA since the simulations are based on spatial interpolations of the precipitation stations. More information on the spatial distribution of precipitation will contribute to the ability of MIPWA to simulate the soil moisture content dynamics.

# 7 Discussion

During the research decisions have been made that influence the outcome of the research, in this chapter these decisions will be discussed. The structure of this chapter is similar to the report, sections represent the chapters of the report

## 7.1 Model and Data

***Soil moisture measurements***

The soil moisture content is measured by ECH2O-TE/EC-TM probes. Several sources of error exist that can influence the measurements by the probes. The first source is the method of measuring, the actual soil moisture content is measured indirectly. The probes measure the dielectric permittivity of the soil and convert it to soil moisture content using a calibration formula. The technical sheet of the probes shows that this formula can lead to measurement errors (Decagon Devices Inc., 2008). A calibration for the soils in Twente has been performed (Dente, et al., 2011); however this has led to an single calibration formula for all soils.

The placement of the probes in the soil might also cause errors in the measurements. The probes determine the volumetric soil moisture content around the entire sensor (Cobos, 2015). During installation the soil has been disturbed, thereby influencing the measurements. The larger pores will cause higher soil moisture contents to be measured than would be expected. The preferential flow paths can cause deeper probes to register precipitation events before shallower probe registers the events (Obakeng, 2007). On a daily basis the influence of the latter is limited, but the large pores might cause the probes to record soil moisture contents that exceed the bulk density based porosity at observation site 4, 12, 15, 18 and 19.

***MIPWA model-set up***

The simulations of MIPWA cover the period between 1989 and 2001, which is used to determine the effect of measures on the groundwater level (Berendrecht, et al., 2007)**.** The model period has been extended to the period of the observations until 2012, using the meteorological condition of this period. However, the model also utilizes data intended for the period 1989 until 2001. A large uncertainty is the groundwater extraction, as no change in extraction amount and location has been implemented into the model. For MIPWA, extraction sites larger than 50.000 $m^3$ a year should be implemented (Snepvangers & Berendrecht, 2007). These large extractions have a significant impact on the water system (Hendriks, et al., 2010). Therefore changes in extraction should also be implemented, which has been omitted from the research. The extent of the effect is dependent on the location of the observation compared to the extraction site and the amount of extraction. The modelled groundwater level is likely to contain inaccuracies due to this and in result the modelled soil moisture content might contain systematic errors compared to the observations.

## 7.2 Method

***Groundwater level classification***

The classification of observation sites based on groundwater level is done based on the average highest groundwater level (GHG). Observation sites with a GHG 40 cm separated from the surface are considered as sites with a shallow groundwater table. Some observation sites are relatively close to this threshold and therefore are placed in a group with other sensors that are relatively far away from this threshold. For the deep groundwater level classification this is particularly an issue, some observation sites have a highest groundwater level 50 cm under surface while other sites have depths of 200 cm under surface. Differences between these observation sites are not researched as part of this research.

***Soil type classification***
The soil type classification is based on two separate classifications, one based on field measurements and 1 based on national classification of the soil. The two classifications have difference in soil type at 8 observation sites, which indicates the soil type in the model might need to change. The in-situ classification only covers the top layer of the soil, provides insufficient information to change the soil type in MIPWA. Within 500 m around the observation sites, no similar soil type is present that has similar properties as the in-situ measurements describe. At the observation site deeper layers also need to be classified to support changing the soil type in the model.

## 7.3 Results

***Observed soil moisture content***
The analysis of the meteorological conditions is only discussed for a single observation site. On a daily resolution this analysis can be conducted for all observation sites. When applied for all observation sites the correlation to meteorological conditions could be used to verify the working of the model.

The analysis of the meteorological conditions shows differences between the vegetation types; however this difference is not further investigated. This is due to the small number of probes that is located inside the field with different vegetation types than grass. Only at a single observation site during a single year, the soil moisture content measurements are available for the entire root zone.

The field data analysis mainly focusses on the surface layer instead of the root zone. This was done since the deeper layers respond dampened to precipitation and evapotranspiration. In further research this could be extended to all measurement depth and the entire root zone, to give a more complete insight into the difference of soil types and groundwater levels.

***Modelled soil moisture content***
The modelled soil moisture content is compared to the measured soil moisture content in the root zone, however for most sites the amount of probes, and therefore depths at which is measured, is limited. Therefore conclusions have to be made based on the observation sites that do have measurements in the unsaturated zone or based on sensors in the shallow layer. The first has the disadvantage that conclusions of an entire soil type are based on a single or two observation sites, problems concerning these specific observation sites can be attributed to the soil type. The disadvantage of the shallow sensors is that they show a strong variability within a month, larger than has been observed in the root zone. This difference causes the model to be less similar to the measurements, influencing the model assessment.

***Improvements***
MIPWA version 2.2 contains porosity lower than the porosities in the Staringsreeks, however the amount of increase of the porosity is debatable. The improvements apply a single scaling factor for all soil types. The actual difference between the porosity in MIPWA and the porosity in the Staringreeks varies. Furthermore Wösten et al (2001) indicated that the porosity is subjected to uncertainty; an uncertainty interval of 0.1 $cm^3/cm^3$ is not uncommon for a soil type. Differences within the soil type cannot be simulated and no perfect match should be expected with the model. A single observation site does not have to be representative for an entire soil type, multiple sites with the same soil types should be used for the validation of the model porosity.

The capillary rise has been identified as a problem within MetaSWAP, especially for observation sites with a shallow groundwater level. In the research this has been adjusted by reducing capillary rise at a certain threshold. Although physically it would be expected that the capillary rise is reduced after the used threshold of 1 m, the current implementation does not replicate the transition that would be expected. A more physically current method is to implement a lower hydraulic conductivity in the model, however to get to similar results the hydraulic conductivity needs to be changed in magnitude. Both measures have their disadvantages and only treat the symptoms of the error in the relation between water content, capillary rise and groundwater level.

# 8 Conclusion and recommendations

The soil moisture simulation of MIPWA has been compared to the soil moisture measurements of the ITC soil moisture network in Twente. The conclusion based on the analysis of the soil moisture model, model performance and model improvements are discussed in this chapter. Finally recommendations are given based on these conclusions.

## 8.1 Conclusions

The objective of the research was to evaluate the ability of MIPWA to simulate the soil moisture by comparing the simulations of MIPWA to measurement data. This was done utilizing three research questions which are answered in this section

> *Which characteristics can be derived from the soil moisture data of the ITC soil moisture monitoring network in Twente?*

From the soil moisture content measurement has been used to derive five properties. The first property is the porosity of the soil, which is based on the maximum observed soil moisture content. The observed porosity shows large difference with the porosity that would be expected from the soil. The observed porosity deviates significantly for 9 out of 20 observation sites from the porosity of the soil type, however at four observation sites the observed porosity could not have been measured in undisturbed soil. Therefore the measured porosity might not be representative for the soil at these sites.

The second important property for this research is the difference in soil moisture content between the seasons. The soil moisture content has a strong seasonal trend, which has a strong relation with the reference evapotranspiration and precipitation deficit. This relation is dependent on the depth of the soil moisture measurement. The third property shows a dampened response over depth. A probe located near the surface at 5 cm depth is more sensitive for the precipitation than a probe located at 40 cm depth. These deeper probes have higher correlation with the reference evapotranspiration. The entire root zone therefore will have different dynamics than the measurements only taken at the surface layer.

The final characteristics of the model are the difference between groundwater level and the difference between soil types. The observation sites with a groundwater table located close to the surface have higher moisture content throughout the year than the sites with a deep groundwater table. At the surface also a clear difference is observed between loamy sandy soils and sandy soils, the latter can contain has lower moisture content throughout the year.

> *What are the differences between the results of the model simulations of MIPWA and the field data of the ITC soil moisture monitoring network?*

The characteristics showed a large difference between the soil type based porosity and measured porosity for 9 observation sites. In MIPWA the porosity is even lower than the soil type based porosity. This creates large differences between the measured and modelled porosity. Only for four observation sites the measured and modelled porosity are similar. These models can simulate the soil moisture content at these 4 sites; both the dynamics and the absolute value are similar at these sites.

Observation sites with a groundwater table close to the surface are unable to replicate the difference in soil moisture content between the seasons. As a result the soil moisture content is relatively high throughout the year in regions with a groundwater table close to the surface. The water loss from evapotranspiration is compensated by capillary rise at these sites, thereby the evapotranspiration directly influences the groundwater level. Observation sites with a deep groundwater table have a difference in soil moisture between seasons.

The difference in soil type shows large differences with the observed soil moisture content. The model simulates the same difference between soil type as has been observed on the surface. However the model is representative for the root zone, which shows an opposite difference between the soil types. Therefore the sandy soils are simulated too dry by the model; while the field measurements indicate the moisture content should be higher.

Overall, the model is capable to simulate the observed soil moisture content dynamics in the root zone. This similarity in dynamics is especially important for the simulation of the groundwater. Only at observation sites with an average highest groundwater table of less than 40 cm, deviations have been found that has a large influence on the simulation of the groundwater level. The soil moisture stress is underestimated. This increases the actual evapotranspiration at these sites and therefore the amount of moisture in the saturated zone.

*Can the ability of MIPWA to simulate soil moisture content possibly be improved and what is the effect of these improvements on the simulation of the groundwater level?*

To improve the soil moisture content in MIPWA two suggestions have been implemented an increase of porosity and a change in the function of capillary rise. The increase of porosity has proven to reduce the difference in absolute value between the model and the measurements. The groundwater level variability of the groundwater is decreased by this improvement. The reduction of capillary rise improves the dynamics of the model at observation sites with a shallow groundwater level. Without capillary rise, the soil moisture content can develop more similar to the measurements. The reduction of capillary rise increases the groundwater level throughout the year. This effect on the groundwater level is positive, as the groundwater level is underestimated in the region of Twente.

The combination of the improvements improves the simulation of the soil moisture content significantly. The groundwater level is systematically increased by the combination, but still decreases the dynamics of the groundwater level. From perspective of the groundwater level modelling, only the capillary rise change should be implemented. However for the simulation of the soil moisture content the combination shows great improvements.

## 8.2 Recommendations

The improvements to MIPWA have showed that the soil moisture content influences the simulation of the ground water level. The parameterization in MIPWA deviates from the parameterization of the BOFEK classification, on which MIPWA is based. Especially the porosity shows large differences. The recommendation is to implement the unaltered Staringsreeks in MIPWA, as this porosity proved to be more similar to the soil moisture measurements.

The decrease of porosity was implemented likely to increase the modelled groundwater table in Twente, as the groundwater level is underestimated in this region. This could better be achieved altering the capillary rise and percolation of the model. During wet periods the percolation rate of the model should be increased, to allow more moisture to enter the saturated zone. During dry periods the capillary rise should be reduced to allow more transpiration reduction due to soil moisture stress. The combination of these measures should increase the groundwater level in Twente better than the porosity. This recommended change would require a calibration of the look-up tables in MetaSWAP.

An improvement for the saturated zone model iMODFLOW would be to restore the relation between groundwater level and saturated zone storage in the top layer of the model. In the current version, this relation is disturbed. Although this might not affect the simulations, it is recommended to restore the relation between groundwater level and saturated zone storage.

The research has not focussed on the effect of vegetation types on the soil moisture content and the ability of the model to replicate this difference in vegetation type. This has been omitted from the research due to lack of observation sites with soil moisture measurements of entire root zone for different vegetation types. The vegetation type influences the potential evapotranspiration rate and the root zone depth, which affects the soil moisture content. The model performance for vegetation should be further investigated to determine whether the model can simulate these differences.

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# Appendix A: Available soil moisture content measurements

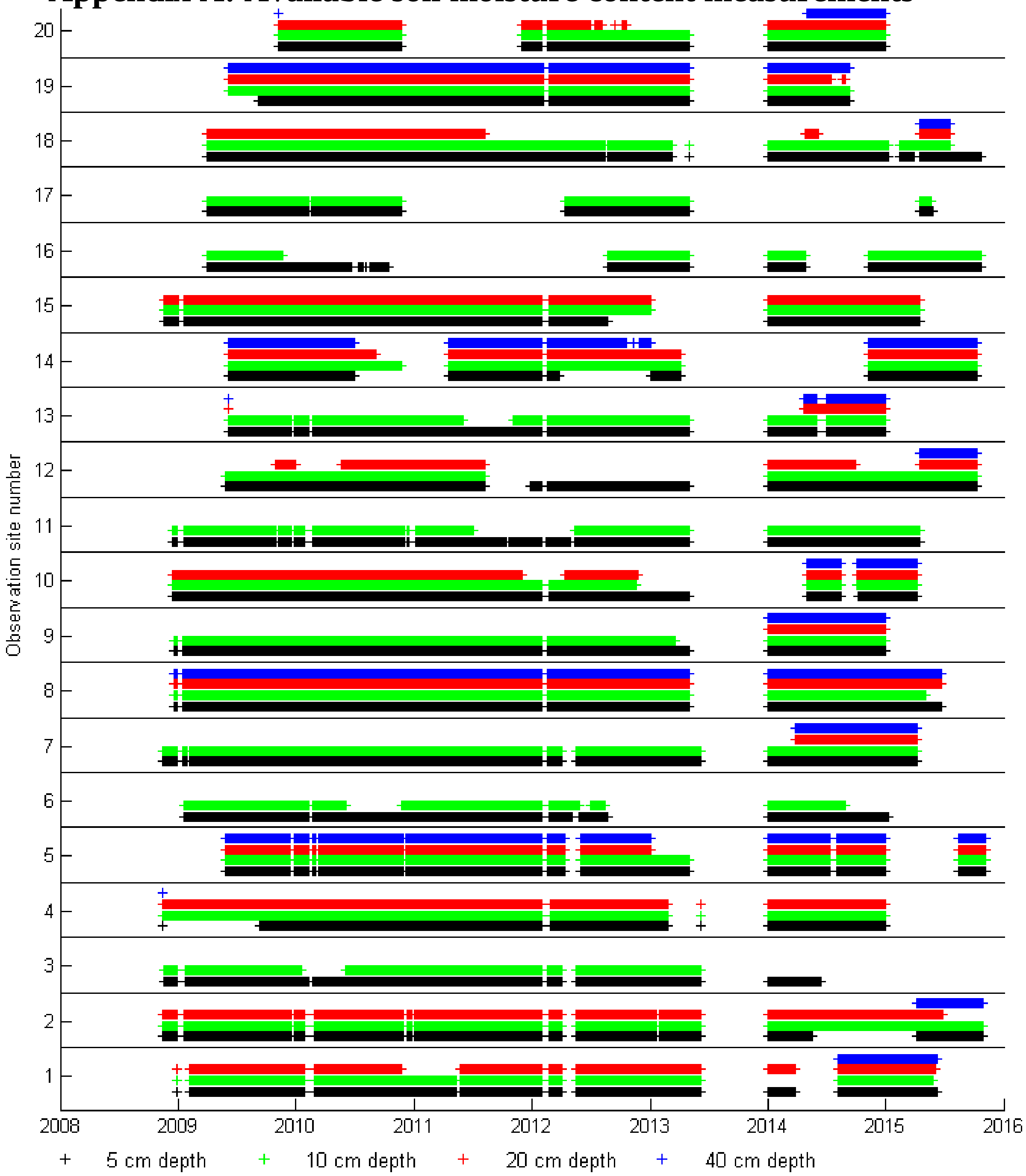


**Figure 9.1: Available soil moisture measurements at each observation site**

# Appendix B: Spatial correction

To the soil type many physical parameters are connected, including the porosity and the hydraulic conductivity. The soil type therefore has a large influence on the modelled soil moisture content. The soil type in MIPWA is based on the BOFEK classification of the soil. The BOFEK classification deviates from the in-situ classification at observation sites 2, 3, 4, 7, 10, 11, 12 and 19. The differences are partly caused by the additional classes of the BOFEK classification. Soils marked by Dente et al. as loamy are classified as clay soils in the BOFEK classification, indicating higher clay content in the soil. This is the case for sites 3, 4, 7, 11 and 12. The cause of the difference in classification at sites 2, 10 and 19 is unknown. Within 250 there are no areas with a matching description of the soil type. Possibly, the difference at sites 2, 10 and 19 is caused by the threshold of clay and silt content used for the classification. Nonetheless due to the lack of comparable soil types in close proximity no changes in soil type are done.

**Table 9.1: Soil type and land use per observation site**

| Observation site | Classification of top 5 cm By Dente et al. (2011) | Classification of top 5 cm by Wösten et al. (2013) |
|---|---|---|
| **1** | NA | Moderate clayey sand |
| **2** | Sand | Fine to medium sand with loam |
| **3** | Loamy sand | Moderate clayey sand |
| **4** | Loamy sand | Heavy clayey sand |
| **5** | Loamy sand | Fine to medium sand with loam |
| **6** | Sand | Fine to medium sand with limited loam |
| **7** | Loamy sand | Moderate clayey sand |
| **8** | Sand | Fine to medium sand with limited loam |
| **9** | Sand | Fine to medium sand with limited loam |
| **10** | Sand | Fine to medium sand with loam |
| **11** | Loamy sand | Peaty sand |
| **12** | Sand | Heavy clayey sand |
| **13** | Sand | Fine to medium sand with limited loam |
| **14** | Loamy sand | Fine to medium sand with loam |
| **15** | Sand | Fine to medium sand with limited loam |
| **16** | Sand | Fine to medium sand with limited loam |
| **17** | Sand | Fine to medium sand with limited loam |
| **18** | Loamy sand | Fine to medium sand with loam |
| **19** | Sand | Fine to medium sand with loam |
| **20** | Sand | Coarse sand |

The land use influences the evaporation rate and root zone depth of model. For each observation sites the land use in MIPWA is compared to the crops planted in 2010 and 2011. Table 9.1 shows the difference between the land use in MIPWA and the actual observed land use in 2010 and 2011. At observation sites 1, 4, 5, 9, 10 and 18 the land use is at least in one year different from the MIPWA classification. For the sites that have in both years different land use than in MIPWA, the observation sites are compared to a nearby area.

**Table 9.2: Land use classification at the observation sites**

| Observation site | CBS 2010 | CBS 2011 | MIPWA |
|---|---|---|---|
| **1** | Grass | Grass | Wet nature |
| **2** | Grass | Grass | Grass |
| **3** | Grass | Grass | Grass |
| **4** | Corn | Grass | Corn |
| **5** | Grass | Grass | Corn |
| **6** | Grass | Grass | Grass |
| **7** | Corn | Corn | Corn |
| **8** | Grass | Grass | Grass |
| **9** | Corn | Grass | Grass |
| **10** | Grass | Grass | Forest |
| **11** | Grass | Grass | Grass |
| **12** | Grass | Grass | Grass |
| **13** | Grass | Grass | Grass |
| **14** | Corn | Corn | Corn |
| **15** | Grass | Grass | Grass |
| **16** | Grass | Grass | Grass |
| **17** | Grass | Grass | Grass |
| **18** | Grass | Grass | Urban Area |
| **19** | Grass | Grass | Grass |
| **20** | Forest | Forest | Evergreen forest |

The actual land use at observation site 5, 10 and 18 differs from the land use in MIPWA in 2010 and 2011.The actual land use at observation site 1 also differs from MIPWA, however no correction for the land use has occurred.  The actual land use of observation site 1 can be interpreted as wet nature due to the proximity to a stream. The land use has changed in between 2010 and 2011 at observation site 4 and 9 no correction has taken place, as MIPWA is unable to change land use during a simulation.

Drainage removes water from the saturated zone, influencing the simulation of the unsaturated zone. To reduce the effect of the drainage, observation sites with active drainage should not be used. Therefore the amount of drainage flux is determined for each observation site. Although drainage is present at some observations sites, the drainage is not active due to low groundwater table.

# Appendix C: Staringreeks

**Table 9.3: Surface layer soil properties based on the Staringreeks, modified after Wösten et al. (2013). Explanation of units: $\theta_r$ – residual moisture content based on soil moisture at pf = 4.2; $\theta_s$ – saturated soil moisture; $K_s$ – Saturated hydraulic conductivity.**

| Topsoil class | Texture | $\theta_r$ ($cm^3/cm^3$) | $\theta_s$ ($cm^3/cm^3$) | $K_s$ (cm/d) | Staringreeks version |
|---|---|---|---|---|---|
| **B1** | Fine sand with no loam | 0.03 | 0.37 | 33.34 | 1987 |
| **B2** | Fine to medium sand with limited loam | 0.05 | 0.43 | 32.21 | 1987 |
| **B3** | Fine to medium sand with loam | 0.07 | 0.45 | 17.81 | 1987 |
| **B4** | Fine to medium sand with much loam | 0.04 | 0.42 | 54.80 | 1987 |
| **B5** | Coarse sand | 0.10 | 0.36 | 52.91 | 2001 |
| **B6** | Boulder clay | 0.10 | 0.38 | 100.69 | 2001 |
| **B7** | Slight clayey sand | 0.11 | 0.40 | 25.10 | 1987 |
| **B8** | Moderate clayey sand | 0.10 | 0.40 | 22.90 | 1987 |
| **B9** | Heavy clayey sand | 0.10 | 0.43 | 1.54 | 1994 |
| **B10** | Light clay | 0.14 | 0.44 | 31.10 | 1987 |
| **B11** | Medium clay | 0.17 | 0.51 | 63.60 | 1987 |
| **B12** | Heavy clay | 0.28 | 0.57 | 98.20 | 1987 |
| **B13** | Sandy loam | 0.06 | 0.42 | 12.98 | 2001 |
| **B14** | Silty loam | 0.12 | 0.42 | 0.80 | 1994 |
| **B15** | Peaty sand | 0.11 | 0.53 | 81.28 | 2001 |
| **B16** | Sandy peat and peat | 0.13 | 0.73 | 13.44 | 1987 |
| **B17** | Peaty Clay | 0.33 | 0.72 | 4.46 | 1994 |
| **B18** | Clayey peat | 0.28 | 0.71 | 34.80 | 1987 |

**Table 9.4: Subsoil soil properties based on the Staringreeks, modified after Wösten et al. (2013). Explanation of units: $\theta_r$ – residual moisture content based on soil moisture at pf = 4.2; $\theta_s$ – saturated soil moisture; $K_s$ – Saturated hydraulic conductivity.**

| **Subsoil** | **Texture** | **$\theta_r$ * ($cm^3/cm^3$)** | **$\theta_s$ ($cm^3/cm^3$)** | **$K_s$ (cm/d)** | **Staringreeks version** |
|---|---|---|---|---|---|
| **O1** | Fine sand with no loam | 0.01 | 0.35 | 99.7 | 1987 |
| **O2** | Fine to medium sand with limited loam | 0.02 | 0.38 | 63.9 | 1987 |
| **O3** | Fine to medium sand with loam | 0.02 | 0.34 | 44.6 | 1987 |
| **O4** | Fine to medium sand with much loam | 0.02 | 0.36 | 53.1 | 1987 |
| **O5** | Coarse sand | 0.01 | 0.33 | 223 | 1987 |
| **O6** | Boulder clay | 0.16 | 0.41 | 5.48 | 1987 |
| **O7** | Slight clayey sand | 0.23 | 0.51 | 39.1 | 2001 |
| **O8** | Moderate clayey sand | 0.07 | 0.42 | 26.4 | 1987 |
| **O9** | Heavy clayey sand | 0.06 | 0.41 | 24.0 | 1987 |
| **O10** | Light clay | 0.12 | 0.44 | 25.6 | 1987 |
| **O11** | Medium clay | 0.18 | 0.42 | 61.0 | 1987 |
| **O12** | Heavy clay | 0.25 | 0.49 | 10.8 | 1987 |
| **O13** | Sandy loam | 0.31 | 0.58 | 38.0 | 1987 |
| **O14** | Silty loam | 0.03 | 0.38 | 0.36 | 1994 |
| **O15** | Fine sand with no loam | 0.11 | 0.43 | 57.4 | 1987 |
| **O16** | Oligotrophic peat | 0.13 | 0.87 | 14.7 | 1987 |
| **O17** | Mesotrophic and eutrophic peat | 0.20 | 0.89 | 30.5 | 1987 |
| **O18** | Peat | 0.11 | 0.57 | 34.5 | 2001 |

# Appendix D: Porosity at each observation site observation site

The porosity has been determined based on soil type and the bulk density of the samples taken at the observation sites. Both methods and results are explained in this appendix.

The soil type based porosity is based on the Staringsreeks, for the classification of the soil the BOFEK classification is used. The BOFEK classification distinguishes multiple layers in the top layer of the soil. For each layer the subsoil identifier of the Staringsreeks is given and therefore the properties for each layer can be determined. This results in the properties for each layer as represented in Table 9.5.

**Table 9.5: Porosity at individual observation sites for each observation depth**

| | 5 cm depth | | 10 cm depth | | 20 cm depth | | 40 cm depth | |
|---|---|---|---|---|---|---|---|---|
| **Observation sites** | $\theta_{wp}$ | $\theta_s$ | $\theta_{wp}$ | $\theta_s$ | $\theta_{wp}$ | $\theta_s$ | $\theta_{wp}$ | $\theta_s$ |
| **1** | 0.10 | 0.40 | 0.10 | 0.40 | 0.12 | 0.44 | 0.02 | 0.34 |
| **2** | 0.07 | 0.45 | 0.07 | 0.45 | 0.07 | 0.45 | 0.07 | 0.45 |
| **3** | 0.10 | 0.40 | 0.10 | 0.40 | 0.12 | 0.44 | 0.02 | 0.34 |
| **4** | 0.10 | 0.43 | 0.10 | 0.43 | 0.12 | 0.44 | 0.12 | 0.44 |
| **5** | 0.07 | 0.45 | 0.07 | 0.45 | 0.07 | 0.45 | 0.07 | 0.45 |
| **6** | 0.05 | 0.43 | 0.05 | 0.43 | 0.05 | 0.43 | 0.02 | 0.38 |
| **7** | 0.10 | 0.40 | 0.10 | 0.40 | 0.12 | 0.44 | 0.02 | 0.34 |
| **8** | 0.05 | 0.43 | 0.05 | 0.43 | 0.05 | 0.43 | 0.02 | 0.38 |
| **9** | 0.05 | 0.43 | 0.05 | 0.43 | 0.05 | 0.43 | 0.05 | 0.43 |
| **10** | 0.07 | 0.45 | 0.07 | 0.45 | 0.07 | 0.45 | 0.02 | 0.34 |
| **11** | 0.11 | 0.53 | 0.11 | 0.53 | 0.11 | 0.53 | 0.13 | 0.87 |
| **12** | 0.10 | 0.43 | 0.10 | 0.43 | 0.10 | 0.43 | 0.12 | 0.44 |
| **13** | 0.05 | 0.43 | 0.05 | 0.43 | 0.05 | 0.43 | 0.02 | 0.38 |
| **14** | 0.07 | 0.45 | 0.07 | 0.45 | 0.07 | 0.45 | 0.02 | 0.34 |
| **15** | 0.05 | 0.43 | 0.05 | 0.43 | 0.05 | 0.43 | 0.05 | 0.43 |
| **16** | 0.05 | 0.43 | 0.05 | 0.43 | 0.05 | 0.43 | 0.02 | 0.38 |
| **17** | 0.05 | 0.43 | 0.05 | 0.43 | 0.05 | 0.43 | 0.02 | 0.38 |
| **18** | 0.07 | 0.45 | 0.07 | 0.45 | 0.07 | 0.45 | 0.02 | 0.34 |
| **19** | 0.07 | 0.45 | 0.07 | 0.45 | 0.07 | 0.45 | 0.02 | 0.34 |
| **20** | 0.10 | 0.36 | 0.01 | 0.33 | 0.01 | 0.33 | 0.01 | 0.33 |

Additionally to soil type based porosity, another method based on density has been used to determine the porosity. The bulk density and the organic matter content have been determined for each observation site in the research of Dente et al. Based on the bulk density these two measurements an estimation of the porosity is made. Equation (10) calculates the porosity based on the bulk density and the organic content, while Equation (11) is based on only the bulk density.

$$\theta_{organic} = 1 - \left(\frac{\rho_b * \varphi_o}{\rho_o} + \frac{\rho_b - \rho_b * \varphi_o}{\rho_m}\right) \quad (10)$$

$$\theta_{mineral} = 1 - \frac{\rho_b}{\rho_m} \quad (11)$$

Where $\theta_{organic}$ is the porosity based on the bulk density and the organic matter content in $m^3/m^3$, $\theta_{bulk}$ is the porosity based on the bulk density in $m^3/m^3$, $\rho_b$ is the bulk density in $kg/m^3$, $\rho_m$ is the mineral density in $kg/m^3$, $\rho_o$ is the organic matter density in $kg/m^3$ and $\varphi_o$ is the organic matter content in $kg/kg$. Locher & de Bakker (Locher & de Bakker, 1991) give a range of 1300 - 1400 $kg/m^3$ for the organic matter density $\rho_o$ and 2600 - 2750 $kg/m^3$ for the mineral density $\rho_m$. For the estimation of the porosity conservative estimates are used for the organic matter density and the mineral density, respectively 1400 $kg/m^3$ and 2750 $kg/m^3$. In Table 9.6 the calculated porosities are shown based on equation (10) and equation (11) respectively.

**Table 9.6: Porosity for each observation site based on bulk density**

| **Observation sites** | **Bulk density** $(kg/m^3)$ | **Organic matter content** $(g/kg)$ | $\theta_{organic}$ $(m^3/m^3)$ | $\theta_{mineral}$ $(m^3/m^3)$ |
|---|---|---|---|---|
| **1** | 1490 | NA | NA | 0.46 |
| **2** | 1130 | 52 | 0.57 | 0.59 |
| **3** | 1430 | 49 | 0.46 | 0.48 |
| **4** | 1290 | 33 | 0.52 | 0.53 |
| **5** | 1240 | 74 | 0.52 | 0.55 |
| **6** | 1170 | 58 | 0.56 | 0.57 |
| **7** | 1550 | 24 | 0.43 | 0.44 |
| **8** | 1130 | 69 | 0.57 | 0.59 |
| **9** | 1290 | 46 | 0.51 | 0.53 |
| **10** | 1210 | 41 | 0.55 | 0.56 |
| **11** | 1470 | 52 | 0.44 | 0.47 |
| **12** | 1400 | 20 | 0.48 | 0.49 |
| **13** | 960 | 70 | 0.63 | 0.65 |
| **14** | 1420 | 36 | 0.47 | 0.48 |
| **15** | 1250 | 51 | 0.53 | 0.55 |
| **16** | 1180 | 104 | 0.54 | 0.57 |
| **17** | 1360 | 19 | 0.50 | 0.51 |
| **18** | 1240 | 22 | 0.54 | 0.55 |
| **19** | 1340 | 43 | 0.50 | 0.51 |
| **20** | 780 | 44 | 0.71 | 0.72 |