Understanding unsaturated soil water dynamics of the Twente region using actual evapotranspiration and soil moisture data

Bachelor Thesis	
Student:	**Thorvald Rorink**
Student number:	**S1810146**
Supervisors:	
Vechtstromen:	**Ir. M. Duineveld** **Ir. S. Monincx**
University of Twente:	**Ir. M. Pezij**
Date:	**01-07-2019**

WATERSCHAP vechtstromen

UNIVERSITY OF TWENTE.

Understanding unsaturated soil water dynamics of the Twente region using actual evapotranspiration and soil moisture data

Author:	T. J. F. P. (Thorvald) Rorink
Studentnr.:	S1810146
Organisation:	Waterschap Vechtstromen
Internship period:	08-04-2019 – 01-07-2019
External supervisors:	Ir. M. (Marieke) Duineveld
	Ir. S. (Sjon) Monincx
Internal supervisor:	Ir. M. (Michiel) Pezij

Final version

Enschede, 01-07-2019

Abstract

The summer of 2018 was one of the driest summers of the 20th and 21st centuries (KNMI, 2018). The regional water authority Vechtstromen is one of the regional water authorities in the Netherlands with the most severe precipitation deficits during the summer of 2018. Droughts have large environmental and economic impacts, for example on agricultural and nature areas as droughts cause harvest losses that lead to economic damage (Schipper, Reidsma, & Veraart, 2018) or cause irreversible ecological damage (Rijksoverheid, 2018; Waterschap Vechtstromen, 2018). To anticipate future drought periods, it is necessary to store water before the growing season starts. The effectiveness of water storage measures and drought management measures partially depends on the current conditions of the subsoil (Hoekstra, 2016; Booij, 2016). This study will focus on the influence of hydrological conditions on the unsaturated zone over the Twente region in 2018.

Several datasets of hydrological conditions and spatial characteristics are selected and assessed on their quality. Next, soil moisture dynamics are analysed for eleven soil moisture monitoring locations at depths of 5 cm and 20 cm below ground level using the Pastas-package for Python 3.7. With the Pastas-package different combinations of hydrological stresses were evaluated to quantify relations between hydrological conditions and soil moisture in the Twente region. Results showed that a combination of precipitation and actual evapotranspiration had the highest explanatory value for soil moisture variability with averages of 83.01% for 5 cm depth and 76.51% for 20 cm depth. Actual evapotranspiration turned out to be the most dominant factor to affect soil moisture variations of the Twente region in 2018.

However, large differences exist between the individual soil moisture monitoring locations. Spatial characteristics as geographic position, elevation, land use and soil type were used to as explanatory factors for the dynamics of soil moisture and hydrological conditions. This analysis resulted in inaccurate results due to a too small amount of usable soil moisture monitoring locations, outdated and oversimplified datasets.

Preface

Since several years is remote sensing a valuable measuring technique to get accurate results. In my opinion, this value will only increase in the future due to increased accuracy and availability of the remotely sensed data. However, in daily water management the products of this technique have not found their place yet. Together with my supervisors, Marieke Duineveld, Sjon Monincx and Michiel Pezij, I tried to capture the drought of 2018 in soil moisture with remote sensing evapotranspiration data.

I would like to express my thanks to my supervisors at the regional water authority of Vechtstromen, Marieke Duineveld and Sjon Monincx, without you this bachelor thesis would not have been possible. Also, I would like to thank the colleagues at the regional water authority Vechtstromen for helping me and offering assistance whenever I needed it.

Next, I would like to thank my supervisor at the University of Twente, Michiel Pezij. Michiel helped me multiple times by giving feedback and offering handles to make this bachelor thesis a well-arranged whole.

Last, I hope that you as a reader enjoy reading this bachelor thesis.

Thorvald Rorink

Enschede, July 1st, 2019

Table of Contents

Figure on title page: Waterschap Vechtstromen stelt opnieuw verbod in om droogte (Lonkhuijsen, 2018)

List of abbreviations, concepts and variables

Table 1: Used abbreviations

Abbreviations:	**Meaning:**
KNMI	Royal Dutch Meteorological Institute *Koninklijk Nederlands Meteorologisch Instituut*
DINO	Data and Information of the Dutch Subsurface *Data en Informatie Nederlandse Ondergrond*
ITC	Faculty of Geo-information Science and Earth Observations
P	Precipitation
ETm	Reference evapotranspiration
ETp	Potential evapotranspiration
ETa	Actual evapotranspiration
ETe	Evapotranspiration deficit
GWL	Groundwater level
EVP	Percentage of variance explained.
Var	Variance

Table 2: Used concepts

Concept:	**Meaning:**
Hydrological conditions	Precipitation, evapotranspiration and groundwater conditions
Evapotranspiration deficit	The potential evapotranspiration minus the actual evapotranspiration
Spatial characteristics	Parameters that vary in location, but not in time. Examples in this research: geographic location, elevation, land use and soil type.
Sabulous sand	*Lichte zavel*
Boggy sand	*Venig zand*

Table 3: Used parameters

Parameter:	**Meaning:**
Res	Residuals
θ	Volumetric water content
T_{max}	Ending time
T_{min}	Starting time

1. Introduction

1.1. Project context

The summer of 2018 was one of the driest summers of the 20th and 21st centuries (KNMI, 2018). With an average maximum precipitation deficit of 309 mm over the Netherlands, this summer had a repetition time of 30 years (Sluijter et al., 2018). However, due to climate change, this repetition time can increase to 10 years in the most extreme scenario (KNMI, 2018). Such droughts will become more common in the future. Droughts have large environmental and economic impacts, for example on agricultural and nature areas as droughts cause harvest losses that lead to economic damage (Schipper, Reidsma, & Veraart, 2018) or cause irreversible ecological damage (Rijksoverheid, 2018; Waterschap Vechtstromen, 2018)

The regional water authority Vechtstromen is one of the regional water authorities in the Netherlands with the most severe precipitation deficits during the summer of 2018. The maximum precipitation deficit was 315 mm (Waterschap Vechtstromen, 2018; Gels, 2018). To cope with this deficit, Vechtstromen pumped three times as much water into its waterways from the IJsselmeer compared to normal years. Furthermore, some areas had restrictions on groundwater abstractions (Waterschap Vechtstromen, 2018). Even months later, the groundwater reservoirs are still not recovered. Due to low groundwater levels, concerns exist for the next growing season (Waterschap Vechtstromen, 2018).

To anticipate future drought periods, it is necessary to store water before the growing season starts. The effectiveness of water storage measures and drought management measures partially depends on the current conditions of the subsoil (Hoekstra, 2016; Booij, 2016). The availability of new remote sensing data concerning actual evapotranspiration and soil moisture information offers new opportunities to understand water system conditions on unprecedented spatial scales (Van der Velde et al., 2018). For example, these data may help us understand the interactions between precipitation, evapotranspiration, soil moisture and groundwater dynamics. The knowledge on these interactions helps to identify the effectiveness of measures on various spatial and temporal scales.

This study will focus on the understanding of the current hydrological conditions of the unsaturated zone by analysing precipitation, evapotranspiration, soil moisture and groundwater data sources. These understandings can help in developing tools to predict the future condition of soils. Such tools are useful in developing effective and robust water management measures for proactive drought management.

1.2. Research aim and research questions

The aim of this study is to give insight in the processes that influence unsaturated zone dynamics. Several hydrological conditions and processes will be taken into account, such as precipitation, evapotranspiration and groundwater levels. The main research question is:

"To what extent is unsaturated soil water influenced by hydrological conditions in the Twente region in the year 2018?"

The main research question is split into sub research questions:

1. Which hydrological datasets are available for the Twente region for 2018 and what is the quality of these datasets?
2. What is the relation between the observed hydrological conditions and unsaturated soil water in the Twente region?
    a. What is the relation between the hydrological conditions and unsaturated soil water at different depths in the Twente region?
    b. What is the relation between hydrological conditions and unsaturated soil water at different locations in the Twente region?
3. What is the relation between hydrological conditions and spatial characteristics in the Twente region?
4. Can the hydrological conditions be used to predict the condition of the unsaturated soil water content in the Twente region?

The relation between the main- and sub research questions is given in Figure 1 below.

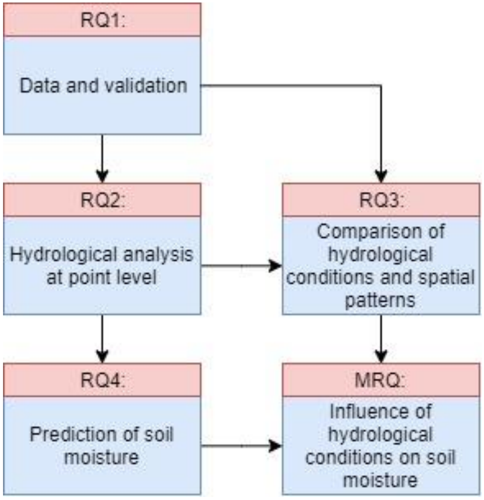


Figure 1: Relation of different research questions to each other.

1.3. Report outline

In chapter 2 the theoretical background of soil moisture in the hydrological cycle is explained. Furthermore, the study area and its characteristics are explained. Chapter 3 focuses on the research methodology. The results are showed in chapter 4 and are discussed in chapter 5. Chapters 6 and 7 give a conclusion on the research question and recommendations for further research and for use of this research in practice. Appendices consist of figures and tables as illustration or reference book and are given in a separate report.

2. Theoretical background and study area

2.1. Theoretical background

The hydrological cycle describes the movement of water on earth and is schematically visualized in Figure 2. In short, water evaporates from the surface into the atmosphere driven by solar radiation. In the atmosphere, the water vapor condenses to clouds and falls as precipitation (rain or snow) onto the surface of the earth (Marshall, 2014). On the earth surface, water either infiltrates into the ground or flows as surface runoff to streams, rivers, lakes or oceans where water ultimately evaporates again. If water infiltrates into the ground, it becomes soil moisture. Soil moisture either transpires through plants back into the atmosphere or it percolates (here given as recharge) into the saturated zone as groundwater (Wetzel, 2001).

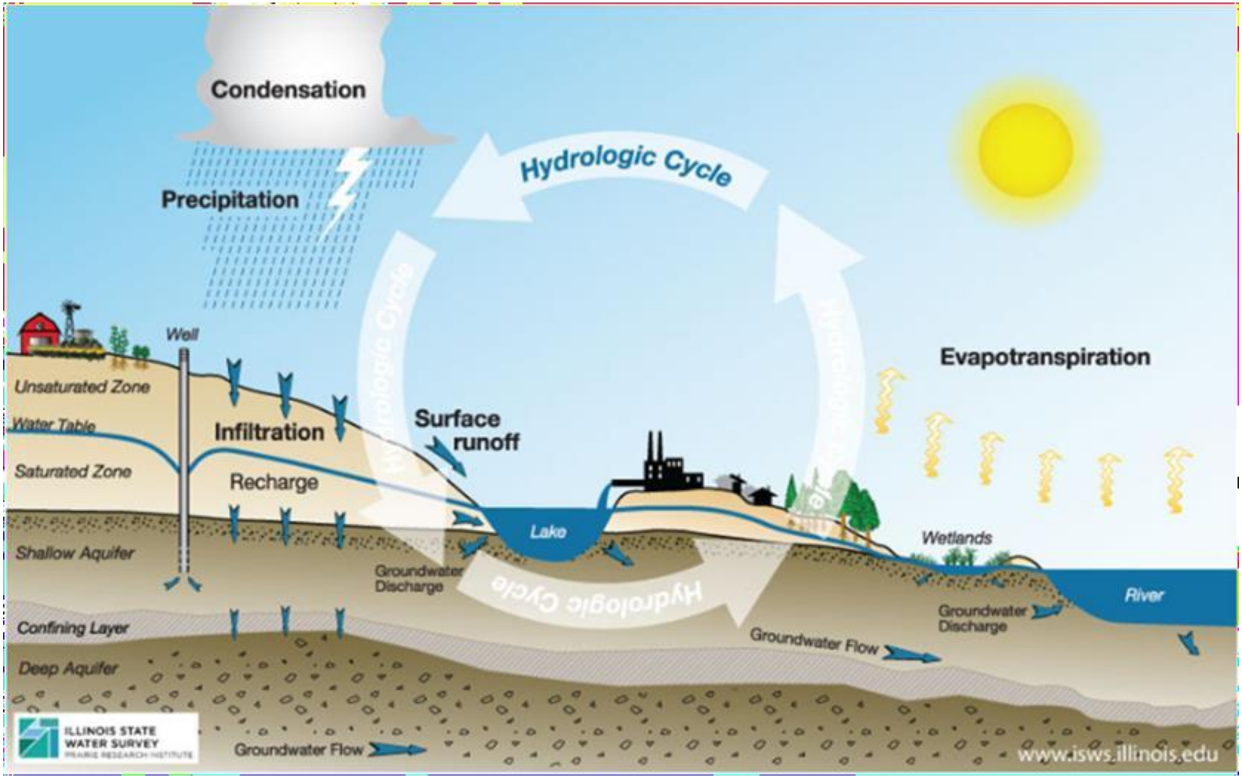
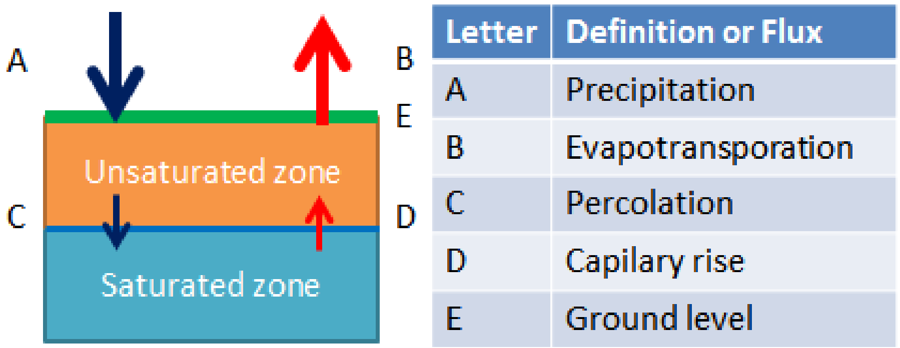


Figure 2: Schematization of the hydrological cycle (Illinois State Water Institute, 2019).

This research focuses on the unsaturated (or vadose) zone. The unsaturated zone is the part of the soil between the surface level and groundwater table and forms the link between precipitation, infiltration, evapotranspiration, percolation and capillary rise (Cassiani, Binley & Ferré, 2006). Below the groundwater table is the saturated zone. Figure 3 gives a schematic view of the unsaturated zone and the fluxes involved in this research.



Letter	Definition or Flux
A	Precipitation
B	Evapotransporation
C	Percolation
D	Capilary rise
E	Ground level

Figure 3: Schematization of the unsaturated zone with fluxes.

Precipitation

Precipitation is any product of condensation of water vapor that falls under gravity towards the earth's surface (KNMI, 2001). For this assignment, the precipitation considered is primarily rain. Precipitation is measured with radar technology and adjusted to measurement data from local raingauges (Schuurmans et al., 2013; KNMI, 2018).

Evapotranspiration

Evapotranspiration is the sum of earth evaporation and plant transpiration. Several types of evapotranspiration can be distinguished, which are listed below

- Reference evapotranspiration is the evapotranspiration of grass with a height of 10 cm and no limitations of water (Allen et al., 1998).
- Potential evapotranspiration is evapotranspiration without limitations of available water and with optimal growing conditions.
- Actual evapotranspiration is evapotranspiration that takes into account that water may not be fully available (Brouwer, 2014; Dam, Feddes & Witte, 2005).
- Evapotranspiration deficit is the difference between potential evapotranspiration and actual evapotranspiration.

Evaporation is hard to measure directly, but can be derived from several meteorological conditions, such as radiation and temperature (STOWA, 2018; Terink et al., 2012; Elbers, Moors & Jacobs, 2009). These meteorological conditions can also be measured with remote sensing, which allows spatial mapping of evapotranspiration (Viergever, Pelgrum & Voogt, 2007).

Percolation and capillary rise

Percolation is downward soil water flow from the unsaturated zone to groundwater (saturated zone) and capillary rise is upward soil water flow from the saturated zone to the unsaturated zone (Dam, Feddes & Witte, 2005). Percolation and capillary rise measurements are hard to obtain and are dependent on the hydraulic gradient and soil characteristics (Ochoa et al., 2012). Through percolation and capillary rise, the soil moisture content can change even if it has not rained.

The importance of the unsaturated zone

Unsaturated zone dynamics affect agricultural activities. If the unsaturated zone becomes too wet, agricultural vehicles slump into the ground, which causes damage to the subsoil and the crops (Van der Velde et al., 2018; Dam, Feddes & Witte, 2005) or crop yield decreases due to the unability for timely farming operations and lack of aeration of crops (Dam, Feddes & Witte, 2005). If the unsaturated zone becomes too dry, crops cannot obtain enough water and the crop yield will decrease, leading to economic damage for farmers. Furthermore, wild animals have trouble feeding themselves as natural food sources become scarce (Kennisportaal Ruimtelijke Adaptatie, 2018).

2.2. Study area

The study area is the management area of Waterschap Vechtstromen within the Twente region, located in the eastern part of the Netherlands. The study area has a size of about 1500 km^2 (Aals, 2016) and mainly consists of sandy and peaty soils. Several glacial ridges are present, which causes elevation differences up to 80m, with the highest point of the region being over 85 m +NAP (Haartsen, 2017). The majority of the study area is covered in a mosaic pattern of grasslands, cultivated fields, forest patches or urban areas (Dente, Zu & Wen, 2012). Also, the study area has many natural ditches (Haartsen, 2017) of which some are visualized in Figure 4.

The soil type in the Twente region can be classifed in four categories: sandy soils, loamy soils, man-made thick sand soils and peaty soils (Dente et al., 2011), with sandy soils and loamy soils most commonly found near the surface (Mehrjardi, 2016).

The Twente region has a C-climate according to the classification of Köppen (Köppen, 1884). Precipitation is spread evenly throughout the year with an average of 760 mm per year (Dente et al., 2011). Average temperatures range from 3° C in January to 17° C in July (Dente et al., 2011). In 2018 the study area coped with extreme drought. Average temperatures were 27°C in July with a precipitation of only 7.7mm, making it the driest region in the Netherlands at that time (Boels & Bekhuis, 2018).

Several soil moisture monitoring stations are placed by the Faculty of Geo-information Science and Earth Observations. Furthermore, several groundwater monitoring wells and KNMI-precipitation measurment stations are present. Figure 4 gives an overview of the locations of all these stations.

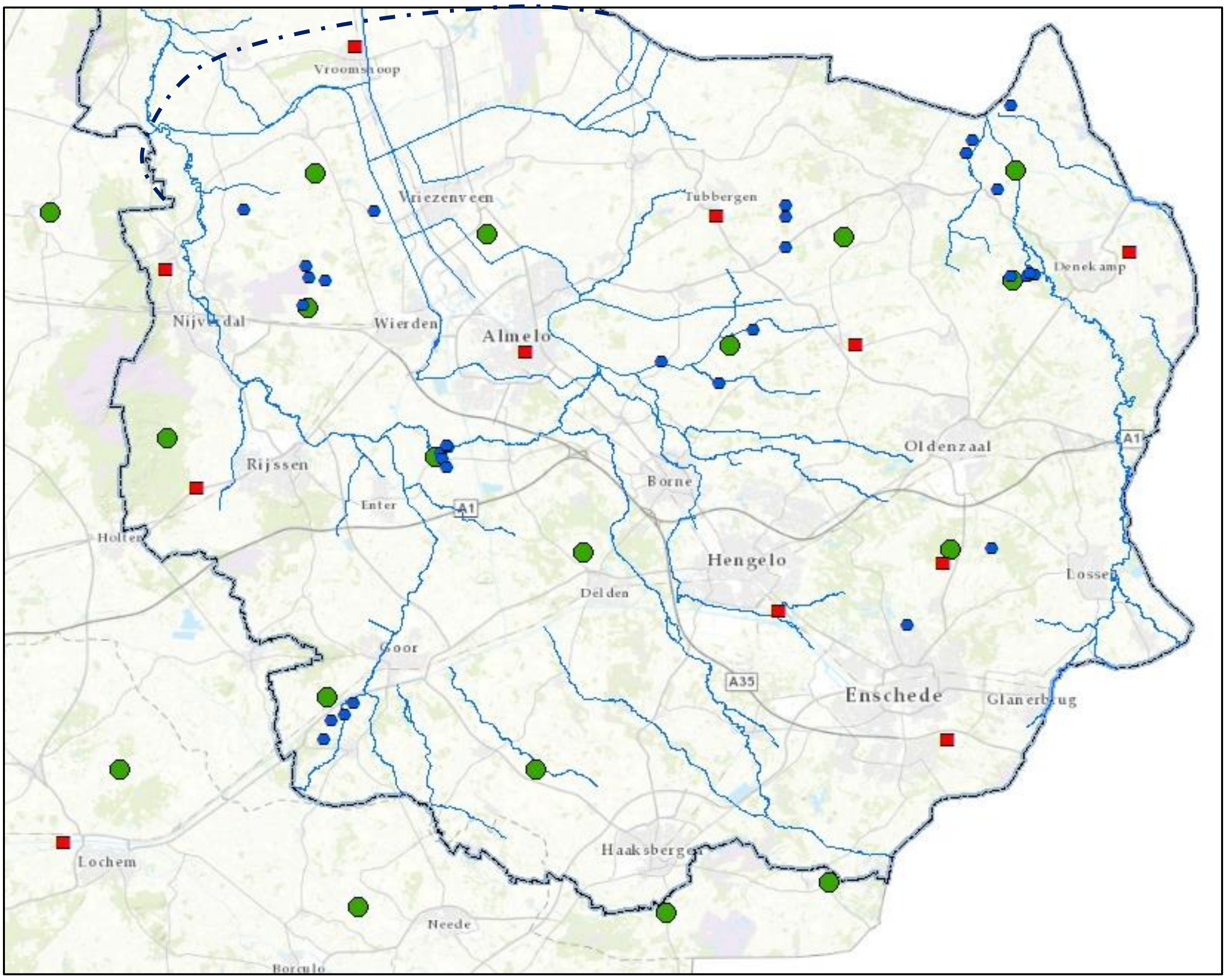


Figure 4: Overview of the southern part of Waterschap Vechtstromen and the study area.

3. Research Methodology

The research methodology of this research can be divided in five steps; four steps each focus on answering one sub research question and the fifth step focusing on combining the answers of the sub research question to answer the main research question. A schematic overview of the research methodology is given in Figure 5. Each of the blocks is explained in the next sections.

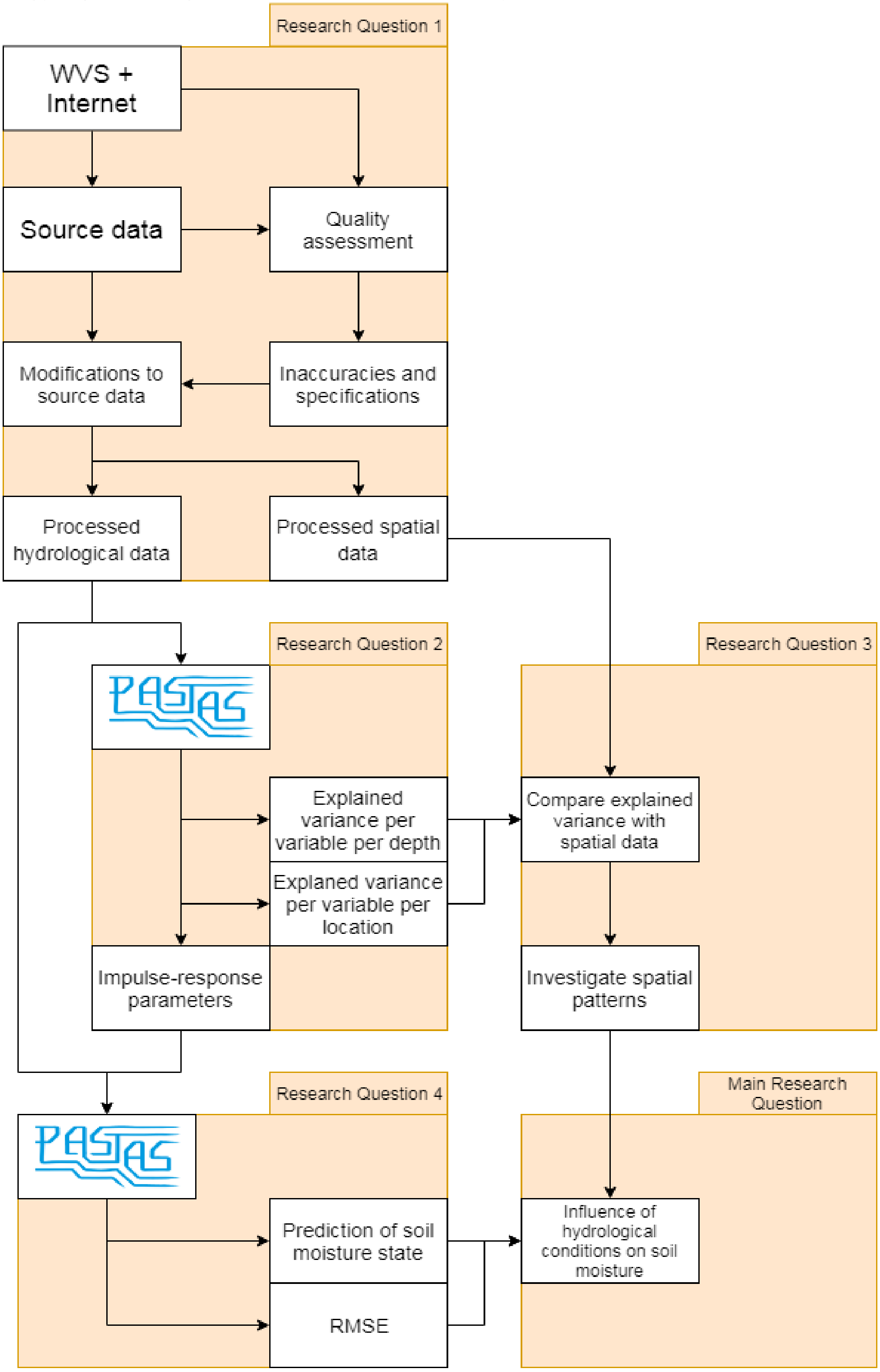


Figure 5: Overview of research methodology.

3.1. RQ1: Availability and quality of datasets

Several datasets are used to analyse the influence of different hydrological conditions on the soil moisture content in the study area. Research question 1 focuses on the availability and quality of datasets that are used in the assignment. The goal of research question 1 is to obtain usable datasets for the next research questions and give insight in the quality of these datasets. The steps to achieve this goal are given in Figure 6.

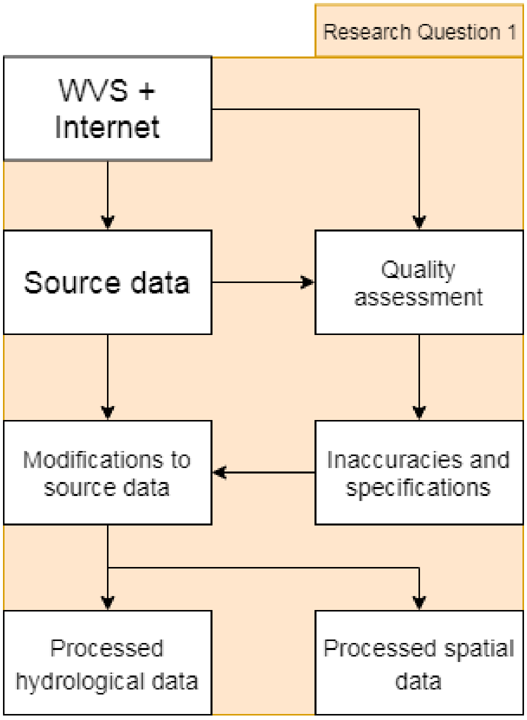


Figure 6: Methodology of research question 1.

Several datasets are selected from the database of the Waterschap Vechtstromen. If the Waterschap Vechtstromen has no data (or too small datasets), the datasets are obtained from the internet. All datasets that are selected are assessed on their quality to give insight in the properties of these datasets. This quality assessment is based on the elements of spatial data quality (Van Oort, 2006). Not all elements described in Van Oort (2006) are taken into account as not every dataset used is spatial and this causes excessive amounts of time for minimal results. Therefore, the criteria by Van Oort (2006) are used as inspiration for self-induced criteria for the quality assessment of the datasets used. Used criteria of the assessment and the corresponding criteria of Van Oort (2006) are given in Table 4.

Table 4: Used criteria for the quality assessment of the used datasets.

Number:	**Criterion by Van Oort (2006):**	**Induced criteria:**
1	Lineage	Production and transformation Data unit Data type Resolution
2	Completeness	Interval Time period
3	Accuracy	Smallest measurable value Deviation of measured value from actual value Time of measurement
4	Variation in accuracy	Variation in accuracy between locations Variation in accuracy over time

1. **Lineage**

In short, lineage is the 'history' of the dataset. It is a description of the measurement of source data and the conducted operations to obtain the current dataset. Furthermore, lineage includes also the present data unit (for example mm/day) and dataset type (such as raster, vector, or point) and resolution (if the data is in raster format).

2. **Completeness**

The completeness (in this research) indicates the absence of data during different periods in 2018. Furthermore, the number of measurements per day (or measurement interval) is also an indication of the completeness of the dataset.

3. **Accuracy**

Van Oort (2016) describes multiple forms of accuracy, such as postitional accuracy, attribute accuracy, semantic accuracy and temporal accuracy. Accuracy in this research is defined as a measure of the representativeness of the measurements in a certain area at a certain time. This comes down to three things; First, accuracy is the smallest measurable value. Second, accuracy is the difference of the measured value and the actual value. Another important factor when comparing the datasets is the time of measurement. An example: Data gathered on 08:00 in the morning may differ from data gathered on 14:00 or 20:00 and may not be representative for the situation over the whole day.

4. **Variation in accuracy**

The accuracy of the dataset can vary in two ways and it is important for the reliability of the dataset to have insight in the variation of accuracy:

a. The accuracy of measurements can vary in location; for example measurements below ground level have lower accuracy than measurements at ground level
b. The accuracy of measurements can vary in time; for example measurements during the winter period have lower accuracy than measurements during the summer period.

After the quality assessment the datasets are modified to make a comparison between datasets possible. To be comparable, the datasets must have the same features. These target features are listed in Table 5.

Table 5: Target specifications for the used datasets.

Variable	**Data unit:**	**Data type:**	**Interval:**	**Time period:**
Hydrological conditions				
Soil moisture	m^3/m^3	Point	24h	January 1st, 2018 – December 31th, 2018
Precipitation	mm/day	Point	24h	January 1st, 2018 – December 31th, 2018
Evapotranspiration	mm/day	Point	24h	January 1st, 2018 – December 31th, 2018
Groundwater levels	m +NAP or m -ground level	Point	24h	January 1st, 2018 – December 31th, 2018
Spatial characteristics				
Elevation	m +NAP	Point	-	-
Soil composition	BOFEK	Point	-	-
Land use	LGN4	Point	-	-

To obtain these target features for all datasets the following procedure is followed:

1. Reprojecting the coordinate systems to the 'Rijksdriehoekstelsel'-projection to make sure the datasets have the same geographic location.
2. Plotting of data to see if every location in the study area is covered.
3. Extracting of raster or polygon values to point values.
4. Aggregating the data to intervals of 24 hours.
5. Plotting the data series and compare them to literature and/or historic values.
6. Removing outliers, false measurements and (if possible) interpolate data gaps,

The result of research question 1 is processed data hydrological and spatial data that serves as input for research questions 2, 3 and 4 with well-documented metadata.

3.2. RQ2: Relations between soil moisture and hydrological conditions

Research question 2 focusses on the relation of different hydrological conditions on the unsaturated soil water. To find this relation, a time series modelling analysis on point level is conducted using the 'Pastas'-package. The goal of research question 2 is to explain the variation in soil moisture due to stresses of precipitation, evapotranspiration and groundwater levels. A second goal is to generate impulse-response parameters (which is clarified later) for research question 4. Figure 7 gives an overview of the methodology of research question 2.

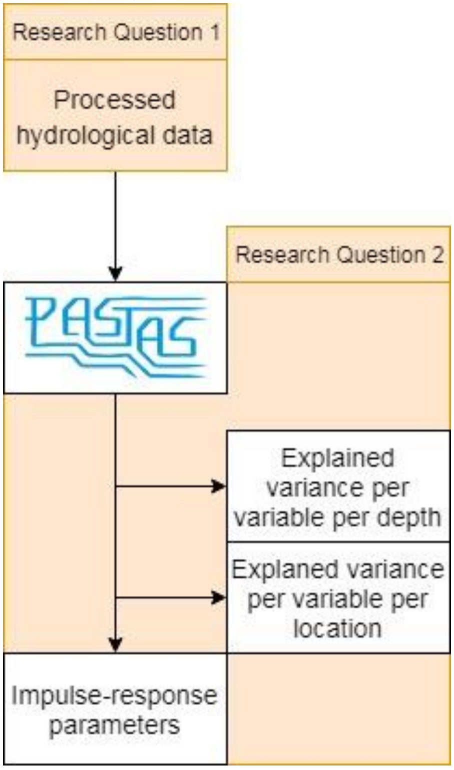


Figure 7: Methodology of research question 2.

Pastas (Python Applied Statistical Timeseries Analysis Software) is an open-source source Python 3 package for processing, simulating and analysing hydrological time series (Collenteur et al., 2019). Originally developed for groundwater time series modelling, we apply this methodology now for soil moisture modelling. Pastas makes use of time series analysis with impulse-response functions (which will be clarified later). This is a fairly new technique to model groundwater dynamics. The biggest advantage is that the method is completely data-driven and only requires time series of the observed groundwater heads and stresses (Bakker et al., 2018). However, the biggest downside is that manual impulse-response distributions have to be chosen which can have major influences on the output (Bakker et al., 2018). The source code of Pastas is given in Collenteur et al. (2019).

Working of Pastas

Pastas makes use of autoregressive-moving-average (ARMA) modelling. ARMA-modelling consists of two parts; autoregressive (AR) and moving average (MA). Autoregressive means that the value of the observed variable is based on the previous value of the variable. An example: the ground water level of tomorrow is strongly influenced by the ground water level of today. The same holds for soil moisture: Soil moisture state on day 't+1' is dependent on de soil moisture state on day 't' plus the changes in soil moisture. Moving average indicates that the value of the observed variable dependent is on current and past values of a stochastic error term (The Pennsylvania State University, 2019; Adhikari & Agrawal, 2013; Von Asmuth et al. 2002).

The ARMA-model is given in Equation 1.

$$h_s(t) = \sum_{i=1}^{k} h_i(t) + d + \eta(t)$$

Equation 1: The basic equation of a discrete ARMA-model (Von Asmuth, 2007).

Where:

- $h_s(t)$ is the observed state variable at time 't', in this case soil moisture.
- $\sum_{i=1}^{k} h_i(t)$ is the total contribution of each stress 'k' at time 't'
- d is a base level (the state if no stresses are present)
- $\eta(t)$ is noise or residual series.

Contribution of stresses

The contribution of each stress 'k' at time 't' is described using a convolution of an impulse-response function with a time series of that specific stress (Bakker et al., 2018). This is schematically visualized in Figure 8 with two stresses: precipitation and evapotranspiration. Pastas uses the method of least squares to find parameters for the impulse response functions of each stress 'k' such that the squared error of the deviation between the observed state variable and the simulated state variable is minimized (Collenteur et al, 2018).

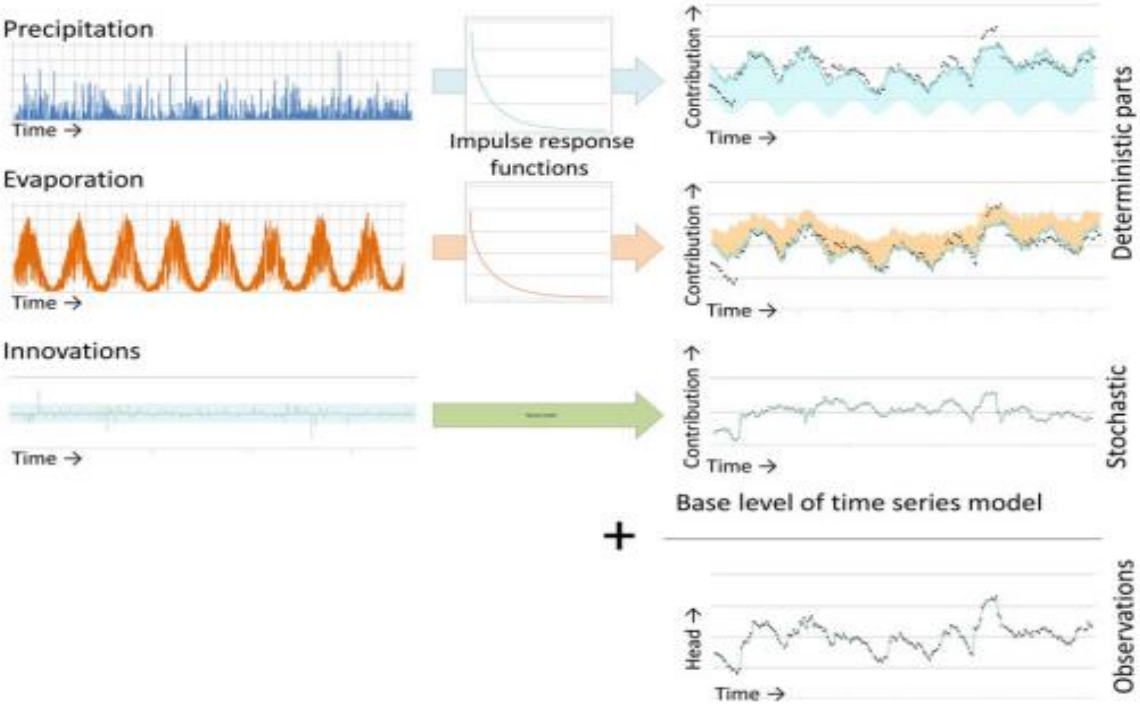


Figure 8: Schematic overview of modelling with impulse-response functions (Zaadnoordijk, 2018).

Impulse-response functions

Figure 8 shows that the stresses generate a certain contribution to the soil moisture state through an impulse-response function. Impulse response function show the response of the observed state variable (in this case soil moisture) due to 1mm of stress (in this case precipitation or evapotranspiration) at day 1 (Von Asmuth & Maas, 2001). The total response of soil moisture due to a stress is obtained by integrating the area beneath the impulse-response function (Von Asmuth & Maas, 2001). The shape and area of the impulse-response function are very dependent on the hydrological in situ conditions. An example of the impulse-response function of precipitation and actual evapotranspiration at location ITCSM_10 (The exact location of this station is given in Figure 11) at 5cm depth is given in Figure 9.

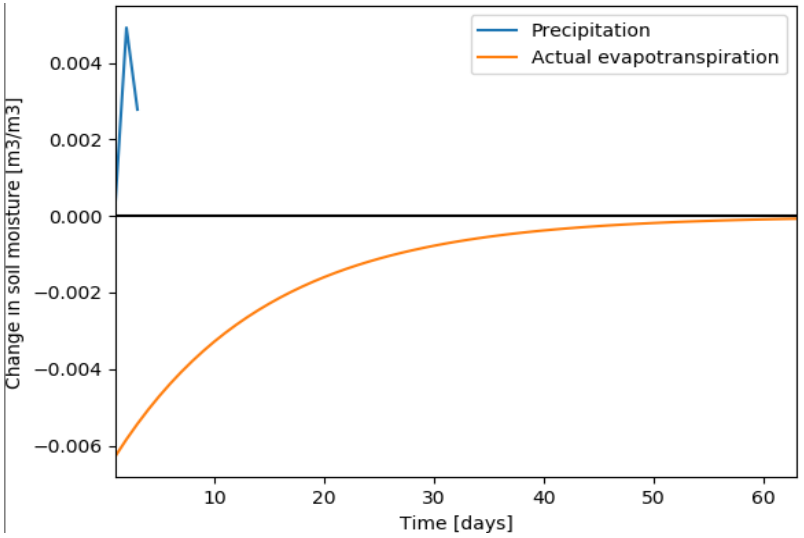


Figure 9: Impulse response distribution of precipitation and actual evapotranspiration for ITCSM_10 at 5cm depth.

Impulse-response distributions

The impulse response functions are derived from impulse response distributions. Every stress influences the soil moisture in a different way, so every stress has a different impulse-response distribution. As stated before, the impulse-response functions are very dependent on de hydrological conditions at the location in situ. Therefore, every impulse-response function will have different parameters. Pastas optimizes these parameters to simulate the observed state variable (soil moisture) as best as possible. Table 6 gives an overview of the different stresses used in this research and their consequent impulse-response distributions (including formulas and parameters).

Table 6: Overview of stresses, impulse-response distributions and parameters.

Stress	**Impulse-response distribution:**	**Step-response (integral of impulse-response) formula (Collenteur et al., 2019):**	**Parameters:**
Precipitation	Gamma	$s(t) = A * \frac{1}{\Gamma(n)} \int_{0}^{t} \tau^{n-1} * e^{-\frac{t}{a}} d\tau$	A, n, a
Actual evapotranspiration	Exponential	$s(t) = A * (1 - e^{-\frac{t}{a}})$	A, a
Evapotranspiration deficit	Exponential	$s(t) = A * (1 - e^{-\frac{t}{a}})$	A, a
Groundwater level	Gamma	$s(t) = A * \frac{1}{\Gamma(n)} \int_{0}^{t} \tau^{n-1} * e^{-\frac{t}{a}} d\tau$	A, n, a

It is chosen to use a gamma distribution for precipitation and exponential distribution for actual evapotranspiration and evapotranspiration deficit, since these distributions gave the highest amount of variance explained. For groundwater levels, a gamma distribution is recommended (Collenteur et al., 2019).

Application of Pastas in this research

In this research, the pastas package is used to calculate the explained variance of soil moisture per stress per location and depth. By choosing different stresses (and their corresponding impulse-response distributions), pastas simulates the soil moisture level (observed state variable) based on the contributions of the chosen stresses. The contribution of a stress to the soil moisture is expressed in the EVP, or explained variance percentage. The EVP is the amount of variation of soil moisture that is explained by a specific stress . The calculation of the EVP is given in Equation 2.

$$EVP = \frac{var(\theta) - var(res)}{var(res)} * 100\%$$

Equation 2: Calculation of EVP.

Were:

- ‘Θ’ is the volumetric water content (in $m^3/m^3$3)
- ‘res’ are the residuals (the amount of soil moisture that cannot be explained by the chosen stresses)

As stated before, Pastas uses an algorithm that maximizes the EVP and minimizes the residuals by the method of least squares. Different combinations of stresses are examined to simulate the soil moisture state of the Twente region in 2018 as best as possible. Table 7 gives an overview of the examined combinations of stresses. The EVP and impulse-response parameters are compared on the different soil moisture monitoring locations and at depths of 5cm and 20cm.

Table 7: Examined combinations of stresses.

Run number:	Simulation of:	Unit:	Incorporated stresses	Unit:
1	Volumetric water content	m^3/m^3	• Precipitation	mm/day
2	Volumetric water content	m^3/m^3	• Actual evapotranspiration	mm/day
3	Volumetric water content	m^3/m^3	• Evapotranspiration deficit	mm/day
4	Volumetric water content	m^3/m^3	• Precipitation • Actual evapotranspiration	mm/day mm/day
5	Volumetric water content	m^3/m^3	• Precipitation • Evapotranspiration deficit	mm/day mm/day
6	Volumetric water content	m^3/m^3	• Ground water level	m –ground level
7	Volumetric water content	m^3/m^3	• Precipitation • Actual evapotranspiration • Groundwater level	mm/day mm/day m – ground level

First, all seven runs will be made to obtain the simulation with the highest average EVP over all soil moisture monitoring locations. Then, the simulation of soil moisture with the average highest EVP is decomposed to get the contributions of the individual stresses per location and per depth. These contributions are used in research question 3. Last, two different periods are simulated to investigate the flexibility of the EVP’s. These periods are an annual period and a spring period. A side-note here is that if there is no data available for the complete annual period, the maximal available time values are used. Table 8 gives an overview of the length of the different time periods.

Table 4: Starting and ending times for the simulated periods.

Period:	Tmin:	Tmax:
Annual	01-01-2018	31-12-2018
Spring	01-03-2018	01-05-2018

3.3. RQ3: Investigation of spatial patterns of soil moisture

Research question 3 aims to get insight in possible spatial patterns of soil moisture variation. By assigning the spatial characteristics of research question 1 to the soil moisture monitoring locations and evaluating differences in EVP, contribution of stresses or impulse-response parameters of research question 2, spatial patterns in soil moisture dynamics are investigated. Figure 9 gives an overview of the methodology of research question 3. The comparison will take several steps, which are explained below Figure 9.

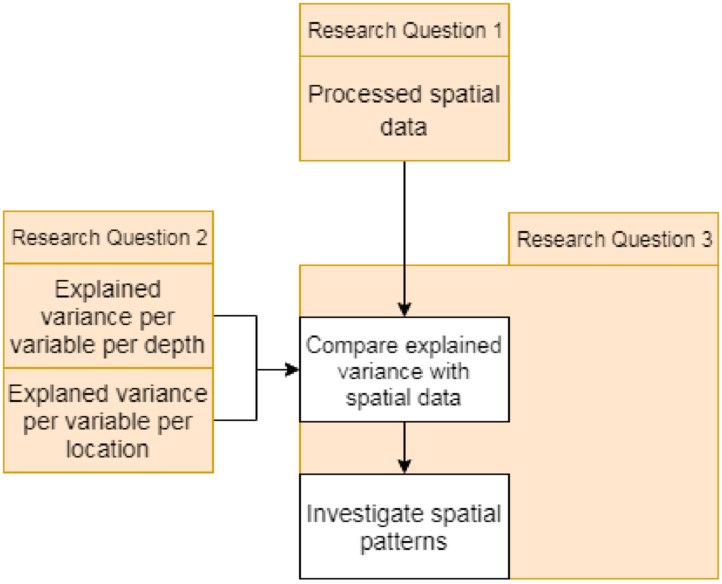


Figure 9: Methodology of research question 3.

Assign spatial characteristics

Every soil moisture monitoring location has several characteristics which may influence soil moisture dynamics. These spatial characteristics are gathered in research question 1. In research question 3, the spatial characteristics are assigned to the soil moisture monitoring stations. This way, the soil moisture monitoring stations are grouped based on their differences in elevation, soil type or land use. Next, the assigned spatial characteristics are compared to literature of Dente et al. (2011).
The difference in EVP and contribution of individual stresses is compared based on different spatial characteristics. Criteria for the comparison are given in Table 9 and are based on discussions with the supervisors. Since the comparison is only based on one value without standard deviation or average a quantified analysis is not conducted, but the results are discussed with the Waterschap Vechtstromen.

Table 9: Criteria for participation spatial analysis.

Criterion:	**Value**
Minimum value of EVP	>70%
Maximum value of standard deviation of impulse-response parameters	<100%

Next, the total EVP's and the contribution of the individual stresses to the EVP are compared based on spatial criteria to see if these criteria have an influence on the explicability of soil moisture variations or on the sensitivity of soil moisture for individual stresses. Table 10 gives an overview of the comparison. For every spatial criterion the total EVP and the contribution of individual stresses to the total EVP will be compared for all locations and for two different depths.

Table 10: Overview of comparison.

Spatial criteria:	Compared factors:	Compared depths:
Geographic location	• Total EVP • Contribution of individual stresses to EVP	• 5cm • 20cm
Elevation	• Total EVP • Contribution of individual stresses to EVP	• 5cm • 20cm
Soil type	• Total EVP • Contribution of individual stresses to EVP	• 5cm • 20cm
Land use	• Total EVP • Contribution of individual stresses to EVP	• 5cm • 20cm

3.4. RQ4: Prediction of soil moisture state

Research question 4 gives aims to predict the soil moisture state in the Twente region to anticipate on future (drought) events. Like in research question 2, the modelling of the prediction of the soil moisture state is done using the Pastas-package. Input for the prediction are the hydrological data that is gathered in research question 1 and the impulse-response parameters for the impulse-response functions that is obtained with the methodology of research question 2. Output of research question 4 are the prediction of the soil moisture and the 'Root Mean Square Error'-value (RMSE). The general methodology of research question 4 is schematically given in Figure 10 and is explained in the next section. Due to time reasons results are not fully worked out.

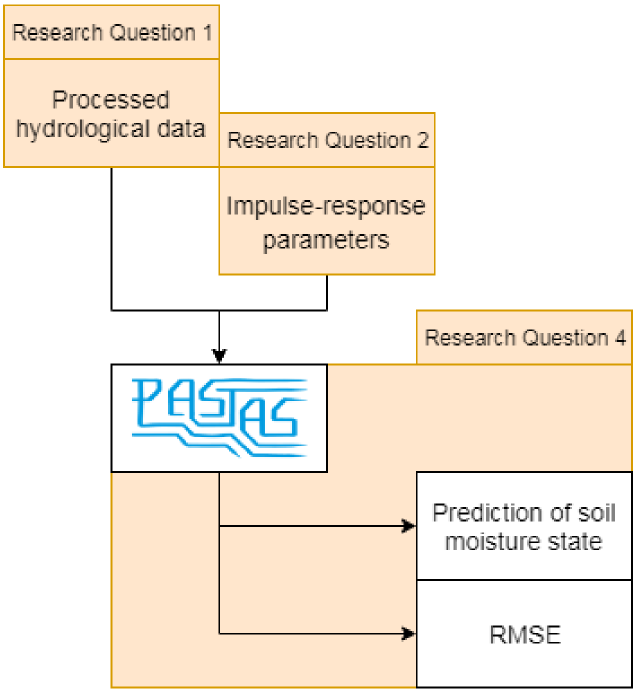


Figure 10: Methodology of research question 4.

Input of soil moisture prediction

As stated above, input of the soil moisture prediction consists of two factors:

1. Processed hydrological data
2. Impulse response parameters

The hydrological data gathered and processed with the methodology of research question 1 is the input as a stress which affects the soil moisture state. The hydrological conditions that are taken into account follow from the analysis of research question 2, as in research question 2 it is investigated what combination of stresses simulates the soil moisture state in 2018 best.

The impulse-response parameters are gathered from the analysis with pastas of research question 2. As stated in the methodology of research question 2, Pastas makes use the convolution of impulse-response functions with a stress time series. Those impulse-response functions are characterized by an impulse-response distribution (stress-dependent) with several impulse-response parameters (location- and depth-dependent) (Collenteur et al., 2019).

The soil moisture predicting process

Simulating soil moisture with pastas is done in two periods:

1. A training period
2. A simulation period

The training period is similar as the analysis conducted in the methodology of research question 2. Pastas uses an algorithm (the Solver) to optimize the impulse-response parameters of the given impulse-response distribution. Furthermore, the 'Solver'-algorithm minimizers the difference between the simulated series and the observed series according to the least squares method (Collenteur et al., 2019). From the training period, the impulse-response parameters are optimized. These impulse-response parameters are used in the simulation period.

In the simulation period, the optimized impulse-response parameters are used again in the impulse-response functions. Pastas simulates the soil moisture state based on the contribution of different stresses. These contributions are calculated with the convolution of the impulse-response functions and the stress series (Collenteur et al., 2019), which is similar as in research question 2. If the training period contains more variation, the simulation period is able to simulate soil moisture variation better.

Output of soil moisture prediction

The output of the soil moisture simulation consists of two things:

1. Value of soil moisture
2. Root Mean Square Error (RMSE)

The primary output of the soil moisture simulation is the value of soil moisture during every moment in the simulation period.

Furthermore, it is possible to calculate the Root Mean Square Error 'RMSE'. The RMSE is a measure to quantify the accuracy of the predicted values of a model (in this case soil moisture) and is the square root of the quadratic mean of the difference of the simulated and observed value (Chai & Draxler, 2014). Calculation of the RMSE is given in Equation 3.

$$RMSE = \sqrt{\frac{\sum_{t_{min}}^{t_{max}}(\theta_{sim} - \theta_{obs})^2}{t_{max} - t_{min}}}$$

Equation 3: Calculation of RSME (Chai & Draxler, 2014)

Where:

- t_{min} is the starting time of the simulation (in days)
- t_{max} is the ending time of the simulation (in days)
- θ_{sim} is the simulated value of soil moisture on day 't' (in m^3/m^3)
- θ_{obs} is the observed value of soil moisture on day 't' (in m^3/m^3)

For an accurate simulation, the RMSE should be as close to zero as possible. Since the values of soil moisture lie between 0 m^3/m^3 and 1 m^3/m^3, the value of the RMSE will also be between 0 and 1. Simulations are found to be accurate if the RSME is below 0,1.

4. Results

4.1. RQ1: Availability and quality of datasets

Several datasets have been investigated following the methodology described in chapter 3.1. The results of the quality assessment are given in this paragraph.

4.1.1. Soil moisture dataset

In this research, in situ soil moisture data from the ITC soil moisture monitoring network, which are set up and calibrated by Dente, Su & Wen (2012), is used. The locations of the soil moisture monitoring stations are given in Figure 11. Spatial characteristics of the used soil moisture monitoring locations described in section 4.1.5.

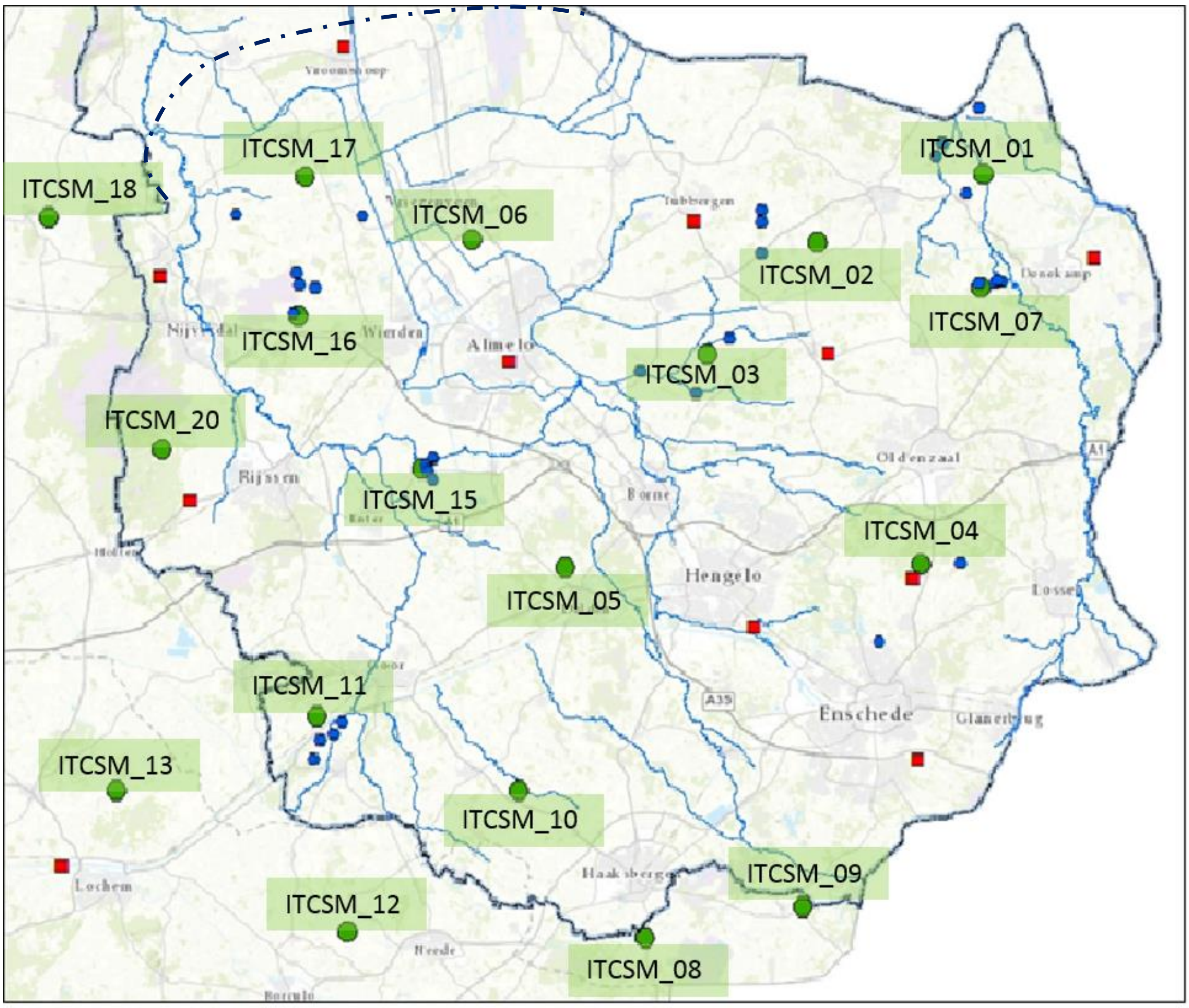


Figure 11: Locations of soil moisture measuring stations.

Thirteen soil moisture monitoring stations are present within the study area. Figure 11 gives an overview of the data availability of the soil moisture monitoring stations that are located in the study area over 2018. Faded lines indicate that soil moisture data is not available during the full period of one month and that data gaps are present.

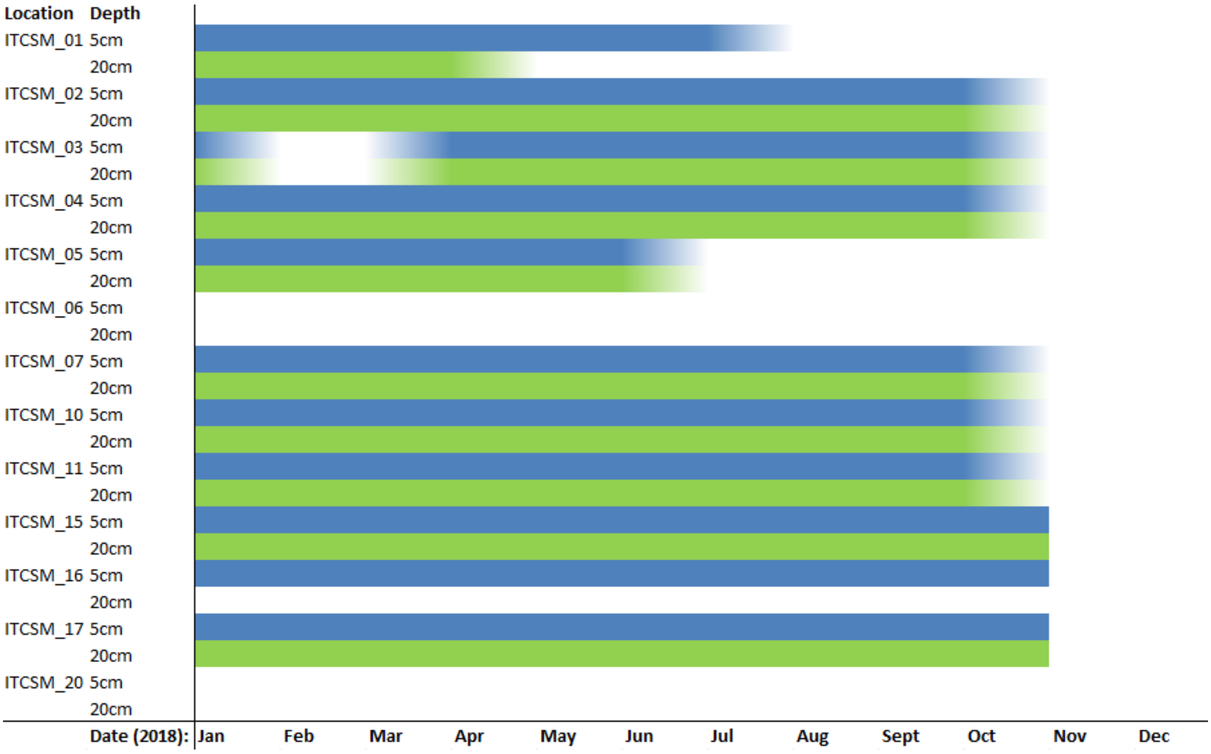


Figure 12: Data availability of the soil moisture measuring stations in the study area over 2018.

Figure 12 shows that most stations have between nine and ten months of data over 2018. Two stations (ITCSM_06 and ITCSM_20) do not have data over 2018 at all. Furthermore, station ITCSM_01 and ITCSM_05 have only data available until halfway the summer period in June and July. Last, ITCSM_03 has a data gap during the period of February and March and ITCSM_16 only has data available for 5cm depth. Figure 13 shows a graph of the soil moisture state during 2018 at location ITCSM_04. Graphs of the soil moisture state at other locations are given in Appendix A.1 of the appendix report.

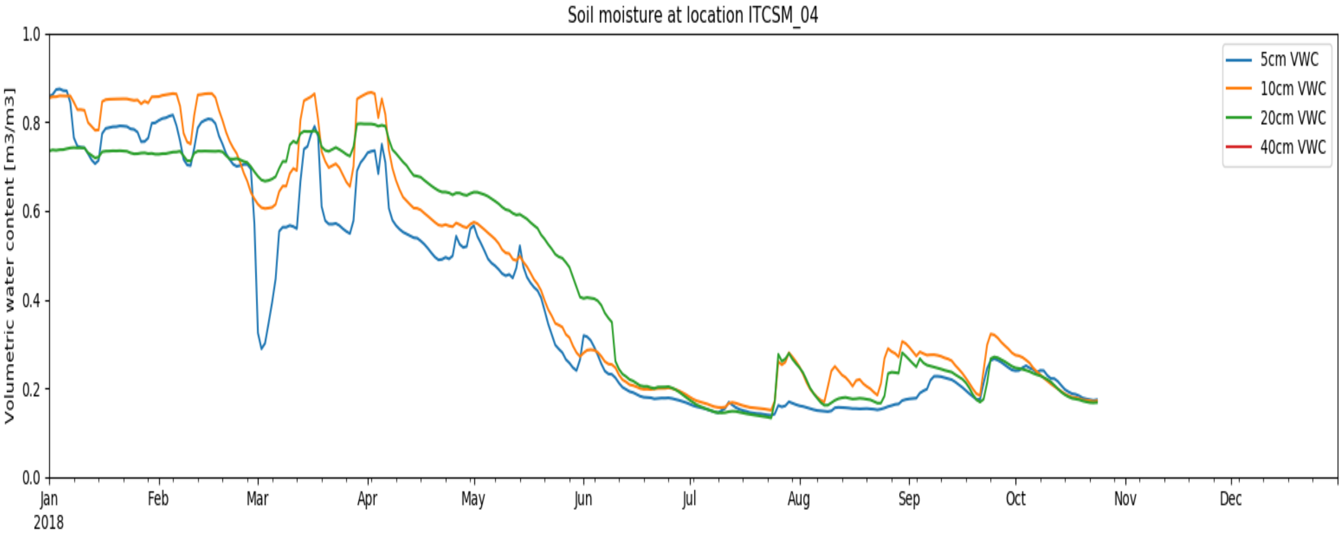


Figure 13: Soil moisture state at location ITCSM_04 during 2018.

Clearly visible are the numerous dips in soil moisture during the winter and early spring period (January – May), followed up by a slow decline of soil moisture in the summer period (May-July). At the end of the summer period, the soil moisture partially recovers. The results of the quality analysis of the soil moisture datasets is given in Table 11.

Table 11: Results of the quality assessment of the soil moisture dataset.

Criteria by Van Oort (2006):	**Induced criteria:**	**Value:**
Lineage	Production and transformation	Described below table
	Data unit	Volumetric water content (m^3/m^3)
	Data type	Point
	Resolution	-
Completeness	Interval	15 minutes
	Time period	Differs per location. For an overview see Figure 12.
Accuracy	Smallest measureable value	$0.0008m^3/m^3$ (METER Group, 2010)
	Deviation of measured value from actual value	- $0.03m^3/m^3$ base (METER Group, 2010) - $0.02m^3/m^3$ depending on the soil type (METER Group, 2010) This can be decreased to $0.01\text{-}0.02m^3/m^3$ if calibrated soil-specific (Dente, Su, & Wen, 2012)
	Time of measurement	00:00 and every 15 minutes after that
Variation in accuracy	Variation in accuracy between locations	Described below table
	Variation in accuracy over time	Described below table

The soil moisuture is expressed in volumetric water content and measured by the Decagon 5TM volumetric water content and temperature sensor. The sensor uses an electromagnetic field to measure the dielectric permittivity of the surrounding medium (METER Group, 2010; Dente et al., 2011). 2 scenarios exist in which the 5TM sensor does not work properly: frozen soil water and very low quantities of soil water. Soil water that reaches the temperature below 0 °C freezes cannot be measured (Gurp, 2016). Therefore, days with an average temperature below 0 °C are not taken into account in the remainder of the research. Figure 14 gives an overview of the average temperature at location ITCSM_04. Other locations showed similar patterns.

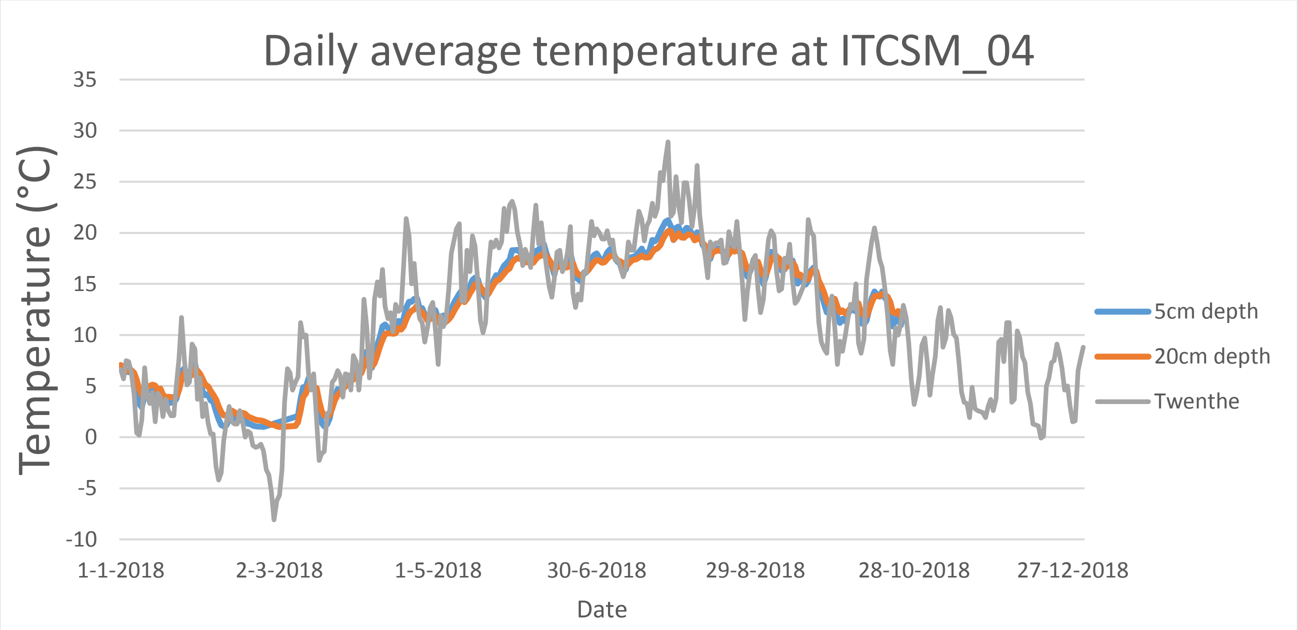


Figure 14: Average temperature at location ITCSM_04.

KNMI temperature data is obtained from the KNMI weather monitoring station 'Twenthe'. the KNMI Data Centre and have an accuracy of 0.1°C (KNMI, 2019). The soil moisture temperature data is obtained from the 5TM sensors and has an accuracy of 1,0 degree Celsius (METER Group, 2010). In the results of this paper, the average temperature of the 5TM sensor is used to locate data gaps, which resulted in removal of zero measurements of all soil moisture monitoring station. Yet, the dip in soil moisture in the beginning of March in Figure 13 is caused by frozen soil water, as the KNMI-data suggests. The KNMI-data was only used in a late stadium of this research when it became known that the 5TM sensor is likely to overestimate the soil temperature (Gurp, 2016). It was too late to redo all of the analysis, although in Appendix A.4 of the appendix report a comparison is made for location ITCSM_04 at 20 cm depth between different periods of data removal. A combination of precipitation and actual evapotranspiration (ETa), potential evapotranspiration (ETp) and Makkink reference evapotranspiration (ETm) is analyzed. The graphs do not show much difference and only in the case of manual removal of days that seem to have got invalid soil moisture measurements, some deviations are visible.

4.1.2. Precipitation dataset

Two comparable precipitation datasets were available at the Waterschap Vechstromen; a precipitation dataset of the National Rain Radar (NRR) and a precipitation dataset of the KNMI. For this research, the KNMI-dataset is chosen as this dataset is the largest of the two. Characteristics of the precipitation dataset are given in Table 12.

Table 12: Results of the quality assessment of the KNMI-precipitation dataset (KNMI, 2001).

Criteria by Van Oort (2006):	**Induced criteria:**	**Value:**
Lineage	Production and transformation	Described below table
	Data unit	24h-sum of precipitation in mm/day
	Data type	Raster
	Resolution	1000x1000m
Completeness	Interval	24h
	Time period	2018-01-01 until 2018-12-31
Accuracy	Smallest measureable value	0.1mm (KNNMI, 2001)
	Deviation of measured value from actual value	2% (KNMI, 2001)
	Time of measurement	08:00
Variation in accuracy	Variation in accuracy between locations	Described below table
	Variation in accuracy over time	Not found

The precipitation dataset is made using data from two Doppler-radars in the Netherlands, located in Den Helder and Herwijen (KNMI, 2019). The radar values are adjusted to KNMI-precipitation station data using 'Kriging with external drift (KED) (Schuurmans & Vossen, 2013). This method corrects the radar value based on the distance to different measuring stations and is considered to be the most accurate method to merge radar and gauge values (Sánchez-Diezma et al, 2000; Goudenhoofdt & Delobbe, 2008). However, values for quantitative decrease of accuracy based on distance to precipitation measuring stations are not found. A detailed explanation on the gathering of the data is given in Schuurmans & Vossen (2013).

4.1.3. Evapotranspiration dataset(s)

We use evapotranspiration data from eLEAF. Specifically, we use the following datasets:

a. Actual evapotranspiration
b. Evapotranspiration deficit (which is the difference between potential and actual evapotranspiration)

Characteristics of the evapotranspiration datasets are given in Table 13.

Table 13: Results of the quality assessment of the evapotranspiration datasets.

Criteria by Van Oort (2006):	**Induced criteria:**	**Value:**
Lineage	Production and transformation	Described below table
	Data unit	• Actual evapotranspiration in mm/day • Evapotranspiration deficit in mm/day
	Data type	Raster
	Resolution	250x250m
Completeness	Interval	24h
	Time period	2018-01-01 until 2018-09-08
Accuracy	Smallest measureable value	0.1mm (Viergever, Pelgrum & Voogt, 2017)
	Deviation of measured value from actual value	0.04-0.45mm/day (Viergever, Pelgrum & Voogt, 2017)
	Time of measurement	Differs per day
Variation in accuracy	Variation in accuracy between locations	Described below table
	Variation in accuracy over time	Described below table

The actual evapotranspiration (and evaporation deficit data) are obtained by the ETLook-model (Pelgrum et al., 2010; Bastiaanssen et al., 2012). This model solves the Penman-Monteith equation for evapotranspiration calculations in two steps: one for evaporation and one for transpiration (Viergever, Pelgrum & Voogt, 2017). The ETLook-model uses satellite observations with radiation from the visible, near-infrared and microwave spectrum as input to calculate the evapotranspiration according to Allen et al. (1998)

The satellite observations that serve as input for the parameters of the model are corrected by a quality parameter, scaling from 0 to 1. This quality parameter gives an weighted quantitative value about the accuracy of the satellite observations based on cloudiness and observation angle, since observations may be inaccurate if the observation angle is not vertical above the earth's surface or if the weather is cloudy. If the quality parameter is below 0.4, satellite observations are not accurate enough and the observations are not taken into account (Viergever, Pelgrum & Voogt, 2017). In case the observations are rejected, evapotranspiration is calculated based on the last available satellite observations and the meteorological conditions of the present day. However, for each day without satellite observations the quality parameter will reduce by 10% A more detailed explanation of production and plausibility of the evapotranspiration datasets is given in Vellekoop, Pelgrum & Voogt (2017) and in Viergever, Pelgrum & Voogt (2017). The effect of the quality parameter is not taken into account in this research, since it was not accessible at the Waterschap Vechtstromen; all available evapotranspiration data is used.

4.1.4. Groundwater dataset

The groundwater dataset consists of several groundwater monitoring wells that lie in close proximity to the soil moisture measuring stations. These monitoring wells obtained from the DINO-loket. Characteristics of the groundwater dataset are given in Table 14. An overview of the groundwater state near each of the soil moisture monitoring stations is given in Appendix A.2 in the appendix report.

Table 14: Results of the quality assessment of the groundwater dataset.

Criteria by Van Oort (2006):	**Induced criteria:**	**Value:**
Lineage	Production and transformation	Groundwater level
	Data unit	• m +NAP • m –ground level
	Data type	Point
	Resolution	-
Completeness	Interval	• 1h (datalogger) • 24h (datalogger) • 14 days (manual)
	Time period	Differs per location
Accuracy	Smallest measureable value	0.001m (automatic)
	Deviation of measured value from actual value	• 1cm (manual) (Ritzema et al., 2012) • 3mm (automatic) (Ritzema et al., 2012)
	Time of measurement	Differs per location
Variation in accuracy	Variation in accuracy between locations	Described below table
	Variation in accuracy over time	Not found

To measure the groundwater level, a filter is installed in the unsaturated zone. The filter is connected to a tube where water levels are measured. Groundwater can infiltrate in the filter and through hydrostatical pressure it is pushed up to an equilibrium at the groundwater table (DINOloket, 2019).

Since most groundwater wells are not in close vicinity of the soil moisture monitoring stations, the groundwater level data does not directly reflect the groundwater conditions at the exact location of the soil moisture monitoring station. The closer the distance between groundwater monitoring stations and the soil moisture monitoring stations, the larger the representativeness of the groundwater monitoring well for the groundwater conditions at the soil moisture monitoring station. If several groundwater monitoring stations are present near a soil moisture measuring station that all follow the same pattern, it is assumed that the groundwater situation at the soil moisture measuring station is similar. Another issue is that many groundwater monitoring wells are not up-to-date and did not monitor the groundwater levels of 2018. Table 15 gives an overview of the used wells, their distance to the nearest soil moisture monitoring station and the availability of data over 2018.

Table 15: Distance of groundwater monitoring points to soil moisture monitoring points and amount of data per well.

Monitoring well:	Corresponding soil moisture monitoring station	Distance to station (km):	Starting date:	Ending date:	Number of days with measurements:
B29A0103	ICTSM_01	2.79	02-01-2018	03-01-2019	21
B29A0108	ITCSM_01	1.10	01-01-2018	11-11-2018	315
B28H0570	ITCSM_03	1.18	01-01-2018	24-10-2018	293
B29C1497	ITCSM_04	1.71	01-01-2018	09-11-2018	308
B34F3245	ITCSM_04	3.63	03-01-2018	23-10-2018	15
B34B1257	ITCSM_11	1.78	01-01-2018	21-08-2018	233
B34B1258	ITCSM_11	0.98	01-01-2018	21-08-2018	233
B34B1259	ITCSM_11	1.07	01-01-2018	21-08-2018	233
B34B1308	ITCSM_11	1.13	01-01-2018	21-08-2018	233
Hogelaars_T302	ITCSM_16	0.24	01-01-2018	31-12-2018	365
Bekkenhaar	ITCSM_17	2.99	04-05-2018	16-09-0218	136
B28B0237	ITCSM_17	3.28	01-01-2018	31-12-2018	365

Table 15 shows a clear distinction between manual groundwater monitoring stations (which have fewer days with measurements) and automatic groundwater monitoring stations (which have more days with measurements). Furthermore, very few groundwater monitoring wells have data covering the full year of 2018.

4.1.5. Spatial characteristics

Each soil moisture monitoring station has several spatial characteristics which are distinctive for that soil moisture monitoring location. Spatial characteristics that are taken into account in this research are elevation (AHN), land use (LGN) and soil type (BOFEK). These spatial characteristics were available at the Waterschap Vechtstromen. The spatial characteristics per soil moisture monitoring location are given in Table 16. Table 16 also shows the assigned spatial characteristics according to Dente et al. (2012). Although Dente et al. (2012) specifies more spatial characteristics than land use, soil type and elevation, Waterschap Vechtstromen had no data available of other spatial characteristics.

Table 16: Spatial characteristics of the used soil moisutre monitoring stations.

Station:	Elevation (m +NAP):	Land use (Waterschap Vechtstromen):	Land cover (Dente et al.):	Soil type (Waterschap Vechtstromen):	Soil type (Dente et al.):
ITCSM_01	20.48	Fresh water	Grass bush	Sabulous sand	-
ITCSM_02	33.62	Grass	Grassland	Sand	Sand
ITCSM_03	11.96	Grass	Grassland	Sabulous sand	Loamy sand
ITCSM_04	49.71	Corn	Grassland	Loam	Loamy sand
ITCSM_05	22.23	Grass	Grassland	Sand	Loamy sand
ITCSM_07	22.56	Grass	Corn	Sabulous sand	Loamy sand
ITCSM_10	16.16	Grass	Grassland	Sand	Sand
ITCSM_11	10.75	Grass	Grassland	Boggy Sand	Loamy sand
ITCSM_15	9.33	Grass	Grassland	Sabulous sand	Sand
ITCSM_16	9.07	Build-up area	Grassland	Sand	Sand
ITCSM_17	10,35	Grass	Grassland	Sand	Sand

Numerous differences exist between the used spatial characteristics that were available at the Waterschap Vechtstromen and the spatial characteristics described by Dente et al. (2012). These differences are largely explained by the fact that the data gathered by Dente et al. (2012) was gathered later and is more specific. However, due to lack of spatial distribution of the data of Dente et al. (2012) it is chosen to work with the data that was available at the Waterschap Vechtstromen (AHN2, LGN4, Grondsoortenkaart-2006). Results of the quality assessment of the spatial characteristics are given in Table 17.

Table 15: Results of the quality assessment of the spatial characteristics.

Criteria by Van Oort (2006):	**Induced criteria:**	**Elevation (AHN2):**	**Land use (LGN4):**	**Soil type (Grondsoortenkaart 2006):**
Lineage	Production and transformation	LIDAR-technology (AHN, 2012)	Satellite images (De Wit, 2001)	Described below table.
	Data unit	m +NAP	LGN class	Soil class
	Data type	Point cloud	Vector (GIS-layer)	Vector (GIS-layer)
	Resolution	26 points/m^2 (AHN, 2012)	-	-
Completeness	Interval	-	-	-
	Time period	2012	2000	2006
Accuracy	Smallest measureable value	Not found	-	Scale 1:50,000
	Deviation of measured value from actual value	Maximum 20 cm (Van der Zon, 2013)	7.7% of the pictures is not accurate or reliable (De Wit, 2001)	10 – 25 m
	Time of measurement	-	-	-
Variation in accuracy	Variation in accuracy between locations	Described in Van der Zon (2013)	Described in De Wit (2001)	Described in Wageningen UR-Alterra (2006)
	Variation in accuracy over time	Not found	Not found	Not found

Elevation

Elevation is gathered from AHN2, the actual elevation register of the Netherlands (*Actueel Hoogtebestand Nederland*). Detailed specifications of the AHN2 can be found in Van der Zon (2013).

Land use

Land use is gathered from LGN4, which is part of a series of documentation of land use in the Netherlands (*LandGebruik Nederland*). Detailed specifications of the LGN4 can be found in De Wit (2001).

Soil type

Soil types are gathered from the simplified soil map of the Netherlands (*Grondsoortenkaart 2006)*, which is derived and simplified version of the from the with only ten classes of soil types that are representative to a depth of 1.0 meter below ground level. Specifications on the soil types are given in Wageningen UR - Alterra (2006)

4.1.6. Total overview

Table 18 gives an overview of the starting and ending dates of all datasets used over the year of 2018.

Table 18: Overview of starting and ending dates per dataset.

Dataset	Starting date	Ending date
Soil moisture	See Figure 12	See Figure 12
Precipitation	01-01-2018	31-12-2018
Actual evapotranspiration	01-01-2018	08-09-2018
Evapotranspiration deficit	01-01-2018	08-09-2018
Groundwater levels	See Table 15	See Table 15

Tables 15, 18 and Figure 12 and indicate that it is not possible to use the complete year of 2018, since it is not fully covered by the evapotranspiration datasets. Next to that, numerous data gaps exist. Therefore, the period covered (with some exceptions) is January 1st, 2018 until September 8th, 2018.

4.2. RQ2: Relations between soil moisture and hydrological conditions

Comparison of average EVP

Several combinations of stresses are used to explain the variance in soil moisture. Figure 15 gives an overview of the average percentage of explained variance per combination of stresses over all soil moisture monitoring stations. The period over which these averages is computed is January 1st, 2018 until September 8th, 2018. In Appendix C.1 in the appendix report the graphs for individual locations and depths are shown and in Appendix C.2 the corresponding impulse response parameters.

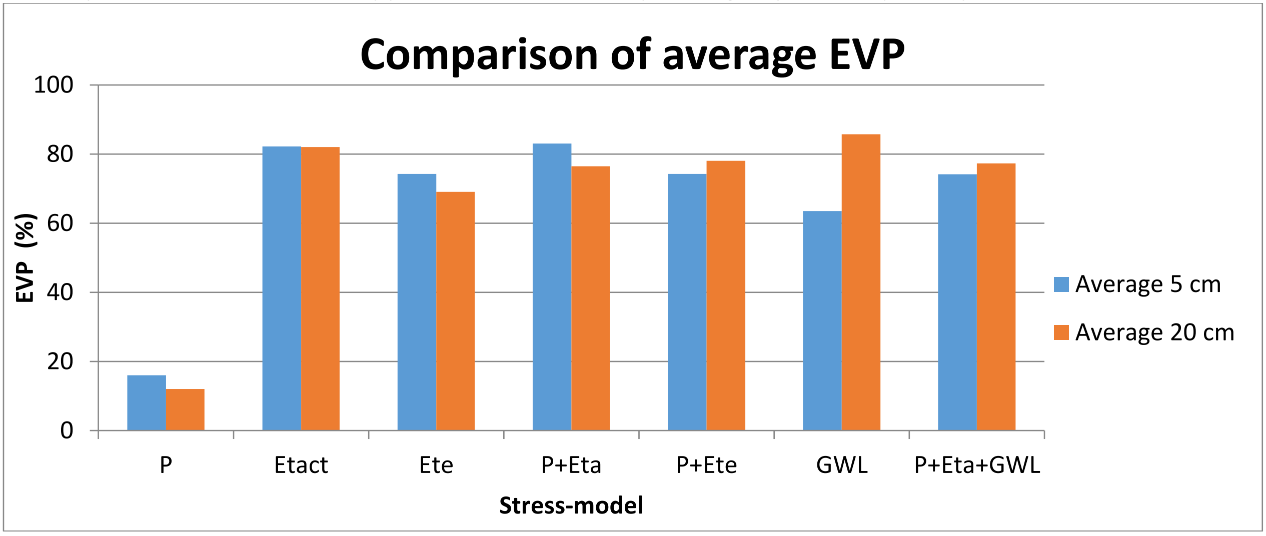


Figure 12: Comparison of average percentage of explained variance over all soil moisture monitoring stations.

Only taking precipitation into account has a minor effect on the variation in soil moisture in the Twente region in 2018, while only taking actual evapotranspiration or evapotranspiration deficit has a very large effect. All soil moisture monitoring stations registered a decrease in soil moisture over the period of 2018, which explains that decreasing factors (such as evapotranspiration) were more influential than the increasing factors (such as precipitation). Another thing that stands out is that the groundwater level is much more influential at 20 cm depth than at 5 cm depth and that evapotranspiration is more influential at 5cm depth. Since the soil moisture monitoring sensors at 20 cm depth lie closer to the groundwater table than the soil moisture monitoring sensor at 5 cm depth, groundwater variation has a larger effect on soil moisture at 20 cm depth than it has on soil moisture at 5 cm depth.

Generally, analysis of the soil moisture variation that includes evapotranspiration as (one of the) stress(es) generally gives a high percentage of explained variance (usually above the 70% mark). However, the graph above does not give a complete picture. The graph only shows the average overall explained variance percentage and not the daily events. In Appendix B.1 of the appendix report, an overview of the analysis of soil moisture at location ITCSM_01 at 5cm depth is given as an example. With different figures it is illustrated that evapotranspiration gives a good indication of the seasonal trends, but to explain short-term (or daily) events it is necessary to include precipitation in the analysis. Other locations and depths followed similar patterns. Of the two types of evapotranspiration (actual evapotranspiration and evapotranspiration deficit), actual evapotranspiration gives the best results as it simulates the decline of soil moisture levels during the summer period much better than evapotranspiration deficit.

Furthermore, if too many stress models are taken into account, interference takes place and the model is unable to accurately estimate the impulse-response parameters. This is the case with the combination of precipitation, actual evapotranspiration and groundwater levels. Figure 16 gives an example of the soil moisture analysis at location ITCSM_04 at 5cm depth. Three stresses are included: precipitation, actual evapotranspiration and groundwater levels.

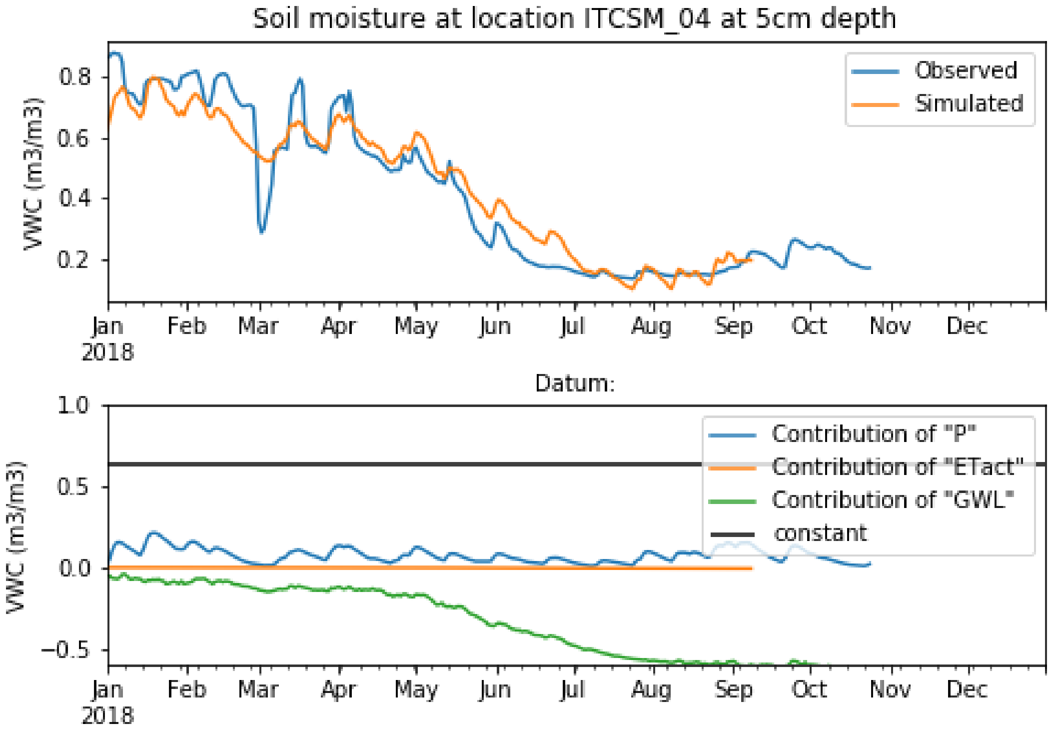


Figure 16: Analysis of soil moisture at location ITCSM_04 at 5 cm depth with precipitation, actual evapotranspiration and groundwater stresses.

The contributions of the stresses indicate that actual evapotranspiration has almost no influence on soil moisture. However, the parameters of the impulse response function of actual evapotranspiration are exceptionally high (which indicate that actual evapotranspiration has very little influence, but the influence is spread out over a very long time) and have very large deviations (of over 500%), which indicates that the algorithm of Pastas cannot simulate the exact contribution accurate. Therefore, it is stated that the combination of stress models precipitation and evapotranspiration are found to give the best simulation of soil moisture. This combination can simulate the seasonal trend of soil moisture while still taking the short-term events into account.

Comparison of different types of evapotranspiration

As mentioned in the theoretical background, different types of evapotranspiration can be distinguished:

- Reference evapotranspiration
- Potential evapotranspiration
- Actual evapotranspiration
- Reference evapotranspiration

For location ITCSM_04 (KNMI-station 'Twenthe'), the four types of evapotranspiration were available. Figure 17 gives a comparison of the average EVP and the contribution of precipitation and these different forms of evapotranspiration at 5 cm and 20 cm depth. The simulations that are accessory to Figure 17 are given in Appendix A.3.

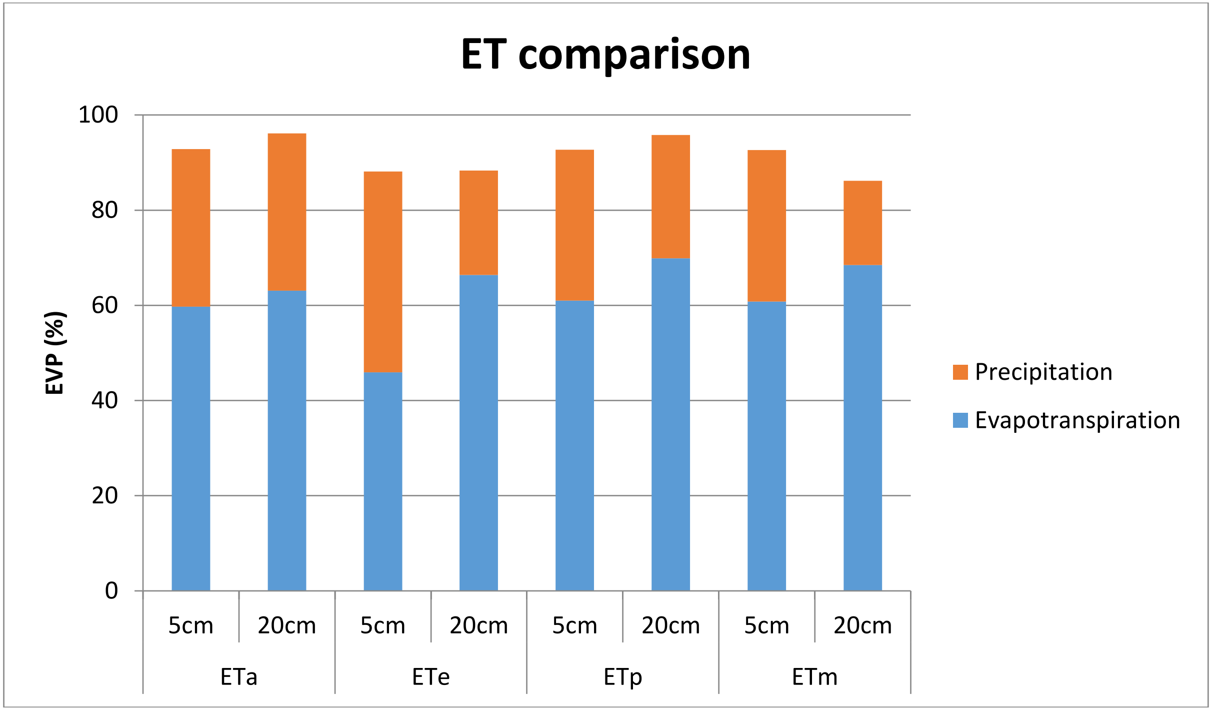


Figure: 17: Comparison of different types of evapotranspiration at ITCSM_04.

Figure 17 shows that for all types of evapotranspiration investigated the contribution of precipitation is less than the contribution of the investigated form of evapotranspiration. However, the contribution of evapotranspiration deficit at 5 cm depth is much smaller than any of the other forms of evapotranspiration. Another interesting fact is that the differences in EVP for all forms of evapotranspiration exceed the 70% mark of EVP, which indicates that soil moisture can be simulated with all forms of evapotranspiration.

Comparison of contribution to EVP for precipitation and actual evapotranspiration per monitoring station

As stated before, simulation of soil moisture with the stresses of precipitation and actual evapotranspiration gives the best results. Figures 18 and 19 give an indication of the percentage of explained variance per soil moisture monitoring location based on the stresses precipitation and actual evapotranspiration. The impulse response parameters are given in Appendix B.2 in the appendix report.

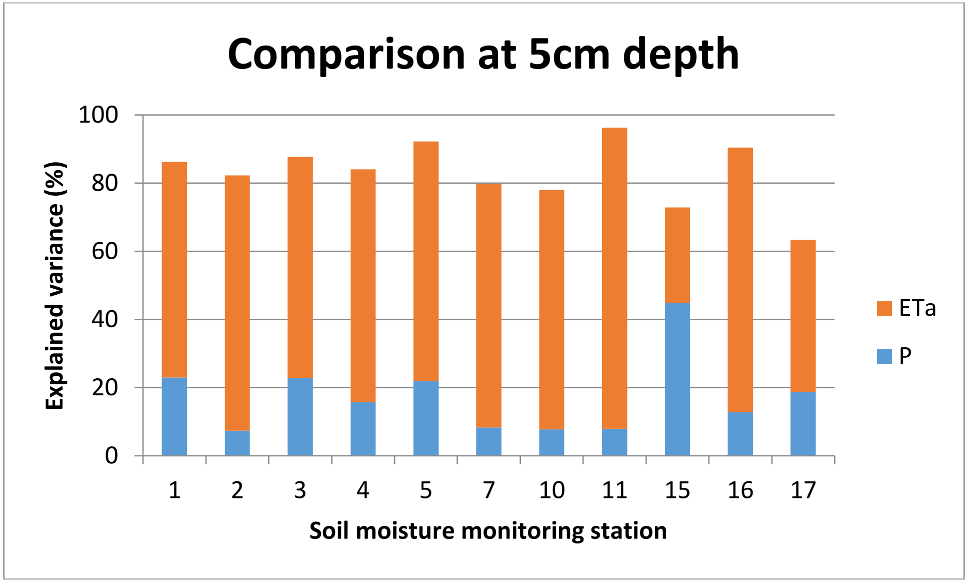


Figure 18: Percentage of variance explained based on precipitation and actual evapotranspiration at 5 cm depth.

According to Figure 18, the total EVP is almost at every station more than 80% and the vast amount of variability of soil moisture is due to (actual) evapotranspiration except for ITCSM_15. Most soil moisture monitoring locations had a short period with excessive rain at the end of May and from halfway August until September that causes the soil moisture levels to increase rapidly. Station ITCSM_15 reacted much more on this period, which explains the relative high contribution of precipitation.

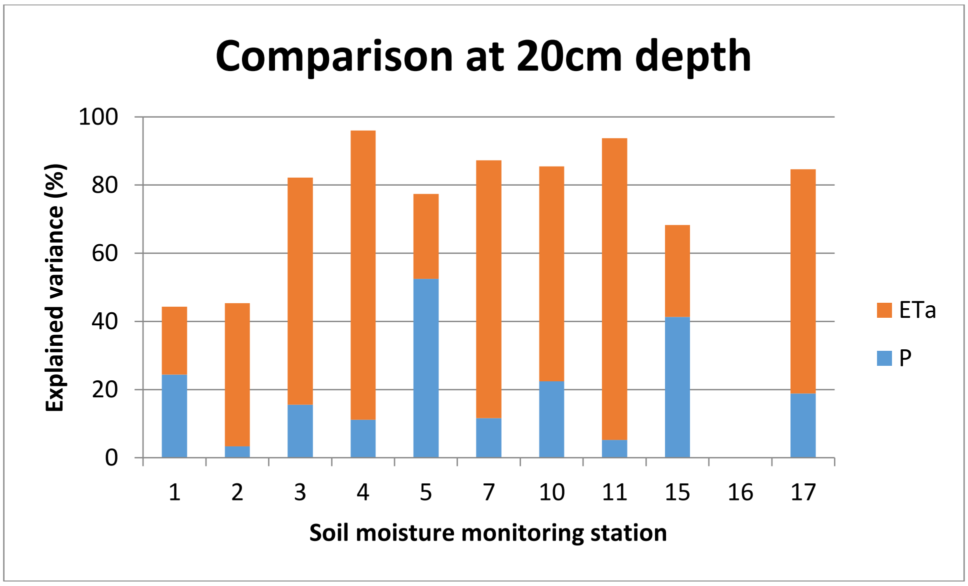


Figure 19: Percentage of variance explained based on precipitation and actual evapotranspiration at 20 cm depth.

According to Figure 19, the total EVP differs per location. Clearly, other factors (such as groundwater) are of importance as well, or the length of the used data series is too short to cope with the longer response time at 20 cm depth. Still, evapotranspiration seems more dominant than precipitation for most stations. ITCSM_01, ITCSM_05 and ITCSM_15, as precipitation seems more dominant at these stations. As stated in the comparison at 5 cm depth, station ITCSM_15 reacted much more on the heavy rainfall events at the end of May 2018, which can be a reason for the high contribution of precipitation to the overall explained variance.

For stations ITCSM_01 and ITCSM_05, the amount of observations is shorter than for the other stations. Stations ITCSM_01 and ITCSM_05 only have observations from January until halfway June. During this period the soil moisture at 20 cm depth is much more constant when compared to observations that contain the complete summer period. A possible result of this is the more even influence of precipitation and actual evapotranspiration on soil moisture.

Table 19 shows the average explained variance while taking precipitation and actual evapotranspiration into account as stresses. Note that these averages are including the simulations that do not exceed the 70% mark of EVP.

Table 19: Average percentage of variance explained with precipitation and actual evapotranspiration.

Depth:	**Total EVP (%)**	**Contribution of 'P' (%)**	**Contribution of 'ETa' (%)**
5 cm	83.01	17.38	65.64
20 cm	76.51	20.62	55.86

In general, the EVP at 5 cm depth is higher than at 20 cm depth based on actual evapotranspiration and precipitation stresses. Precipitation contribution increases at 20 cm depth when compared with 5 cm depth. Actual evapotranspiration contribution decreases when comparing 5 cm depth with 20 cm depth. A possible explanation for this is the dampened response of soil moisture at 20 cm depth when compared to 5 cm depth. The average contribution at 20 cm depth of both stresses converges. If this trend is continued at even deeper layers of soil moisture is not investigated. However, the impulse-response parameters in Appendix B.2 show large differences that cannot be explained by comparing the values of 5 cm and 20 cm depth.

4.3. RQ3: Investigation of spatial patterns of soil moisture

Geographic comparison

A spatial distribution of the values of the explained variance percentage is given in Figure 20. The top value indicates 5 cm depth and the bottom value indicates 20 depth. Of the analysis at 5cm, two stations had no data at all and one station had invalid data. These are not included in the averages that are displayed in the figure.

Station
🟧 EVP < 70
🟩 EVP >70
⬜ No data

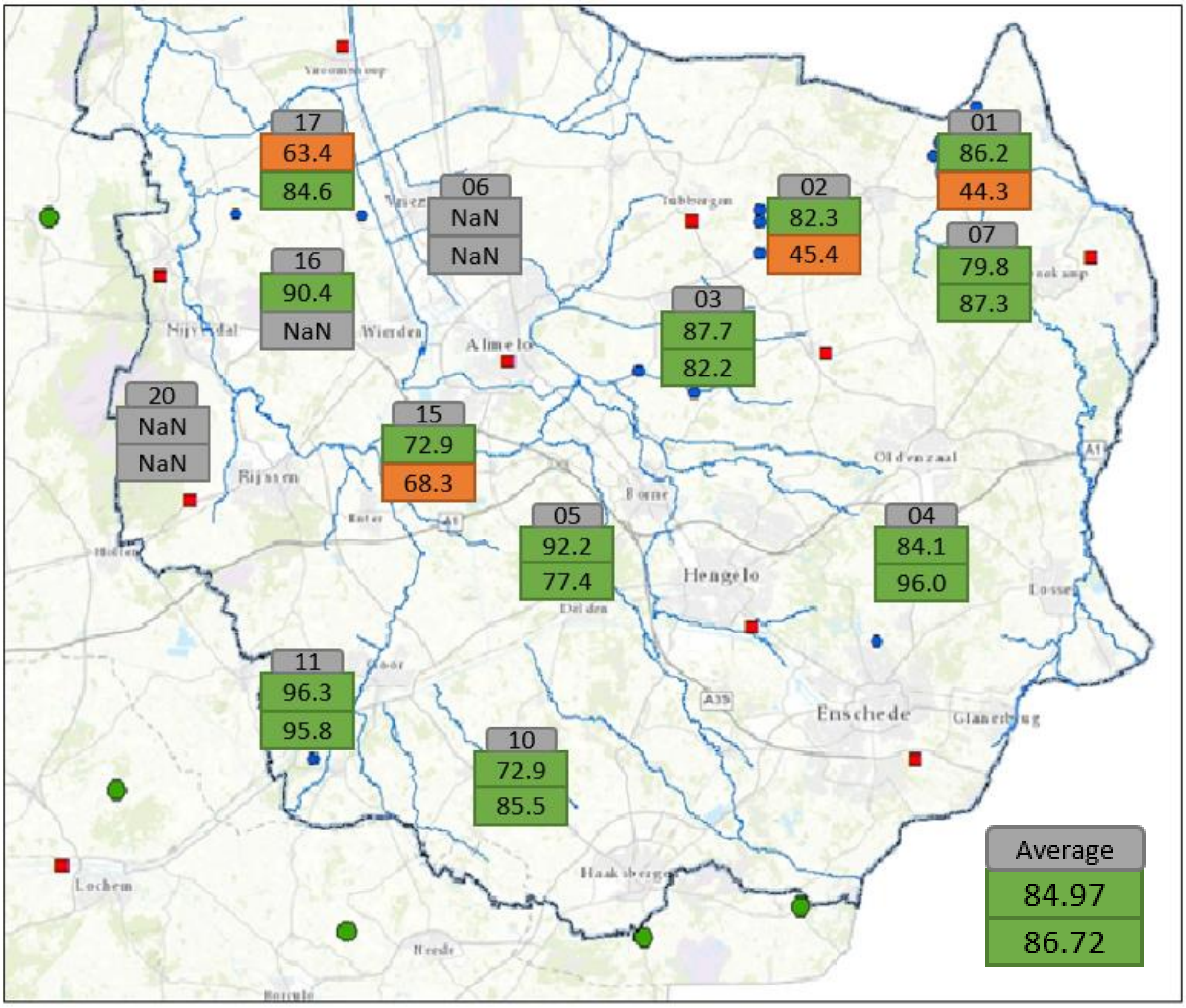


Figure 20: Spatial distribution of overall percentage of explained variance.

Based on Figure 20, no conclusions can be drawn. The figure shows a fairly even distribution of high and low overall EVP values; there exist no significant differences between 5 cm and 20 depth. However local differences can exist, but these are not forming spatial patterns. Figures 21 and 22 give an overview of the contribution of precipitation and actual evapotranspiration to the overall percentage of explained variance.

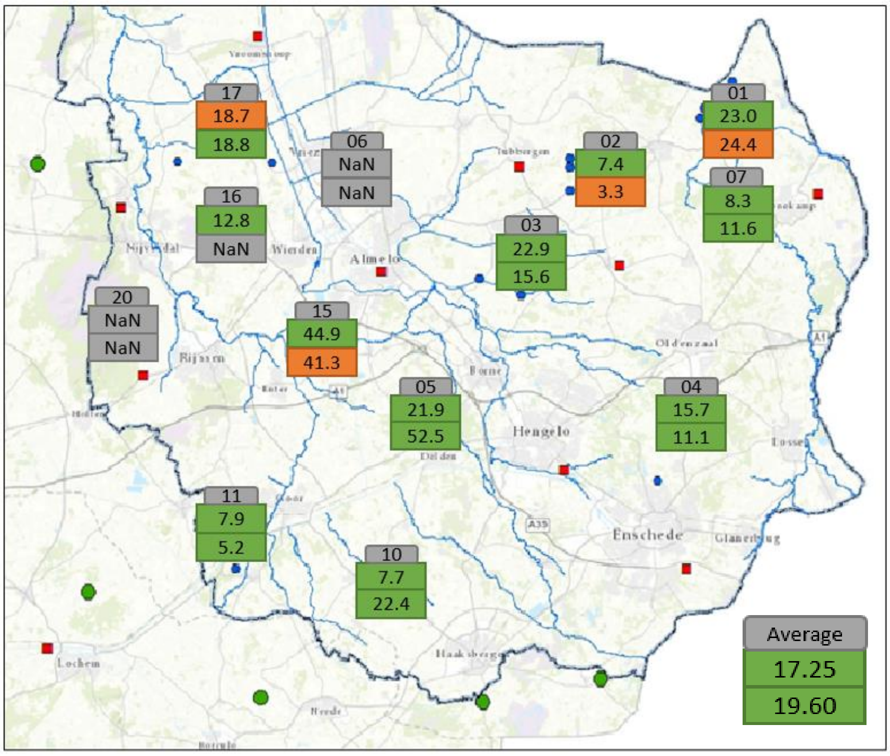


Figure 21: Spatial distribution of the contribution of precipitation to the overall EVP

Figure 21 shows that between Almelo and Hengelo are two stations (ITCSM_05 and ITCSM_15) that all have relative high above average precipitation values. To the southwest region, two stations (ITCSM_10 and ITCSM_11) are present with relative low values of precipitation (at 5 cm depth). To the north east, stations ITCSM_02 and ITCSM_07 show the same pattern of low contribution due to precipitation stress. This may indicate the local rainfall that affected the soil moisture during the period at the end of May 2018.

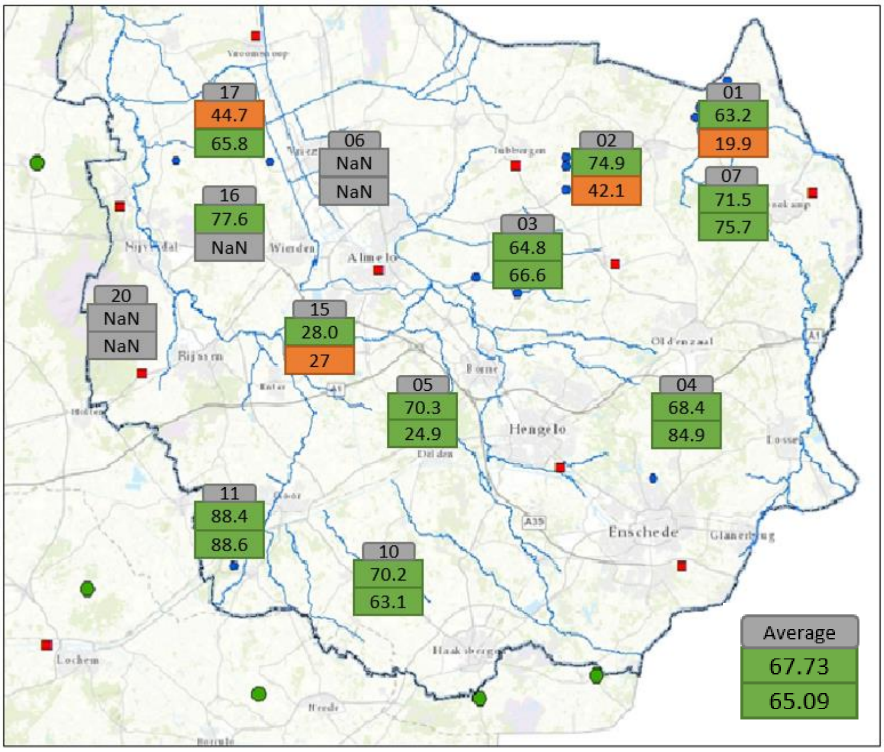


Figure 22: Spatial distribution of the contribution of actual evapotranspiration to the overall EVP.

Based on Figure 22, no clear spatial pattern for the contribution of actual evapotranspiration can be found. However, three stations show interesting results.

- Station ITCSM_11 shows both at 5 cm and 20 cm depth really high contributions to soil moisture variability due to actual evapotranspiration stresses.
- Station ITCSM_04 indicates that the soil moisture at 20 cm is more influenced by actual evapotranspiration than the soil moisture at 5 cm, which is counterintuitive.
- Station ITCSM_05 shows a very large difference between the contribution of actual evapotranspiration at 5 cm depth and at 20 cm depth. The short length of the time series which only covers the first half of 2018 may be an explanatory factor here

A part of the variability in soil moisture may be explained by the base level of soil moisture when the stresses are zero. Figure 23 shows the base level of soil moisture.

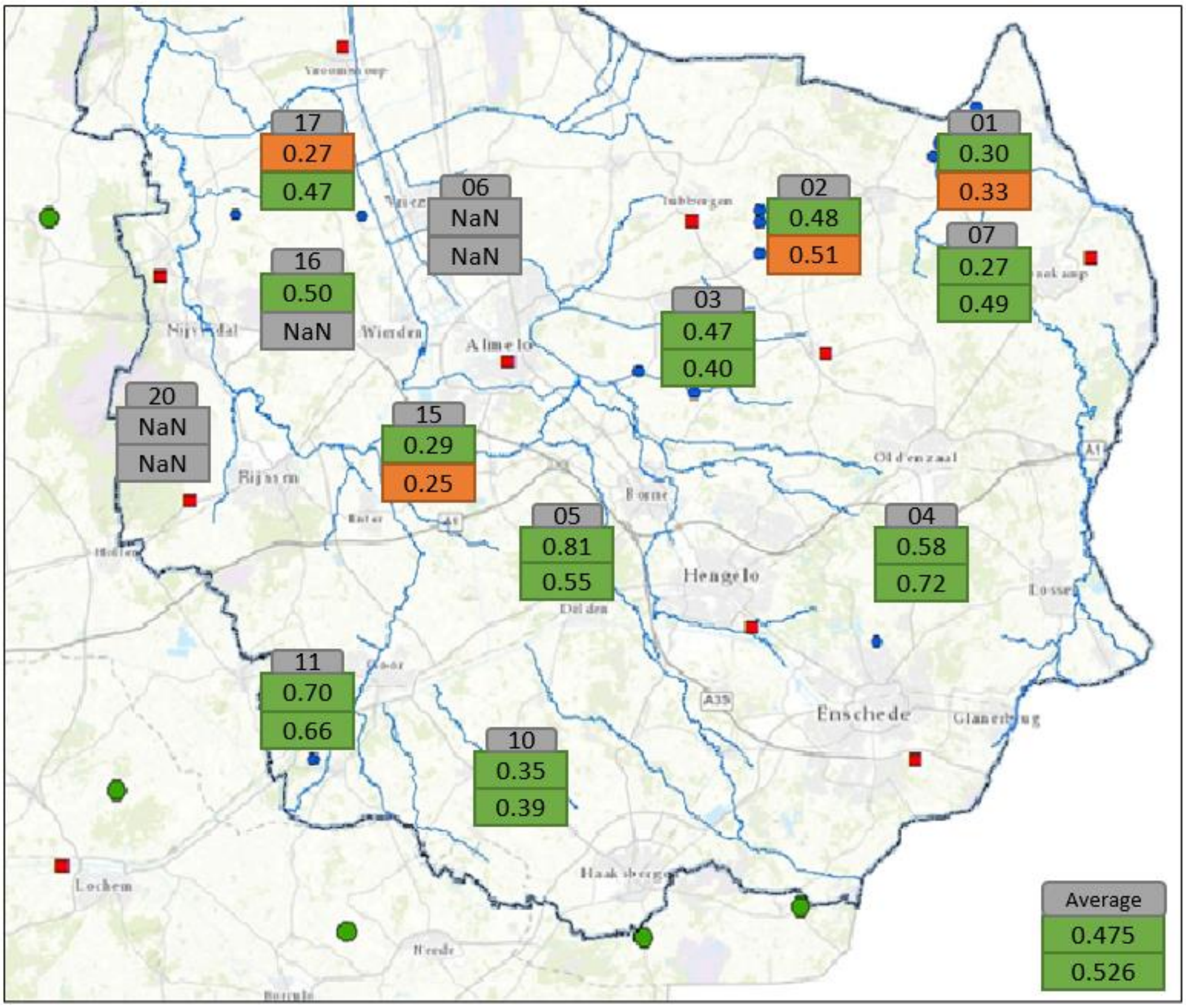


Figure 23: Base level of soil moisture in the analysis that includes precipitation and actual evapotranspiration stresses.

In Figure 23, Location ITCSM_05 does show a much higher base level at 5 cm depth than at 20 cm depth. This location also showed a much larger contribution of actual evapotranspiration at 5 cm depth than at 20 cm depth. Location ITCSM_04 shows a much higher base level at 20 cm depth than at 5 cm depth. This location also showed a much larger contribution of actual evapotranspiration at 20 cm depth than at 5 cm depth. This is also the case at location ITCSM_17 (although this location did not fulfil the 70% criterion in the analysis) and location ITCSM_07 (but the effect is not as big as at the other three locations).

Elevation

Table 20 gives a comparison of the overall explained variance percentage and the contributions of precipitation and actual evapotranspiration. The values 'Inv.' indicate invalid values since the EVP did not exceed the 70% criterium.

Table 20: Comparison of EVP based on elevation of the soil moisture monitoring station.

Elevation (m +NAP):	Station:	EVP 5 cm total (%)	EVP 20 cm total (%)	EVP 'P' 5 cm (%)	EVP 'P' 20 cm (%)	EVP 'ETa' 5 cm (%)	EVP 'ETa' 20 cm (%)
49.71	ITCSM_04	84.09	96.07	15.7	11.1	68.4	84.9
33.62	ITCSM_02	82.25	Inv.	7.4	Inv.	74.9	Inv.
22.56	ITCSM_07	79.88	87.34	8.3	11.6	71.5	75.7
22.23	ITCSM_05	92.12	77.43	21.9	52.5	70.3	24.9
20.48	ITCSM_01	86.16	Inv.	23.0	Inv.	63.2	Inv.
16.16	ITCSM_10	77.86	85.56	7.7	22.4	70.2	63.1
11.96	ITCSM_03	87.71	82.3	22.9	15.6	64.8	66.6
10.75	ITCSM_11	96.34	93.76	7.9	5.2	88.4	88.6
10.35	ITCSM_17	Inv.	84.61	Inv.	18.8	Inv.	65.8
9.33	ITCSM_15	72.88	Inv.	44.9	Inv.	28.0	Inv.
9.07	ITCSM_16	90.41	NaN	12.8	NaN	77.6	NaN

Based on Table 20 no relation exists between explained variance percentage and elevation. No clear trend is visible in changing EVP and changing relations. However, the fact that no patterns are seen does not mean that no patterns exist since only eleven stations are used in the comparison.

Soil type

A comparison of percentage of explained variance based on soil type at 5 cm depth is given in Figure 24. The distinction in soil type is based on Grondsoortenkaart (2006), which distinguishes ten classes of soil type. The soil types present at the soil moisture monitoring locations are ordered in grain size, from sabulous sand (large) to loam (small) and a separate class for boggy sand (which has more organic material).

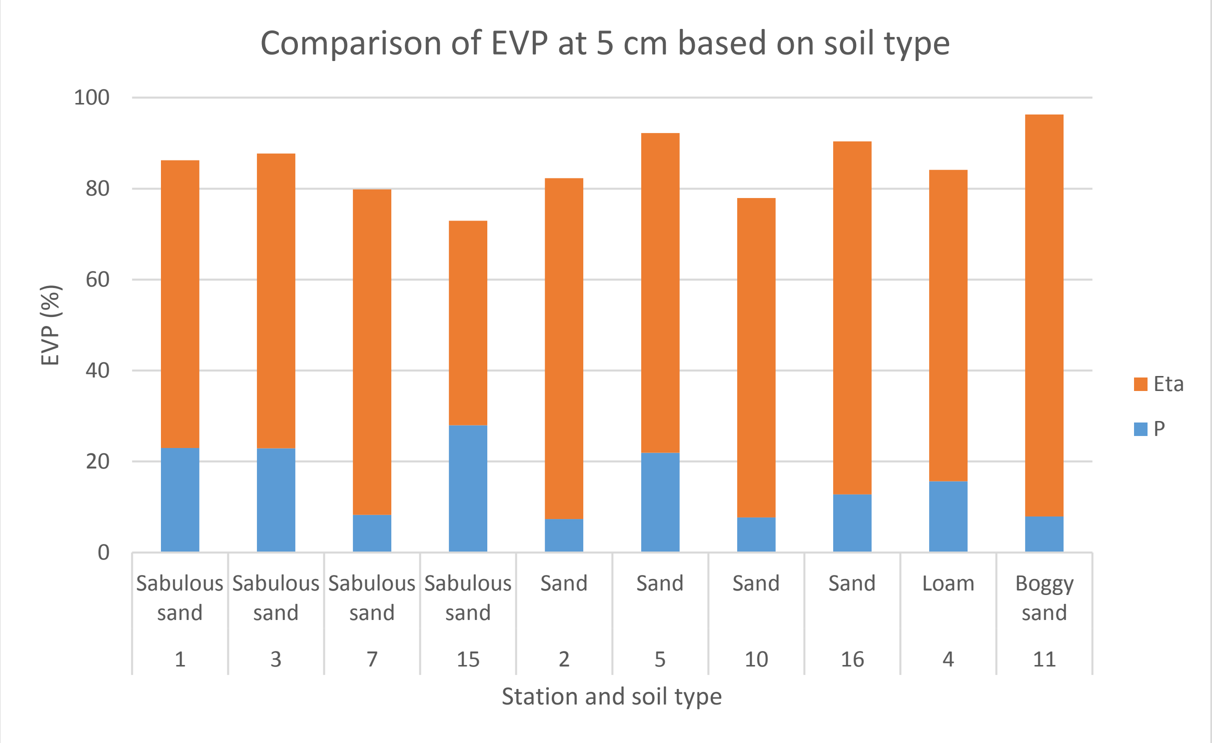


Figure 24: Comparison of percentage of variance explained due to different stresses at 5 cm depth based on soil type.

Figure 24 shows mixed results of percentage of variance explained and contribution to that explained variance based on soil type. Sabulous sand seems to have a larger contribution of precipitation to the overall percentage of explained variance than sand or boggy sand (which both have smaller grains). A possible explanation for this can be hysteresis (delay time). Water infiltrates faster in soils with larger grains than in soils with smaller grains (Dam, Feddes & Witte, 2005). Therefore, the initial reaction of soil moisture due to precipitation will be much higher and much more direct in soils with large grains than in soils with smaller grains. Another interesting fact is the very small contribution of precipitation and very large contribution of actual evapotranspiration at location ITCSM_11, which is located in boggy sand. However, conclusions about this location cannot be drawn, since the sample size of boggy sand is too small.

Figure 25 gives a comparison of percentage of explained variance based on soil type at 20 cm depth. Since much more soil moisture monitoring locations were not able to simulate the soil moisture at 20 cm depth based on actual evapotranspiration and precipitation with an EVP that exceeded the 70% mark this dataset is much smaller. The results of this comparison are therefore much more liable to coincidence rather than actual relations.

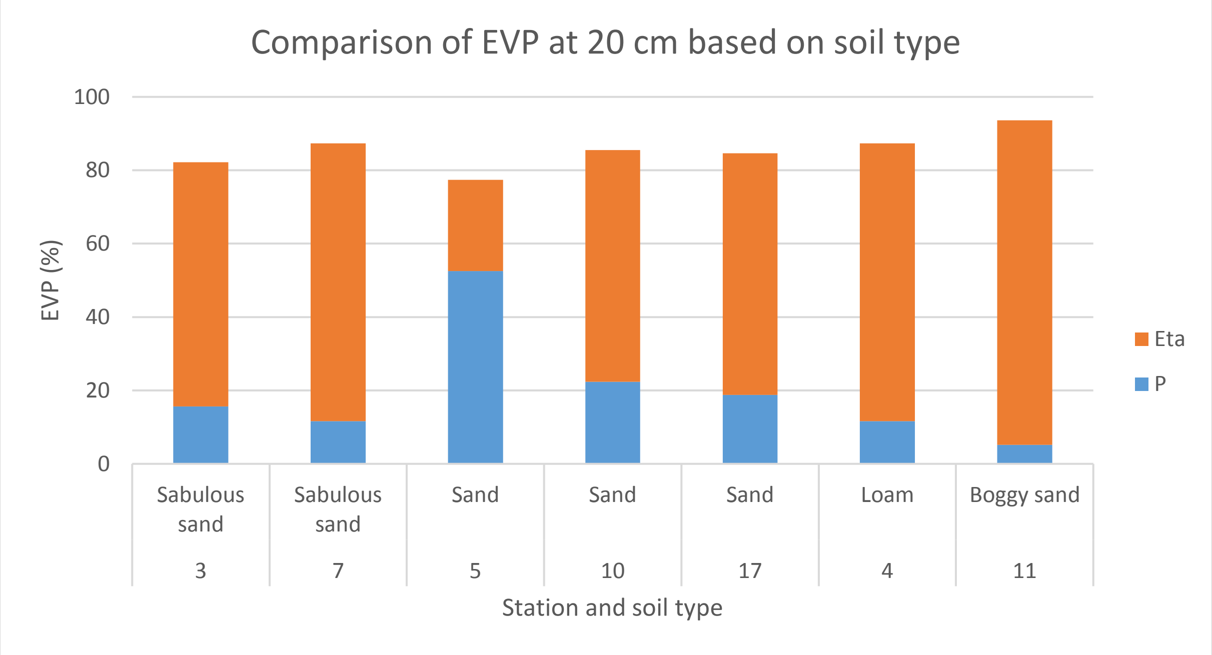


Figure 25: Comparison of percentage of variance explained due to different stresses at 20 cm depth based on soil type.

As with the comparison at 5 cm depth, the contribution of precipitation at location ITCMS_11 (boggy sand) is very small compared to other locations. Location ITCSM_04 (loam) also shows an under average contribution based on precipitation. Remarkable is the large contribution of precipitation at station ITCSM_05, but it is believed that this is not due to soil types since other stations with sandy soils do not show these large contributions of precipitation.

Land use

The last category that formed the basis of a spatial comparison is land use. The comparison of land use is based on the LGN4 map, which is developed in 1999 for the study area. Most stations were situated in grasslands. Figure 26 shows the results of the comparison of EVP at 5 cm based on land use.

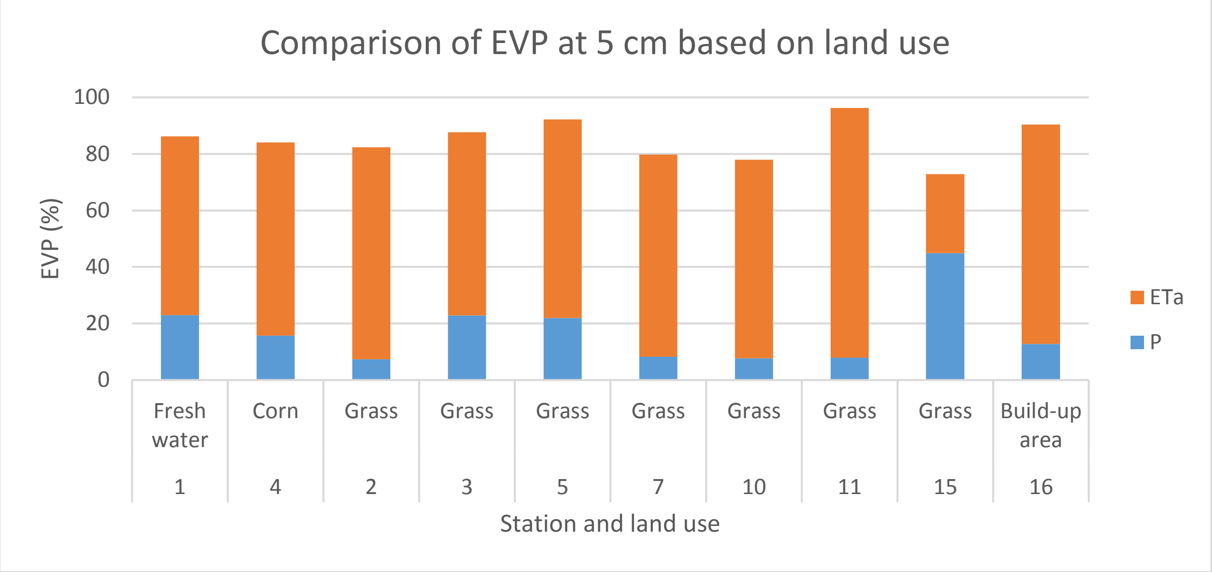


Figure 26: Comparison of percentage of variance explained due to different stresses at 5 cm depth based on land use.

More than half of the analysed locations were stationed in grasslands. The grasslands show large variety in the contribution of different stresses, which makes it hard to distinguish the effect of land use on the amount of variance explained and on the contribution of each stress. It was estimated that differences between corn, grass and build-up area would exist since these have a different Leaf Area Index (which is used to calculate evapotranspiration), but from Figure 26 this cannot be determined. Figure 27 shows the comparison of variance explained due to different stresses at 20 cm depth based on land use.

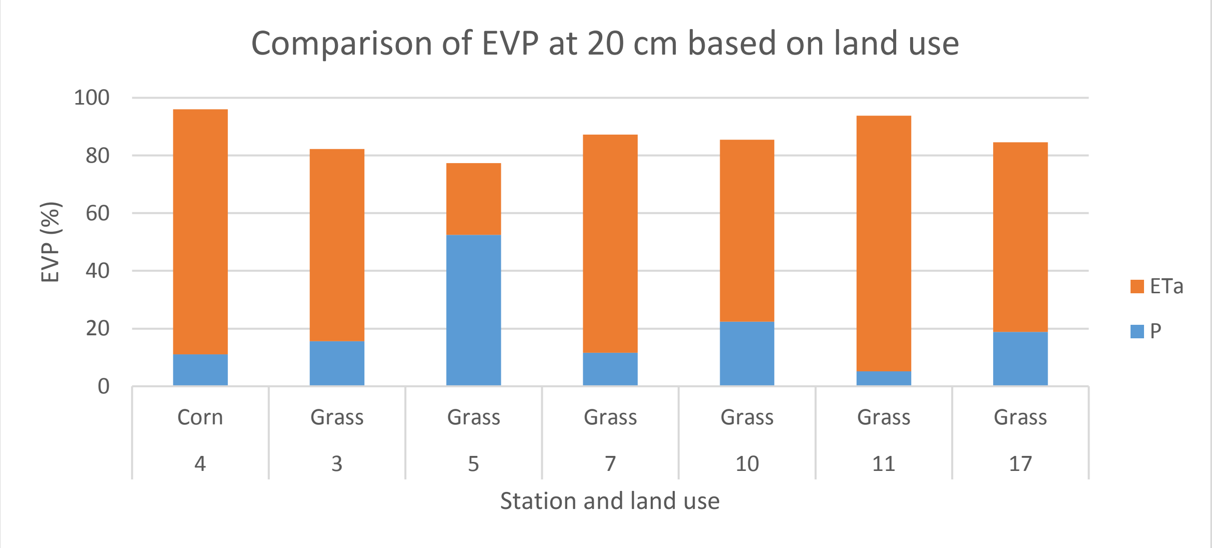


Figure 27: Comparison of percentage of variance explained due to different stresses at 20 cm depth based on land use.

As with soil types, the amount of suited soil moisture monitoring stations to conduct a spatial analysis with is less than at 5 cm. At 20 cm depth, seven station were suited of which six were located in grasslands and one in a corn field. Since there are so little stations and the variation between locations is large, this analysis is considered unreliable and no clear conclusions can be drawn from Figure 27.

5. Discussion

During the bachelor thesis several choices have been made which have impacted the results. These choices and their impact are described in this chapter. Several major discussion points are listed below according to their research question.

RQ1: Datasets and quality

Several datasets are assessed on their quality in research question 1. However, all of the datasets used are measured indirectly and the necessary variable is calculated through an algorithm.

- For soil moisture the dielectric conductivity is measured, which is hard to measure accurately when temperatures are below 0 °C (METER Group, 2010). It is hard to determine which variation in soil moisture is caused by inaccuracy of the 5TM-sensor and which accuracy is caused by the actual stresses themselves. Data inaccuracies that occur at the 1st of March, 2018 should have been removed, but were neglected.
- Actual evapotranspiration is calculated by using remotely sensed data as input in the Penman-Monteith equation to calculate the actual evapotranspiration. The use of the quality parameter that eLEAF delivers can give some steering to estimate the reliability of the calculated evapotranspiration value, although it has not been used. The accuracy of the actual evapotranspiration is between 0.04-0.45 mm/day, which equals up to 140 mm during the entire analysed period. Furthermore, the grid size of 250x250 meter is very large to represent the actual evapotranspiration at one point as is described in Brouwer (2014).
- Precipitation is calculated based on an algorithm that uses the amount of radar reflection by clouds. The grid size of 1000x1000 meter is quite large, but can easily be corrected with ground truth values.
- Groundwater has been measured directly, but the groundwater monitoring wells used were not situated at the location of the soil moisture monitoring stations.

Furthermore, the amount of usable data points was limited. Evapotranspiration datasets were only available from January 1st, 2018 until September 9th, 2018 and soil moisture monitoring stations ITCSM_01, ITCSM_05 and ITCSM_03 had data gaps during that period. This resulted in a total use of 8 soil moisture monitoring stations that covered (on average) 8 months, which is very small for an area of over 1500 km^2.

RQ2: Analysis of relations

For the analysis using the Pastas-package, several remarks can be made.
The results of research question 2 were that (actual) evapotranspiration everywhere had a major influence on the soil moisture during the period 2018. As 2018 was one in of the driest years of the 20th century, this comes as no surprise. Longer time series are necessary to increase the accuracy of the results. It is important to analyse years that are not as exceptional as 2018.

Furthermore, Pastas was unable to successfully analyse soil moisture with more than two stresses. If the time series had sufficient lengths, it might be possible to calculate the effects of additional stresses with Pastas. The results are directly influenced by the stresses that are incorporated. Especially at 20 cm depth, results would be more accurate.

Next, the impulse response distribution of precipitation is assumed to be a gamma distribution. However, the largest effect of precipitation on soil moisture becomes visible in less than 24 hours. As this research uses time steps of one day, it becomes clear that the impulse response distribution of precipitation should be exponential as exponential impulse response distribution have the highest effect on the day of the event itself.

Lastly, irrigation has not been taken into account in the analysis. Irrigation is artificial precipitation that is extracted from groundwater to increase the soil moisture. Usually irrigation is used during dry periods in the summer.

RQ3: Spatial comparison

No spatial patterns of soil moisture variability were found during this research as the spatial differences were too small to get (accurate) results from a spatial comparison. Two different reasons can be the cause of this and should be taken into account in future research:

1. The amount of soil moisture monitoring stations that were suited for the comparison were severely limited. In general ate least 30 points are necessary from an arbitrary sample to get insight in the soil dynamics in a region.
2. Land use and soil type maps were very simple and not up to date. Especially the land use map was more than 15 years old and can change quite a lot in such a period. Furthermore, the soil type map was too general to get distinctive results. A comparison with soil types described in Dente et al. (2012) is a good way to a more reliable results since soil types in Dente et al. (2012) are taken specifically from 0-40 cm, which is a much more accurate representation of the soil type. The problem with using soil types from Dente et al. (2012) is that a spatial representation is much harder outside the soil moisture monitoring locations since a raster map of the top soil was not available at the Waterschap Vechtstromen.

6. Conclusion

RQ1: Which hydrological datasets are available for the Twente region for 2018 and what is the quality of these datasets?

Several hydrological datasets are available for 2018, including soil moisture (point based measurement), precipitation (raster based measurement), actual evapotranspiration and evapotranspiration deficit (both raster based measurements) and groundwater levels (point based measurements). Most of these datasets do not cover the full period of 2018. All datasets are measured indirectly (or used indirectly), which reduces the quality. However, for most hydrological datasets are alternative datasets that can be used in a comparison.

RQ2: What is the relation between the observed hydrological conditions and unsaturated soil water in the Twente region?

(Actual) evapotranspiration has a large effect on soil moisture in the Twente region, especially in 2018. At deeper depths the contribution due to precipitation and due to actual evapotranspiration converges. However, large differences exist between observed locations. Average explained variance per stress is given in Table 21.

Table 21: Percentage of explained variance per stress.

Depth below ground level:	**Total explained variance (%):**	**Contribution of precipitation (%):**	**Contribution of actual evapotranspiration (%):**
5 cm	83.01	17.38	65.64
20 cm	76.51	20.62	55.86

With the used methods and the available length of the data series it was not possible to incorporate more than two stresses and get accurate results. Other processes seem significant as well; especially at deeper depths since the total explained variance drops compared to shallower depths.

RQ3: What is the relation between hydrological conditions and spatial characteristics in the Twente region?

No relation between hydrological conditions and spatial characteristics has been found (yet). The amount of observed data points is too small to observe significant differences. Furthermore, the use of outdated and simplified datasets of spatial characteristics in the comparison made results not usable.

MRQ: “To what extent is unsaturated soil water influenced by hydrological conditions in the Twente region in the year 2018?”

From the research it became apparent that the soil moisture in the Twente region in 2018 was heavily influenced by (actual) evapotranspiration. Although large differences exist between the individual soil moisture monitoring locations, most stations show the same trend. Furthermore, no significant spatial relations between soil moisture and elevation, land use and soil type have been found with the used datasets. This is primarily caused by the use of too few comparison points and outdated or generalized datasets.

7. Recommendation

Recommendations for further research

Four main recommendations for future research are given based on this bachelor thesis:

a) Using more soil moisture monitoring locations
b) Using longer (or different) time series that include less extreme years such as 2018
c) Including more stresses
d) Use of newer spatial characteristics

More soil moisture monitoring locations were present, but these lie outside of the study area. Some of these soil moisture monitoring locations (ITCSM_08 and ITCSM_09) lie very close to the study area and could be incorporated in a similar research. Furthermore, if longer time series are used (for example 2016-2018) results would be more accurate and the contribution of precipitation and (actual) evapotranspiration may shift. These contributions may shift even more if other stresses such as irrigation and groundwater can be included successfully.

Lastly, during research question 3 it became apparent that there was not enough data available to analyse the effect of different spatial characteristics on soil moisture in the Twente region in 2018. Using updated maps could reveal spatial patterns of soil moisture variation. Especially land use can change a lot over the years and sometimes even during the year.

Recommendations for use in practice

Waterschap Vechtstromen has several core tasks and ambitions (for example optimizing water quantity), which sometimes require monitoring networks. Soil moisture information can help with the execution of those core tasks and ambitions, for example in optimizing the response delay in the calibration stage in precipitation-runoff models. Another example is monitoring the resilience of different areas after a period of drought (such as 2018) or as reference information for citizens and farmers about the state of the soil. However, there is no one-size-fits-all, since different tasks require different types of monitoring networks with different monitoring frequencies and accuracies. Therefore, Waterschap Vechtstromen should discuss internally what the added value of soil moisture monitoring is for execution of her core tasks and what type of monitoring network is required.

8. Bibliografie

Van Aals, J.W. (2016) Veiligheidsregio Twente, impressie van het landschap en indeling van gemeenten (2017). Retrieved from www.wikipedia.nl: *https://nl.wikipedia.org/wiki/Veiligheidsregio_Twente#/media/File:2017-R05-Twente.jpg*

Adhikari, R., and Agrawal, R. (2013*). An Introductory Study on Time Series Modeling and Forecasting. LAP Lambert Academic Publishing*. doi:DOI: 10.13140/2.1.2771.8084

Allen, R., Pereira, L., Raes, D., and Smith, M. (1998). Crop Evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56*. Rome: FAO.*

Bakker, M., Collenteur, R., Calje, R., and Schaars, F. (2018). Untangling groundwater head series using time series analysis and Pastas. *20th EGU General Assembly, EGU2018, Proceedings from the conference held 4-13 April, 2018 in Vienna, Austria* (p. 7194). Vienna, Austria: Copernicus. doi:2018EGUGA..20.7194B

Bastiaanssen, W., Cheema, M., Immerzeel, W., Miltenburg, I., and Pelgrum, H. (2012). Surface energy balance and actual evapotranspiration of the transboundary Indus Basin estimated from satellite measurements and the ETLOOK model. *Water Resour. Res.*, 48, W11512, doi:10.1029/2011WR010482

Benninga, H.-J. F., Carranza, C. D. U., Pezij, M., van Santen, P., van der Ploeg, M. J., Augustijn, D. C. M., and van der Velde, R. (2018) The Raam regional soil moisture monitoring network in the Netherlands, Earth Syst. Sci. Data, 10, 61-79, doi:10.5194/essd-10-61-2018.

Booij, M. (2016). Waterbeheer. *Enschede: University of Twente.*

Boels, J., and Bekhuis, M. (2018, July). Twente is de droogste regio van Nederland. *Tubantia*.

Caljé, R., Schaars, F., and Heijkers, J. (2014). Vergelijking van enkele schattingsmethoden voor de actuele verdamping*. Amersfoort: STOWA.*

Chai, T., and Draxler, R. (2014). Root mean square error (RMSE) or mean absolute error (MAE)? – Arguments against avoiding RMSE in the literature. *Geoscientific Model Development*, 1247-1250.

Collenteur, R., Bakker, M., Caljé, R., and Schaars, F. (2019). Pastas: open-source software for time sereis analysis in hydrology (version 0.10). *Zenodo.* doi:http://doi.org/10.5281/zenodo.1465866

Dam, J., Feddes, R., and Witte, J. (2005). Soil physics and agrohydrology*. Wageningen: Wageningen University and Research Centre*

Decagon. (2010). 5TM Manual*. Pullman: Decagon Devices.*

Dente, L., Vekerdy, Z., Su, Z., and Ucer, M. (2012). Twente Soil Moisture And Soil Temperature Monitoring Network*. Enschede: Faculty of Geo-Information Science and Earth Observation (ITC).*

Dente, L., Su, Z., and Wen, J. (2012). Validation of SMOS Soil Moisture Products over the Maqu and Twente Regions. *Sensors*, 9965-9986.

Goudenhoofdt, E., and Delobbe, L. (2008). Evaluation of radar-gauge merging. *Hydrology and Earth System Sciences Discussions*, 2975-3003.

Haartsen, A. (2017). CultGIS: beschrijvingen Overijsselse regio's . Retrieved on: March 2019, from: *www.cultureelerfgoed.nl: https://cultureelerfgoed.nl/sites/default/public_ftp/CultGIS/Twente.pdf*

Hoekstra, A. (2016). Water*. Enschede: University of Twente.*

Illinois State Water Institute. (2019). The Water (Hydrologic) Cycle. Retrieved on: March 2019, From: *www.isws.illinois.edu: https://www.isws.illinois.edu/groundwater-science/gs-archive/the-water-cycle*

Kennisportaal Ruimtelijke Adaptatie. (2018). De effecten van droogte en hitte. Retrieved on:March 2019, from: www.ruimtelijkeadaptatie.nl: *https://ruimtelijkeadaptatie.nl/actueel/actueel/nieuws/2018/effecten-droogte/*

KNMI. (2000). Handboek Waarnemingen; 1. Meetstation algemeen. *De Bilt: KNMI.*

KNMI. (2001). Handboek Waarnemingen; 6. Neerslag*. De Bilt: KNMI.*

KNMI. (2013, April). KNMI-neerslagstations in Nederland. Retrieved from www.knmi.nl: *https://www.knmi.nl/kennis-en-datacentrum/uitleg/vrijwillige-neerslagmeters*

KNMI. (2018). Historisch verloop neerslagtekort. Opgeroepen op February 2019, van www.knmi.nl: *https://www.knmi.nl/nederland-nu/klimatologie/geografische-overzichten/historisch-neerslagtekort*

KNMI. (2018). Neerslagradar KNMI: Uitgebreide toelichting. Retrieved from: www.KNMI.nl: *https://www.knmi.nl/kennis-en-datacentrum/achtergrond/neerslagradar-knmi-uitgebreide-toelichting*

KNMI. (2018). Droogterapport 2018*. De Bilt: KNMI.*

Köppen, W. (1884). Die Wärmezonen der Erde, nach der Dauer der heissen, gemässigten und kalten Zeit und nach der Wirkung der Wärme auf die organische Welt betrachtet. *Meteorologische Zeitschrift*, 215-226.

Mehrjardi, M. (2016). Upscaling of in-situ measurements using spatially distributed model similations for validation of sattelite soil moisture products. *Enschede: Faculty of Geo-Information Science and Earth Observation (ITC).*

Obergfell, C., Bakker, M., and Maas, K. (2019, April 18). Identification and Explanation of a Change in the Groundwater Regime using Time Series Analysis. *Wiley Periodicals.* doi:https://doi.org/10.1111/gwat.12891

Ochoa, C., Fernald, A., Guldan, S., Shukla, M., & Tidwell, V. (2012). Deep percolation and water table fluctuations in response to irrigation inputs: Field observations. *New Mexico Journal of Science*, 89-104.

Rijksoverheid. (2018). Droogte in Nederland vraagt om verdeling water. Retrieved on: March 2019, from: www.rijksoverheid.nl*: https://www.rijksoverheid.nl/onderwerpen/droogte-en-hitte/nieuws/2018/08/02/droogte-in-nederland-vraagt-om-verdeling-water*

Sánchez-Diezma, R., Sempere-Torres, D., Creutin, J., Zawadzki, I., and Delrieu, G. (2000). Factors affecting the precision of radar measurement of rain. An assessment from an hydrological perspective. *Conference on Radar Meteorology of the American Meteorological Society*, 251-256.

Schipper, P., Reidsma, P., and Veraart, J. (2018). Effecten klimaatverandering op landbouw. *Wageningen: STOWA.* Retrieved from *http://deltaproof.stowa.nl/pdf/Effecten_klimaatverandering_op_landbouw?rId=11*

Schuurmans, H., and Vossen, J. (2013). Nationale Regenradar: Toelichting operationele neerslagproducten. *Noorderzijlvest: Waterschap Noorderzijlvest.*

Schuurmans, H., Verbree, J., Leijnse, H., Heeringen, K.-J., Uijlenhoet, R., Bierkens, M., and Houten, G. (2013). Spatial rainfall data in open source environment. *Geophysical Research Abstracts*.

Simons, G., and Droogers, P. (2016). Verkenning van remote sensing producten voor het waterbeheer. *Wageningen: FutureWater.*

Sluijter, R., Plieger, M., van Oldenborgh, G., Beersma, J., and de Vries, H. (2018). De droogte van 2018: Een analyse op basis van het potentiële neerslagtekort. *De Bilt: KNMI.*

The Pennsylvania State University. (2019). 2.1 Moving Average Models (MA models). Retrieved from Applied Time Series Analysis: *https://onlinecourses.science.psu.edu/stat510/lesson/2/2.1*

Terink, W., Droogers, P., Immerzeel, W., and Eertwegh, G. (2012). SPHY – Een hydrologisch model gericht op de berekening van bodemvocht in de wortelzone en de actuele verdamping. *Wageningen: FutureWater.*

Van Gurp, H. (2016). Soil moisture simulations on a regional level. *Enschede: University of Twente.*

Van Lonkhuijsen, R. (2018). Waterschap Vechtstromen stelt opnieuw verbod in om droogte. *ANP.*

Van Oort, P. (2006). Spatial data quality: from description to application. In *Publications on Geodesy 60*. Retrieved from: *http://library.wur.nl/WebQuery/wdab/1788022*

Vellekoop, S., Pelgrum, H., and Voogt, M. (2017). Plausibiliteitstoets SAT-DATA 2.0. *Wageningen: eLEAF BV.*

Viergever, K., Pelgrum, H., and Voogt, M. (2017). Methodiek SAT-DATA 2.0. *Wageningen: eLEAF BV.*

Von Asmuth, J. (2007). Modeling Time Series of Ground Water Head Fluctuations Subjected to Multiple Stresses. *Ground Water*, 30-40. doi:DOI: 10.1111/j.1745-6584.2007.00382

Von Asmuth, J., and Maas, K. (2001). The method of impulse response moments: a new method integrating time series-, groundwater- and eco-hydrological modelling. *Impact of Human Activity on Groundwater Dynamics* (pp. 51-58). *Maastricht: IAHS Scientific Assembly.*

Von Asmuth, J., Bierkens, M., and Maas, K. (2002). Transfer function-noise modeling in continuous time using predefined impulse response functions. *Water Resources*, 23/1 - 23/12. doi:10.1029/2001WR001136

Voortman, B., Witte, J.-P., Rheenen, H., Bosveld, F., Elbers, J., Bolt, F., and Voogt, M. (2016). Een nieuwe en handzame lysimeter: eerste stap naar een nationaal netwerk voor de werkelijke verdamping? In KWR, *Een kosteneffectief systeem voor het meten van de verdamping* (p. 104). *Nieuwegein: KWR.*

Waterschap Vechtstromen. (2018). Terugkijken op droogteperiode 2018. Retrieved in: March 2019, from: *www.vechtstromen.nl: https://www.vechtstromen.nl/over/klimaat/droogte/updates-droogte/@40655/terugkijken/*

Waterschap Vechtstromen. (2018). Zorgen over komende groeiseizoen. Retrieved in: March 2019, from: *www.vechtstromen.nl: https://www.vechtstromen.nl/over/klimaat/droogte/updates-droogte/@40634/zorgen-komende/*

Wetzel, R. (2001). Water Economy. *London: Academic Press*

Zaadnoordijk, W. (2018). TIME SERIES MODELING OF PIEZOMETRIC HEADS: DETERMINATION OF PRECIPITATION RESPONSE IN THE PRESENCE OF OTHER STRESSES AND HYDROGEOLOGICAL HETEROGENEITY. *Earth and Space Science Open Archive.* doi:https:/doi.org/10.1002/essoar.10500086.1