INFLUENCE OF DIFFERENT REFERENCE EVAPORATION METHODS ON THE ESTIMATED SOIL MOISTURE FOR AGRICULTURE IN THE NETHERLANDS DURING DROUGHT PERIODS

CLAUDE HABIMANA
July, 2020

SUPERVISORS:
dr.ir. C. van der Tol
Ir. G.N. Parodi

ADVISOR:
Liduin Bos-Burgering
Consultant/Researcher at Deltares

INFLUENCE OF DIFFERENT REFERENCE EVAPORATION METHODS ON THE ESTIMATED SOIL MOISTURE FOR AGRICULTURE IN THE NETHERLANDS DURING DROUGHT PERIODS

CLAUDE HABIMANA
Enschede, The Netherlands, July, 2020

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Water Resources and Environmental Management

SUPERVISORS:
dr.ir. C. van der Tol (first supervisor)
Ir. G.N. Parodi (second supervisor)

ADVISOR:
Liduin Bos-Burgering
Consultant/Researcher at Deltares

THESIS ASSESSMENT BOARD:
prof.dr. Z. Su (Chair)
Dr.Michiel Pezij (External Examiner, University of Twente)
dr.ir. C. van der Tol (first supervisor)
Ir. G.N. Parodi (second supervisor)

ABSTRACT

Different methods for assessing reference evaporation (ETo) can significantly affect the performance of land surface models in estimating the soil water dynamics. An accurate understanding of the influence of different reference evaporation methods is crucial for agriculture management decisions. Three ETo methods are discussed: One is based on the reference evapotranspiration presented in FAO-56 paper and is denoted FAO-Penman Monteith (FAO-PM). It is internationally recognized and ranked as the best method for the all-weather condition. The second is the modified Makkink reference evaporation based method. It is the standard method of the Royal Dutch Meteorological Institute (KNMI). The last one is DeBruin Method (here referred to as DeBruin-2016), it is a new remote sensing-based evapotranspiration method which is intended to present an estimate of the reference evapotranspiration from the reference area of grass growing in a wide field. In this study, these methods have been used to estimate the reference evaporation on 30 stations around The Netherlands for the period of 2018. The result indicated significant differences between these methods. In dry conditions, FAO-PM tends to overestimate the reference evaporation compared to the other two methods. The Makkink and De Bruin-2016 methods systematically showed almost the same estimation values of ETo. These different reference evaporation (ETo) forces the hydrological models. However, the national hydrological model (LHM) requires gridded data map of ETo. Therefore, Inverse Distance Weighting (IDW) interpolation method was applied to estimate the grid map. Furthermore, the national hydrological model (LHM) couples MetaSWAP and MODFLOW to simulate the rootzone soil moisture based on the three types of reference evaporation. The result indicated that the simulated soil moisture values for both Makkink and DeBruin method are higher than that of Penman-Monteith, except some months of the winter period (January and February). The soil moisture simulated based on Penman-Monteith depleted faster in the dry season than that of the other two methods. In comparison with the in situ measurement of the Raam soil moisture network, the result indicated that the soil moisture simulated based on the Penman-Monteith are in closer agreement with the in situ measurement at 20 cm depth during the growing season defined from April 1 to October 31, 2018.

Key words: Reference evaporation ; Soil moisture; rootzone; dry season.

ACKNOWLEDGEMENTS

First of all, all thanks go to Almighty God.

I would like to express my sincere gratitude to the Government of the Netherlands through the Netherlands Scholarship Program (NFP / OKP) for the opportunity offered to me to pursue my Masters of Science in the Netherlands.

I would like to thank the University of Twente through its Faculty of Geoinformation Science and Earth Observation and the Department of Water Resources for all the help that has allowed me to improve my knowledge and my academic background. Many thanks to all the speakers and staff for making my stay pleasant and informative.

Special thanks to my supervisors Dr.ir. C. van der Tol (first) and Ir. G.N. Parodi (second) for their dedication and critical comments on my research. Your advice and suggestions were handy for the realization of this thesis.

Special thanks to my advisor Liduin Bos-Burgering, Consultant / Researcher at Deltares. Your advice, suggestions and critical comments helped me a lot to finish this thesis.

Special thanks to my colleagues (Frank Mugabe, Elie Byukusenge, Jean de la Croix Ishimwe, Olvier Nzamuye) for their friendship and support during my stay in the Netherlands/ Enschede. Guys, I will forever cherish the memories; we have shared for 2 years (Ndabemera cyane).

Special thanks to my family for their encouragement and moral support(Ndabakunda cyane).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATION

ETo:	Reference evaporation
ETa:	Actual evapotranspiration
ETp:	Potential evapotranspiration
FAO:	Food Agriculture Organisation
KNMI:	Koninklijk Nederlands Meteorologisch Instituut (Royal Dutch Meteorological Institute)
LHM:	Landelijk Hydrologisch Model (National Hydrological Model)
NHI:	Netherlands Hydrological Instrument
REGIS:	Regionaal Geohydrologisch Informatie Systeem (Regional Geohydrological Information System)
SVAT:	Soil-Vegetation-Atmopshere-Transfer
SWAP:	Soil–Water-Atmosphere-Plant
BOFEK2012:	Bodemfysische Eenhedenkaart (Soil Physical Units Map)
RMSE:	Root Mean Square Error
IDW:	Inverse Distance Weighting
S01:	Soil water Storage at rootzone
Dprzk:	Rootzone depth
MSM:	Measured Soil Moisture
PSM:	Predicted Soil Moisture

1. INTRODUCTION

1.1. Background and Motivation

Reference evaporation (ETo) is a significant variable for hydrological and climatological studies, as well as for agriculture water resources management. It provides necessary information on the evaporative demand of the environment. Allen et al. (1998) defined reference evaporation as the evaporation rate of a hypothetical grass reference crop with an expected crop height of 0.12 m, a fixed surface resistance of 70 s/m and an albedo of 0.23, very similar to the evaporation of a larger area of uniformly growing green grass, actively growing, completely shading the soil and not lacking water (Allen, Luis, RAES, & Smith, 1998). The concept of reference evaporation was introduced to study the evaporative demand of the atmosphere independently of plant type, development stage and management activities (Allen et al., 1998). As the reference evaporation surface is at field capacity, the soil factors do not affect ETo. Moreover, reference evaporation expresses the evaporating power of the atmosphere at a specific location and time. Therefore, ETo is climatic weather dependent.

Reference Evaporation (ETo) has been widely used in different research fields for various purposes. ETo has been incorporated in drought severity and evolution analysis (Hobbins et al., 2016). It is also used as a representative index of environmental energies and ecosystem productivity (Currie, 1991). When estimating reference evaporation (ETo), it is assumed that the meteorological station is in an extensive area of grass well supplied with water. In dry weather, the soil of the area becomes dry, and the grass around the measurement station is not watered, the effect of drought occurs: the air temperature is much higher, and the relative humidity is much lower. The result is that most evaporation formulas overestimate the reference evaporation. Even if the measurement station is appropriately irrigated, the warm, dry air is supplied from the dry environment. This effect is called local advection; it provides additional energy for reference evaporation surface. Consequently, this effect does not only overestimate the reference evaporation but also has an effect on the simulated soil moisture.

Various methods are currently used to estimate the reference evaporation (ETo) for proper crop water management. They have been developed, revised and recommended for various types of climatic conditions over the years. Some of these methods require many input weather parameters, while others require fewer. These methods include Penman-Monteith, Makkink, Turc, Priestley–Taylor, Hargreaves, DeBruin methods (here referred to as DeBruin-2016), and others. In the Netherlands, the simplified equation notably the Makkink have been forced since 1987 as the standard for determining the reference evaporation. However, the FAO Penman-Monteith based evaporation model, which had presented in FAO-56 paper (FAO-PM) is internationally recognized and ranked as the best model for the all-weather condition. Allen et al. (1998) showed that ETo calculated using Penman-Monteith based methods gives the value closer to the ETo measured values. Therefore, Penman-Monteith has been confirmed as the standard method for defining and calculating reference evaporation from the grass reference surface.

The simplified Makkink equation has been established in the Netherlands for various reasons. It is simple and requires smaller input parameters for the calculation. It is based empirically on global radiation as well as a climatic coefficient (Jacobs & Bruin, 1998). It requires only global radiation and air temperature as input data observed directly in the Netherlands on a sufficient number of routine stations. Many research confirmed the validity of Makkink equation in the growing season (Hooghart, 1987; Jacobs & De Bruin, 1998).

A new method called Debruin-2016 can be used in comparison with other methods in the Netherlands. DeBruin and Trigo (2016) apply a thermodynamic theory model to estimate the actual evapotranspiration of a reference area of grasses growing in a wide field (H. A. R. de Bruin et al., 2016). It is not influenced by local aridity or by the effects of advection. It is therefore particularly suitable for large-scale climate assessments, including drought monitoring and appropriate estimates of irrigation requirements for water management. The DeBruin method uses daily global radiation and air temperature as input data which is also available at monitoring stations in the Netherlands. Therefore, these empirical methods should be used to estimate the baseline evaporation in order to quantify their effect on the simulated soil moisture.

Reference evaporation is often used as input for hydrological models, such as the National Hydrological Model (LHM) of the Dutch country. The behaviour of the hydrological model in response to these changes in reference evaporation affects the fluxes of the model. One of the model fluxes that has been affected by surface evaporation is soil moisture. In the Netherlands, the maximum water content needed for the soil in agriculture is increasing in the dry periods. Agriculture can be characterized by intensive use of the soil, a need for proper drainage conditions in winter and additional water consumption in summer. The upper part of the soil, the unsaturated zone, constitutes the medium between the atmosphere and the saturated system of underground water. This area is crucial for the biological, chemical and physical processes involved in the soil-plant system. The unsaturated zone is modelled using the National Hydrological model (LHM) couples of MetaSWAP and MODFLOW (Delsman, Veldhuizen, & Snepvangers, 2008). The MetaSWAP is a soil moisture simulation metamodel of LHM model. It is developed based on the SWAP model(Soil Water Atmosphere Plant) which is the deterministic column-model of the unsaturated zone, and the interaction of the soil with its supported vegetation and the atmosphere. Comparison of MetaSWAP with the original SWAP model shows excellent agreement, while calculation times have been reduced by several orders of magnitude (P. E. V. van Walsum & Groenendijk, 2008). In this Thesis research, MetaSWAP applied to quantify the soil moisture content for the three input datasets of reference evaporation estimated by Makkink, FAO Penman-Monteith and DeBruin-2016 Method.

1.2. Research problem statement

This research topic focused on the methodological difficulties of estimating reference evaporation for quantifying their effect on the simulated soil moisture under dry conditions. Different countries in the world, especially the western, were facing the problem of the heatwave in the years called dry years. 2018 was one of the driest years recorded (only 1976 was drier), but it was also the hottest year in the Netherlands. This year was very challenging for agriculture activities. Many formulas that are typically used to estimate the reference evaporation from the surface overestimate their values in dry condition. Moreover, these formulas not only to overestimate the reference evaporation but also affect the soil moisture content at the root zone. Reference evaporation (ETo) is used as the driving force of national hydrological model (LHM) for soil water flow in the unsaturated zone. This explains the performance of the model dependently to the reference evaporation method used. Therefore, it is necessary to understand the ETo estimation methods and their effect on the estimated soil moisture content at different spatial and temporal scales.

At the end of this research, the quantity of alternatives reference evaporation formulations on simulated soil moisture will be highlighted, as well as the precise method.

1.3. Main Objective

The objective of this research is to quantify the effect of different reference evaporation formulations of Makkink, DeBruin-2016, and Penman-Monteith on the simulated soil moisture content of the root zone using LHM model.

1.3.1. Sub-objectives

The research sub-objectives of this study are identified:

1. To apply the methods for estimating the time series of ETo for The Netherlands stations for 2018.
2. To estimate the gridded time series of ETo for The Netherlands for 2018.
3. To evaluate the differences between the estimated reference evaporation under dry condition.
4. To simulate the soil moisture content at the root zone for three datasets of gridded time series of reference evaporation using LHM model.
5. To evaluate the effect of different reference evaporation on the simulated rootzone soil moisture under dry condition.
6. To validate different estimated root zone soil moisture with the in situ measurement.

1.3.2. Research questions

To address the objectives above this question should be posed:

1. What are the differences between the different reference evaporation methods?
2. What method should be used to estimate the grid time series of ETo?

3. What is the cause of the differences between the estimated reference evaporation?
4. How to simulate the rootzone soil moisture content using the LHM model?
5. What is the effect of different reference evaporation on the simulated soil moisture under dry condition?
6. What is the validity of the different estimates of soil moisture in the root zone compared to the measurement?

1.4. Thesis structure

The outline of this thesis is made up of six chapters and is presented as follows:
The first chapter presents the introduction and motivation of this study. The second chapter provides a review of the literature, which discusses the findings of reference evaporation methods and the interaction between reference evaporation and soil moisture based on the National Hydrological model (LMH). The third chapter describes the study area. The fourth chapter presents the research methodology and the data used for this study with a discussion of the processing. The fifth chapter presents and discusses the results, including the validation result. The sixth chapter presents the conclusion and recommendation, including the limitation of the study.

2. LITERATURE REVIEW

2.1. Daily Evapotranspiration Method

Reference evaporation is one of the driving forces of the hydrological model. In the Netherlands, roughly 70% of the precipitation that falls evaporates (Hiemstra & Sluiter, 2011). This fact makes evaporation an essential driving force for any hydrological model. There are several methods to calculate the reference evaporation (Winter, Rosenberry, & Sturrock, 1995) from several meteorological parameters. In this research, Makkink, Penman-Monteith (FAO-PM) and De Bruin-2016 methods applied to estimate the reference evaporation from the surface under the same meteorological and environmental conditions. These methods have been selected according to their applications.

2.1.1. Makkink method

April 1, 1987, the Royal Netherlands Meteorological Institute (KNMI) replaced the regular basis reference evaporation (ETo) with the Penman formula by the formula proposed by Makkink (Hooghart, 1987). The Makkink method was first proposed by **Makkink (1957)** for the estimation of grass evaporation. It is remarkably simple, and it requires only the mean air temperature and incoming shortwave radiation as input data observed directly in the Netherlands on a sufficient number of routine stations. **De Bruin (1981, 1987)** have shown that an even purer form of modified Makkink equation is reliable for ETo estimates **(1)** (H. A.R. De Bruin & Lablans, 1998).

$$\mathbf{ET_0 = 0.65 \frac{\Delta}{(\Delta+\gamma)L_v} R_s} \tag{1}$$

Where,

- ET_0= reference evaporation[mm.day^{-1}]
- Δ=slope vapour pressure curve [kPa. ^{o}C^{-1}]
- γ=psychrometric constant [kPa. ^{o}C^{-1}]
- L_v= the latent heat of vaporisation [MJ/kg]
- R_S= is the daily incoming solar radiation [MJ.m^{-2}.day^{-1}]

The modified Makkink is one of the simplest radiation and temperature models. It is widely used in Western Europe such as The Netherlands. In the report "From Penman to Makkink" De Bruin (1988) indicates what were the considerations to be done at the time to step (Hooghart, 1987). This report indicates the main reasons for switching to the Makkink formula. From 1956 to April 1, 1987, Penman formula has presented a set of evaporation numbers which were not determined in the same manner. This created confusion. Early 1983, the TNO Committee for Hydrological Research requested the KNMI to have a closer look at the evaporation numbers. The KNMI then decided, after investigation, to introduce the Makkink formula to be used for the routine calculation of the so-called reference evapotranspiration.

Makkink method has been used in comparative studies with other methods, for instance, the work done by DeBruin(1981) in Cabauw, the potential evaporation that represents the water supply in the root zone is estimated under the dry summer of 1976 (Hooghart, 1987). Makkink and Penman-Monteith equations were used in this work. It is shown that reference evaporation, according to Penman-Monteith, is significantly larger than that of Makkink. Further investigation revealed that also the net radiation depends on the dryness of the soil because of the change of albedo and higher temperature. In 1998, Jacobs and DeBruin (1998) applied these methods to unstress the maize; it appeared that Makkink's method yields slightly better results than that of Penman-Monteith equation (Jacobs & De Bruin, 1998).

2.1.2. Penman-Monteith method

Penman-Monteith equation was recommended by the Food and Agriculture Organization of the United Nations (FAO) to estimate reference evaporation (ETo) from meteorological data collected on short, well-watered grass (Allen et al., 1998). It is chosen as a reference because it is very close to the "ETo" grass of the evaluated site, is physically based on physiological and aerodynamic parameters. The Penman-Monteith method has been used in comparative studies with other methods requiring less meteorological information data in different parts of the world (A. R. Pereira & Pruitt, 2004). Many research confirmed the validity of Penman-Monteith equation (Muhammad et al., 2019; L. S. Pereira, Allen, Smith, & Raes, 2015; Song et al., 2019; Winter et al., 1995). Penman-Monteith methods require solar radiation, air temperature, humidity, and wind speed data as input data. The FAO-PM defines ETo as "the rate of evapotranspiration from a hypothetical crop with an assumed crop height (0.12 m) and a fixed canopy resistance (70 sm-1) and albedo (0.23) which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not lacking water" (Allen et al., 1998). For daily ETo calculation, the FAO-PM method requires daily data on maximum and minimum air temperature (T max and T min), relative humidity (RH), solar radiation (Rs) and wind speed (u).

The Simplified form of the Penman-Monteith equation, which is presented in the FAO-56 bulletin (Allen et al., 1998) is showed below.

$$\mathbf{ETo} = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad \mathbf{(2)}$$

Where,

- ET_0= reference evaporation[mm.day^{-1}]
- R_n = net radiation [MJ.m^{-2}.day^{-1}]
- G= soil heat flux density [MJ.m^{-2}.day^{-1}]
- T= average temperature [°C]
- u_2= wind speed at 2m height [m.s-1]
- e_s= saturation vapour pressure[kPa]
- e_a= actual vapour pressure[kPa]
- $(e_s - e_a)$= saturation vapour pressure deficit [kPa]
- Δ= slope vapour pressure curve [kPa. °C^{-1}]
- γ= psychrometric constant [kPa. °C^{-1}]

2.1.3. De Bruin- 2016 Method

The method of De Bruin (2016) (here referred to as DeBruin-2016) is a new remote sensing-based evapotranspiration method. It is intended to present an estimate of the reference crop evapotranspiration from the reference area of grass growing in a wide field. DeBruin ETo is not influenced by local aridity or by the effects of advection(H. A. R. de Bruin et al., 2016). It is therefore particularly suitable for large-scale climate assessments, including drought monitoring and appropriate estimates of irrigation requirements for water management. DeBruin methods also require daily global radiation and daily mean air temperature, which is both measured at the monitoring stations throughout the Netherlands country. The description of the reference evaporation equation in this research is mainly based on De Bruin(2016) (H. A. R. de Bruin et al., 2016). Also, De Bruin equation is sensitive to the net radiation (Rn) due to the change of albedo and temperature

$$\mathbf{ET_O} = \frac{\mathbf{1}}{\mathbf{L_v}}\frac{\boldsymbol{\Delta}}{\boldsymbol{\Delta+\gamma}}\mathbf{R_n} + \boldsymbol{\beta} \tag{3}$$

$$\mathbf{R_n} = (\mathbf{1} - \mathbf{0.23})\mathbf{R_s} - \mathbf{C_S}\,\frac{\mathbf{R_s}}{\mathbf{R_{ext}}} \tag{4}$$

Where,

- ET_O: Reference evaporation[mm/day]
- R_n : is the Net radiation [MJ.m^{-2}.day^{-1}] formula given by Slob De Bruin
- Rs: is the global (=down-welling shortwave) radiation [MJ.m^{-2}.day^{-1}]
- R_{ext}: is the downwelling shortwave radiation at the top of the atmosphere (extra-terrestrial radiation) [MJ.m^{-2}.day^{-1}]
- Δ=slope vapour pressure curve [kPa. °C^{-1}]

- C_S**:** (Cs=110 wm^{-2}), is an empirical constant which is estimated by field observations
- **β:** constant (20 wm^{-2}) which has been introduced to compensate for the deviation of near-surface conditions from fully saturated air.

2.2. Effect of reference evaporation on soil moisture

The reference evaporation has a large influence on the season behavior of the soil moisture content in the unsaturated zone. Wu et l, (2002) indicated that the seasonal pattern of evapotranspiration is more evident in the soil moisture than the precipitation(Wu et al., 2002), especially since the precipitation is distributed equally over several years in the Netherlands(Jacobs, Heusinkveld, & Holtslag, 2010). Different estimated reference evaporations could be used to assess their influence on the simulated soil moisture. Moreover, there is an online coupling of models (MetaSWAP-MODFLOW) of the National Hydrological Model (LHM) which determine the simulation of the soil moisture in the unsaturated zone with reference evaporation raster grids as input datasets. Description and applicability of the models are explained in the following section.

2.2.1. National Hydrological Model (LHM)

2.2.1.1. Description

The Netherlands Hydrological modelling Instrument consists of an online coupling of hydrological models. MOZART/DM for surface water, MetaSWAP for the unsaturated zone and MODFLOW for saturated groundwater flow (Delsman et al., 2008). Figure 2.1 shows the overview of the hydrological models and coupling between one to Another. The models are modularly coupled, which indicate that the individual model can operate independently. This thesis research focused on the unsaturated zone, which is modelled by an online coupling of MetaSWAP with MODFLOW of the National Hydrological Models (LHM). The National Hydrological model (LHM) is structured on a rectangular grid with a spatial resolution of 250m by 250m and one day simulation time step. MetaSWAP and MODFLOW operate on the same resolution.

2.2.1.2. MetaSWAP

MetaSWAP is soil moisture simulation model. The simulation process lies in the SVAT column, where SVAT stands for Soil Vegetation Atmosphere Transfer (P. E. V. van Walsum & Groenendijk, 2008). The model simulates the processes in one vertical dimension from groundwater levels up to and counting plant-atmosphere interactions. MetaSWAP applies a simplified approach two ordinary differential equations for vertical variations, assuming a steady-state flow and an equation taking into account variations in time. MetaSWAP is a metamodel and was becoming available based on the SWAP model (van Dam, Groenendijk, Hendriks, & Kroes, 2008). SWAP model (Soil Water Atmosphere) is a deterministic column model of the water flow in the unsaturated part of the soil and counting the soil, vegetation and atmosphere interaction.

In the comparison of MetaSWAP with the original SWAP model, MetaSWAP showed excellent agreement, while the calculation times were reduced by several orders of magnitude(P. E. V. van Walsum & Groenendijk, 2008).

Practically, MetaSWAP requires several spatial datasets as input for simulation purpose. Meteorological data, including the option of grid files, Soil elevation, land use, Soil physical data and water management data. Several data have been already processed for the National Hydrological Instruments(NHI), such as data on vegetation development, hydraulic soil properties and data on local and regional water management.

2.2.1.2. MODFLOW

MODFLOW is a model code for simulating the flow of saturated groundwater (McDonald & Harbaugh, 1988). The model area covers the entire mainland of the Netherlands, with the exception of the southernmost part. This area has a distinctly different geological accumulation, consisting of hard rocks instead of unconsolidated sediment in the rest of the Netherlands. The hydrological schematization of MODFLOW in the national hydrological modelling includes seven layers based on the REGIS system (Delsman et al., 2008). The REGIS system stores regional hydrogeological information on the subsoil of the Netherlands. MODFLOW and MetaSWAP coupled via a shared state variable, the level of groundwater for MetaSWAP and the head of groundwater for MODFLOW (P. E. V. Van Walsum & Veldhuizen, 2011). Groundwater levels are determined by the model iterations of MetaSWAP and MODFLOW.

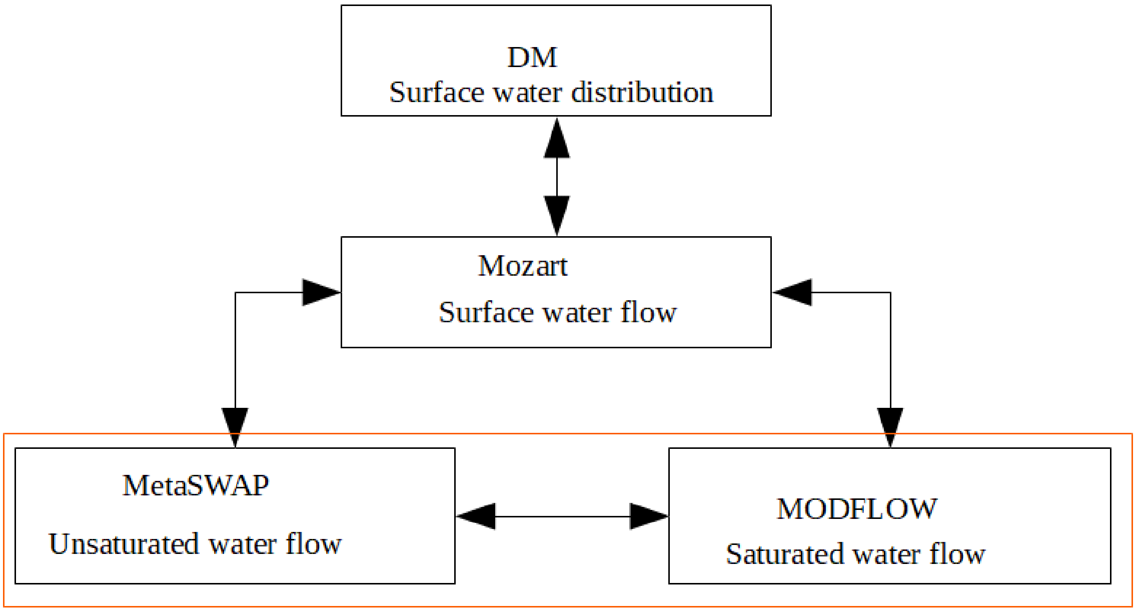


Figure 2.2.1: Schematic overview of Hydrological Model Instrumentation (NHI), the Orange Colour shows the coupling MetaSWAP and MODFLOW.

3. STUDY AREA

3.1. Raam Catchment

The study area is located in the north-east of the province of Noord-Brabant in the Netherlands (Figure 3.1.a). It covers the region of Raam Catchment with 223 square kilometres. The catchment has a temperate oceanic climate on the altitude between 5.1 and 46.5 m above sea level [a.s .l] (figure 3.1.b). The main soil types are sand, clayey and peaty with agriculture being the primary land use (figure 3.1.c). The water supply system is free-flowing, and water management is mainly through the use of weirs and pumps. In dry years, the cumulative precipitation deficit can reach up to 100mm in summer. During these dry periods, farmers irrigate from deep groundwater reservoirs (Benninga et al., 2018). In collaboration with the regional water management authority, they operate a system of weirs and pumping stations to minimize the situations of excess water and droughts. In addition, the regional water management authority continuously discharges surface water into the southern part of the catchment to increase groundwater recharge. Figure 3.1 represents the location and characteristic of the study area and the in-situ soil moisture stations located in the region (Benninga et al., 2018).

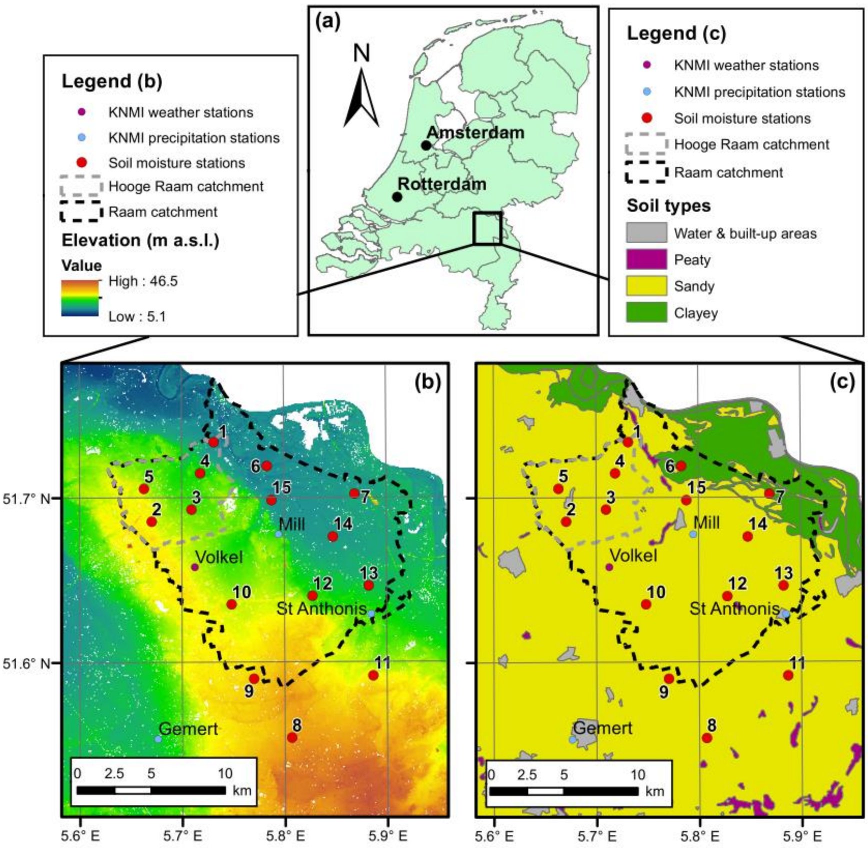


Figure 3.1: Shows the location and characteristic of the study area and the in-situ soil moisture stations located in the region from (Benninga et al., 2018). (a) Location of the study area, Raam catchment (small black box) in the Netherlands. (b) Digital elevation model (DEM). (c) Major soil types classes (Wösten et al., 2013).

3.2. Soil Texture

The Raam soil moisture monitoring network mainly involves sandy soils. 13 stations were located in coarse sandy soils, and the two stations (6 and 7 stations) were placed respectively in clay and loamy sands, in the northeast part of the study area(Raam Catchment). According to the (Benninga et al., 2018), the soil type descriptions was adopted based on the soil physical characteristics of the Netherlands. BOFEK2012 provides the soil physical characteristics (e.g. soil texture, water retention curve and hydraulic conductivity curve) for the soil units in the Netherlands.

Table 3.1: Soil characteristics of the monitoring stations.

Station	Soil description[a]	Soil order[b]	Sand Fraction (> 50 µm) (%)	Silt fraction (50–2 µm) (%)	Clay fraction (< 2 µm) (%)	Organic matter fraction (%)
1	Weakly loamy sandy soil on subsoil of coarse sand (305)	Podzols	91.3	1.9	13.5	3.3
2	Weakly loamy sandy soil on subsoil of coarse sand (305)	Podzols	90.4	3.7	2.1	3.8
3	Weakly loamy Podzol soil (304)	Podzols	93.3	2.4	1.9	2.4
4	4 Weakly loamy sandy soil on subsoil of coarse sand (305)	Podzols	90.0	2.0	2.9	5.2
5	Weakly loamy sandy soil with thick man-made earth soil (311)	Anthrosols	93.1	2.3	1.1	3.5
6	Clayey sand on sand (fluvial) (409)	Anthrosols/Vague soils	83.7	4.8	9.9	1.6

7	Loamy sandy soil with thick man-made earth soil (317)	Anthrosols	82.1	10.5	5.2	2.2
8	Weakly loamy Podzol soil (304)	Podzols	92.8	1.6	1.4	4.1
9	Weakly loamy Podzol soil (304)	Podzols	95.4	1.1	0.8	2.6
10	Weakly loamy Podzol soil (304)	Podzols	96.3	0.8	0.7	2.2
11	Weakly loamy Podzol soil (304)	Podzols	94.8	1.7	1.6	1.9
12	Weakly loamy Podzol soil (304)	Podzols	92.0	2.5	1.7	3.9
13	Weakly loamy soil partly on subsoil of coarse sand (309)	Podzols	96.7	1.1	0.8	1.4
14	Loamy Podzol soil (312)	Podzols	90.0	4.7	2.3	3.0
15	Weakly loamy sandy soil with thick man-made earth soil (311)	Anthrosols	88.6	5.5	2.8	3.1

a Soil description and classification code from BOFEK2012 (Wösten et al., 2013).
b Approximate soil order equivalent in the World Reference base (Hartemink & Bakker, 2004)

3.3. Soil moisture monitoring network

In April 2016, Soil moisture and temperature monitoring network covering an area of $223km^2$ were established in the Raam catchment. The network covers 15 stations equipped with Decagon EM50 data loggers to measure both the soil moisture and the temperature of the soil (Benninga et al., 2018). Figure 3.1 shows the location of the soil moisture stations in the network. The stations measure soil moisture and temperature every 15 minutes at a depth of 5 cm, 10 cm, 20 cm, 40 cm and 80 cm, as shown in figure 3.2. Currently, 15 stations are located in the Raam watershed (area of 223 square kilometres), and 5 of these stations are located in the closed watershed of Hooge Raam (area of 41 square kilometres). The specific ground calibration functions that have been developed for 5TM sensors under laboratory conditions result to an accuracy of 0.02 $m^3 m^{-3}$ (Benninga et al., 2018).

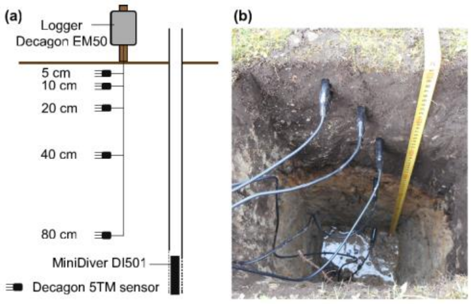


Figure 3.2: Shows a schematic cross-section of the soil moisture monitoring stations and nearby phreatic groundwater level monitoring well (a), and a photo of an installation pit with the soil moisture sensors installed at the five depths (b) (Benninga et al., 2018).

In situ soil moisture content measured at the Raam monitoring network provide a reference for validating Earth observation retrievals and land process models. The combination of in situ measurements at different depths, Earth observation products and Earth process models is essential to obtain reliable information on soil moisture at the time, horizontal and vertical resolutions required for the above applications (Benninga et al., 2018). National Hydrological model (LHM) is one of the Land process models that provide a spatial resolution of 250m by 250m**.** In this research, the in-situ soil moisture measurements were used to validate the simulated results of soil moisture of the metamodel MetaSWAP. For example, Figure 3.3 shows the volumetric soil moisture content measured in 2018 at 15-time steps at station 1, 3, 4, 6, 11 and 14. For more details about the availability of the data , the reader is referred to Benning et al., (2018).

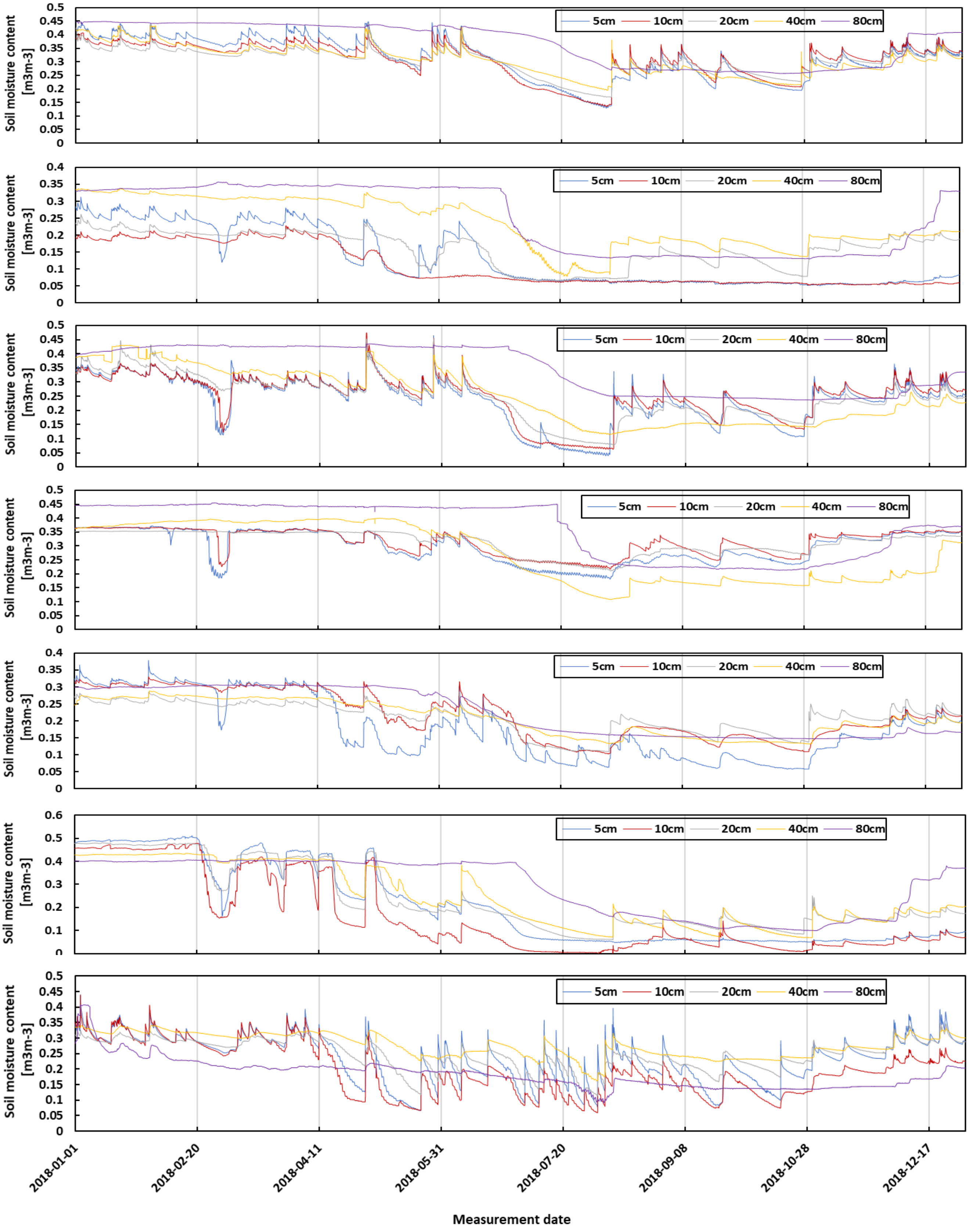


Figure 3.3: Volumetric soil moisture measurements at station 1, 3, 4, 6, 11 and 14 (Top to Down) during the hydrological year of 2018 at 5, 10, 20, 40 and 80 cm depth.

4. RESEARCH DESIGN AND METHODS

4.1. Conceptual Framework

This research thesis aims to quantify the effect of alternative reference evaporation formulations on the simulated soil moisture. The National Hydrological Model (LHM) MetaSWAP of the Netherlands country was used to simulate soil moisture. This model requires the grid reference evaporation as a forcing variable. Therefore, the estimation of the gridded reference evaporation is a crucial variable for the model. This task was carried out by applying the selected reference evaporation methods of Makkink, DeBruin-2016 and FAO Penman-Monteith on 30 selected weather stations across the Netherlands for 2018.

Makkink is the standard method of KNMI, so more tasks were concentrated on the DeBruin-2016 and FAO Penman-Monteith. These methods were evaluated by examining the differences between them in dry conditions as well as the effect of the meteorological variables applied to each method. In addition, gridded time series data were obtained using inverse spatial interpolation weighting (IDW) for the same specification as that of the National Hydrological Model (LHM). Finally, MetaSWAP simulated the soil moisture content, respectively, for each reference evaporation method. Also, the simulated soil moisture was validated with the in situ soil moisture measured using the instrument at the Raam soil moisture monitoring station. For more information, the reader refers to figure 4.1 below.

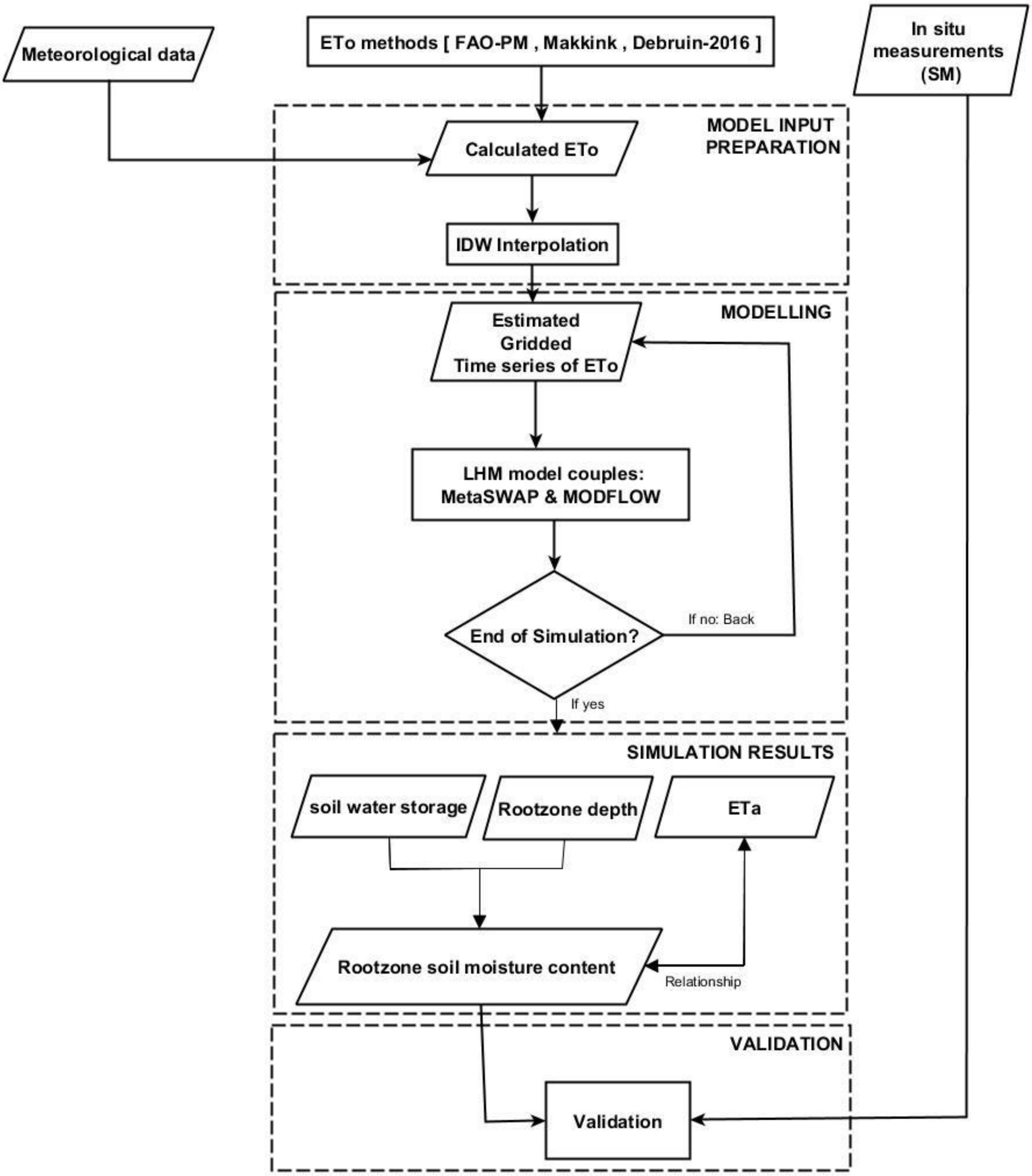


Figure 4.1:conceptual framework of Thesis

4.2. Estimation of daily time series of reference evaporation for The Netherlands for 2018

4.2.1. Data

In this study, we based on the meteorological variables (Global radiation, air temperature, wind speed and relative humidity). In The Netherlands, the meteorological variables are sufficiently available at the monitoring stations throughout the country (KNMI, 2019). Only 30 stations (figure 4.2) were examined and selected due to the availability of data for three reference evaporation based methods. The details of meteorological information of the selected stations are shown in Appendix 1. To estimate ETo for three Methods, we need two types of input data for each method. One is meteorological variable other is calculated data from meteorological variables (Table 4.1). The calculated data for each type of ETo method are shown and explained in the working process. Furthermore, to simplify the process, Makkink and DeBruin-2016 method are named 'Radiation and temperature-based method' because they are only based on radiation and temperature weather variables. The details of input data required for ETo calculation, including the sources is provided in table 4.1.

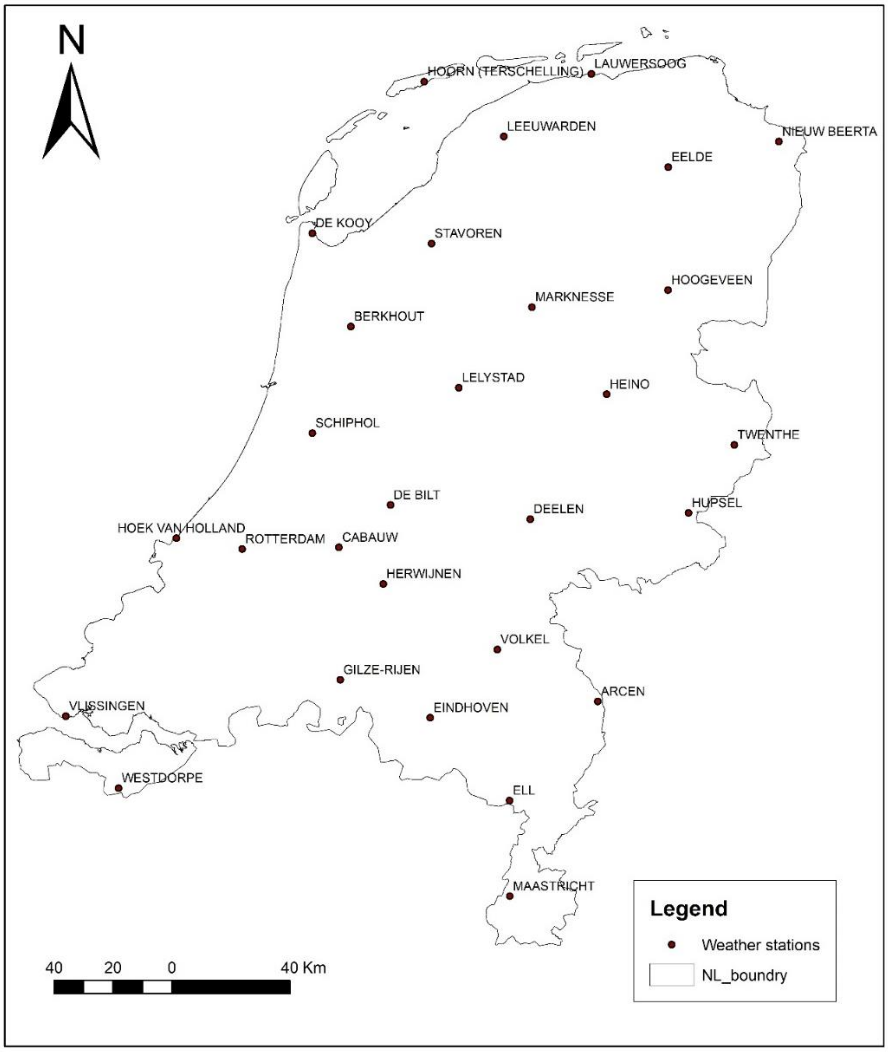


Figure 4.2: Shows the total number of stations used for this Research(Netherlands weather station).

Table 4.1: Daily input data required for each ETo calculation methods

					ETo Methods		
Input data	**Symbol**	**Unit**	**Format**	**Source**	**FAO Penman Monteith**	**Makkink**	**DeBruin -2016**
Incoming global Radiation Rs	Rs	[MJ.m^{-2}.day^{-1}]	Txt	KNMI Station	x	✓	x
Mean daily air Temperature	Ta	[^{o}C]	Txt	KNMI Station	✓	x	x
Mean daily wind speed at 2m height	U_2	[ms^{-2}]	Txt	KNMI Station	✓	x	x
psychrometric constant	γ	[kPa. ^{o}C^{-1}]	_	Calculated	✓	✓	✓
slope vapour pressure curve	Δ	[kPa. ^{o}C^{-1}]	_	Calculated	✓	✓	✓
saturation vapour pressure deficit	es-ea	[kPa]	_	Calculated	✓	x	x
soil heat flux density (=0 , negligible at daily time step)	G	[MJ.m^{-2}.day^{-1}]	_	Calculated	✓	x	x
Latent heat of vaporisation	L_v	[MJ/kg]	_	Calculated	x	✓	✓
Empirical constant equals to 20Wm^{-2}	β	[Wm^{-2}]	_	Literature: (H. A. R. de Bruin et al., 2016)	x	x	✓
Net radiation	Rn	[MJ.m^{-2}.day^{-1}]	_	Calculated	✓	x	✓

4.2.2. Radiation and temperature-based method for ETo estimates

The methods of the Makkink and De Bruin-2016 require daily global radiation and the average daily air temperature to estimate the daily baseline evaporation. However, Makkink's ETo has already been estimated by the KNMI. To estimate De Bruin-2016, extra-terrestrial radiation ($\mathbf{R_{ext}}$), i.e. short wave radiation entering the top of the atmosphere was required. This type of radiation has been estimated from the solar constant, the solar declination and the time of year. In this study, we applied the NOAA method for the calculation. Daily $\mathbf{R_{ext}}$ was estimated from January 1 to December 31, 2018 for each specific location station. However, $\mathbf{R_{ext}}$ is not the same for all stations. Therefore, it is necessary to specify the coordinates of each station location separately. The formula (5) was used to estimate the daily extra-terrestrial radiation.

$$\mathbf{R_{ext}} = \frac{24(60)}{\pi} \mathbf{G_{SC} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)]} \tag{5}$$

Where,

- **R_{ext}** : Extra-terrestrial radiation [MJ m-2 day-1],
- **Gsc**: Solar constant equals to 0.0820 [MJ m-2 min-1],
- **d_r**: Inverse relative distance Earth-Sun
- ω_s : sunset hour angle [rad],
- $\boldsymbol{\varphi}$: latitude [rad] and
- $\boldsymbol{\delta}$: solar declination [rad]

The latitude $\boldsymbol{\varphi}$, expressed in radians is positive for the northern hemisphere and negative for the southern hemisphere. The change from decimal degrees to radians is given by:

$$[\textbf{Radians}] = \frac{\pi}{180} [\textbf{decimal degrees}] \tag{6}$$

The inverted relative distance Earth-Sun (dr), and the solar declination angle (δ), are provided by:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \tag{7}$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \tag{8}$$

Where, J is the number of the day of the year between 1 (January 1) and 365 or 366 (December 31). The sunset hour angle, ωs, is provided by

$$\omega_s = arccos[-\tan(\varphi) \tan(\delta)] \tag{9}$$

After calculating the extra-terrestrial radiation, the calculation continues, the description of reference evaporation in this section is mainly based on **De Bruin(2016)** (H. A. R. de Bruin et al., 2016). The daily net radiation (**Rn**) was configured and estimated in 2018 at each station using the equation **(4)**. It is developed by Slob-De Bruin for a potential state and has been successfully applied in various research activities to estimate net radiation (H. A. R. De Bruin, Cob, Trigo, & Gavilán, 2006; H. A. R. de Bruin et al., 2016; Henk A.R. de Bruin & Trigo, 2019; Hooghart, 1987).

According to De Bruin and Trigo (2016), the reference evaporation based model relates daily reference evaporation to the net radiation (H. A. R. de Bruin et al., 2016). The equation **(4)** is introduced in **(3)** to produce equation **(10).** Therefore, the DeBruin-2016 reference evaporation formula is described below

$$\mathbf{ET_O} = \frac{1}{L_v} \frac{\Delta}{\Delta + \gamma} \left((1 - 0.23) R_s - C_S \frac{R_s}{R_{ext}} \right) + \beta \tag{10}$$

Where

- ET_O: Reference evaporation [mm/day]
- The slope of the curve of saturation water vapor pressure is related to mean daily temperature [kPa°C−1]

$$\Delta = 4098 * 0.6108 * \exp^{\frac{(17.27 * T_{mean})/(T_{mean}+237.3))}{(T_{mean}+237.3)^{\wedge}2}} \tag{11}$$

- The saturation vapour pressure is also related to mean daily temperature [Kpa]

$$\mathbf{e_s = 0.6108 * exp^{\frac{(17.27*T_{mean})}{(T_{mean}+237.3)}}} \qquad \textbf{(12)}$$

- γ : psychrometric constant [kPa. $^{o}C^{-1}$] is also related to daily mean air temperature (T, °C) (Schuurmans & Droogers, 2010):
- $\boldsymbol{\gamma = 0.0646 + 0.00006 * T_{mean}}$ **(13)**
- $\boldsymbol{L_v}$ is also related to mean air temperature
- $\mathbf{L_{v=}(2.502 * 10^\wedge 6) - (2250 * T_{mean})) * 10^\wedge - 6}$ **(14)**
- β: constant (20 Wm^{-2}) which has been introduced to compensate for the deviation of near-surface conditions from fully saturated air.

This parametrization of De Bruin-2016 was based on the daily global radiation and daily mean air temperature, that are both measured at monitoring stations throughout the Netherlands country.

4.2.3. FAO-Penman-Monteith reference evaporation estimates

The equation **(2)** provided in chapter 2 was used to estimate the daily time series of reference evaporation for FAO-PM for the period of 2018. The description of computation is referred to the Allen et al.,1998. Using the weather data obtained from the KNMI (see table 4.1), the following parameter is calculated to determine ETo for FAO Penman-Monteith.

- The saturation vapour pressure ($\mathbf{e_s}$) for the FAO Penman-Monteith is calculated using equation **(12)**
- Actual vapour pressure ($\mathbf{e_a}$): To estimate actual vapour pressure, saturation vapour pressure in function of mean air temperature $\boldsymbol{e_s}(\mathbf{T_{mean}})$ and mean relative humidity ($\mathbf{RH_{mean}}$) are used. The equation is described as follow:

  $$\mathbf{e_a = e_s(T_{mean}) * \frac{RH_{mean}}{100}} \qquad \textbf{[kPa]} \qquad \textbf{(15)}$$

- The slope of the relationship between saturation vapour pressure and temperature for the Penman-Monteith is given in the equation **(11)**
- Net radiation **(Rn)**: The net radiation is based on the computation of the Slob-DeBruin rather than that of the expert of FAO reported in the paper of Irrigation and Drainage N0.56. (Allen et al., 1998). (H. A.R. De Bruin & Stricker, 2000) indicated that the calculation using equation **(4)** gives a better result than that of the FAO expert. It has been validated in the Netherlands on several stations, including the cabauw site.
- Soil heat flux **(G):** Since the heat flux of the soil is low compared to **Rn**, in particular when the surface is covered with vegetation and the calculation time steps are 24 hours, the estimate of **G** is ignored in the calculation and assumed to be zero. This assumption is reported in the FAO Irrigation and Drainage Paper for daily calculation time step (Allen et al., 1998).

4.3. Estimation of gridded time series of reference evaporation for The Netherlands for 2018.

Time series of reference evaporation ETo is estimated for the period of 2018. However, the National hydrological model (LHM) requires a gridded map of ETo, which include estimates of reference evaporation at unmeasured locations. Therefore, the interpolation method was applied to obtain the gridded data (raster map).

4.3.1. Interpolation methods of daily observations

In a spatial context, interpolation is the process of estimating a variable at unmeasured locations using surrounding locations that do have a measurement of that variable. To obtain a gridded map, an interpolation estimate is made at each grid node until the map filled. Spatial interpolation is required when weather conditions in the study area and period of interest can't be obtained from local observation sensors. The nearest meteorological station may not have data for the period of interest, or it may be located too far to be representative of the study area.

In this thesis research, I estimated reference evaporation using DeBruin and FAO-PM methods using 30 stations located around the Netherlands country, the other ETo of Makkink was estimated by KNMI for the same stations. This reference evaporation was a point data respectively to each stations location.

The interpolation is a mathematical function that estimates the values at locations where no measured values are available. Although there are several methods to perform spatial interpolation such as inverse distance weighting (IDW), Kriging, Spline, nearest neighbour method etc. Therefore, this thesis research applied inverse distance weighting (IDW) for interpolation of daily baseline evaporation data series provided based on defined locations (normally weather stations). The description inverse distance weighting (IDW) is provided below.

4.3.1.1. Inverse distance weighted interpolation (IDW)

Inverse distance weighting interpolation (IDW) method is one of the most commonly used spatial interpolation methods in Geosciences (Lu & Wong, 2008). It estimates the values of an attribute at unsampled points using a linear combination of values at the sampled points weighted by an inverse function of the distance between the point of interest and the sampled points. The assumption is that the sampled points closer to the unsampled point are more similar to it than those more distant in their values. The weight of reference evaporation (ETo) at each station is referred to $\boldsymbol{W}_{(x_o)}$ in this formula. Therefore, $\boldsymbol{W}_{(x_o)}$ at unmeasured location $\boldsymbol{x_o}$ can be expressed as

$$\boldsymbol{W}_{(x_o)} = \frac{\sum_{i=1}^{n} w(x_i) Z(x_i)}{\sum_{i=1}^{n} w(x_i)} \tag{16}$$

where $\boldsymbol{w(x_i)}$ is the weight that the observation at location $\boldsymbol{x_i}$ receives, and $\boldsymbol{Z(x_i)}$the observation at location $\boldsymbol{x_i}$. The weight is related to the distance by:

$$\boldsymbol{W_{x_i}} = \|\boldsymbol{x_i} - \boldsymbol{x_o}\|^{-\boldsymbol{p}} \tag{17}$$

where $\|\boldsymbol{x_i} - \boldsymbol{x_o}\|$ is the Euclidian distance and $\boldsymbol{p}$ is a power that determines how fast the weight drops with distance. Note that when the prediction location is equal to one of the observation locations, the weight of this observation becomes infinite. Therefore, prediction equals observation. This means that IDW is an exact interpolator. In this study, we applied the IDW interpolation with power 2, when the power increases, the weight decreases more quickly with the distance, and the pattern becomes more oriented locally. Daily data-frame with the coordinates and ETo values was done for 30 stations from January 1, 2018, to December 31, 2018, i.e. 365 daily data-frame at each station. The interpolation result was obtained by the use of Python packages with ArcGIS Pro spatial environment. The output files were in GeoTiff format and were converted into ASC format using SDM toolbox (Brown, Bennett, & French, 2017) It is basically more applicable for spatial batch processing. This processing was done to obtain the appropriate data required for the LHM model (format: ASCII, coordinate: X_1=0,X_2=300000,Y_1=300000,Y_2=625000 RD new, resolution=1000x1000m).

4.4. National Hydrological model run (LHM)

The national hydrological model (LHM) couples MetaSWAP and MODFLOW to simulate the water flow in the unsaturated zone. The simulations are made available at the aggregate scale of the control boxes (appendix 2), this study based on box 1 that represent the root zone. The volumetric soil moisture can be extracted from the MetaSWAP simulations such as the water storage and the thickness of the root zone. In this study, the rootzone soil moisture is simulated to assess its relation to the reference surface evaporation estimated on the spatial and temporal scale. Makkink, DeBruin-2016 and FAO Penman-Monteith have already been used to estimate the surface reference evapotranspiration. In this section, the reference evaporation forces the LHM model. Therefore, I ran the model separately with the Makkink, DeBruin-2016 and Penman-Monteith methods.

4.4.1. Model set-up

In this study the three simulations were identical, except for the ETo input variables, and that all other inputs were standard, as already earlier calibrated by Detlares. Therefore, ETo data, including the option of grid files, was specified. I have implemented Makkink, DeBruin-2016 and Penman-Monteith in the same model working directory. However, they are in a separate operating process. In this configuration, I considered that each evapotranspiration method affects the output of the model. A full year from January 1 to December 31, 2018, was used to assess the change in the model output due to the estimated baseline evaporation types. For further information either on the model set up or model processing, the reader is referred to Veldhuizen & Groenendijk, (2016) and P. E. V. Van Walsum, (2017)

4.4.2. MetaSWAP output retrievals

4.4.2.1. Soil moisture retrieval

The model has been run three times separately, and the result was obtained in a different domain. For the entire MetaSWAP domain, the output files contain different formats such as IDF or CSV format. Each IDF file only refers to one model variable. I used the IDF file MSW_SO1, which generates the soil water storage in the root zone. It is aggregated in dekad time step (8,10 or 11 days). This file has been converted to Geotiff format for further processing. As MetaSWAP metamodel discretizes the unsaturated zone into several control boxes, the rootzone control box has been selected for Volumetric soil moisture (θ_{rz}) calculation. It can be calculated from water storage by dividing it by the depth of the root zone. The root zone depth as parametrised in MetaSWAP is dynamic in time. In this research, I used the dynamic depth defined by **dprzk** to calculate the volumetric water content because this variable represents the depth values of the root zone of the unsaturated zone. Finally, volumetric soil moisture was spatially extracted at location stations for comparison to the soil moisture measured by the instrument in the Raam network. This is done three times, according to the model runs (Makkink, DeBruin-2016 and Penman-Monteith).

$$\boldsymbol{\theta_{rz}} = \mathbf{S01(t)/dprzk(t)} \tag{18}$$

Where,

θ_{rz}=Volumetric soil moisture [m^3m^{-3}]

S01(t)= soil water storage [m^3m^{-2}]

Dprzk (t)= rootzone depth [m]

t = is the time step.

4.4.3. Actual evapotranspiration

Actual evapotranspiration (ETa) has resulted in the model with IDF format and resolution of 250m.This format is converted to Geotiff format for further analysis. The equation **(19)** defined by (Feddes, Kowalik, & Zaradny, 1987) is used for the effect of limiting the soil moisture condition on the evapotranspiration. The reduction coefficient for root water uptake (Alpha) is in the function of soil moisture content as defined by Feddes et al., (1987). The ratio of ETa/ETo is lower as the soil moisture decreases. Thus, this function is used in this research thesis to evaluate the change in soil moisture over the root zone.

$$\mathbf{ET_a = \alpha_E * ET_p = \alpha_{E*k_c*ET_0}} \tag{19}$$

$$\mathbf{\alpha_{E*k_c} = \frac{ET_a}{ET_0}} \tag{20}$$

where:

ET_a= actual evapotranspiration rate [m^3/m^2]

ET_0= potential canopy transpiration rate [m^3/m^2]

α_E= soil moisture reduction factor (-)

k_c= is the crop factor

4.5. The estimate of rootzone soil moisture content from the in situ measurement

The Raam network contains the soil moisture measurements at different depths (Chapter 3, section 3.3). In this study, Both soil moisture of the model and the measurement are comparable for the periods with the similar rootzone depth. The depths of the root zone as configured in the MetaSWAP is dynamic over time, it varies depends on the length of the season, 20 cm for the winter and 20-30 cm for the growing season specifically to each station of the Raam soil moisture network (Table 4.2). Table 4.2 shows the statistical values of the root zone depths of the MetaSWAP extracted spatially to each station of the Raam network. Then, to compare the rootzone soil moisture of the MetaSWAP to that of in-situ measurement, I defined the in-situ rootzone soil moisture along the growing season (April 1, 2018 -October 31, 2018). As the first aggregation box of MetaSWAP represents the root zone up to 30 cm depth in the growing season at each station of the Raam network, I aggregated the in situ measurements to 20 cm depth for selected stations in the growing season. Then, a depth of 20 cm is considered to be representative of the growing season measurement defined from April 1, 2018, to October 31, 2018.

Table 4.2: Shows the depth of the root zone as parameterized in the MetaSWAP model for each station of the Raam soil moisture network.

Station	Winter (January 1 -March 31) Depth [m]	Growing season (April 1 -October 31) Min-Max Depth [m]
1	0.2	0.2-0.3
3	0.2	0.2-0.3
4	0.2	0.2-0.3
6	0.2	0.2-0.25
11	0.2	0.2-0.3
12	0.2	0.2-0.3
14	0.2	0.2-0.25

Additionally, in the MetaSWAP metamodel, the soil moisture content was spatially extracted according to the location of the 15 stations. However, the measurement of soil moisture shows the data gaps for certain specific stations. Therefore, I considered the validation of soil moisture for some specific stations due to the availability of data throughout the validation period. Station 1, 3, 4, 6, 11, 12, and 14 have been considered for the validation period. Figure 4.3 and 4.4 are made available to see the variability of the in situ soil moisture with the influence of the nearest precipitation station of the KNMI (KNMI, n.d.) located in the Raam catchment.

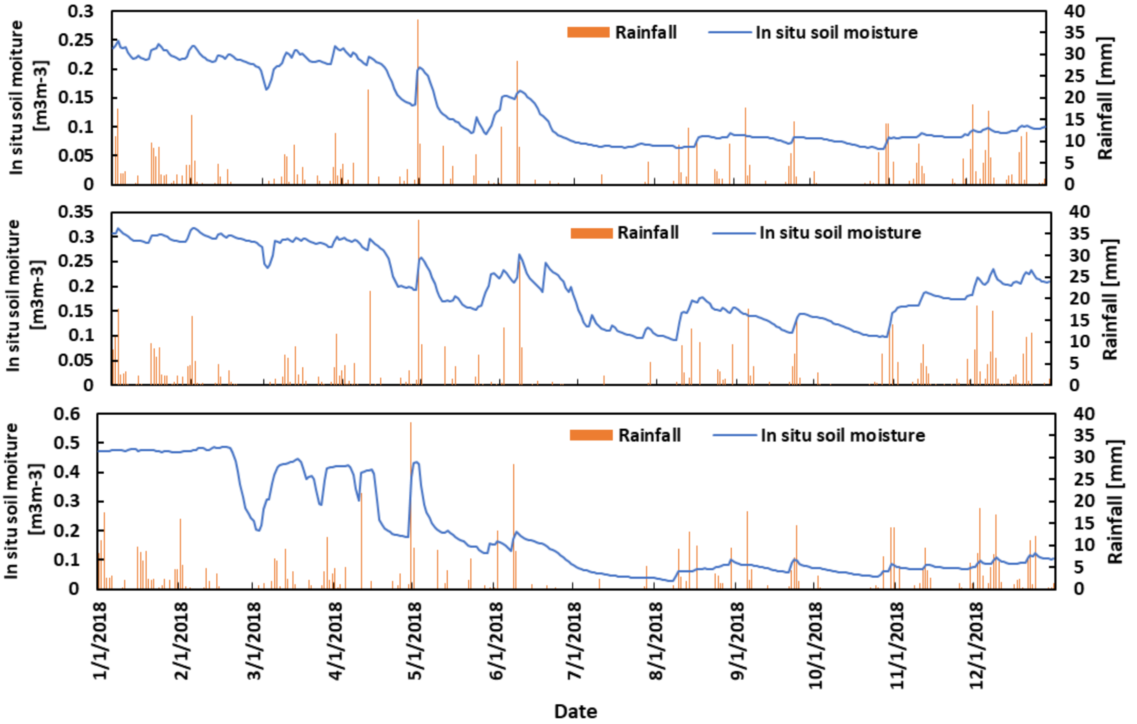


Figure 4.3: Daily mean soil moisture available at stations 3, 11 and 12 (top to down) in 20 cm depth, with rainfall collected at the nearest KNMI precipitation station (St. Anthonis, see figure 3.1).

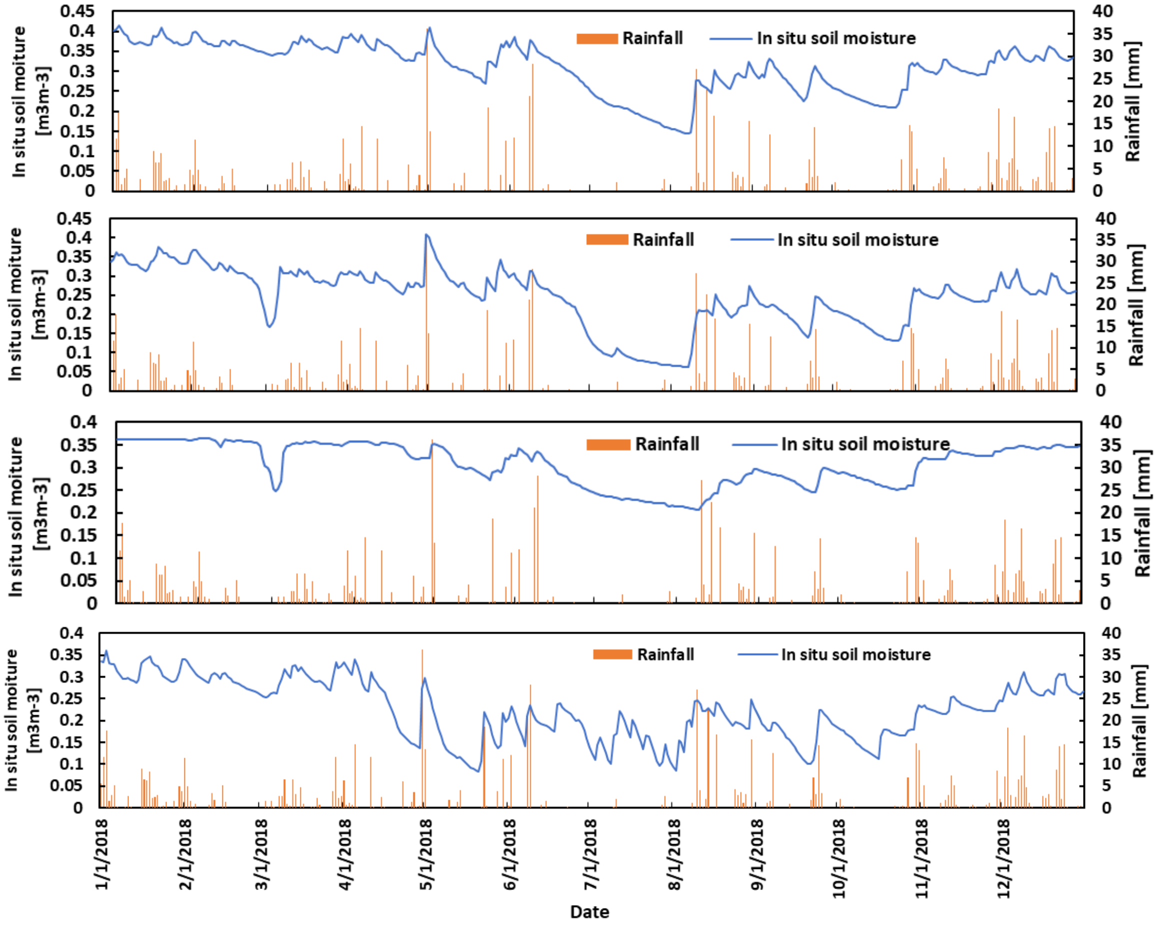


Figure 4.4: Daily mean soil moisture available at stations 1, 4, 6 and 14 (top to down) in 20 cm depth, with rainfall collected at the nearest KNMI precipitation station (Mill, see figure 3.1).

4.6. Validation Design

This research thesis considers the in-situ soil moisture measured by the instrument for verifying the accuracy of the soil moisture content estimated by the model. Figure 4.5 shows the validation design of soil moisture simulated from MetaSWAP metamodel.

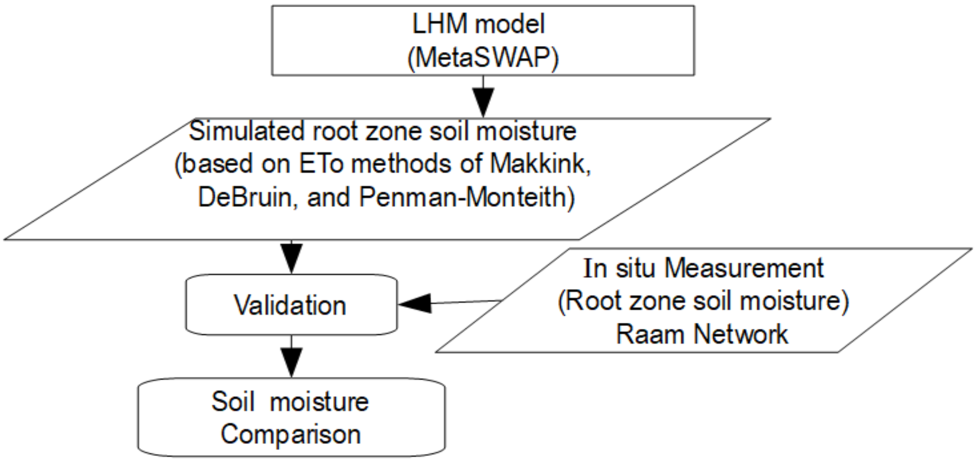


Figure 4.5: shows the validation design of the soil moisture simulated from the model with in situ data.

4.6.1. Performance Matrixes

To assess the performance of the model, several performance indicators were used similarly to the previous study (Pezij et al., 2019). These indicators were assessed for each run (Makkink, DeBruin-2016 and Penman-Monteith). The Pearson correlation coefficient **r** for the dynamics, the model bias for the systematic deviation, and the RMSE for the absolute deviation. The Pearson correlation coefficient **r** is defined as:

$$\mathbf{r} = \frac{\sum_{i=1}^{N}(\theta^{MSM} - \overline{\theta^{MSM}})(\theta^{PSM} - \overline{\theta^{PSM}})}{\sqrt{\sum_{i=1}^{N}(\theta^{MSM} - \overline{\theta^{MSM}})^2}\sqrt{\sum_{i=1}^{N}(\theta^{PSM} - \overline{\theta^{PSM}})^2}} \tag{21}$$

Where, $\overline{\theta^{MSM}}$ is the averaged rootzone measured soil moisture at station and $\overline{\theta^{PSM}}$ is the averaged predicted rootzone soil moisture estimated by the model. θ^{MSM} and θ^{PSM} are the measured soil moisture and predicted soil moisture, respectively and N is the number of measurements. The correlation coefficient **r** can range between −1 and 1. A value of 1 and -1 indicates a perfect positive and negative linear relationship between measured rootzone SM and predicted rootzone SM respectively.

The model bias is defined as:

$$\mathbf{Bias} = \frac{\sum_{i=1}^{N}(\theta_i^{MSM} - \theta_i^{PSM})}{N} \tag{22}$$

The closer the bias is to zero, the less biased the model predictions are.

Finally, the RMSE is defined as:

$$\mathbf{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(\theta_i^{MSM} - \theta_i^{PSM})^2}{N}} \tag{23}$$

The closer the RMSE is to zero, the more accurate the model predictions are.

5. RESULT AND DISCUSSION

5.1. Reference evaporation result

5.1.1. Comparative analysis of reference evaporation time series

One year of daily weather data was used to estimate the commonly used ETo baseline evaporation. Figure 5.1 shows the time series of ETo estimated with three methods in 2018. Using the Penman-Monteith equation, ETo is higher than that of Makkink and DeBruin-2016 methods. This is due to fact that the reference evaporation estimated by Penman-Monteith refer to a hypothetical crop under ideal conditions with no water shortage. However, in the case of very dry conditions, there is a shortage of water. As a result, the air near the ground was dry and warm, which implies that the saturation vapour deficit $(\boldsymbol{e_s} - \boldsymbol{e_a})$ became large (figure 5.1). Consequently, because $(\boldsymbol{e_s} - \boldsymbol{e_a})$ appears in the last term of Penman-Monteith equation, ETo values were relatively large, leading to a relatively large value of the crop water requirement. This term does not appear in the Makkink and DeBruin equations. They are solely based on radiation and temperature. This explains why the Makkink method and DeBruin-2016 differ from FAO Penman-Monteith in dry conditions. Moreover, Makkink and DeBruin-2016 are not sensitive to wind speed and relative humidity compared to the FAO Penman-Monteith method.

Both Makkink and DeBruin-2016 method showed almost the same variability of ETo values (figure 5.1). However, they are different in terms of input variables to estimate ETo. To differentiate them, equations [1], [3] and [4] are used. [3] and [4] are based on the DeBruin method. DeBruin estimates the net radiation using equation [4], while Makkink has a coefficient by which Rs is a multiple factors in equation [1].

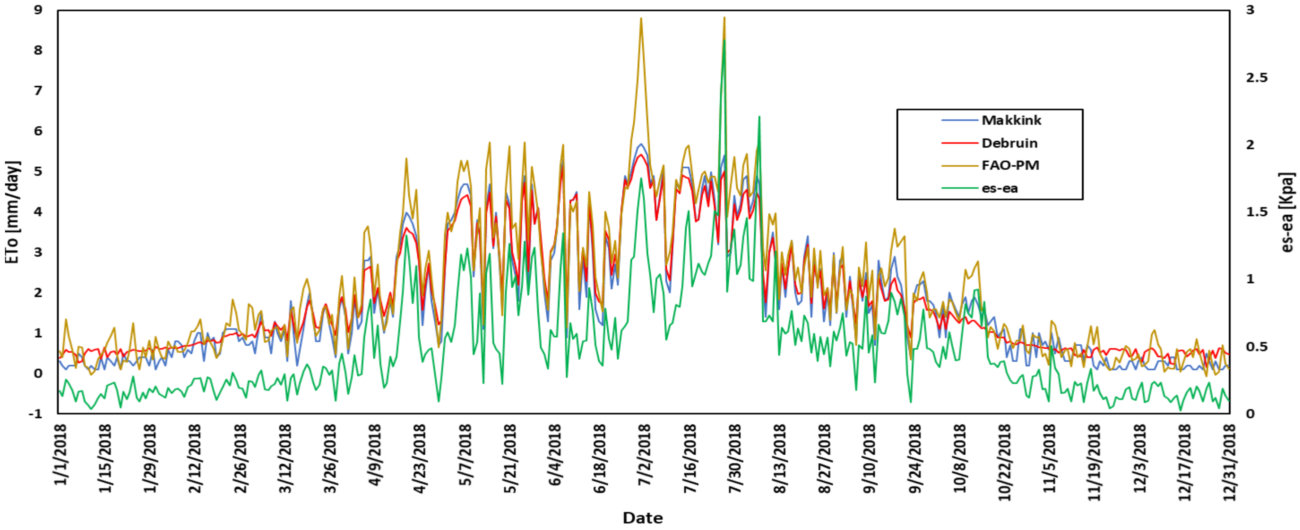


Figure 5.1: Result of ETo at De Bilt station. Makkink (blue line), DeBruin (Red line) and FAO-PM (yellow line) represent the estimated reference evaporation (ETo), and the green line represents vapour pressure deficit (**es-ea**).

5.1.2. Spatial variation of reference evaporation over the Netherlands

The spatial distribution of seasonal reference evapotranspiration is plotted in figure 5.2. Figure shows the spatial distribution of the estimated gridded reference evaporation for three methods and representation was based on the seasonal ETo across the region of the Netherlands. The contribution of each station to the value at any point in the map is identical for the three methods because I used the same stations and the same interpolation method (IDW). The differences in spatial patterns are caused by the differences in ETo at individual stations. It can also be seen that the seasonal variations of meteorological variables at the individual station caused the differences in the seasonal variations of the reference evapotranspiration (ETo) in different regions (figure 5.2). For all-season of the year (Winter, Spring, Summer, Autumn), the ETo variation for the Penman-Monteith method showed high values than that of Makkink and DeBruin method. This is due to the effect of wind speed and relative humidity values at each station which effectively affects the spatial patterns in the Penman-Monteith equation.

A small difference of spatial patterns of reference evaporation in the map is revealed between Makkink and DeBruin-2016 method. Because both methods use the same variation of meteorological variables (incoming shortwave radiation and air temperature). An exception for lower values on the map for all seasons is indicated in the southwest for the Makkink method. Also for DeBruin in the northwest for Spring and Summer showed lower values. Compared to other seasons, autumn has a relatively homogeneous spatial distribution except in a few isolated points.

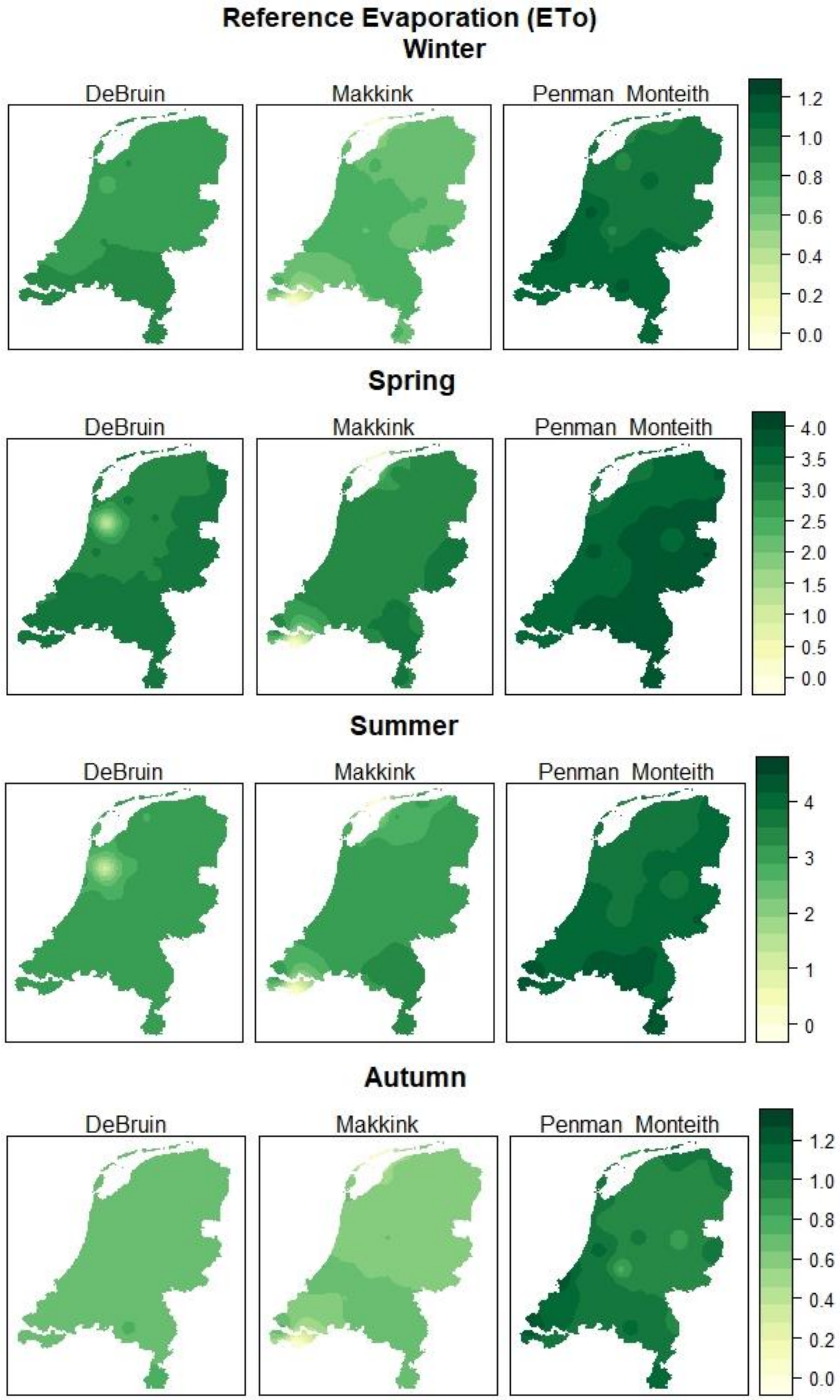


Figure 5.2: Spatial distribution of mean seasonal reference evaporation based on the three Methods in 2018 .

5.2. Model result

5.2.1. Rootzone soil moisture estimate

This section presents and discusses the findings of the reference evaporation data into the MetaSWAP metamodel. Figure 5.3 shows an overview of the local-scale soil moisture result of the metamodel MetaSWAP under different reference evaporations at Raam catchment. The local soil moisture estimate was spatially extracted from the regional soil water storage estimated by the model for different Methods runs. A comparison of Makkink, DeBruin-2016 and FAO Penman-Monteith runs showed the differences for all seasons of the year. The simulated soil moisture values for both Makkink and DeBruin method are higher than that of Penman-Monteith, except some months of the winter period (January and February). At the beginning of the year, a small difference between the soil moisture content for the three input data sets is revealed. This difference is expected since the evaporation in winter is low compared to the rainfall. Thus, the soil moisture content is more determined by the soil physical properties, such as soil temperature and texture, as has been discussed in previous studies (Robinson et al., 2008).

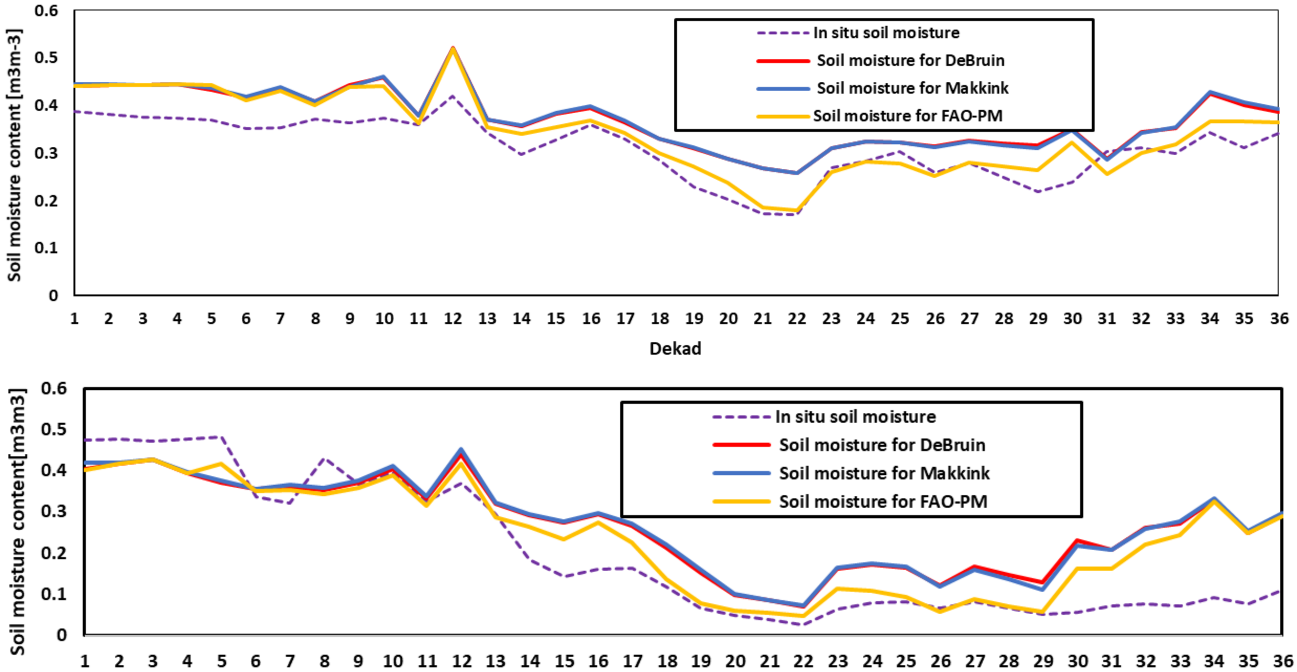


Figure 5.3: Result of measured and modelled volumetric soil moisture content at 20 cm depth for station 1 and 12 (Top to Down). Makkink (blue line), DeBruin-2016 (Red line) and FAO-PM (yellow line) represent the estimates of the soil moisture content extracted spatially based on the type of reference evapotranspiration method, and the dashed purple line represents the averaged in-situ soil moisture measurement at 20 cm depth for the same station.

At dekad 31 for station 1 and 8 for station 12, the discrepancy increased between the simulated soil moisture and the insitu measurements. The reason may be the effect of the incoming water flux (precipitation) on the soil water dynamics. The average daily in situ soil moisture with the daily precipitation is plotted to see what is actually happening. Figure 4.4 shows the daily amount of precipitation increasing in the first ten days of

November at station 1 and Figure 4.3 shows the small amount of precipitation from March 10 to March 21, 2018 at station 12 (Dekad 8).

In the dry period, especially from Dekad 18 to Dekad 22 for Figure 5.3, it is clear that with FAO's standard Penman-Monteith evaporation method, the soil water content becomes depleted more quickly. This is due to evapotranspiration (ET). Using equation **(20)**, alpha **(** α_E) is a function of soil moisture and gives the ratio of actual evapotranspiration and reference evapotranspiration. This ratio depends on the soil moisture; figure 5.4 shows the variation of this ratio with soil moisture estimated in the Raam network on station 1. The ratio (ETa/ETo) slightly decreases with Penman-Monteith reference evaporation methods than the other two methods. As a result, the soil moisture depletes faster.

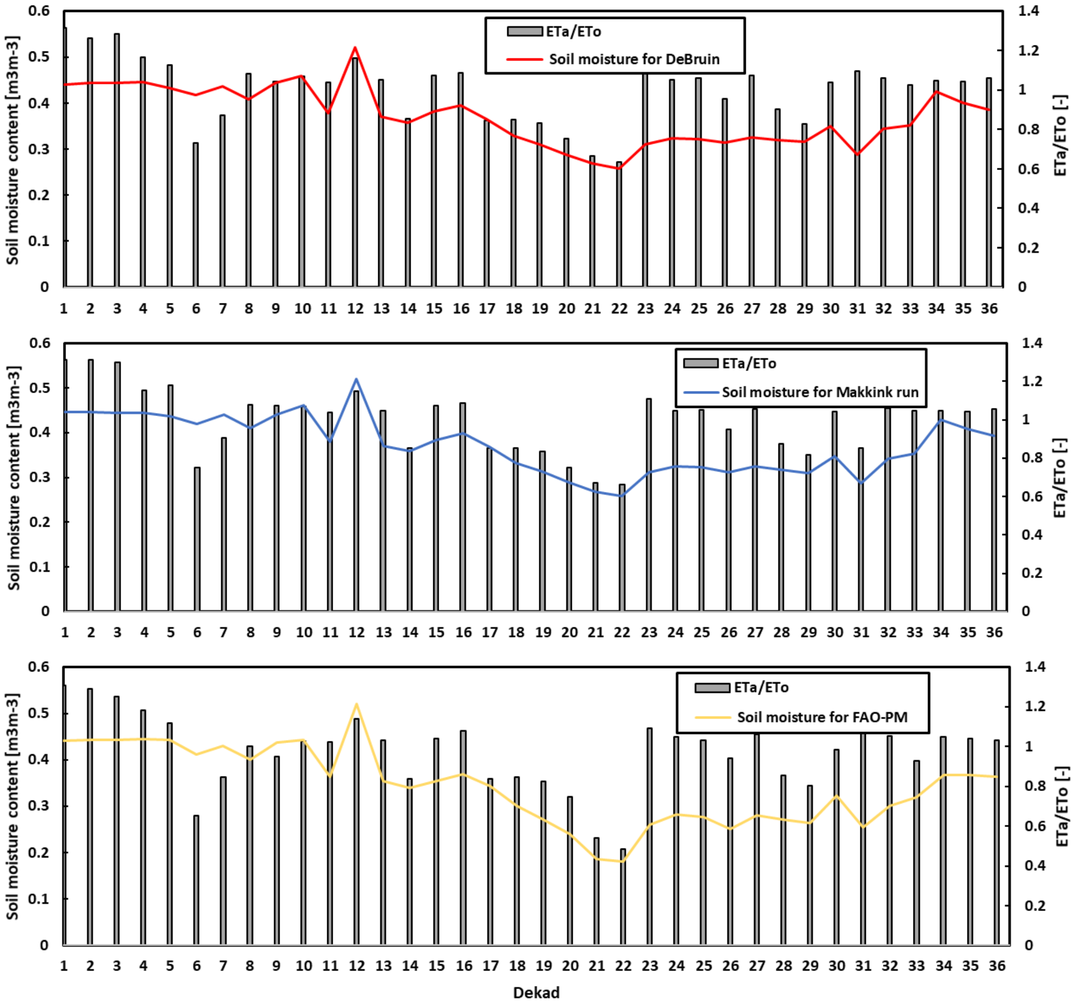


Figure 5.4: Result of soil moisture estimated based on the type of reference evapotranspiration at station 1, Makkink (blue line), DeBruin-2016 (Red line) and FAO-PM (yellow line) and the dark column bar represent the soil moisture reduction (ETa/ETo)

5.3. Validation result

The simulated soil moisture content at rootzone based on three reference evaporation methods was compared with the soil moisture measured in Raam network at soil depths of 20 cm (figure 5.5). Seven stations around the catchment have been used for comparison analysis during the validation period of growing season and summer. The result indicated that using the FAO Penman-Monteith method, the MetaSWAP metamodel systematically providing the best estimate regarding the comparison between simulated soil moisture and in situ observation in growing season. In terms of RMSE, the FAO-PM run shows an average of the RMSE value of 0.082 m^3m^{-3} while Makkink and DeBruin run RMSE values are 0.108 and 0.096 $m^3m^{-3,}$ respectively (Table 5.1). In terms of the Pearson correlation coefficient, the model accuracy increases in the FAO-PM method. It is linearly correlated with in situ observation with 0.82 [-] while Makkink and DeBruin-2016 are 0.80 and 0.793 [-] respectively. The result also indicated that using FAO-PM method; the model is lesser biased with -0.026 m^3m^{-3} while Makkink and DeBruin are -0.074 and -0.079 m^3m^{-3} respectively.

The summer period defined by two months of July and August is used in the validation period to understand the depletion of soil moisture in the model result. In table 5.1 (B), the validation result indicated that the MetaSWAP model simulation with Penman-Monteith is lesser biased with -0.02 m^3m^{-3} while with Makkink and DeBruin method is -0.07 m^3m^{-3}.

Generally, using both Makkink and DeBruin methods, the MetaSWAP showed almost similar trends of soil moisture throughout the growing season. For instance, at stations 3,2,12,11, and 14, the model gives higher values of soil moisture than that of the measurement. The evapotranspiration estimated by both methods causes these values. At high incoming radiation and temperature, the surface is getting dry and warm. So, as these methods don't suffer from the local aridity and advection effect (H. A. R. de Bruin et al., 2016; H. A.R. De Bruin & Lablans, 1998), they resulted in a little depletion of soil moisture.

At stations 4 and 6, based on the Penman-Monteith, the MetaSWAP gives lower values compared to the measurement. This can be explained in section 5.11, Penman-Monteith gives a high value of reference evaporation due to the aridity and advection effect. This resulted in lower actual evapotranspiration with a high depletion of soil moisture. Again, this high depletion can be explained using the model bias obtained in the summer validation period. With the Penman-Monteith equation, the model is strongly biased with 0.02 and 0.07 m3m-3 respectively at stations 4 and 6 than the other two methods (Table 5.1 .B)

Based on visual comparison and performance matrixes, If we apply Makkink and DeBruin method in a small field under dry conditions, we will experience local advection, by which the actual evapotranspiration will be enhanced as a result of the horizontal energy transfer. Thus, both formulae are expected to fail. Comparing Makkink and Penman-Monteith, previous studies have indicated that Makkink performs slightly better than Penman-Monteith as long as the crop grows in a large, extensive field (H. A.R. De Bruin & Lablans, 1998; Jacobs & De Bruin, 1998). Again, H.A.R. De Bruin at al 2006 indicated that Makkink could be forced instead of Penman-Monteith, not mean to replace it, but if the appropriate input data are available (H. A. R. De Bruin et al., 2006).

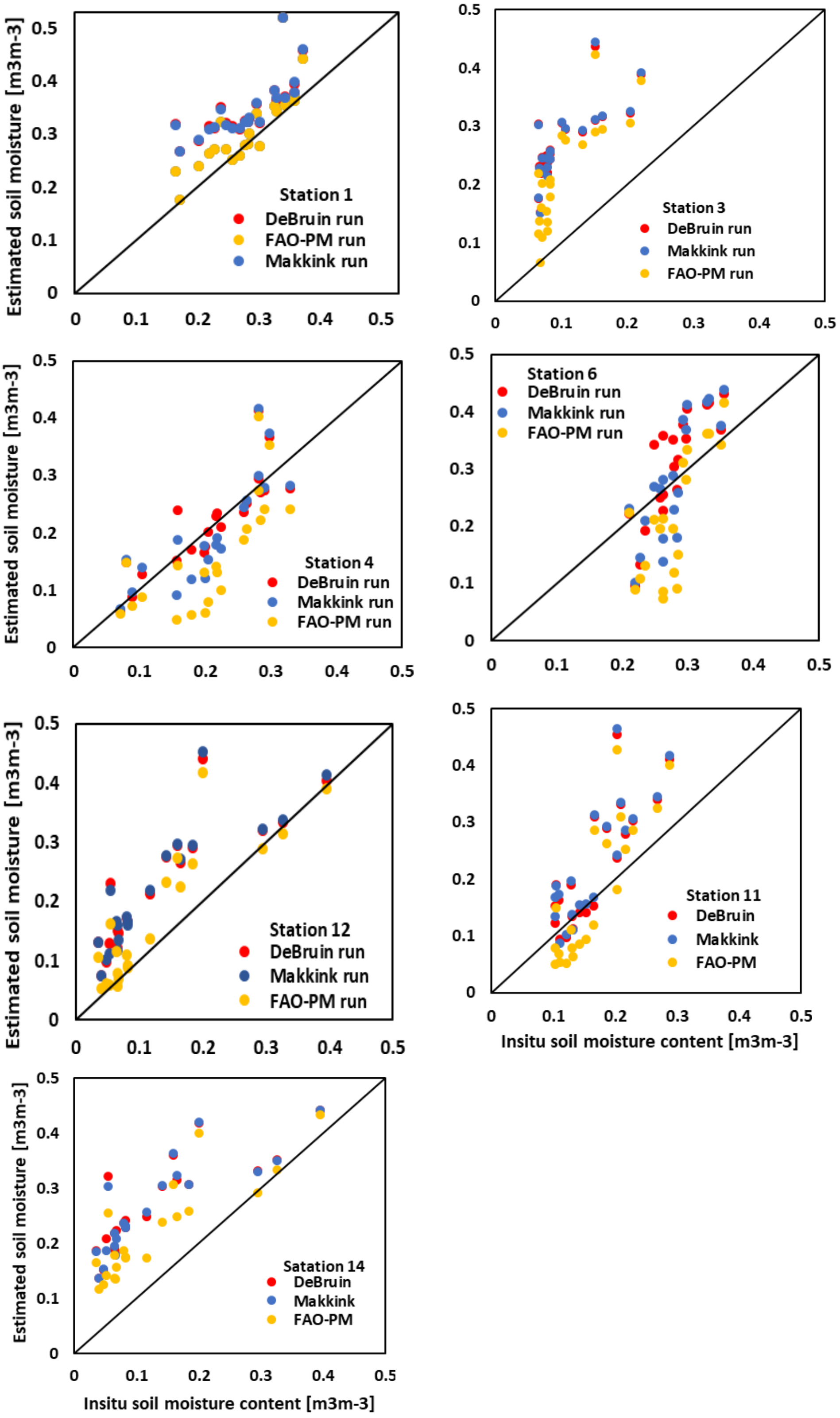


Figure 5.5 Verification result of simulated soil moisture at each station

Table 5.1: RMSE, bias, and correlation coefficient for local soil moisture based on the type of reference evapotranspiration method in Growing season and Summer period of 2018.

A. Growing Season(April 1 to October 30)

	Penman-Monteith			Makkink			DeBruin-2016		
Station	**r [-]**	**RMSE $[m^3m^{-3}]$**	**Bias $[m^3m^{-3}]$**	**r [-]**	**RMSE $[m^3m^{-3}]$**	**Bias $[m^3m^{-3}]$**	**r [-]**	**RMSE $[m^3m^{-3}]$**	**Bias $[m^3m^{-3}]$**
1	0.88	0.002	-0.03	0.74	0.079	-0.068	0.74	0.006	-0.068
3	0.82	0.125	-0.110	0.77	0.171	-0.166	0.76	0.171	-0.166
4	0.77	0.08	0.048	0.80	0.051	0.0057	0.78	0.053	-0.009
6	0.76	0.125	0.052	0.79	0.115	-0.010	0.80	0.109	-0.033
11	0.86	0.079	-0.012	0.82	0.091	-0.062	0.83	0.086	-0.055
12	0.87	0.068	-0.041	0.85	0.104	-0.089	0.85	0.103	-0.088
14	0.86	0.103	-0.091	0.84	0.145	-0.135	0.82	0.148	-0.137
Average value	**0.82**	**0.083**	**-0.026**	**0.80**	**0.108**	**-0.074**	**0.793**	**0.096**	**-0.079**

B. Summer (July 1 to August 30)

	Penman-Monteith			Makkink			DeBruin-2016		
Station	**r [-]**	**RMSE $[m^3m^{-3}]$**	**Bias $[m^3m^{-3}]$**	**r [-]**	**RMSE $[m^3m^{-3}]$**	**Bias $[m^3m^{-3}]$**	**r [-]**	**RMSE $[m^3m^{-3}]$**	**Bias $[m^3m^{-3}]$**
1	0.89	0.024	-0.01	0.93	0.076	-0.07	0.94	0.075	-0.071
3	0.49	0.177	-0.169	0.40	0.197	-0.189	0.42	0.193	-0.186
4	0.68	0.05	0.02	0.81	0.038	-0.007	0.92	0.03	-0.01
6	0.45	0.09	0.07	0.66	0.06	0.02	0.76	0.08	0.01
11	0.80	0.043	0.04	0.20	0.048	-0.03	0.10	0.040	-0.02
12	0.56	0.03	-0.032	0.81	0.08	-0.079	0.80	0.07	-0.076
14	0.67	0.09	-0.09	0.82	0.13	-0.13	0.80	0.13	-0.13
Average value	0.69	0.072	-0.02	0.66	0.08	-0.07	0.65	0.08	-0.07

6. CONCLUSION AND RECOMMENDATION

The effect of different reference evaporation formulations of Makkink, DeBruin-2016, and Penman-Monteith on the simulated soil moisture content of the root zone has been quantified. The soil moisture simulation of LHM model (MetaSWAP) has been compared to the soil moisture measurements of the Raam network in the northeast of the province of Noord-Brabant. The conclusion is based on the findings of the study (findings of the ETo estimated based on the three ETo methods, Findings of rootzone soil moisture simulated by the model and validation result). Finally, recommendations are made based on these conclusions.

6.1. Conclusion

Makkink, DeBruin-2016 and Penman-Monteith were used to estimate the time series of reference evaporation on 30 stations around the Netherlands. The result indicated significant differences between these methods. In dry conditions, Penman-Monteith tends to overestimate the reference evaporation compared to the other two methods. The Makkink and De Bruin-2016 methods systematically showed almost the same estimation values. Using IDW interpolation methods, The contribution of each station to the value at any point in the map is identical for the three methods. The differences in spatial patterns are caused by the differences in ETo values and variation of meteorological variables at the individual station.

The simulated soil moisture values for both Makkink and DeBruin method are higher than that of Penman-Monteith, except some months of the winter period (January and February). In the winter, evaporation is low compared to the rainfall; thus, the soil moisture content is more determined by the soil physical properties. Furthermore, the soil moisture simulated based on the Penman-Monteith depleted faster than the other two methods in the dry season. This was explained by more water consumption mainly due to evapotranspiration (ET) indicating that for Penman-Monteith method overestimates ET compared to the other two methods in the dry season. Again, the soil moisture reduction factor gives a lower ratio of (ETa/ETo) as the soil moisture decreases (Figure 5.4)

The root zone soil moisture result was compared with the in situ measurements at Raam soil moisture network on seven stations. The result indicated that the soil moisture simulated based on the Penman-Monteith has good agreement with the in situ observation at 20 cm depth comparing to the other two methods. The comparison of the Makkink and DeBruin reference evaporation methods has no significant differences between the measured and simulated root zone soil moisture. One could be used instead of the other since they showed almost similar performance (Table 5.1. A and B).

In general, based on the study purpose, the reference evaporation methods (Makkink, DeBruin-2016 and FAO Penman-Monteith) were correctly used to estimate ETo. Different ETo was correctly used to quantify the soil moisture at the root zone. FAO-Penman-Monteith has shown good agreement with the measurement of the Raam soil moisture network. Therefore, this research is successful.

6.2. Recommendation

In this research, the reference evaporation methods (Makkink, DeBruin and FAO Penman-Monteith) were used to estimate the reference evaporation. Because the National hydrological model(LHM) requires a gridded map of ETo which include estimates of reference evaporation at unmeasured locations, the Inverse distance weighting (IDW) interpolation method was applied to obtain the gridded data map. However, different interpolation methods exit and can provide either better or the same result. Therefore, further investigation is required; various methods such as Kriging should be applied to check whether the model simulates the same result.

This research did not focus on the effect of vegetation types on soil water content. This was excluded from the research due to the lack of observation sites with soil moisture measurements of the entire root zone for different types of vegetation. The type of vegetation influences the rate of potential evapotranspiration and the depth of the root zone, which affects the water content of the soil. The model's performance for vegetation should be studied further to determine if the model can simulate these differences.

This research based on one simulation of a dry year (2018). However, several dry years exist in the Netherlands. Therefore, a different simulation of the dry year is recommended to assess the differences between them regarding the influence of the ETo methods on the soil moisture calculated in the root zone.

LIST OF REFERENCES

Allen, R. G., Luis, S. P., RAES, D., & Smith, M. (1998). FAO Irrigation and Drainage Paper No. 56. Crop Evapotranspiration (guidelines for computing crop water requirements). *Irrigation and Drainage*, *300*(56), 300. https://doi.org/10.1016/j.eja.2010.12.001

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

Brown, J. L., Bennett, J. R., & French, C. M. (2017). SDMtoolbox 2.0: The next generation Python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses. *PeerJ*, *2017*(12). https://doi.org/10.7717/peerj.4095

Currie, D. J. (1991). Energy and Large-Scale Patterns of Animal- and Plant-Species Richness Author (s): David J . Currie Source : The American Naturalist , Vol . 137 , No . 1 (Jan ., 1991), pp . 27-49 Published by : The University of Chicago Press for The American Society, *137*(1), 27–49.

De Bruin, H. A. R., Cob, A., Trigo, I. F., & Gavilán, P. (2006). Estimates of reference crop evapotranspiration obtained from LSF SAF products derived from the Geostationary Satellite ..., (January).

de Bruin, H. A. R., Trigo, I. F., Bosveld, F. C., Meirink, J. F., Bruin, H. A. R. de, Trigo, I. F., … Meirink, J. F. (2016). A Thermodynamically Based Model for Actual Evapotranspiration of an Extensive Grass Field Close to FAO Reference, Suitable for Remote Sensing Application. *Journal of Hydrometeorology*, *17*(5), 1373–1382. https://doi.org/10.1175/JHM-D-15-0006.1

De Bruin, H. A.R., & Lablans, W. N. (1998). Reference crop evapotranspiration determined with a modified Makkink equation. *Hydrological Processes*, *12*(7), 1053–1062. https://doi.org/10.1002/(SICI)1099-1085(19980615)12:7<1053::AID-HYP639>3.0.CO;2-E

De Bruin, H. A.R., & Stricker, J. N. M. (2000). Evaporation d' une pelouse dont le sol est bien alimenté en eau. *Hydrological Sciences Journal*, *45*(3), 391–406. https://doi.org/10.1080/02626660009492337

de Bruin, Henk A.R., & Trigo, I. F. (2019). A new method to estimate reference crop evapotranspiration from geostationary satellite imagery: Practical considerations. *Water (Switzerland)*, *11*(2). https://doi.org/10.3390/w11020382

Delsman, J. R., Veldhuizen, A. A., & Snepvangers, J. (2008). Netherlands Hydrological Modeling Instrument. *Proc. of Modflow and More: Ground Water and Public Policy*, (April 2014). Retrieved from http://www.nhi.nu/documenten/Modflowandmore_Netherlands_hydrological_modeling_instrument.pdf

Feddes, R. A., Kowalik, P. J., & Zaradny, H. (1987). *Simulation of Field Water Use and Crop Yield. Pudoc, Wageningen, The Netherlands* (Vol. 129).

Hartemink, A. E., & Bakker, D. E. (2004). Classification Systems : Netherlands. *Encyclopedia of Soil Science*, 1–4. https://doi.org/10.1081/E-ESS-120022907

Hiemstra, P., & Sluiter, R. (2011). Interpolation of Makkink Evaporation in the Netherlands. *De Bilt, 2011 | Technical Report; TR-327*, 78. Retrieved from http://www.numbertheory.nl/files/report_evap.pdf

Hobbins, M. T., Wood, A., McEvoy, D. J., Huntington, J. L., Morton, C., Anderson, M., & Hain, C. (2016). The evaporative demand drought index. Part I: Linking drought evolution to variations in evaporative demand. *Journal of Hydrometeorology*, *17*(6), 1745–1761. https://doi.org/10.1175/JHM-D-15-0121.1

Hooghart, J. C. (1987). *TNO Committee on Hydrological Research: Evaporation and weather. Proceedings and information No. 39.*

Jacobs, A. F. G., & Bruin, H. A. R. de (Wageningen A. U. D. of M. D. 2, 6701 A. W. (Netherlands)). (1998). Makkink's equation for evapotranspiration applied to unstressed maize. *Hydrological Processes (United Kingdom)*. Retrieved from http://agris.fao.org/agris-search/search.do?recordID=GB1997045921

Jacobs, A. F. G., & De Bruin, H. A. R. (1998). Makkink's equation for evapotranspiration applied to unstressed maize. *Hydrological Processes*, *12*(7), 1063–1066. https://doi.org/10.1002/(SICI)1099-1085(19980615)12:7<1063::AID-HYP640>3.0.CO;2-2

Jacobs, A. F. G., Heusinkveld, B. G., & Holtslag, A. A. M. (2010). Eighty years of meteorological observations at Wageningen, the Netherlands: Precipitation and evapotranspiration. *International Journal of Climatology*, *30*(9), 1315–1321. https://doi.org/10.1002/joc.1957

KNMI. (n.d.). Climate Explorer: Found station data. Retrieved July 1, 2020, from https://climexp.knmi.nl/getdutchstations.cgi?id=someone@somewhere&TYPE=rr

KNMI. (2019). KNMI - Daggegevens van het weer in Nederland. Retrieved July 1, 2020, from https://www.knmi.nl/nederland-nu/klimatologie/daggegevens

Lu, G. Y., & Wong, D. W. (2008). An adaptive inverse-distance weighting spatial interpolation technique. *Computers and Geosciences*, *34*(9), 1044–1055. https://doi.org/10.1016/j.cageo.2007.07.010

McDonald, M. G., & Harbaugh, A. W. (1988). *A modular three-dimensional finite-difference ground-water flow model. Techniques of Water-Resources Investigations*. https://doi.org/10.3133/twri06A1

Muhammad, M. K. I., Nashwan, M. S., Shahid, S., Ismail, T. bin, Song, Y. H., & Chung, E. S. (2019). Evaluation of empirical reference evapotranspiration models using compromise programming: A case study of Peninsular Malaysia. *Sustainability (Switzerland)*, *11*(16). https://doi.org/10.3390/su11164267

Pereira, A. R., & Pruitt, W. O. (2004). Adaptation of the Thornthwaite scheme for estimating daily reference evapotranspiration. *Agricultural Water Management*, *66*(3), 251–257. https://doi.org/10.1016/J.AGWAT.2003.11.003

Pereira, L. S., Allen, R. G., Smith, M., & Raes, D. (2015). Crop evapotranspiration estimation with FAO56: Past and future. *Agricultural Water Management*, *147*, 4–20. https://doi.org/10.1016/j.agwat.2014.07.031

Pezij, M., Augustijn, D. C. M., Hendriks, D. M. D., Weerts, A. H., Hummel, S., van der Velde, R., & Hulscher, S. J. M. H. (2019). State updating of root zone soil moisture estimates of an unsaturated zone metamodel for operational water resources management. *Journal of Hydrology X*, *4*, 100040. https://doi.org/10.1016/J.HYDROA.2019.100040

Robinson, D. A., Campbell, C. S., Hopmans, J. W., Hornbuckle, B. K., Jones, S. B., Knight, R., … Wendroth, O. (2008). Soil Moisture Measurement for Ecological and Hydrological Watershed-Scale Observatories: A Review. *Vadose Zone Journal*, *7*(1), 358–389. https://doi.org/10.2136/vzj2007.0143

Schuurmans, J. M., & Droogers, P. (2010). Penman-Monteith reference crop-evapotranspiration: inventarisation avaibility and possibilities for regionalisation (in Dutch). *STOWA Reports*, 50.

Song, X., Lu, F., Xiao, W., Zhu, K., Zhou, Y., & Xie, Z. (2019). Performance of 12 reference evapotranspiration estimation methods compared with the Penman-Monteith method and the potential influences in northeast China. *Meteorological Applications*, *26*(1), 83–96. https://doi.org/10.1002/met.1739

van Dam, J. C., Groenendijk, P., Hendriks, R. F. A., & Kroes, J. G. (2008). Advances of Modeling Water Flow in Variably Saturated Soils with SWAP. *Vadose Zone Journal*, *7*(2), 640–653. https://doi.org/10.2136/vzj2007.0060

Van Walsum, P. E. V., & Veldhuizen, A. A. (2011). Integration of models using shared state variables: Implementation in the regional hydrologic modelling system SIMGRO. *Journal of Hydrology*, *409*(1–2), 363–370. https://doi.org/10.1016/j.jhydrol.2011.08.036

van Walsum, P. E. V., & Groenendijk, P. (2008). Quasi Steady-State Simulation of the Unsaturated Zone in Groundwater Modeling of Lowland Regions. *Vadose Zone Journal*, *7*(2), 769–781. https://doi.org/10.2136/vzj2007.0146

Veldhuizen, A. A., & Groenendijk, P. (2016). Simgro 7.2.27 Theory and model implementation. *Alterra-Report 913.1*, 1–93.

Winter, T. C., Rosenberry, D. O., & Sturrock, A. M. (1995). Evaluation of 11 Equations for Determining Evaporation for a Small Lake in the North Central United States. *Water Resources Research*, *31*(4), 983–993. https://doi.org/10.1029/94WR02537

Wösten, H., De Vries, F., Hoogland, T., Massop, H. T. L., Veldhuizen, A. A., Vroon, H., … Bolman, A. (2013). BOFEK2012, de nieuwe, bodemfysische schematisatie van Nederland [BOFEK2012; the new soil physical schematization of the Netherlands, in Dutch]. *Alterra Report*, *2387*, 92. Retrieved from http://edepot.wur.nl/247678

Wu, W., Geller, M. A., Dickinson, R. E., Wu, W., Geller, M. A., & Dickinson, R. E. (2002). The Response of Soil Moisture to Long-Term Variability of Precipitation. *Http://Dx.Doi.Org/10.1175/1525-7541(2002)003<0604:TROSMT>2.0.CO;2*. https://doi.org/10.1175/1525-7541(2002)003<0604:TROSMT>2.0.CO;2

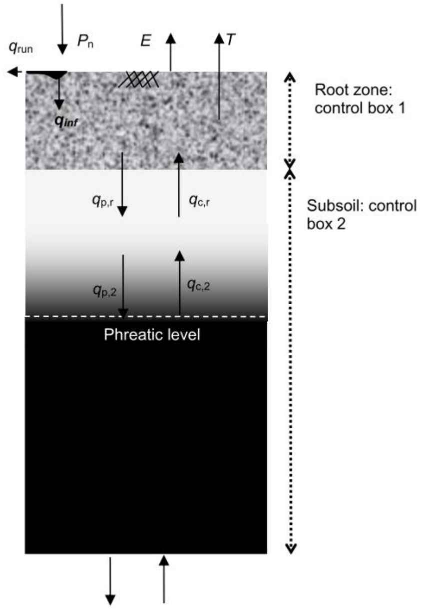
Appendix 1: Meteorological information of the selected stations

This table shows the geographical and mean annual meteorological information of the selected stations.

Station	Longitude (X)	Latitude (Y)	Altitude (m)	Air temperature (^{0}C day^{-1})	Relative Humidity (% day^{-1})	Wind speed (ms^{-1}day^{-1})	Global radiation (Wm^{-2})
Arcen	6.197	51.498	1.2	11.79	73.60	2.71	133.82
Maastricht	5.762	50.906	-3.3	11.8	73.70	3.72	136.47
Ell	5.763	51.198	-2.4	11.52	75.53	3.32	134.61
Volkel	5.707	51.659	0.7	11.52	75.09	3.50	135.87
Eindhoven	5.377	51.451	8.5	11.75	73.83	3.58	143.95
Herwijnen	5.146	51.859	1.9	11.37	77.25	3.69	134.71
Gilze-Rijen	4.936	51.566	-1.3	11.71	74.69	3.61	133.58
Cabauw	4.926	51.97	-3.7	11.40	77.67	4.11	134.89
Rotterdam	4.447	51.962	1.2	11.53	77.62	4.13	131.98
Hoek Van Holland	4.122	51.992	48.2	11.52	79.45	6.82	133.77
Westdorpe	3.861	51.226	2.9	11.64	77.26	3.91	132.70
Vlissingen	3.596	51.442	3.6	11.87	77.81	5.91	136.97
Twenthe	6.891	52.274	15.8	11.17	74.73	3.50	133.30
Nieuw Beerta	7.15	53.196	5.2	10.56	78.41	4.76	130.9
Hupsel	6.657	52.069	29.1	11.30	75.17	3.2	135.61
Eelde	6.585	53.125	-0.2	10.66	77.52	3.96	127.15
Hoogeveen	6.574	52.75	34.8	10.78	77.57	3.89	132.86
Heino	6.259	52.435	8	10.99	77.11	2.9	132.86
Lauwersoog	6.2	53.413	1.7	11.0	79.82	6.09	127.28
Deelen	5.873	52.056	11.9	11.24	75.41	3.6	130.79
Marknesse	5.888	52.703	19.2	11.79	73.60	2.71	133.82
Leeuwarden	5.752	53.224	-4.3	10.67	79.62	4.54	129.22
Lelystad	5.52	52.458	-0.7	11.31	76.92	4.2	131.84
Stavoren	5.384	52.898	14.9	10.80	80.63	5.39	132.28
De Bilt	5.18	52.1	0.7	11.40	76.32	3.36	129.80
Hoorn (Terschelling)	5.346	53.392	22	10.5	83.27	6.05	132.01
Berkhout	4.979	52.644	30	10.9	80.30	4.71	132.60
Schiphol	4.79	52.318	114.3	11.50	76.74	4.80	131.66
De Kooy	4.781	52.928	19.5	11.09	80.21	5.2	132.71

Appendix 2: Unsaturated zone boxes and water balance equation for rootzone

This appendix represent the unsaturated boxes(figure) and equation ($Vcr_{\_r}$) represent the water balance for the rootzone (box1)



$$Vcr_{\_r} = -[q_{inf} + \mathbf{decS1} + \mathbf{Ebs} + ET_a + \mathbf{qmr}]$$

Where,

q_{inf} : Inflitation on the soil surface [m^3/m^2]

decS1: The decrease of water storage in the rootzone box 1 [m^3/m^2]

Ebs: Evaporation of bare soil [m^3/m^2]

ET_a : Total actual transpiration [m^3/m^2]

qmr : Flow-through bottom of box 1, root zone [m^3/m^2]

$Vcr_{\_r}$: Water balance [m^3/m^2]

Figure: Schematic view of the unsaturated zone into several control boxes. Explanation of symbols: $\mathbf{P_n}$: net precipitation; $\mathbf{q_{inf}}$: infiltration; $\mathbf{q_{run}}$: surface runoff; **E**: evaporation of bare (Ebs) soil; T=:total actual transpiration (ETa); $\mathbf{q_p}$: percolation; $\mathbf{q_c}$: capillary rise (Veldhuizen & Groenendijk, 2016)