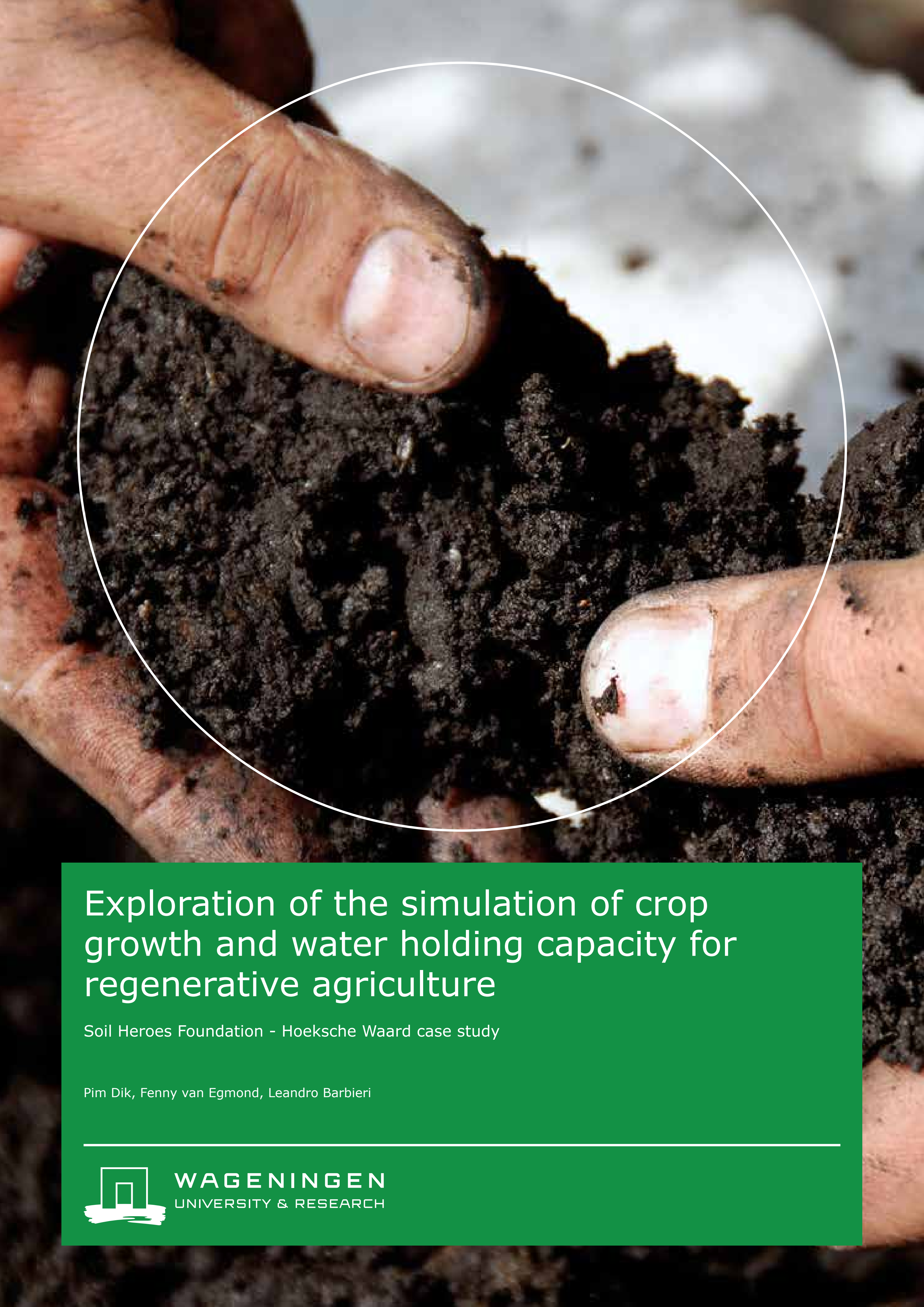

Exploration of the simulation of crop growth and water holding capacity for regenerative agriculture

Soil Heroes Foundation - Hoeksche Waard case study

Pim Dik, Fenny van Egmond, Leandro Barbieri

WAGENINGEN
UNIVERSITY & RESEARCH

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Pim Dik[1], Fenny van Egmond[1], Leandro Barbieri[2]

1 Wageningen Environmental Research
2 Soil Heroes Foundation

This report is written by Wageningen Environmental Research and commissioned by Stichting Soil Heroes Foundation.

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Soil Heroes has been initiated by farmers, for farmers. The initiative is based on first-hand experiences with the transition to regenerative practices and the observation of the results (improved soil health and soil structure, increased organic matter content and soil biology, less artificial inputs and pesticides, higher resilience and mitigation against extreme weather conditions, higher (quality) yields) and driven by the need to create a large-scale change in the way the world is farming. In this report the simulation of several measures connected to regenerative agriculture is presented. This researches focusses on water availability, runoff and drainage to canals.

Keywords: Soil water, Regenerative Agriculture, SWAP, Crop, Water availability, Drainage, Runoff.

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date: April, 21, 2022

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name: Mirjam Hack

date: November, 23, 2022

The Soil Heroes foundation

Soil Heroes wants to approach farming in balance with nature, contributing to:

- **Improved soil health** by restoring natural processes, based on a balanced cycle.
- **Improved position of farmers** through supporting them in the transition to regenerative farming and to offer them additional business models and income flows via the Soil Heroes Fairchain platform.
- **Improved perspective** for next generation farmers by making a shift from low margins and high volumes to high value and quality produce.
- **Improved health and taste** by building soils and restoring natural processes.

In order to substantiate the framework of thinking, processes and models behind the platform, a monitoring program of soil quality parameters was designed and started on a reference farm in Zuid-Holland, The Netherlands. Since 2018 this farm in Hoeksche Waard has been set up as a farm to showcase regenerative farming and to compare farm management on fields which have been under either regenerative or conventional management for several years. The fields of the showcase farm are in various stages of transition from conventional to regenerative farming, which allows a good analysis between those practices. A set of farm fields has been under regenerative agriculture since 2010, some fields were shifted to regenerative agriculture at the start of the experiment, and some fields are still under conventional practices.

Summary

This report describes the analysis of the water availability for crops and the change of runoff and drainage fluxes to canals. Fields of both regenerative and conventional agriculture are studied. The simulation model SWAP (Kroes et al., 2017) is used to analyze the soil water dynamics. Collected data on soil properties and water contents are used to parameterize and calibrate the model. The model is used to determine the effect of several measures connected to regenerative agriculture. This research focusses on water availability, runoff and drainage to canals. For the farmers the water availability is of major importance to the development of the crop. For the waterboard the runoff and drainage fluxes to the canals are crucial. Regenerative agriculture can enhance several key factors. These are extra organic matter, enlarged rooting depth, less soil compaction, higher infiltration capacity, and increased permeability. This report describes the analysis of the contribution of these key factors and their effect on water availability for the crops and the effects on the water system.
In a separate report the analysis of measured data on for instance soil compaction and soil organic carbon will be presented[1]. Another report contains a literature study on Regen Ag (Regenerative Agriculture) and the modelling of soil organic carbon[2].

The scenario analyses give insight in the effects on several metrics.
For the farmers the metric Transpiration is chosen. Transpiration is linked to the yield: the higher the transpiration the higher the yield, also leaves are greener and less irrigation is necessary.
For the waterboard the metrics Drainage and Runoff are crucial: especially during high rainfall events. Drainage and Runoff determine the amount of water that flows to the canals.

In Table 1 the results of the scenario-analysis is presented: in Table 2 the 5 point scale is presented.

Table 1 *Effects of measures on Transpiration and Runoff/Drainage*

Measure	Effect on Transpiration	Effect on Runoff	Effect on Drainage
Extra organic matter	+	+[1] ?	0/+[1] ?
Enlarged rooting depth by less soil compaction	++	0[2]	0/+[2]
Higher infiltration capacity	0	0/+[2]	0
Increased permeability (till 80 cm-ss)	0	0	0
Lower bulk density	-/+ ?	0 ?	0/+ ?

? uncertain: due to uncertainties in the method

[1] not calculated

[2] dependent on the soil

---

[1] This report will appear in 2023.

[2] This report will appear in 2022.

Table 2 *Quantification to a 5 points scale of the effect on Transpiration and Runoff/Drainage*

Classification	Effect on Transpiration (mm/y)	Effect on Runoff (mm/d)	Effect on Drainage (mm/d)
++	> 15	<-5	<-5
+	5 till 15	-5 till -2	-5 till -2
0	-5 till 5	-2 till 2	-2 till 2
-	-15 till -5	2 till 5	2 till 5
--	<-15	> 5	> 5

For transpiration (linked to the yield) the most sensitive parameter is the rooting depth. The effective rooting depth depends on soil compaction, the presence of macropores and the presence of fungi. Fungi can help crops to get more water: it increases the depth to which the roots can extract water. Regen Ag influences all these dependencies in a positive way.

For runoff the most sensitive parameters are soil texture and structure and as a result of that the infiltration capacity. The soil texture and structure determine the air-filled porosity at different degrees of wetness. This determines the water holding capacity. This parameter determines the amount of runoff in combination with the infiltration capacity. The simulations show a low runoff in the reference situation. As a result the decrease of runoff at higher infiltration capacities is quite low.

For drainage fluxes to the canals the scenario’s show a varied picture. There can be a positive effect due to regenerative agriculture, but it depends on the circumstances (wet or dry soil).

Overall extra organic matter, enlarged rooting depth, less soil compaction, higher infiltration capacity, and increased permeability will have a neutral or positive effect on transpiration, runoff and drainage. All the effects of Regen Ag will occur at the same time. So overall it is expected that regenerative agriculture will have positive effects on 1) water availability for the crops and 2) reduction of runoff and drainage fluxes to the canals. These results are in line with the farmer’s observations (2022): “In general we experience from the field and farm that the regenerative plots show better results (especially the dry summer of 2022) in yields (potato test), soil texture/structure (root development, smell, colour, moisture, how long the plants survive/have green leaves) and input (irrigation). For example we see that our soy beans and brown beans didn’t need irrigation at all despite this hot and dry summer.”

1 Introduction

1.1 General

Soil Heroes was started in 2017 from the firm belief that (re-)building soils through the practices of regenerative agriculture (Regen Ag) is a principal solution for the current degradation of agricultural soils all over the world and that the transition to regenerative (organic) farming practices will structurally sustain and improve the world's capacity to provide healthy, nutritious and tasty food for a growing world population. Part of this belief is that regenerative farming also provides answers to climate change and to biodiversity and nature loss, resulting from an agricultural system that is broken.

Soil Heroes has been initiated by farmers, for farmers. The initiative is based on first-hand experiences with the transition to regenerative practices and the observation of the results (improved soil health and soil structure, increased organic matter content and soil biology, less artificial inputs and pesticides, higher resilience and mitigation against extreme weather conditions, higher (quality) yields) and driven by the need to create a large-scale change in the way the world is farming.

Soil Heroes wants to approach farming in balance with nature, contributing to:

- **Improved soil health** by restoring natural processes, based on a balanced cycle with as essential elements: 1) organic matter, improving soil structures and providing suitable conditions for the roots, 2) improved mineral content, as essential inputs for the plants and natural processes and as a key element for healthy and tasty produce and food (from farm to fork) and 3) improved soil biology, supporting essential natural processes. Improved organic matter content and related to that, Carbon sequestration plays an important role in that process.
- **Improved position of farmers** through supporting them in the transition to regenerative farming and to offer them additional business models and income flows via the Soil Heroes Fairchain platform.
- **Improved perspective** for next generation farmers by making farmers part of the solution rather than the problem and to turn around the downwards spiral farmers are locked in today (majority of the risks reside with the farmers, whereas profits are being made further up in the value chain) and making a shift from low margins and high volumes to high value and quality produce.
- **Improved health and taste** by building soils and restoring natural processes; essential elements and building blocks will become available in the soil again and improved biology will make these available for plant life; leading to produce and end products with higher nutrients density and as a result, more healthy and tasty food.

In order to substantiate the framework of thinking, processes and models behind the platform, a monitoring program of soil quality parameters was designed and started on a reference farm in Zuid-Holland, The Netherlands. As of 2018 this farm in Hoeksche Waard has been set up as an experience farm to showcase regenerative farming and to compare farm management on fields which have been managed years under either regenerative, or conventional management. The fields of the experience farm are in various stages of the transition from conventional to regenerative farming, which allows a good analysis between those practices. A set of farm fields have been under regenerative agriculture since 2010, some fields which were shifted to regenerative agriculture at the start of the experiment, and some fields are still under conventional practices. This variety across stages of transition creates an ideal set-up for field experiments. The experimental design has been set up by Wageningen University to monitor and analyse data through indicators which relate to soil health.

Throughout the following 2 years the experiment monitored biophysical parameters (carbon content, water content, soil structure, etc.) as well as more qualitative parameters such as biodiversity, on fields under either regenerative or conventional practices.

A detailed description of Soil Heroes' interpretation of regenerative agriculture in the Netherlands is given in Soil Heroes, 2022.

This report describes the analysis of the water availability for crops and the change of the runoff in the fields. Both regenerative and conventional agriculture are studied and compared to each other. The simulation model SWAP (Kroes et al., 2017) is used to analyze the effects. In this study collected data on soil properties and water contents is used to parameterize and calibrate the model.

1.2 Objective

The objective of this report is to compare regenerative agriculture to conventional agriculture on moisture supply capacity, drainage to canals and runoff.

1.3 Approach

The objective can be translated to this question: does Regen Ag enhance the water availability in comparison to conventional agriculture and what are the effects of this transformation on drainage and runoff?

In the field several parameters are measured, such as: soil profile description, moisture content, bulk density, penetration resistance, organic matter content, water retention and permeability characteristics. These measurements give an indication of parts of the water-soil-crop system. To analyze the system as a whole and to answer the questions related to the objective a model is used. The SWAP-WOFOST model is chosen for this exploration (Kroes et al., 2017). The sites with the different treatments are modelled separately. The challenge is to attribute the differences in the simulations to the management of Regen Ag and to discriminate these from differences in site specific characteristics (in soil composition and compaction, surface water levels). As will be shown in this report the sites do differ in soil type. Comparing the fields to determine the effect of Regen Ag is therefore not feasible. This report investigates for all fields with the model the possible effects of changes in the soil system as a result of Regen Ag. For instance, Regen Ag aims to less soil compaction in comparison to conventional agriculture and as a result a greater rootable depth. Simulations help to clarify the effect on the transpiration, runoff and other water balance components.

In a separate report the analyses of changes in measured soil characteristics will be described and analyzed. For instance the changes in time for the organic material content will be described and also the penetrologger data will be analyzed in its development in time. Together with this explorative report this will give insight in the changes in water availability.

Questions to be answered:
1. What is the effect of Regen Ag in comparison to Conventional Agriculture (moisture supply capacity, drainage and runoff)?
2. Can SWAP simulations help with the analysis/interpretation of measured data?

In this report the main activities are ordered as follows:
- Analysis of data regarding the water and soil system (Chapter 2)
  Data is available on among others soil physical properties, water contents, soil compaction and groundwater level measurements.
- SWAP-WOFOST simulation (Chapter 3)
  Scenario analysis soil-water-crop-system for several changes in conditions affected by Regen Ag.
- Synthesis and conclusions (Chapter 4).

2 Data

2.1 Location

The study area is located in the Hoeksche Waard in the western part of the Netherlands. The agricultural fields are located at three different locations in this area (Figure 2-1):

- regenerative fields for a long time (LT)
  These fields are located in the North
- regenerative fields since 2015, for a short time (ST)
  These fields are located in the West
- conventional agriculture fields (CA)
  These fields are located in the South (CA group)

The areas of the fields are given in Table 2-1.

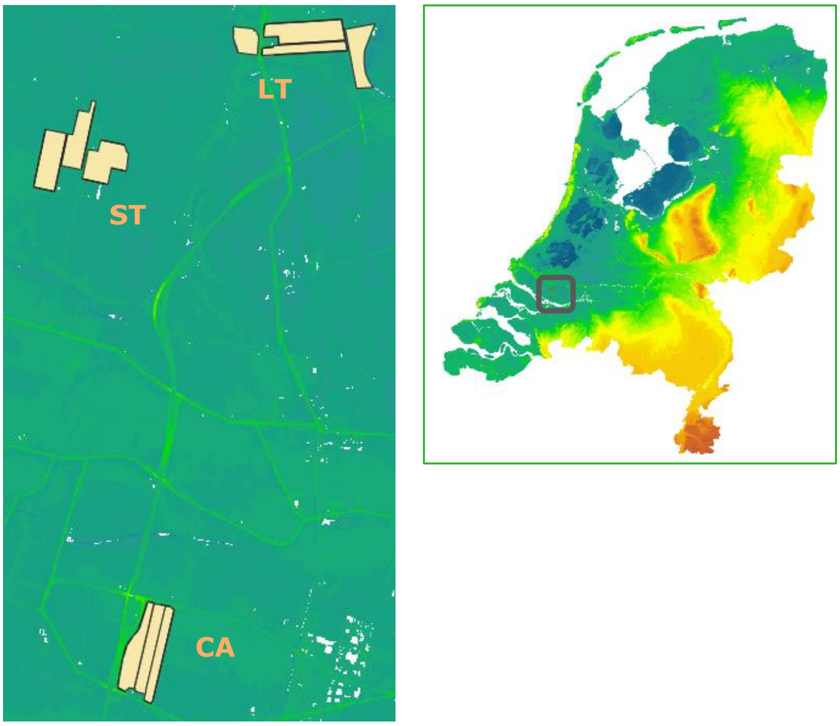


Figure 2-1 *Locations of the field experiments*

Table 2-1 *Fields and area*

Fields	**Area (ha)**
LT.1	6
LT.2	17.6
LT.3	9.1
LT.4	11.7
ST.1	14.5
ST.2	11.3
ST.3	14
CA.1	13.5
CA.2	11
CA.3	10

2.2 Meteorological data

Figure 2-2 shows the precipitation and (Makkink) reference evaporation of Rotterdam station for the years 2011 to 2020. This is the nearest KNMI station (Royal Dutch Meteorological Institute). The rainfall surplus in the summer (or better evaporation surplus) has often been negative over the last 10 years, but also the years 2003 and 2009 were occasionally dry, even drier than in recent years (Figure 2-3). Recent years seem to indicate a trend to more summer droughts.

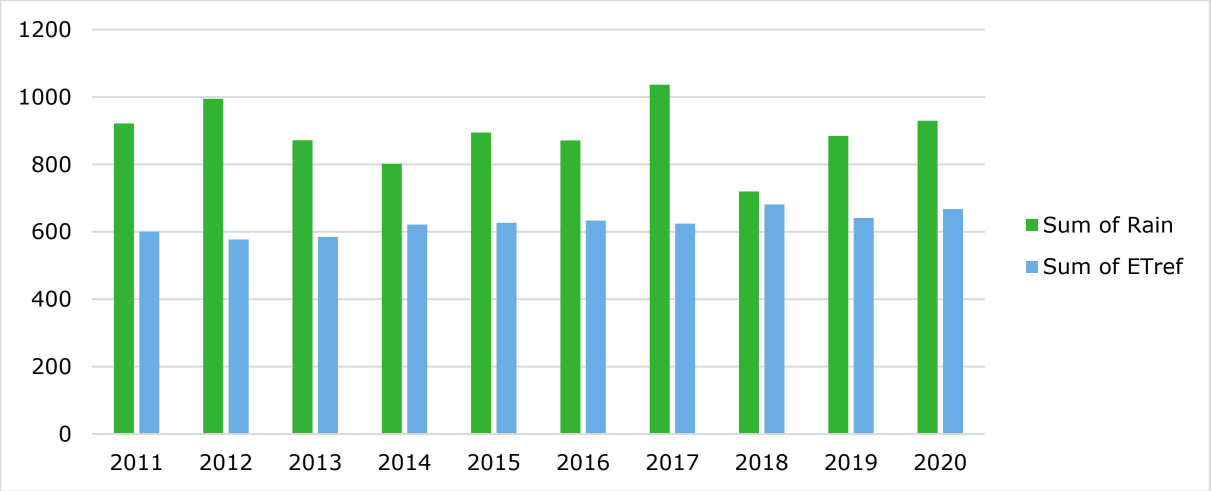


Figure 2-2 *Precipitation and reference crop evaporation per year at Rotterdam meteostation (in mm)*

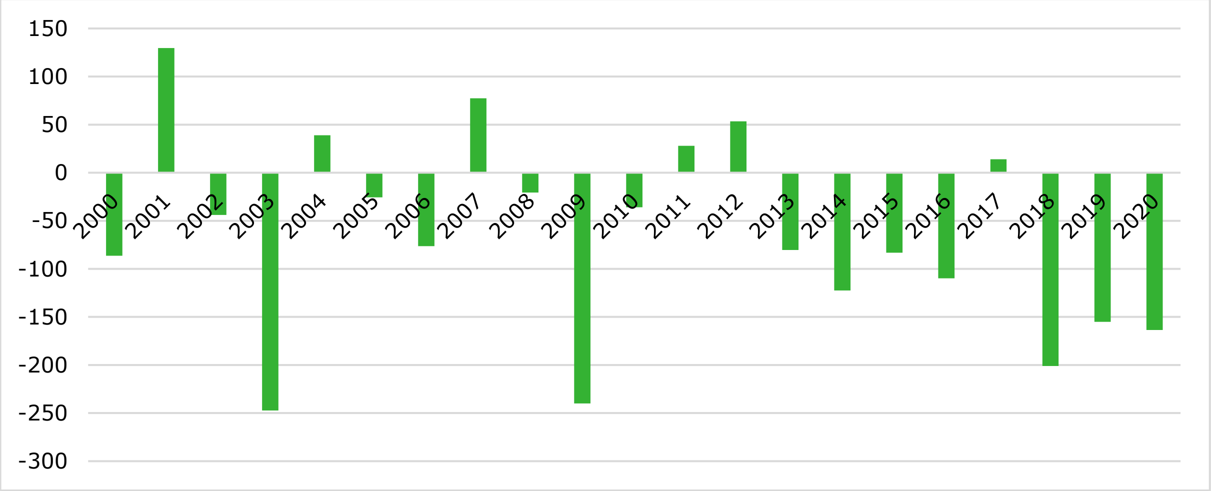


Figure 2-3 *Summer precipitation surplus per year at Rotterdam meteostation (in mm)*

2.3 Surface level

In Table 2-2 the variation in surface level is displayed for fields. The ground level differences are quite limited.

Table 2-2 *Surface level (in reference to the Mean Sea Level, MSL)*

Location	Mean level (m+MSL)	Range (m+MSL)	Scatter (m)
LT	-0.01	-0.17 to +0.15	0.32
ST	-0.21	-0.32 to -0.10	0.22
CA	0.08	-0.16 to +0.32	0.48

2.4 Soil description

2.4.1 BOFEK (general available data)

The soil physical units map BOFEK2020 (Heinen et al., 2021) is based on the soil map of the Netherlands and the database of soil physical properties, i.e., water retention and hydraulic conductivity. For the Netherlands a total of 79 units have been distinguished. The BOFEK units can be used in numerical simulations for the water in the unsaturated zone. To every soil layer soil physical properties of the Staring series are assigned (Heinen et al., 2020).

In Figure 2-4 the BOFEK units of the different parcels are displayed. In Table 2-3 the areas are shown.

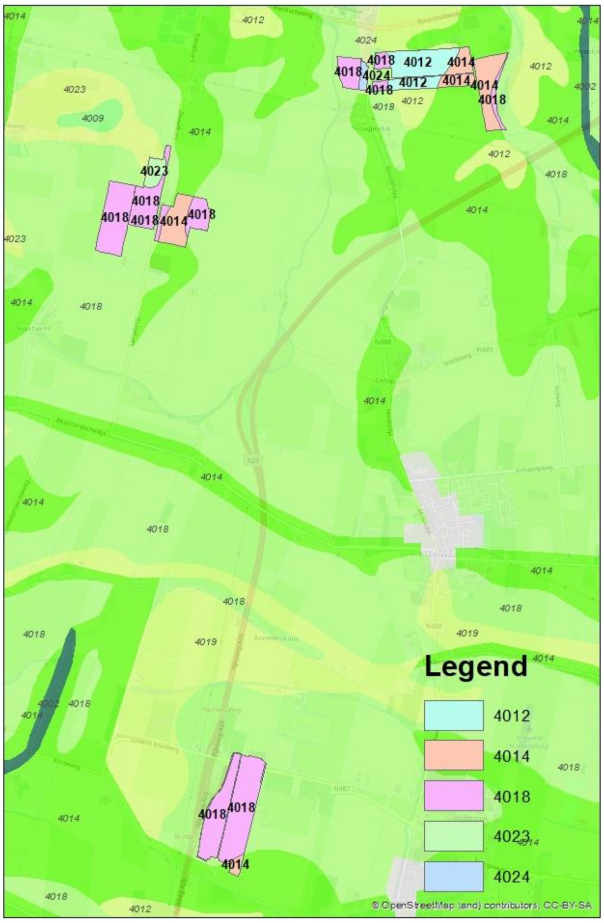


Figure 2-4 *BOFEK-units (in green the base map of the BOFEK units)*

Validation plots have 5 BOFEK units: 4012, 4014, 4018, 4023, 4024: for the profile description see Table 2-3. Units 4023 and 4024 contribute little to the total area. The soil profiles are given in Figure 2-5. The BOFEK unit with the largest area is unit 4018. More information on the expected composition of the soil layers of BOFEK 4018 is given in Table 2-4.

Table 2-3 *Description BOFEK units (Heinen, 2021)*

BOFEK	Description	Dominant soil unit	Area (ha)
4012	Clay on sand (marine)	Mn82A	17
4014	Clay on homogeneous profile (sometimes with peat)	Mn35A (agricultural)	27
4018	Heavy sablon homogeneous profile (sometimes with peat)	Mn25A	74
4023	Light sablon homogeneous profile	Mn15A (grass)	4
4024	Sablon on sand	Mn22A	2

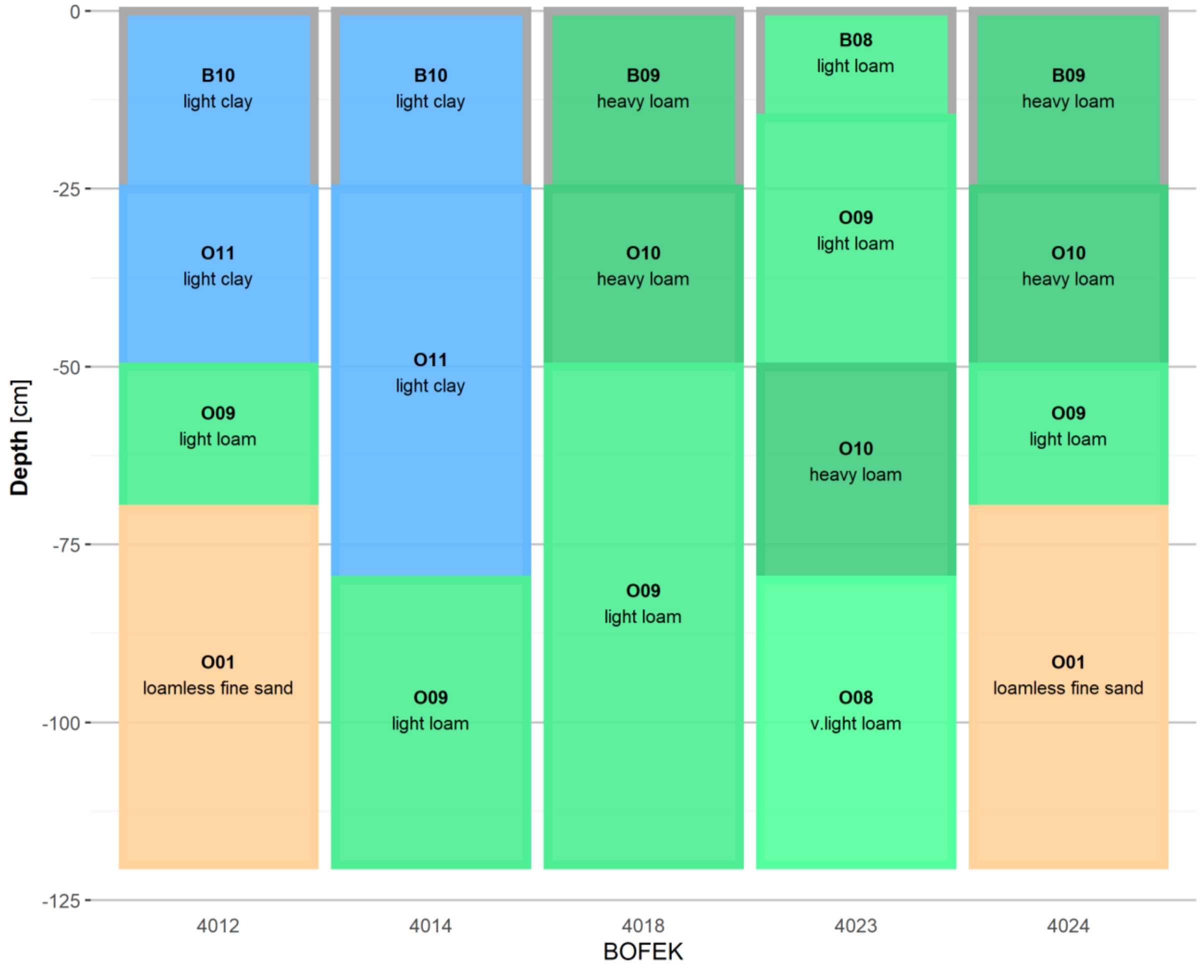


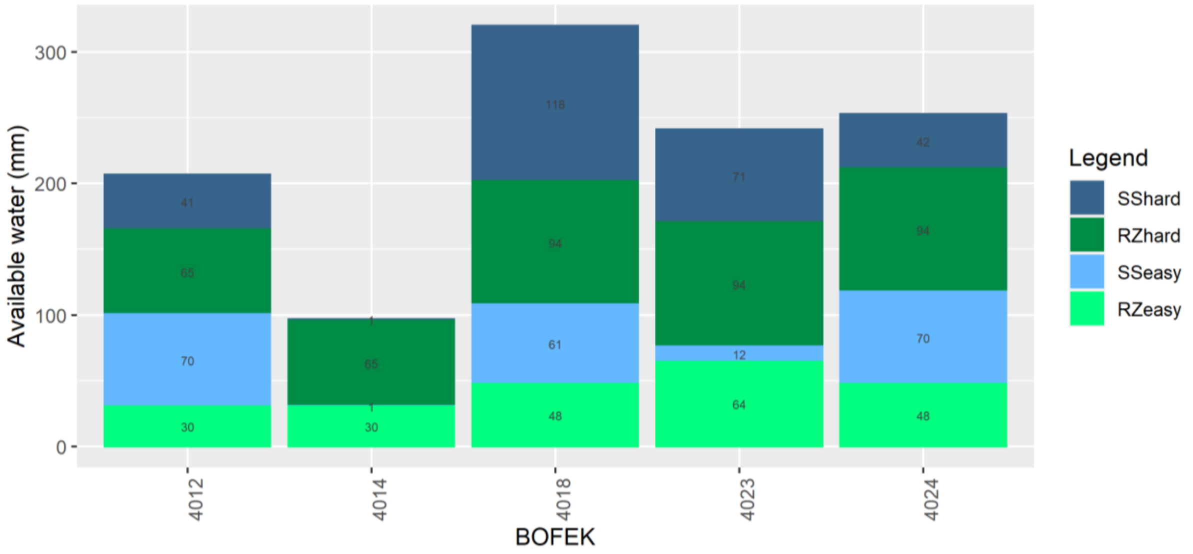
Figure 2-5 *BOFEK units soil profiles*

Table 2-4 *Profile description BOFEK 4018: dominant profile unit 90115270*

Soil physical unit	Top cm-ss	Bottom cm-ss	Bulk density kg/m³	Clay fraction	Silt fraction	Sand fraction	Org. matter fraction	pH
B09	0	25	1406.322	0.22	0.43	0.35	0.02	7.4
O10	25	50	1435.383	0.22	0.43	0.35	0.012	7.4
O09	50	120	1537.758	0.14	0.34	0.52	0.006	7.4

The BOFEK-profiles are characterized by their water availability (Figure 2-6). As can be seen the water availability differs quite a lot per profile, which is due to the soil hydraulic properties. The heavier the clay in the soil is the lower the water availability (lowest 100 mm and highest 320 mm). As can be concluded from the BOFEK information there is a natural variation in soil composition over the fields.

In Figure 2-7 profile 4018 is given together with the water content and the pressure head at a capillary flux of 1 and 2 mm/d.



SShard: Hardly available capillary water, flux 2 till 1 mm/d (dark blue)
RZhard: Hardly available water root zone, pF 1.85 till 2.6 (dark green)
SSeasy: Easily available capillary water, field capacity till a flux of 2 mm/d (light blue)
RZeasy: Easily available water root zone, pF 2.6 till 4.2 (light green)

Figure 2-6 *Water availability per profile (rootzone thickness 50 cm)*

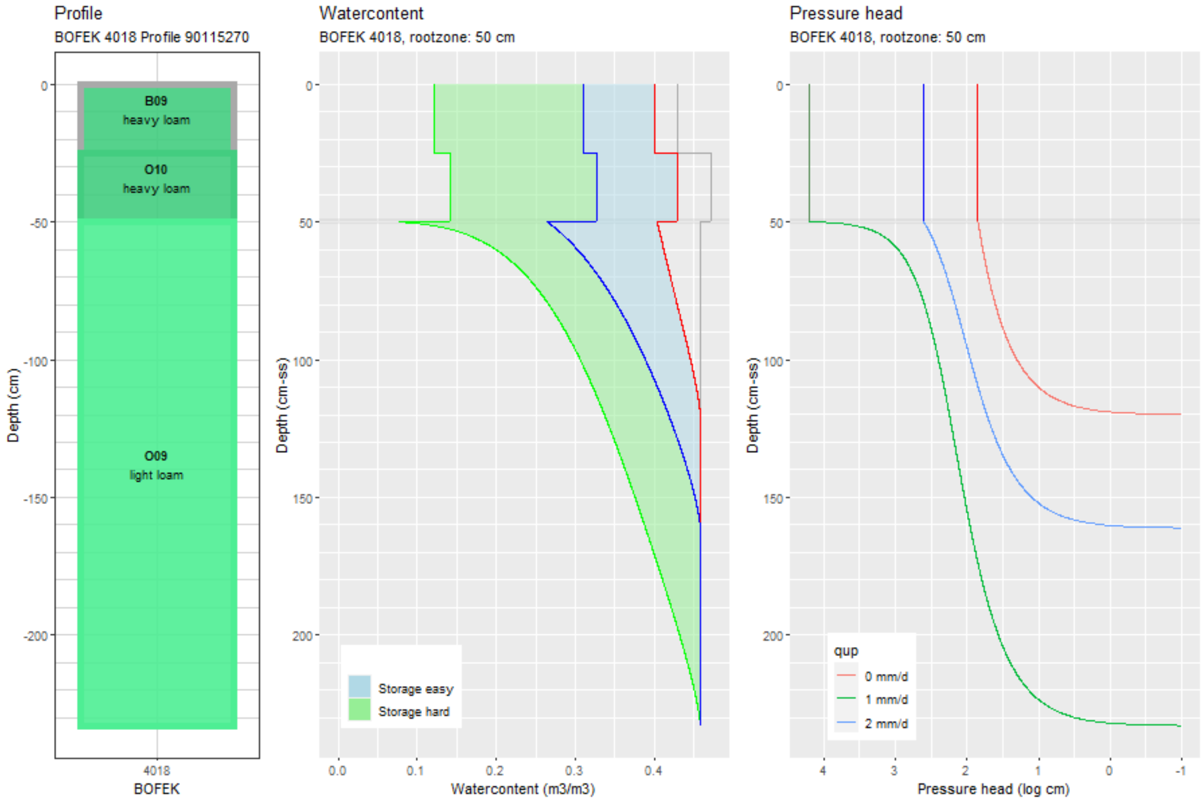
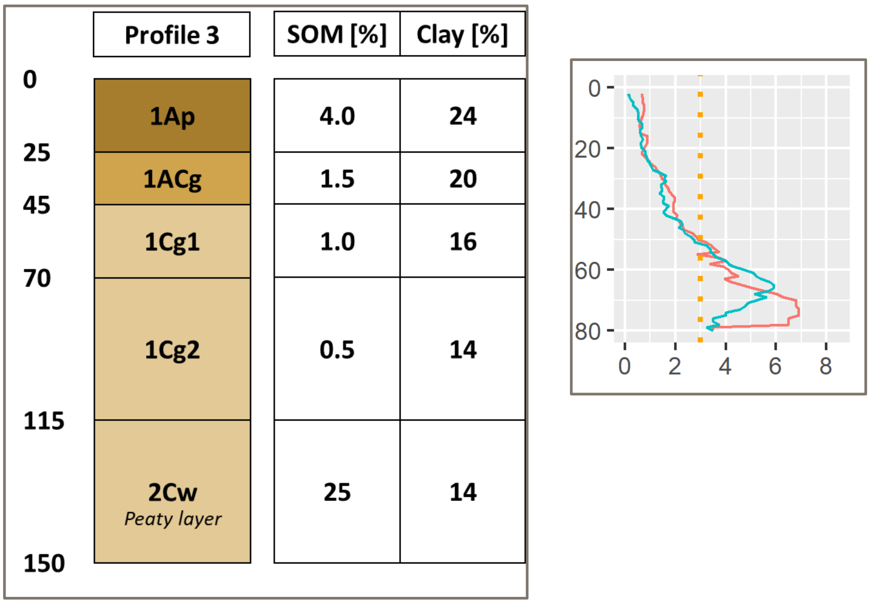


Figure 2-7 *Water content in profile 4018 (rootzone thickness 50 cm)*

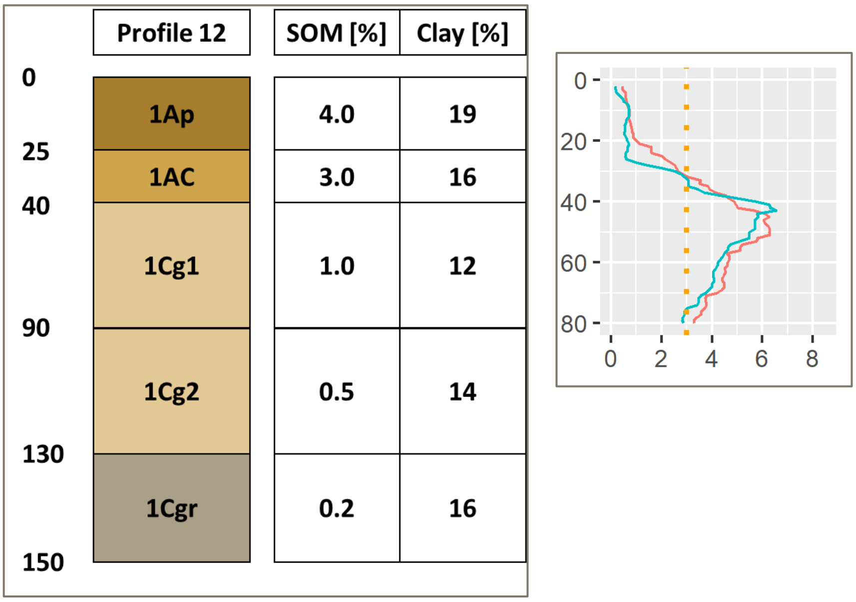
2.4.2 Soil description (local data)

Soil hydraulic parameters (SHP) are measured for one location at each management site (LT, ST, CA). For the three locations soil samples have been taken to derive the soil hydraulic parameters in the lab. The samples were taken at a depth of about 15 and 50 cm -ss. In Figure 2-8 till Figure 2-10 the profile descriptions for each of these locations are given.



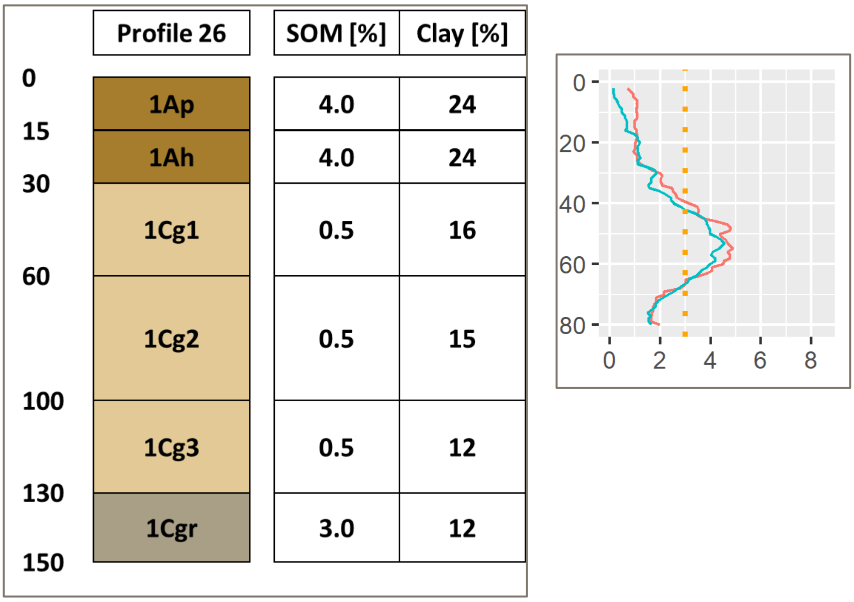
	Profile 3	SOM [%]	Clay [%]
0	1Ap	4.0	24
25	1ACg	1.5	20
45	1Cg1	1.0	16
70	1Cg2	0.5	14
115	2Cw *Peaty layer*	25	14
150			

Figure 2-8 *Profile description, according to the Dutch Soil Classification system, for location 3 in the LT group with field estimates of Soil Organic Matter and Clay percentage estimates per horizon. On the y axis soil depth from soil surface is depicted. To the right the penetrologger measurements are depicted with penetration resistance in MPa on the x axis. Red is 2019, blue is 2020, the orange dotted line represents the 3 MPa border above which we expect difficulties for roots to penetrate this layer.*



	Profile 12	SOM [%]	Clay [%]
0	1Ap	4.0	19
25	1AC	3.0	16
40	1Cg1	1.0	12
90	1Cg2	0.5	14
130	1Cgr	0.2	16
150			

Figure 2-9 *Profile description, according to the Dutch Soil Classification system, for location 12 in the CA group with field estimates of Soil Organic Matter and Clay percentage estimates per horizon. On the y axis soil depth from soil surface is depicted. To the right the penetrologger measurements are depicted with penetration resistance in MPa on the x axis. Red is 2019, blue is 2020, the orange dotted line represents the 3 MPa border above which we expect difficulties for roots to penetrate this layer.*



Profile 26	SOM [%]	Clay [%]
1Ap	4.0	24
1Ah	4.0	24
1Cg1	0.5	16
1Cg2	0.5	15
1Cg3	0.5	12
1Cgr	3.0	12

Figure 2-10 *Profile description, according to the Dutch Soil Classification system, for location 26 in the ST group with field estimates of Soil Organic Matter and Clay percentage estimates per horizon. On the y-axis soil depth from soil surface is depicted. To the right the penetrologger measurements are depicted with penetration resistance in MPa on the x axis. Red is 2019, blue is 2020, the orange dotted line represents the 3 MPa border above which we expect difficulties for roots to penetrate this layer.*

In the SWAP simulation for the fields these local soil profiles are used as a basis to parameterize (see paragraph 2.5.1).

2.4.3 Soil description deeper layers

Figure 2-11 gives an impression of the soil structure till 30 m -ss (meters below soil surface) as available in GeoTop3. The Geotop profile indicates that the soil layers consist of a sequence of clay, peat and sand layers. Probably the sand layers are so-called mudflat sands that are generally fine sands with a limited horizontal conductivity. The thickness of the low permeable layers is larger in the north than in the south and these layers are also more continuous in the north: there are fewer holes in it.

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[3] Geotop website: https://www.dinoloket.nl/detaillering-van-de-bovenste-lagen-met-geotop

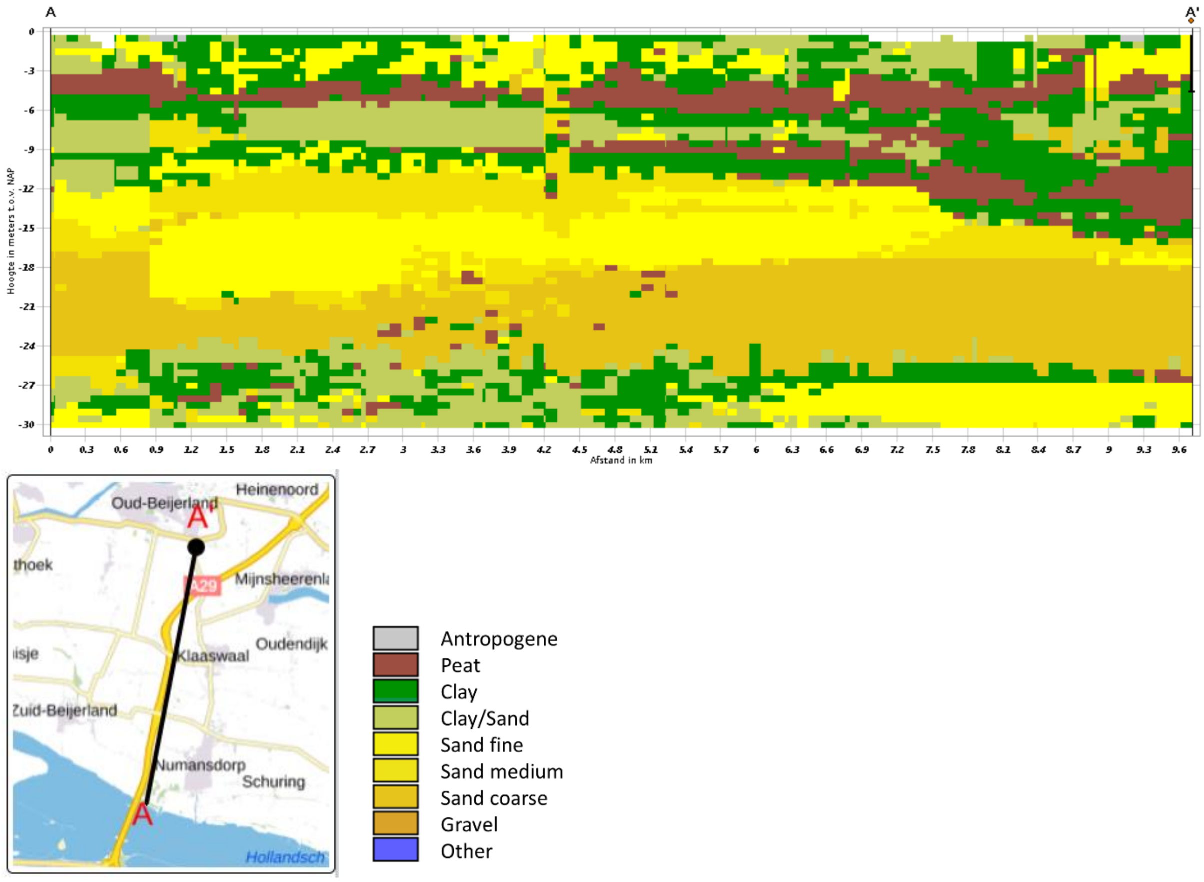


Figure 2-11 *Cross profile A-A′ Geotop (source: Dinoloket.nl) (left under: location, left right: legend, top: cross section)*

2.5 Soil physics

2.5.1 Soil hydraulic properties

Soil samples have been taken at 3 locations and at two depths for which the retention and permeability characteristics have been determined in the lab (Table 2-5). The retention characteristic reflects the relationship between the pressure head and the water content. The permeability characteristic indicates the relationship between the pressure head and the permeability. Both are needed to determine the response of soil moisture to meteorological conditions.

Table 2-5 *Van Genuchten-parameters, measured and Staring building blocks (Heinen et al., 2020) (Ks: fitted Ksat-value for the MvG-equation, Ksatexm: in lab measured Ksat-value)*

Id	Location	Depth (cm-ss)	WCr (cm^3/cm^3)	WCs (cm^3/cm^3)	Alpha (1/cm)	N (-)	M (-)	Lambda (-)	Ks (cm/d)	Ksatexm (cm/d)
3LG1	LT.1	10-20	0.0000	0.4400	0.0123	1.1360	0.1197	-3.0794	3.0490	2685.8697
3LG2	LT.1	45-55	0.0000	0.4067	0.0099	1.2634	0.2085	5.0236	11.5745	14.9162
26LG1	ST.1	5-15	0.0000	0.3960	0.0405	1.1037	0.0939	6.0951	77.0470	192.1742
26LG2	ST.1	35-45	0.0344	0.3900	0.0103	1.5240	0.3438	4.1595	16.4862	21.2318
12LG1	CA.1	5-15	0.0000	0.4296	0.0228	1.1938	0.1623	1.6137	14.1949	16.3727
12LG2	CA.1	45-55	0.0325	0.3647	0.0096	2.8569	0.6500	1.8135	32.3202	42.5184
B09	Staring series		0.0000	0.4295	0.0070	1.2672	0.210845	-2.3871	1.7476	10.Ks
O10	Staring series		0.0100	0.4723	0.0100	1.2457	0.197233	-0.7930	2.3001	10.Ks
O09	Staring series		0.0000	0.458	0.0097	1.3760	0.273142	-1.0131	37.666	10.Ks
O18	Staring series		0.0100	0.5803	0.0127	1.3162	0.240221	-0.7855	35.951	10.Ks

In Figure 2-12 the retention curves for both the top layer and the layer at approximately 40 cm -ss are displayed. The default retention curves of the Staring series (Heinen et al., 2020) are also displayed. For layer 1 (3LG1, 26LG1, 12LG1) the lines are close to each other, but there are also clear differences. For example, the moisture supply capacity (difference in soil moisture content between pF 2 and 4.2) for the ST.1 location is considerably smaller than for the other locations (see Table 2-6).

Table 2-6 *Moisture-supplying capacity and air-filled porosity of layer 1 and 2 (based on the van Genuchten equation, Van Genuchten, 1980)*

Location	**Moisture supply capacity (%)**		**Air filled porosity (%)**	
	layer 1	**layer 2**	**layer 1**	**layer 2**
	pF2 – pF4.2	*pF2 – pF4.2*	*pF2*	*pF2*
LT.1	18%	25%	0.04	0.05
ST.1	13%	25%	0.06	0.08
CA.1	21%	22%	0.08	0.11
Staring series	27%	27%	0.04	0.06

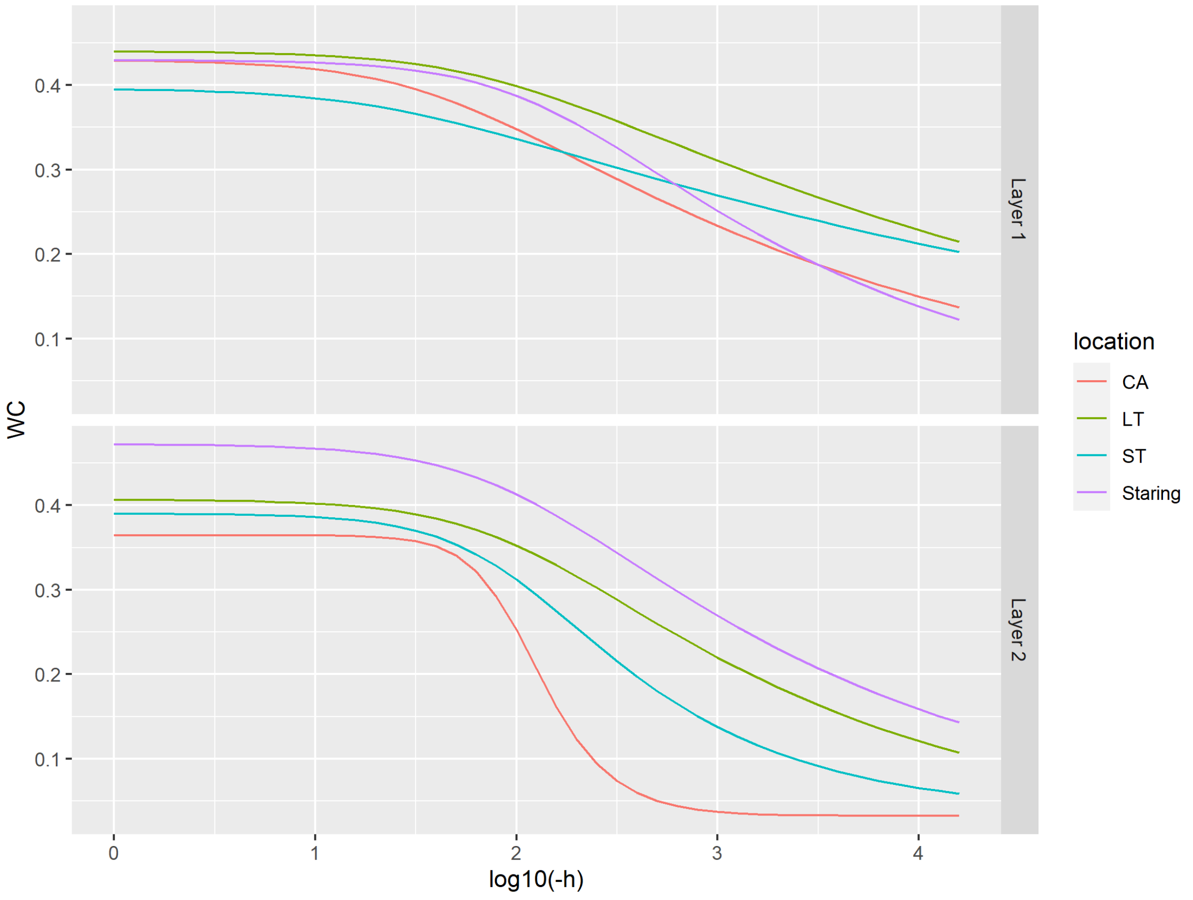


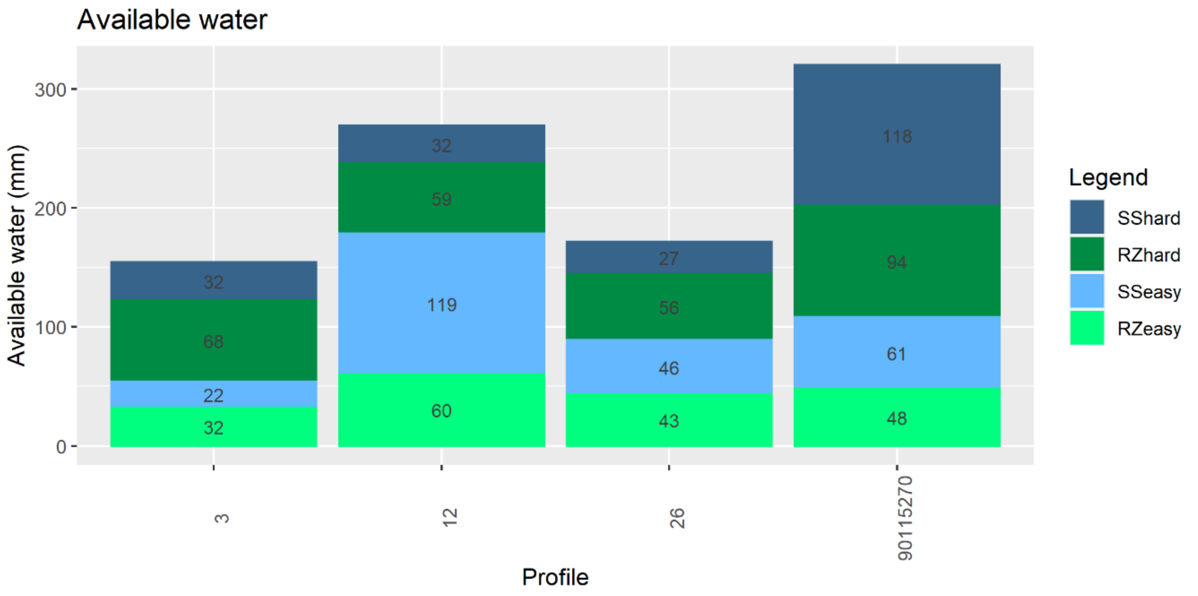
Figure 2-12 *Retention characteristic for the different locations and the Staring-series (top: layer 1, bottom: layer 2)*

For each site a parameterization for the SWAP-simulation has been made (Table 2-7). Per location on two depths the soil hydraulic properties are measured. These are used to parameterize the soil hydraulic relations. For coring 3 at the LT location the peat soil has been parameterized with building block O18 of the Staring series (Heinen et al., 2020).

Table 2-7 *Profile description and assigned soil hydraulic properties. Also, the code of the Staring building block is given. For the SWAP-simulations the locations are numbered 100 (LT), 200 (ST) or 300 (CA)*

Location	Coring	Top (cm-ss)	Bottom (cm-ss)	Horizon	Org. matter (%)	Clay (%)	M50	Silt (%)	Assigned SHP	Layer (cm-ss)	Staring SHP
LT (100)	3	0	25	1Ap	4.0	24		50	3LG1	10-20	B09
LT	3	25	45	1ACg	1.5	20		40	3LG1		B09
LT	3	45	70	1Cg1	1.0	16		30	3LG2	45-55	O09
LT	3	70	115	1Cg2	0.5	14		30	3LG2		O09
LT	3	115	150	2Cw	25.0	14	120	30	O18		O18
ST (200)	26	0	15	1Ap	4.0	24		40	26LG1	5-15	B09
ST	26	15	30	1Ah	4.0	24		40	26LG1		B09
ST	26	30	60	1Cg1	0.5	16		25	26LG2	35-45	O09
ST	26	60	100	1Cg2	0.5	15		25	26LG2		O09
ST	26	100	130	1Cg3	0.5	12		20	26LG2		O09
CA (300)	12	0	25	1Ap	4.0	19		30	12LG1	5-15	B09
CA	12	25	40	1A/C	3.0	16		25	12LG1		B08
CA	12	40	90	1Cg1	1.0	12		20	12LG2	45-55	O09
CA	12	90	130	1Cg2	0.5	14		25	12LG2		O09
CA	12	130	150	1Cgr	0.2	16		25	12LG2		O09

To characterize the difference in water availability in the profile both in the rootzone and in the subsoil (capillary available water) stationary water content profiles have been calculated (Figure 2-7). On base of these figures an indication of the available water is derived, see Figure 2-13. The CA-site (12) has the highest water availability in comparison with LT (3) and ST (26). This difference is in large part due to differences in capillary rise, so due to the characteristics in the subsoil.



SShard: Hardly available capillary water, flux 2 till 1 mm/d (dark blue)
RZhard: Hardly available water root zone, pF 1.85 till 2.6 (dark green)
SSeasy: Easily available capillary water, field capacity till a flux of 2 mm/d (light blue)
RZeasy: Easily available water root zone, pF 2.6 till 4.2 (light green)

Figure 2-13 *Available water (rootzone: blue and capillary: green) for the three sites (LT:3, CA:12, ST:26) and BOFEK 4018 (90115270)*

2.5.2 Bulk density

In Table 2-8 the measured bulk densities of the soil layers are given (100 cm^3 rings used to determine the retention curve and permeability function). As can be seen the bulk density of the top layer is lowest at the CA location. This is probably due to ploughing. The bulk density of the layer at the level of the plough pan (sub layer) is lowest at the LT location.

Table 2-8 *Measured bulk densities*

Id	Location	Top layer		Sub layer	
		Depth (cm-ss)	Bulk density (kg/m3)	Depth (cm-ss)	Bulk density (kg/m3)
3LG1	LT	10-20	1547	45-55	1488
26LG1	ST	5-15	1631	35-45	1601
12LG1	CA	5-15	1388	45-55	1589

2.5.3 Penetrologger measurements

Penetrologger measurements have been made by 1 person at 30 locations and in several years (2019, 2020, 2021 and 2022). These points are specifically chosen after stratification on the most homogeneous management zones per plot based on the soil map, the elevation map and satellite data.
Soil physical and soil chemical parameters have been determined in the lab for 23 locations where differences can be expected based on the profile descriptions. On each block of plots, a representative location has been chosen for extensive sampling on water retention characteristics.
The penetrologger data show the penetration resistance. It is assumed that when it is higher than 3 MPa, the roots cannot pass through the soil (ten Cate et al., 1995 and Eekeren et al., 2010). Table 2-9 shows the average depths at which the penetration resistance exceeds 3 MPa. Based on this, ST has the largest potential rootable depth and CA has the lowest. LT has an average rootability of 50 cm and the other locations deviate 8% from it.

Table 2-9 *Penetrologger measurements (mean, minimum and maximum depth at which 3MPa is exceeded). For the location see Table 2-1*

Location	Average of 3MPa depth	Min of 3MPa depth	Max of 3MPa depth
LT.1	56	51	60
LT.2	43	36	53
LT.3	51	36	60
LT.4	52	47	56
ST.1	43	40	50
ST.2	39	37	42
ST.3	81	81	81
CA.1	44	28	81
CA.2	50	37	63
CA.3	46	26	81
Mean per location			
LT	50	43	57
ST	54	53	58
CA	46	30	75

2.6 Seepage

According to the National Hydraulic Instrument (NHI[4], https://www.nhi.nu/), the Hoeksche Waard is a polder with a moderate (upward) seepage of 40 to 80 mm/y over most of the area. Compared to the precipitation surplus (approximately 300 mm/h), this is a limited amount. This is not surprising given the thickness of the poorly permeable deposits (8 m in the south up to 12 m in the north). However, the flux will vary from place to place due to variations in the soil profile and the resulting conductivity.

2.7 Surface water and drainage

Table 2-10 and Figure 2-14 show the summer and winter levels for the surface water. The summer level is usually 20 till 30 cm higher than the winter level.

Table 2-10 *Summer and winter level by location*

Location	**Surface level average (cm+MSL)**	**Summer water level (cm+MSL)**	**Winter water level (cm+MSL)**
LT	-1	-160	-180
ST	-21	-140	-170
CA	+8	-130	-150
	(cm-ss)**	**(cm-ss)****	**(cm-ss)****
LT	0	159	179
ST	0	119	149
CA	0	138	158

*cm+MSL: centimeters plus mean sea level

**cm-ss: centimeters below soil surface

Tube drainage is located on all plots at approximately 120 cm-ss, the drain distance equals 10 till 15 m.

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[4] NHI: this is a groundwater flow model for the whole of the Netherlands. It simulates groundwater levels, evapotranspiration and drainage fluxes for grids 250x250 m.

Figure 2-14 *Surface water levels for the summer and winter (m+MSL, waterboard)*

2.8 Crop and management

2.8.1 Crop rotation

Crops grown on the farm are depicted in Figure 2-15. The most important crops are (winter) wheat and potato.

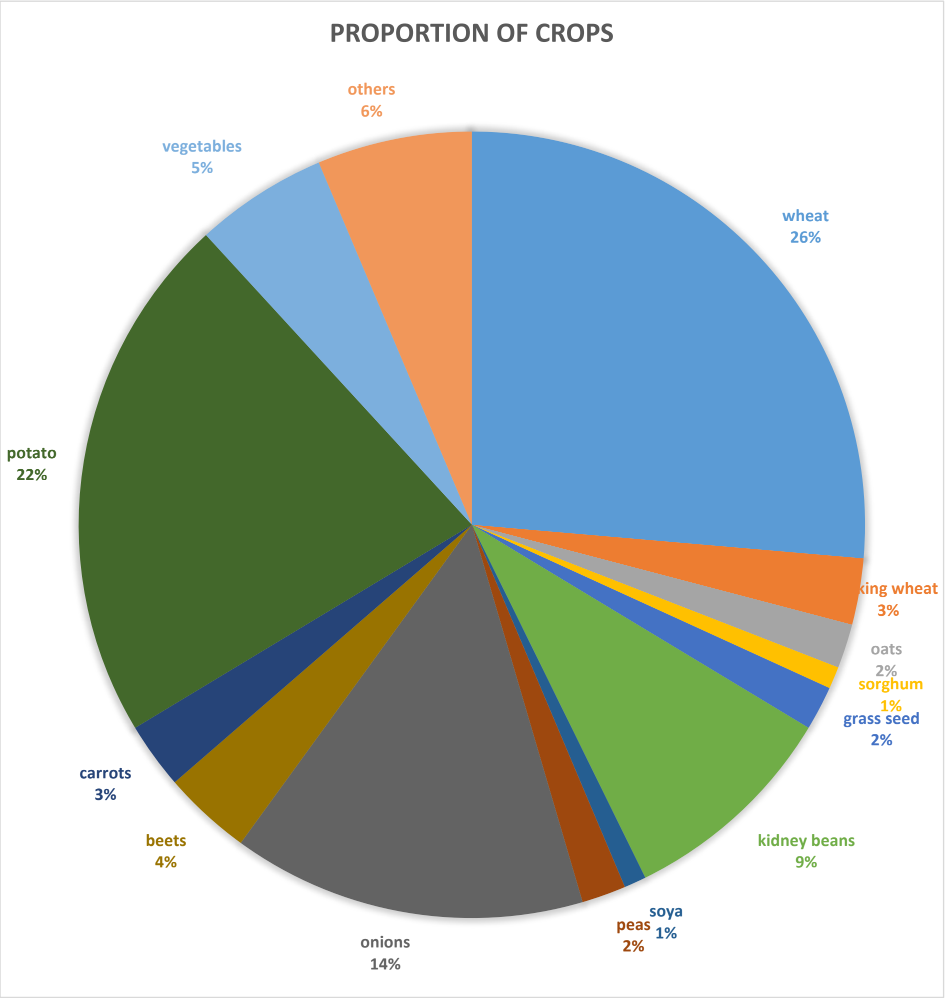


Figure 2-15 *Crops grown on the fields (2010 – 2020)*

2.8.2 Crop development

The NDVI (Normalized Difference Vegetation Index) is a measure for the greenness of the crop and therefore its development (Table 2-11). In Figure 2-16 and Figure 2-17, the NDVI is given from the years 2017 to 2019 for LT.2 and LT.3 (see Table 2-1). These figures show that potatoes develop later in the season than wheat. The NDVI is related to the transpiration history of the crop.

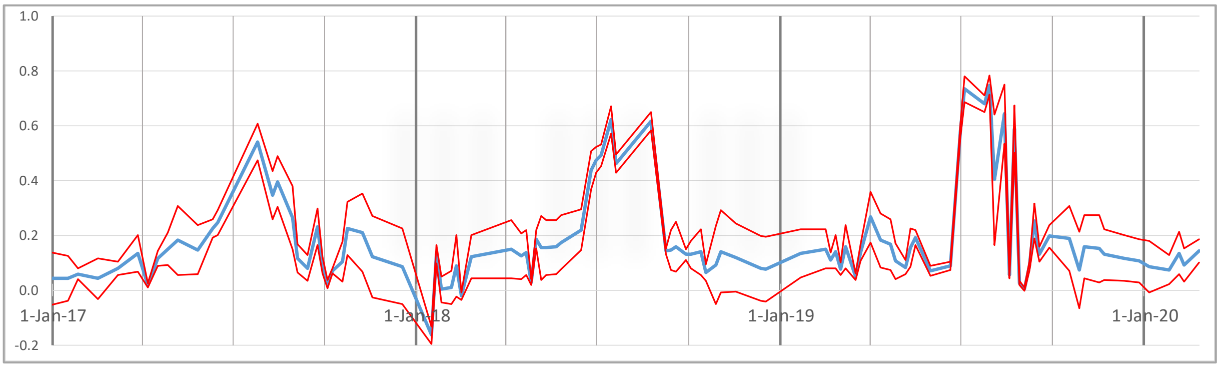


Figure 2-16 *NDVI LT.2 (2017: onions, 2018: kidney beans, 2019: potatoes) (blue: mean NDVI, red: standard deviation)*

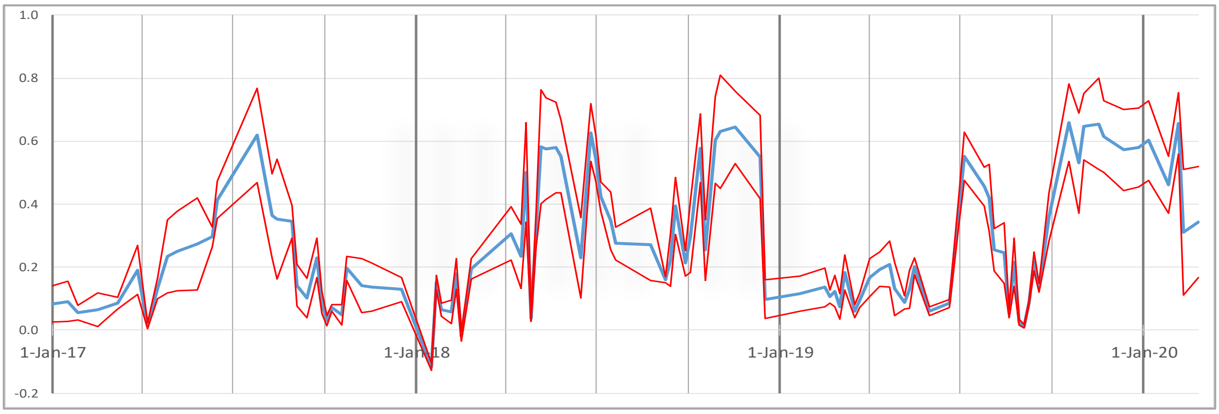


Figure 2-17 *NDVI LT.3 (2017: potatoes, 2018: wheat, 2019: conserves) (blue: mean NDVI, red: standard deviation)*

Table 2-11 *NDVI-values (reference: Roerink and Mucher, 2022)*

NDVI	Crop development
0.2	Ploughed land
0.4	Emerging crops
0.5	Closed crop
0.6	Crop with ca. 2 leaf layers
0.7	Crop with ca. 3 leaf layers
0.8-1.0	Green crops with many leaf layers

2.8.3 Management

Regenerative agriculture is a set of farming practices that work with nature, rather than against it. Core practices includes using fewer chemicals, minimizing tillage, optimized crop rotation, increasing crop diversity, implementing landscape elements such as flower field margins, keeping the soil covered all year long by growing cover crops in-between cash crops, and integrating grazing animals. These practices, among other benefits, rebuild soil organic matter and restore biodiversity - resulting in both carbon storage and water conservation (Giller et al., 2021; Rodale, 2014 and Schreefel et al., 2020).

2.8.4 Roots and water take up, mycorrhiza

The roots and the rooting depth are important for the water uptake and transport by the crop. The rooting depth depends on among others the crop and on the compaction of the soil (van den Akker & de Groot, 2008). In Table 2-12 both the crop specific maximum rooting depth and the soil specific maximum penetration depth for roots is given. This results in a maximum rooting depth for the crop – soil combination.

Table 2-12 *Rooting depth*

Location	Rooting depth Max due to compaction (cm)	Potential rooting depth crop (cm)	Resulting rooting depth (cm)
		Potato	
LT	50	50	50
ST	54	50	50
CA	46	50	46
		Wheat	
LT	50	125	50
ST	54	125	54
CA	46	125	46

Besides the rooting depth the mycorrhiza are of importance for the water uptake. In the following text block an introduction is given on the importance of mycorrhiza for water uptake (https://www.ptagtiv.com/en/blog/water-uptake/).

How do mycorrhizae increase water absorption by plants?

- Mycorrhizae play a major role in actively increasing water uptake by developing a network of filaments that explores the soil and accesses more nutrients and water to transfer to the plant.

Which plants benefit from mycorrhizal fungi?

- Most plant species will benefit from mycorrhizal fungi
  - Urban vegetable crops in soil or trays: onion, garlic, carrots, potatoes, barley, tomatoes, peppers, cucurbits, asparagus, herbs and lettuce.
  - Annuals in planters or flower beds: salvia, ornamental grasses, canna, ferns, aloe, gerbera.

How do mycorrhizae help in plant nutrient uptake?

- Mycorrhizae can create a vast connection between the roots of a plant and with the soil around them, which allows for the fungus to uptake nutrients such as nitrogen and phosphorus for the plant and increase the surface area of the roots.

Are mycorrhizal fungi good for all plants?

- Mycorrhizal fungi can be particularly beneficial for plants in areas with nutrient poor soils. Some mycorrhizal fungi can also aid plants by making them more resistant to soil-borne pathogens and diseases.

How can I improve mycorrhizal fungi?
Advice about boosting the health of arbuscular mycorrhizal fungi is probably best started with the list of three “do-not” commandments.

- Do not till. Tillage breaks up the myriad of hyphae/mycelium, most of which can never reconnect. ...
- Do not provide much phosphorus. ...
- Avoid pesticides as much as possible.

Another source is Spurgeon et al. (2013) where it is shown that increasing earthworm abundances and functional group compositions are positively correlated with water infiltration rates (dependent on tillage regime and habitat characteristics); while positive changes in fungal biomass measures were positively associated with soil microaggregate stability.

2.9 Groundwater levels

Together with the soil description also the MHG and MLG (mean highest and mean lowest groundwater level) are estimated from hydromorphic features. These are given in Table 2-13. As an overall approximation the MHG equals 60 cm-ss and the MLG 140 cm-ss. As these values are based on hydromorphic features, it can possibly reflect a past situation. Therefore, these values should be compared to measured water levels in piezometers.

Table 2-13 *Groundwater level characteristics (MHG and MLG: mean highest and lowest groundwater level), bases on hydromorphic features and probably reflecting a past situation*

Location	**MHG cm-ss**	**MLG cm-ss**
Hydromorphic (former age)		
LT	56	134
CA	56	142
ST	60	unknown
Piezometer B43E0289	110	190

There are some piezometers in the surroundings. When comparing the groundwater levels with the values based on the hydromorphic features it must be concluded that the hydromorphic features indeed reflect a past situation. Therefore, these are neglected.

In the figure below the locations of groundwater level measurements of the waterboard are given. There are only few long term measurement series available.

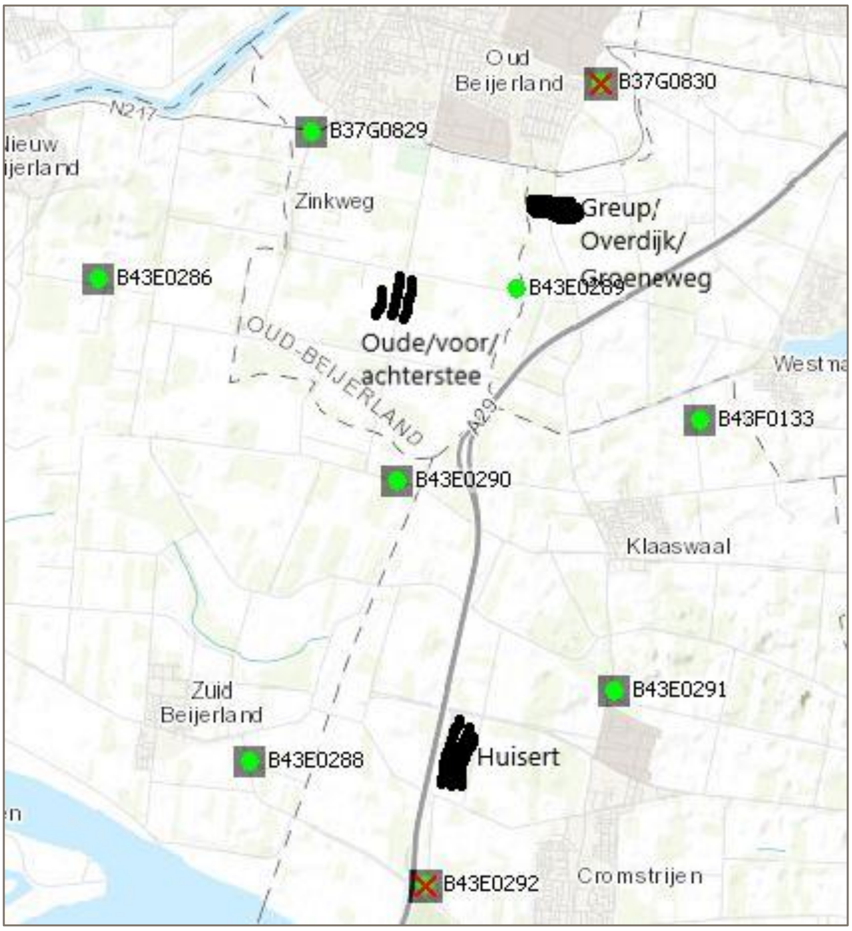


__Figure 2-18__ Groundwater level measuring points

Figure 2-19 shows that the groundwater level varies between 1 to 2 m-sl (filter from 2 to 3 m-sl) and the hydraulic head at a deeper level (filter from 11 to 12 m-sl) is higher. The figures indicate that seepage will occur from the deeper layers to the shallow layers and that the permeability of the clay and peat layers add up to a considerable hydraulic resistance (assumption: dh = 0,8 m and q = 0.2 mm/d, results in C = dh/q = 0.8/0.0002 = 4000 d).

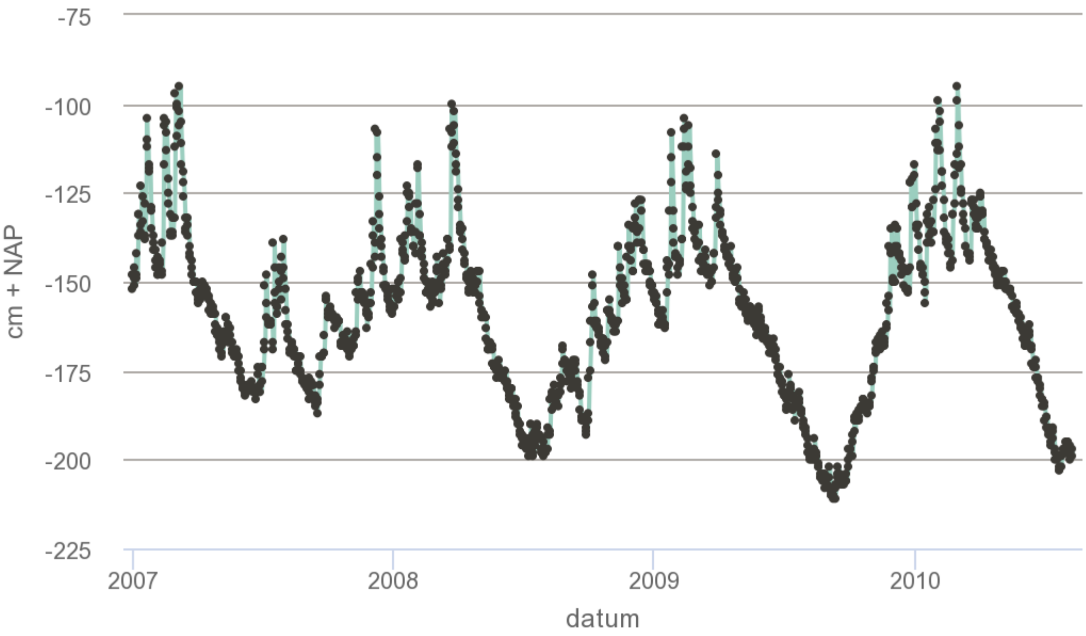


__Figure 2-19__ Groundwater level B43E0289 (filter 1 MSL -2,09 till -3,09 m)

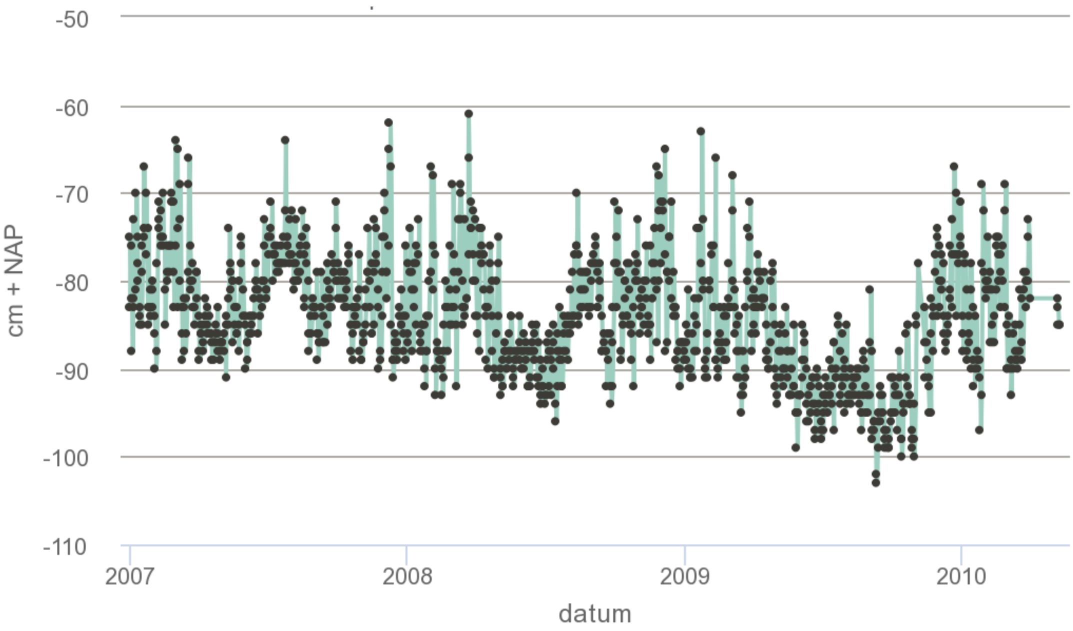


__Figure 2-20__ Groundwater level B43E0289 (filter 2 MSL -10,93 till -11,93 m)

2.10 Moisture contents

Several types of moisture sensors are installed in the fields to determine their usability. In Annex 2 the measurements are discussed. The SMAP-series and the Dacom series for location LT.2 will be used in the model improvement (calibration). These measurements are used in a relative way, i.e. indicating dryer and wetter periods. A linear transformation was used ensuring that the average and the standard deviation of measurements and simulations match each other. In this way, the trend in the measurement data is compared with the trend in the simulations.

$$\theta_{o,scaled} = \frac{stdev(\theta_m)}{stdev(\theta_o)} \cdot \left(\theta_o - mean(\theta_o)\right) + mean(\theta_m)$$

with θ_m: moisture content of the simulation(model) and θ_o: moisture content of the observation.

2.11 Functioning of the soil-water-crop system

The soil type, as the profiles show, is clay. In the deeper subsoil there is a sequence of clay, sometimes peat and sand. This means that, in general, water exchange with the aquifer is limited: there is a slight upward seepage. Groundwater levels are strongly influenced by the canals and the drain tubes. Given the moderate permeability of the upper layers, tube drainage has been applied by the farmer at all locations.

For the crop, the rootable depth is important. From the penetrologger data it follows that for the three different locations the rootable depth equals around 50 cm (LT 50 cm, ST 54 cm and CA 46 cm). Water availability is enhanced by capillary rise and to a certain extent by fungi.

3 Simulation SWAP-WOFOST

3.1 General

In this chapter the parameterization of the model(s) (paragraph 3.2), the model improvement (paragraph 3.3), the validation of the model (paragraph 3.4) and a scenario analysis (paragraph 3.5) is concisely described.

3.2 Parameterisation of the model

The following simulations have been set up:

- Locations: LT, ST and CA.
- Period: years 2016 to 2020
  The first year in the simulation is used as a startup year: the results of this year will be ignored.
- Meteorological: Meteorological station Rotterdam.
- Ground level: averaged surface level (sl) per location.
- Soil: location-specific parameters are assigned, as determined in the lab.
- Drainage:
  - Main canals: drainage resistance 1000 d, infiltration resistance 4000 d.
  - Pipe drainage: drainage resistance 50 d, no infiltration, depth 1.20 cm -sl.
  - Ditches: drainage resistance 10 d, no infiltration, depth 5 cm.
- Surface water levels:
  Summer and winter level by location. Position relative to ground level depending on polder level and surface level.
- Upward seepage: assumed is a flux of 0.2 mm/d.
- Crops: winter wheat and potato
  SWAP modelling has been based on two crops, namely potato and winter wheat. The same crop is grown every year in each SWAP simulation. In this way, the influence of the different meteorological years on the crop growth is calculated. NB Usually winter wheat is followed by a catch crop, but because winter wheat is sown in October in the simulation, a catch crop does not fit into the simulations. This means that in the period from mid-July to mid-October there is no crop on the field.
- Crop damage due to too wet and dry conditions: wet and drought damage are both simulated using the Feddes concept (Kroes et al., 2017). Dynamic water uptake by the roots is simulated using compensation according to the Jarvis-concept (Jarvis, 2011) for root water uptake for both drought and wetness stress (ALPHACRIT = 0.7).
- Rooting depth: per location depending on penetration resistance and crop (Table 2-12).

Summarizing: location-specific data have been allocated for surface level, surface water levels, soil parameters and rooting depths.

3.3 Model improvement

The model simulations are compared to the measured moisture contents and groundwater levels. For the calibration of the model several parameters have been adapted. These are:

- Drainage resistance of the tube drains: it turned out that a value of 50 d resulted in good resemblance of the measured groundwater levels.
- Wet damage: there are two concepts to simulate wet damage for the crops. The Feddes concept turned out to perform the best: it doesn’t exaggerate the wet damage and results in plausible transpiration and crop development.
- Root distribution: for the root distribution the following has been chosen: first half of the rooting depth a block distribution, for the second half: linear decreasing till 0.25 (Figure 3-1).

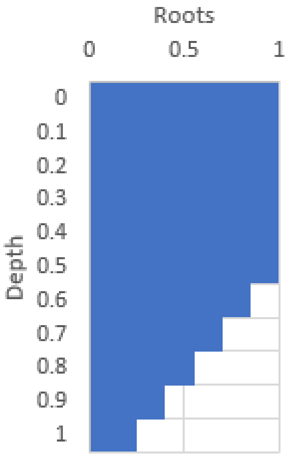


Figure 3-1 *Relative root distribution*

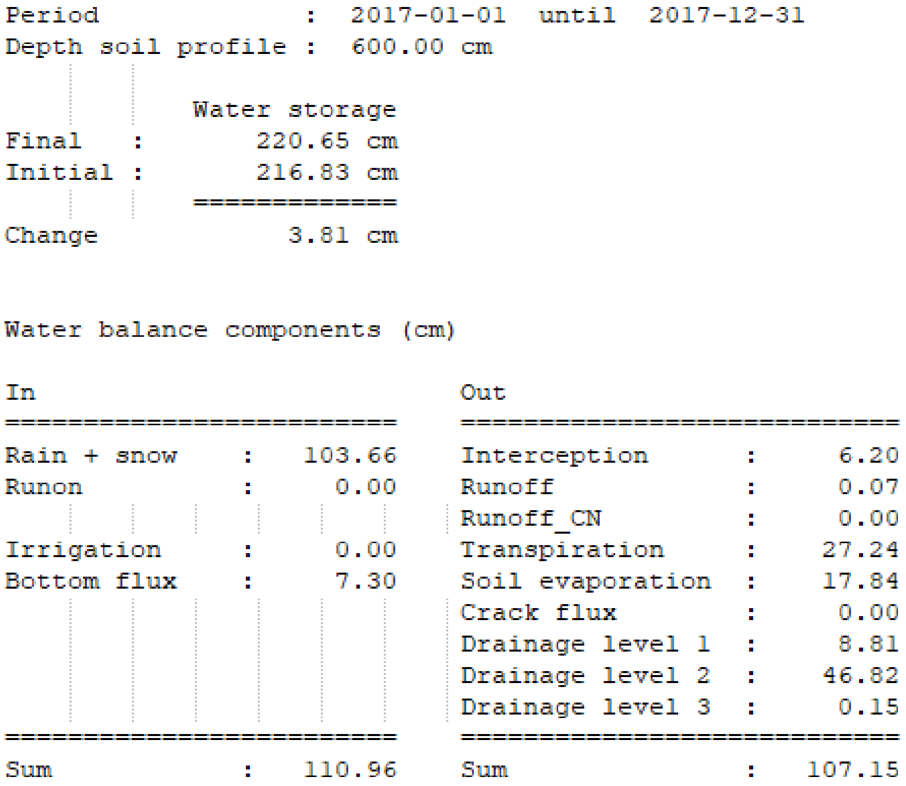
- Water uptake compensation: Dynamic water uptake by the roots is simulated using the Jarvis-concept for root water uptake for both drought and wetness stress (ALPHACRIT = 0.7). Also, a value of 0.5 has been tested but that hardly affects the results. Therefore, the generally used value of 0.7 has been applied.

3.4 Validation with measurements

3.4.1 Water balance

In Table 3-1 the water balance for the year 2017 is presented. The difference between the In and Out term is the difference in water storage: in the example below 38 mm. The most important terms are Precipitation – 1037 mm, Evaporation – 178 mm, Transpiration – 272 mm and Drainage or dewatering – 558 mm. For drainage, most important is tube drainage (level 2).

Table 3-1 *Waterbalance 2017 (example CA with winterwheat)*



```
Period             :  2017-01-01  until  2017-12-31
Depth soil profile :  600.00 cm

            Water storage
Final   :       220.65 cm
Initial :       216.83 cm
            =============
Change            3.81 cm


Water balance components (cm)

In                           Out
=========================    ============================
Rain + snow    :   103.66    Interception       :     6.20
Runon          :     0.00    Runoff             :     0.07
                             Runoff_CN          :     0.00
Irrigation     :     0.00    Transpiration      :    27.24
Bottom flux    :     7.30    Soil evaporation   :    17.84
                             Crack flux         :     0.00
                             Drainage level 1   :     8.81
                             Drainage level 2   :    46.82
                             Drainage level 3   :     0.15
=========================    ============================
Sum            :   110.96    Sum                :   107.15
```

Figure 3-2 shows the contribution of the different evaporation terms for the ST-field with winter wheat. As can been seen the lowest evaporation is simulated for 2018.

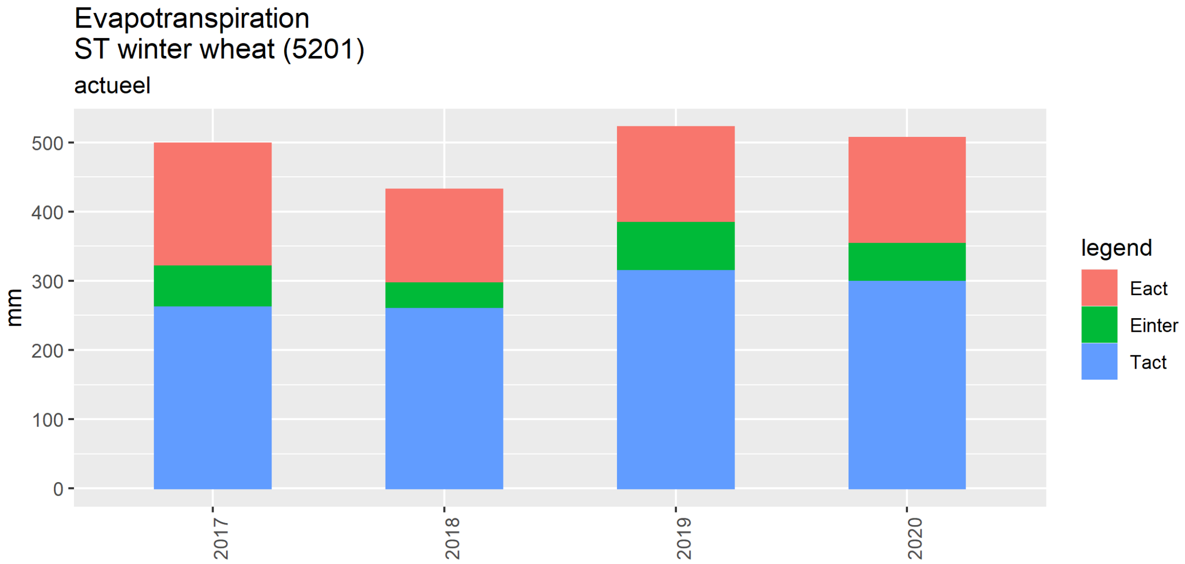


Figure 3-2 *Distribution of evaporation terms for ST with winter wheat (Eact: evaporation soil, Einter: interception evaporation, Tact: transpiration)*

3.4.2 Soil moisture

In Figure 3-3 the comparison of the scaled measurements of the Dacom sensors with the model results is given (for scaling see paragraph 0). The peak in mid-June is recognizable for both simulations and measurements. But beyond that, the agreement is only moderate.
In Figure 3-4 the simulation for winter wheat is given compared to the scaled SMAP data. The dynamics correspond well with an exception from mid-August to October 1, when the crop is of the land and there is no more transpiration.
In Figure 3-5 the image for potato is shown. Here the deviation is mainly at the beginning of the growing season. The combination of winter wheat and potato best reflects the SMAP data. As the resolution of the SMAP data is 10 km, this is understandable as it shows an average image.

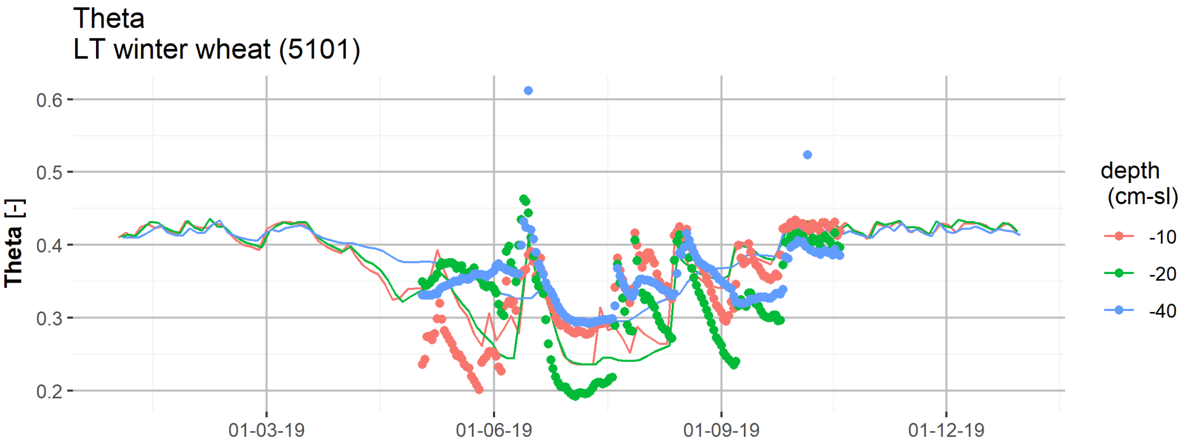


Figure 3-3 *Simulated (lines) and scaled measured (dots) moisture levels Dacom at different depths (location LT, winter wheat)*

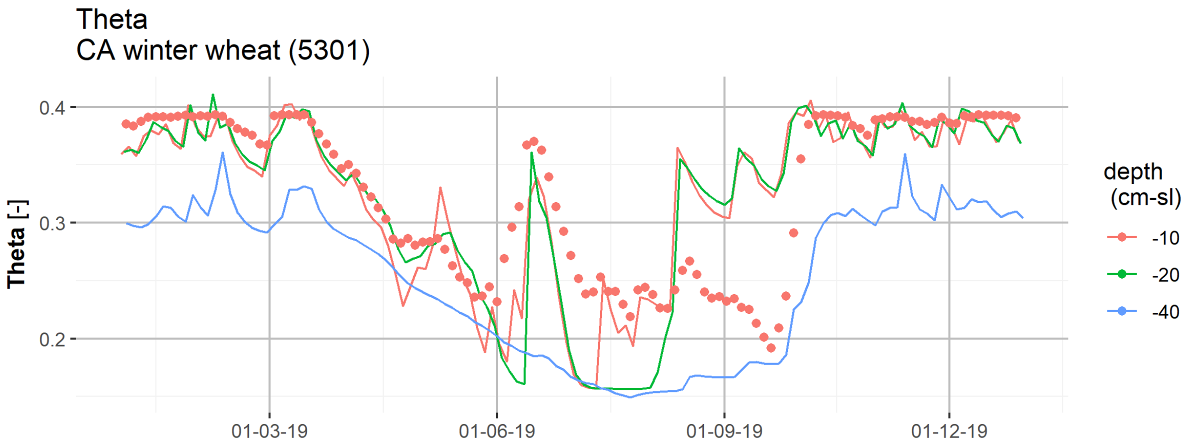


Figure 3-4 *Simulated (location CA, winter wheat) and scaled measured moisture levels SMAP. Points SMAP data*

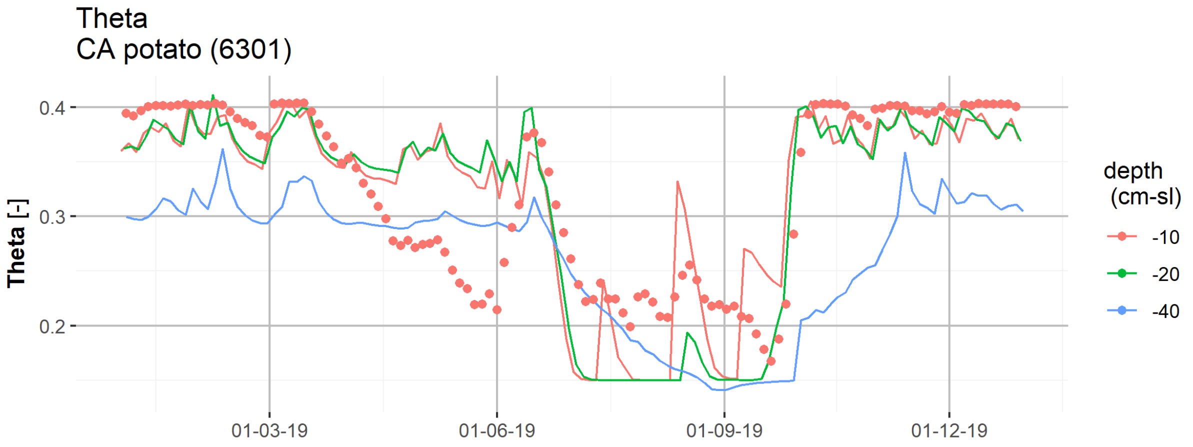


Figure 3-5 *Simulated (location CA, potato) and scaled measured moisture levels. Points SMAP data*

Figure 3-6 shows the dynamics in moisture content, as simulated for the different locations, depths and crops. The 3 locations differ in several ways:

- Location and soil: the soil hydraulic properties are reflected in the figure with the highest water content at a depth of 10 cm for location LT. At a depth of 100 cm the fluctuation in water content is smallest at the LT location. At this location and at that depth peat was found.
- Crop: the crop that is grown, is directly connected to length of the growing season. This is also present in the change of the water content.

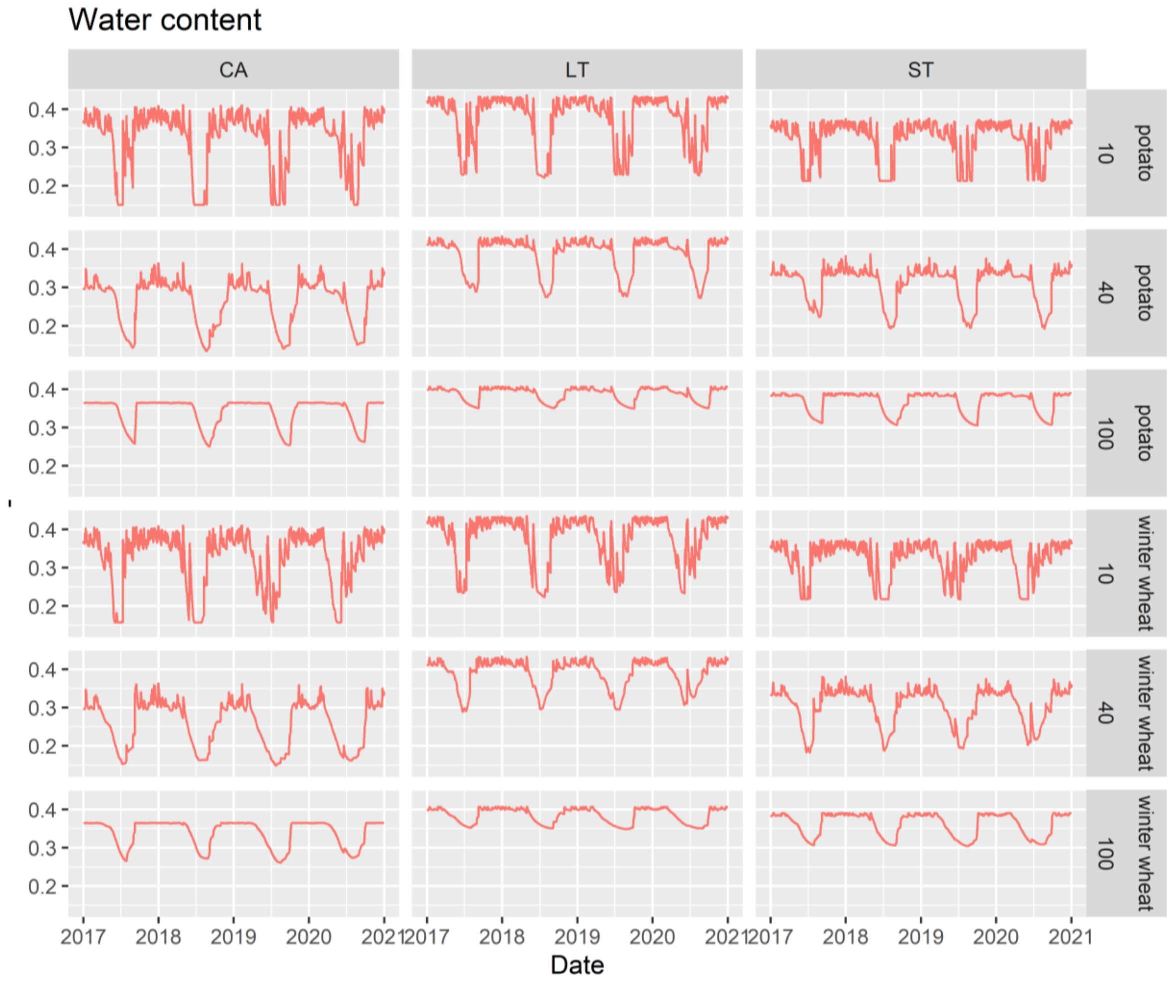


Figure 3-6 *Simulated moisture levels (m^3/m^3) at 3 locations and 3 depths (cm-ss) for winter wheat and potato*

3.4.3 Groundwater levels

Groundwater levels at the specific locations have not been measured. From available measurements in the surroundings, it follows that the groundwater levels fluctuate between approximately 110 and 190 cm-ss (MHG and MLG). The figures below show that the simulated groundwater levels are in this range. Groundwater levels in winter wheat drop earlier in spring due to the earlier growth of the crop in comparison with potato.

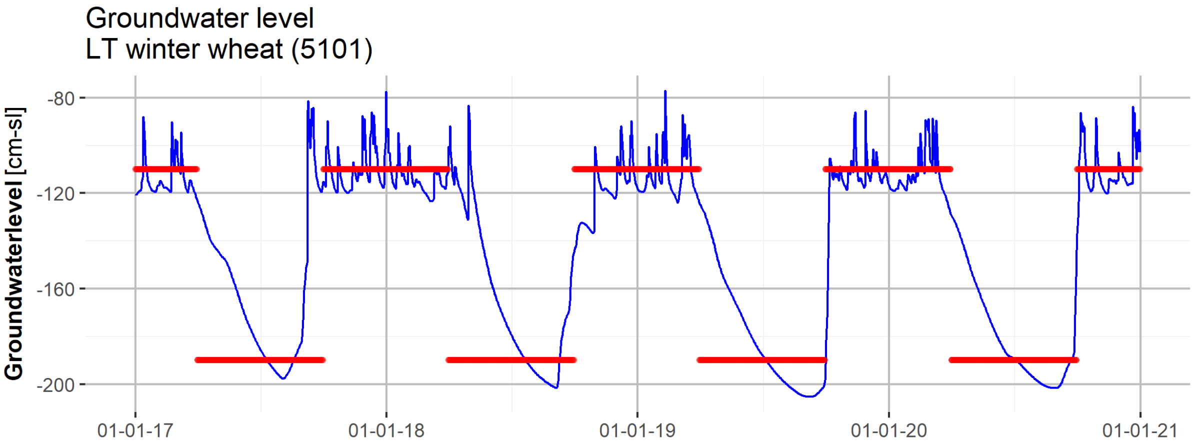


Figure 3-7 *Simulated groundwater level in comparison with the MHG and MLG based on groundwater level measurements (in red)*

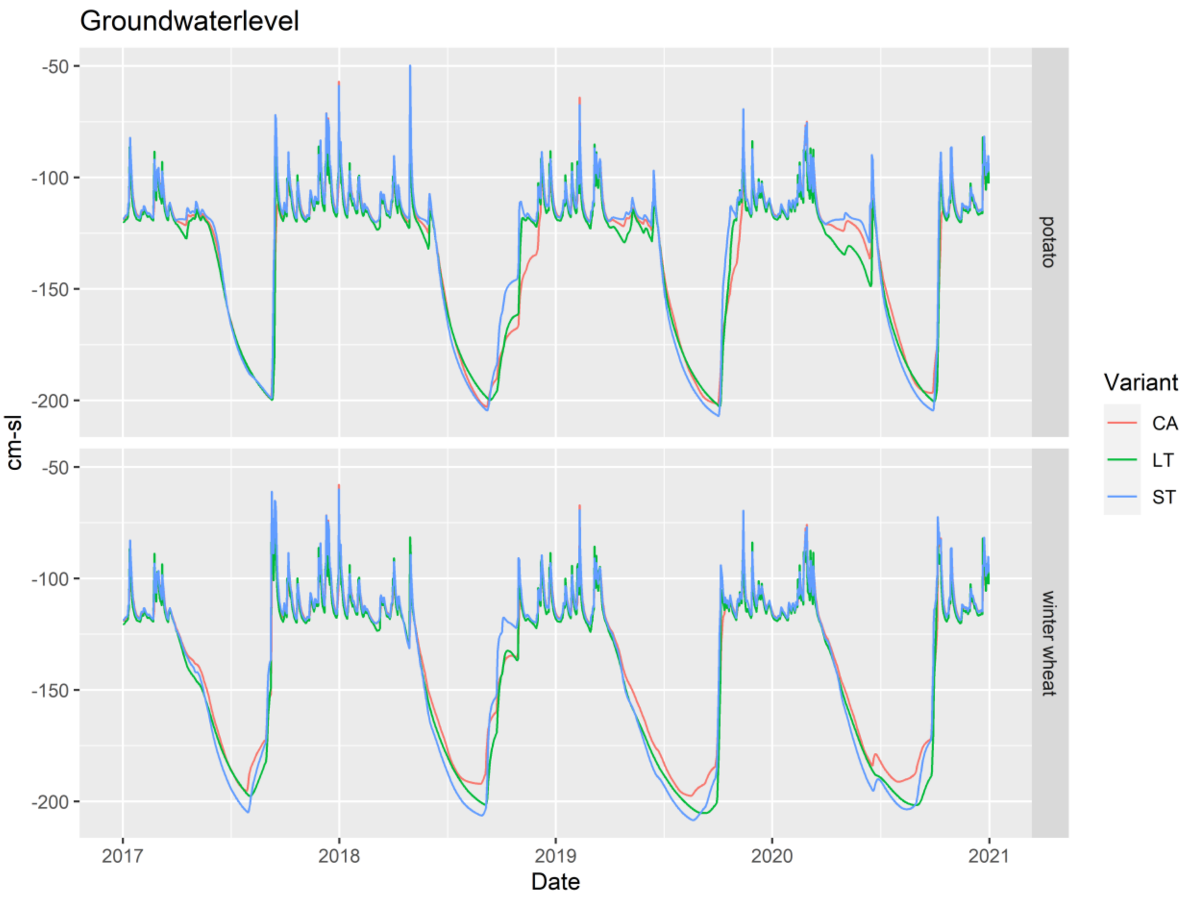


Figure 3-8 *Simulated groundwater levels for the three sites and both crops*

3.4.4 Overall conclusion validation and use of the model

Comparison of measured values and simulations leads to the following conclusions:

- Water balance: the components of the water balance are plausible.
- Soil moisture: several measurement data are available, which are used in a relative way. The simulations correspond reasonably well with the measurements.
- Groundwater level: there are not a lot of piezometers, only one and out of date. The seasonal dynamics correspond quite well with the simulations as shown in the figures.

There are still several discrepancies between measurements and simulation. The model will be used in a sensitivity analysis while focusing on the relative effects.

3.5 Scenario analysis

3.5.1 General

Influence of Regen Ag

Regen Ag has the objective to improve the soil characteristics due to more biological activity/ a better balance (see paragraph 2.8.3). This possibly results in the following soil physical effects on the soil:

- Organic matter: increase in organic matter content due to increased supply of organic matter (crop residues and cover crops) with associated effects on water retention.
- Soil compaction and structure: preventing or reducing soil compaction and improving soil structure by increasing biological activity, growing cover crops and reducing tillage and using lighter machinery. This affects:

- soil physical relationships
  The water holding capacity can change due to a higher pore volume and the permeability or infiltration capacity can also change, especially in wet periods through macropores.
- rooting depth
  Increase of the potential rooting depth for crops.
- macropores
  The amount of macro pores can increase due to increased activity of earthworms and reduction of tillage.

- Fungi: soil biology and especially fungi can enhance the water uptake of crops and the nutrient uptake.

In the paragraphs below, the effects of several enhancements or changes are determined by running different scenarios in the parameterized model as described in 3.1-3.4. These results are compared with the reference simulation, i.e., the simulation with the base parameterization for the field – crop.

Interpretation of the simulations: metrics
Several effects can be assessed, as there are several goals for the different stake holders. This results in the assessment criteria as presented in Table 3-2.

Table 3-2 *Metrics to assess the scenario analyses. The mean over the years consists of the years of the simulation period (2017-2020)*

	Mean years	**Dry year 2018**
Water balance		
Evapotranspiration	x	x
Transpiration	x	x
Drainage	x	x
Runoff	x	x
Groundwater		
GHG	x	x
GLG	x	x
Moisture availability		
number of days pF > 3 (at 15 cm-ss)	x	x
Crop		
Wet damage	x	x
Dry damage	x	x
Indirect damage	x	x
Fresh water demand (surface water)		
Infiltration from surface water to groundwater (June till August)	x	x

3.5.2 Organic matter content

Regen Ag aims to increase the amount of organic matter in the soil. An increase in soil organic matter generally leads to an increase in water holding capacity. This contribution to the soil water availability was studied in an overview paper, covering the available literature (Wösten en Groenendijk, 2019). This report states:

> *"Clay soils generally have good natural soil fertility. Sandy soils are highly dependent on organic matter for nutrient supply. In these soils, the availability of nutrients is largely determined by interactions of soil life with the organic matter in the soil."*
>
> *"There is a clear correlation between the organic matter content and the soil structure (Faber et al., 2011). As more organic matter is present, the soil structure will be better. A good soil structure is essential for the bearing capacity, infiltration capacity, reduction of surface compaction sensitivity, reduced risk of soil compaction, reduced susceptibility to soil diseases and increased crop yield."*

> *"In the Netherlands, an increase in organic matter content will have the most effect on water retention in the green- and yellow-colored sandy soils in Central and East Brabant, the Achterhoek and Twente. The nature reserves (e.g. Veluwe) and clay soils along coast and rivers are not relevant. The agricultural plots on clay already have a large water retention capacity, regardless of the organic matter content (Van den Berg et al., 2017)"*
>
> *"In the range of 1 to 3% organic matter initially, an increase of 1% organic matter results up to an increase of 2 -3 mm of available water in a layer of 20 cm, that equals less than a day of extra transpiration."*

In view of the above, there is no added value to do a sensitivity analysis regarding the organic matter content.

3.5.3 Enlarged rootable depth

By improving soil structure, soil biology and reducing soil compaction, Regen Ag aims to influence the rootable depth. The reached root depth of a plant depends on several factors:

1. Crop properties
   Potato has a potential root depth of 50 cm and winter wheat 125 cm.
2. Soil properties
   The soil can limit the potential root depth due to various causes: 1) aeration (too little air-filled pores), 2) acidity (pH may be too low), 3) penetration resistance.
3. Water availability
   Roots do not grow into the groundwater and do not grow deeper than necessary to obtain enough water for transpiration and growth.
4. Fungi
   Enhanced water uptake by fungi. This can be regarded as a kind of **extended** rooting depth.

Enlarged rooting depth
In Table 3-3 it is assumed that due to less soil compaction, better aeration and help of fungi the rootable depth increases for potato till 70 cm and for wheat till 75 cm, compared to ca. 50 cm in the actual soils.

Table 3-3 *Scenario Rooting depth (between parentheses the resulting rooting depth for the reference simulation)*

Location	Rooting depth Max compaction / gwl (cm) Soil	Rooting depth Max crop (cm)	Resulting rooting depth (cm)
		Potato	**Potato**
LT	75 (50)	70 (50)	70 (50)
ST	75 (50)	70 (50)	70 (50)
CA	75 (46)	70 (50)	70 (46)
		Wheat	**Wheat**
LT	75 (50)	125 (125)	75 (50)
ST	75 (50)	125 (125)	75 (54)
CA	75 (46)	125 (125)	75 (46)

Results
Figure 3-9 shows the development of rooting depth in time. The model results show that the greater rootable depth leads to an increased transpiration (Figure 3-10). A higher transpiration usually results in a higher growth rate and therefore a higher yield. Due to the higher transpiration the groundwater level drops (Figure 3-11). Also the drainage to canals and tubes changes (Figure 3-12). As shown the drainage is mainly reduced directly after a dry summer period. Figure 3-14 shows that in some situations with high drainage fluxes in the reference situation the daily drainage is much lower. In most situations there is almost no reduction in high drainage fluxes. The runoff is quite low for the fields (Figure 3-13). The extra rooting depth hardly influences the runoff, because in the reference situation there is almost no runoff.

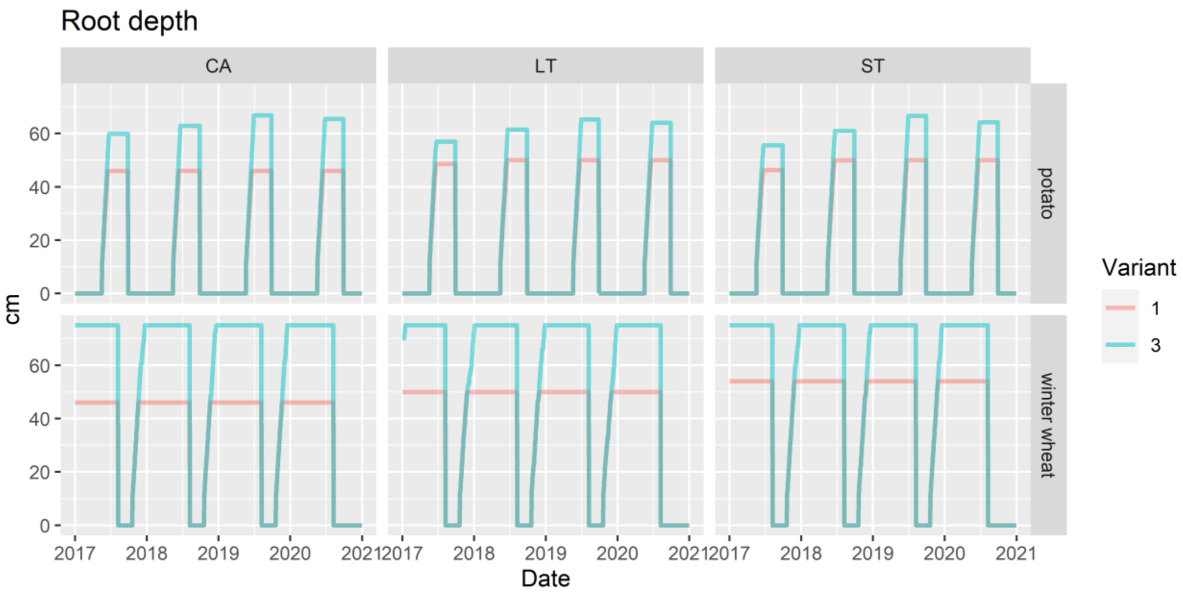


Figure 3-9 *Development of rooting depth (Variant 1: reference, Variant 3: extra rooting depth)*

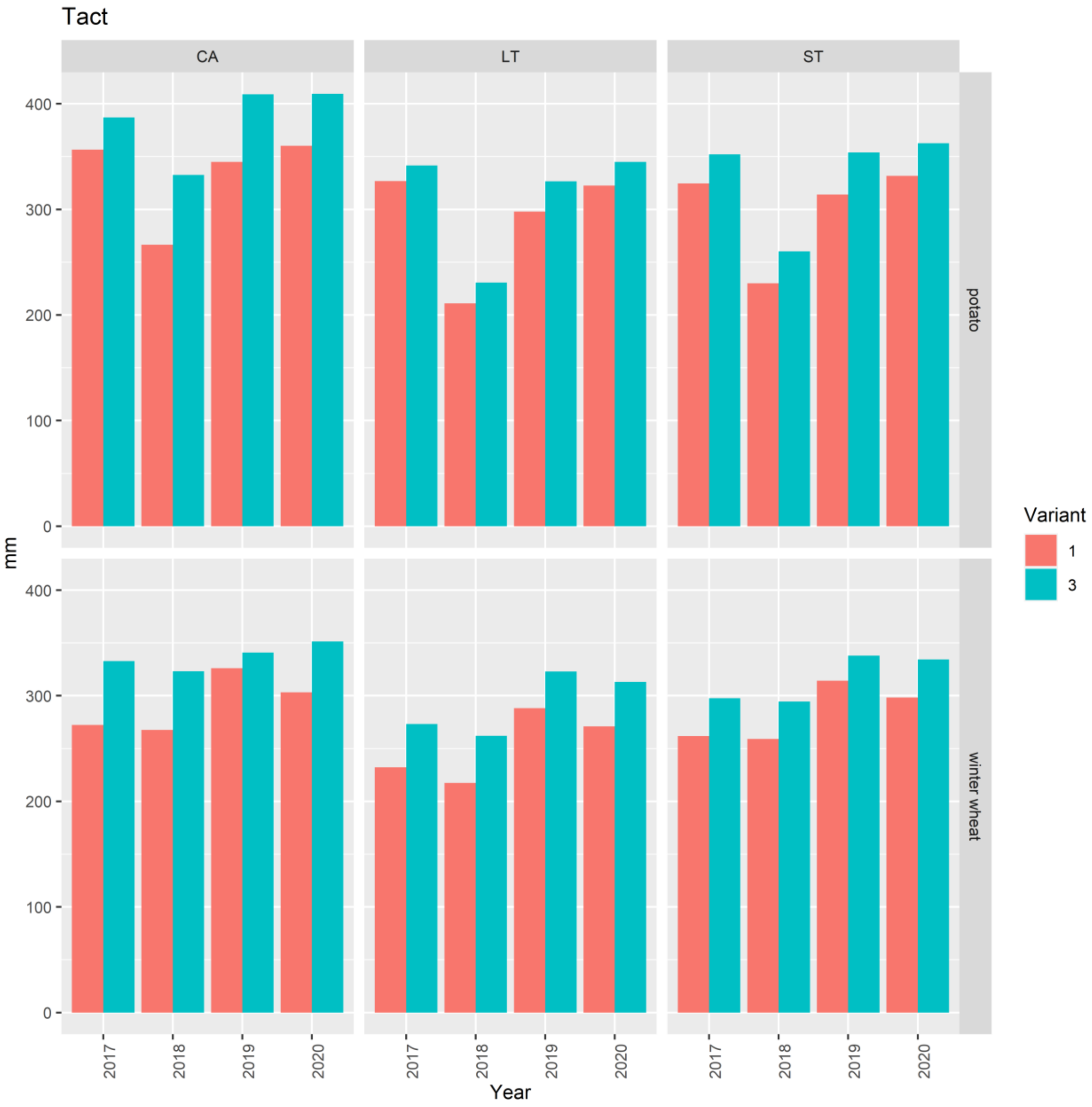


Figure 3-10 *Effect on the transpiration (Variant 1: reference, Variant 3: extra rooting depth)*

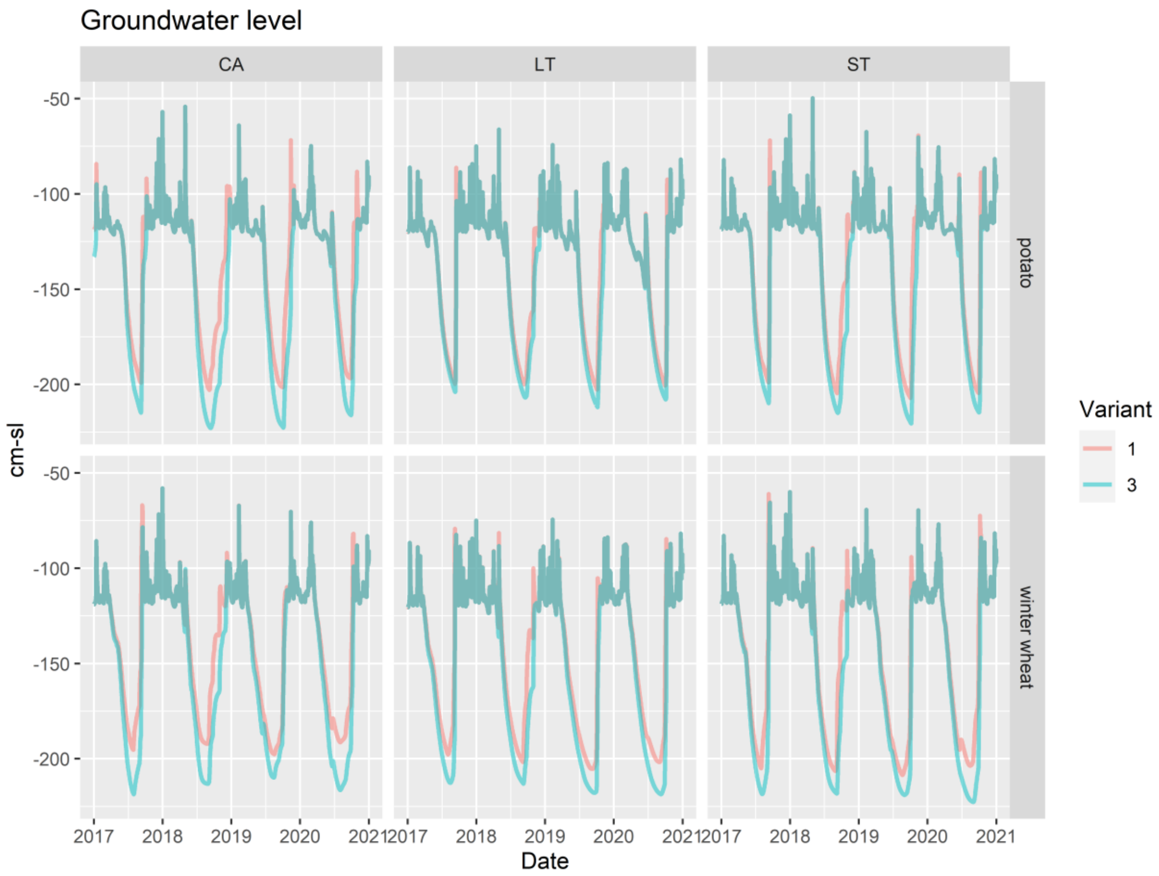


Figure 3-11 *Effect on the groundwater level (Variant 1: reference, Variant 3: extra rooting depth)*

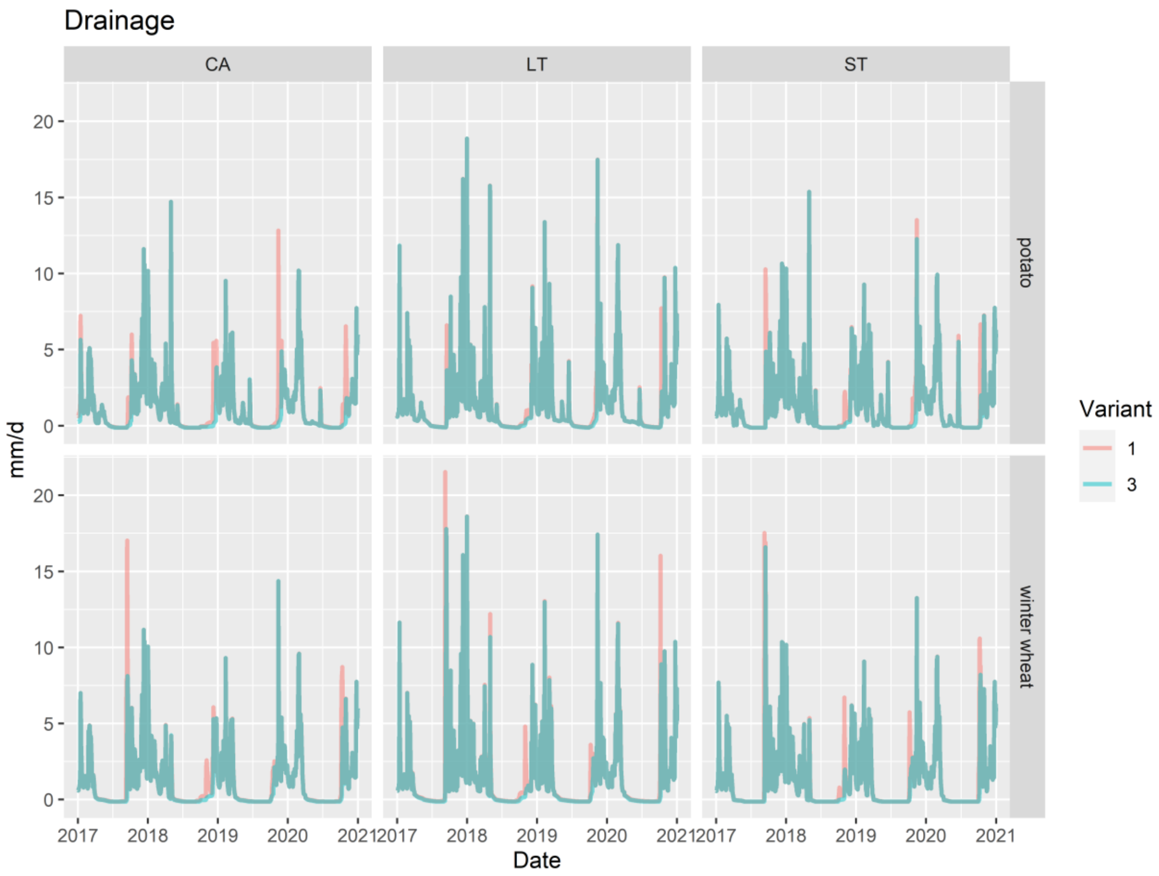


Figure 3-12 *Effect on the drainage to canals and drain tubes, presented chronological (Variant 1: reference, Variant 3: extra rooting depth)*

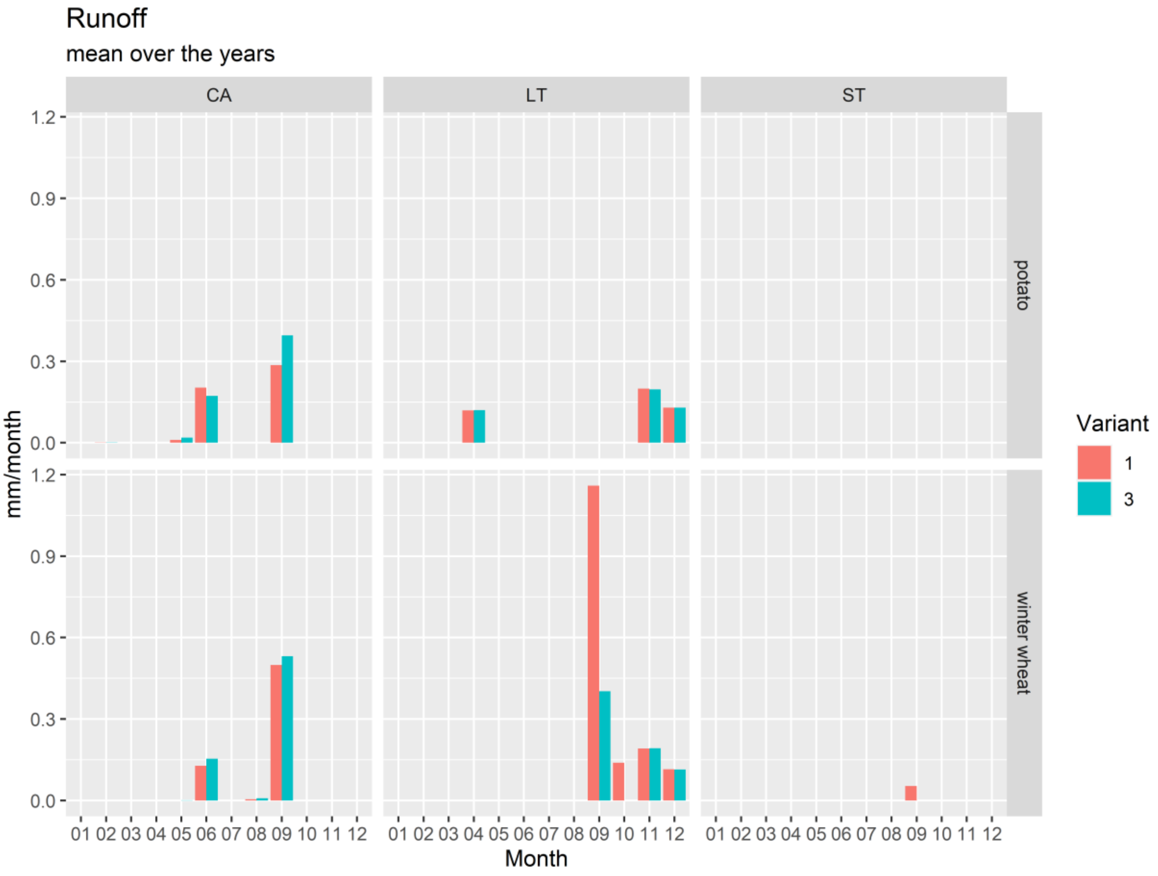


Figure 3-13 *Effect on runoff (Variant 1: reference, Variant 3: extra rooting depth)*

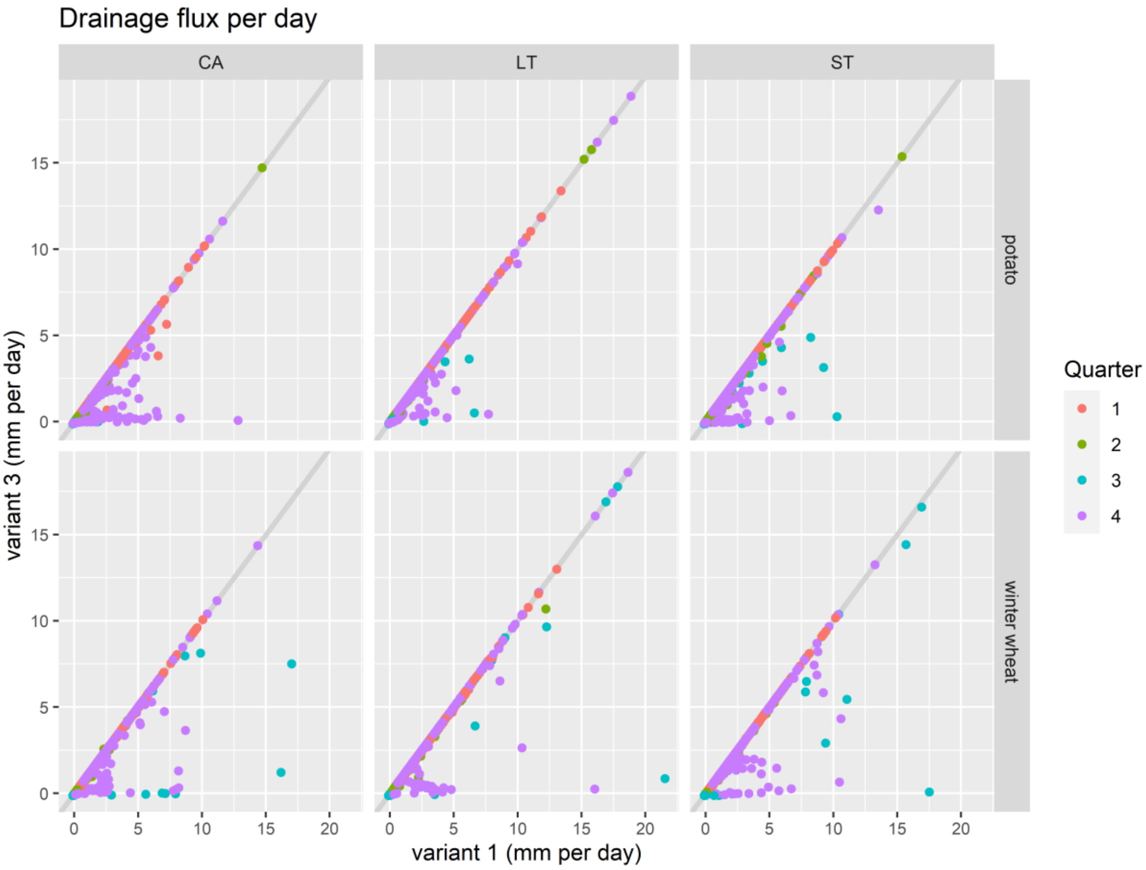


Figure 3-14 *Effect on the daily drainage quantities to canals and drain tubes, presented as a x-y plot (Variant 1: reference, Variant 3: extra rooting depth). With the quarter of the year indicated. A point below the grey 1:1 line means that the drainage flux is lower in case of the extra rooting depth.*

3.5.4 Infiltration capacity

Due to an increase in biological activity and an improved soil structure the infiltration capacity can be enhanced (Spurgeon, 2013). To simulate this, three infiltration capacities are assumed for the top layer with a thickness of 25 cm: 10, 50 and 250 cm/d. The lowest value represents a soil that has a poor infiltration capacity (about 4 mm per hour), the highest value represents a soil with a high permeability (about 100 mm per hour). A precipitation event of 50 mm in 1 hour is a problem for the low infiltration capacity but not for the latter.

Results

The results show that on most of the metrics there is no change. Only the calculated runoff is influenced by the change in infiltration capacity (Figure 3-15), but these are small because in the reference situation there is almost no runoff (Figure 3-13). As can be seen in (Figure 3-15) the LT-site is most vulnerable to runoff. Because in the current situation at the LT-field (Regen Ag) the infiltration capacity is high (Table 2-5) there is almost no runoff. Figure 3-15 shows that the effect of a higher infiltration capacity is (of course) a lower runoff. Runoff is a process where infiltration capacity is a determining factor but also the free (air filled pores) storage capacity is of importance. This air-filled porosity depends on the texture and structure of the soil. Table 3-4 shows that the air-filled porosity at pF2 at the LT site is lowest (according to the retention curve). Probably due to ploughing the air-filled porosity is quite high at the CA field. So, the capacity of the soil to store water in the top layers during a big rainfall event is according to the water retention curve lowest at the LT-site.

Periods with high rainfall intensities usually occur in the summer period. In these months the highest runoffs are simulated (see Figure 3-13).

So the conclusion is that at the infiltration capacity is only influencing the runoff. But because in the reference situation there is almost no runoff, the effect of the infiltration capacity is small.

Table 3-4 *Air-filled porosity (or available storage) at several pressure heads (degrees of wetness at various pF-values) for the layer 0-20 cm-ss*

location	**airfilled_pF2** **Field capacity** **Wet soil**	**airfilled_pF3**	**airfilled_pF4.2** **Welting point** **Dry soil**
CA	0.08	0.20	0.29
LT	0.04	0.13	0.22
ST	0.06	0.13	0.19

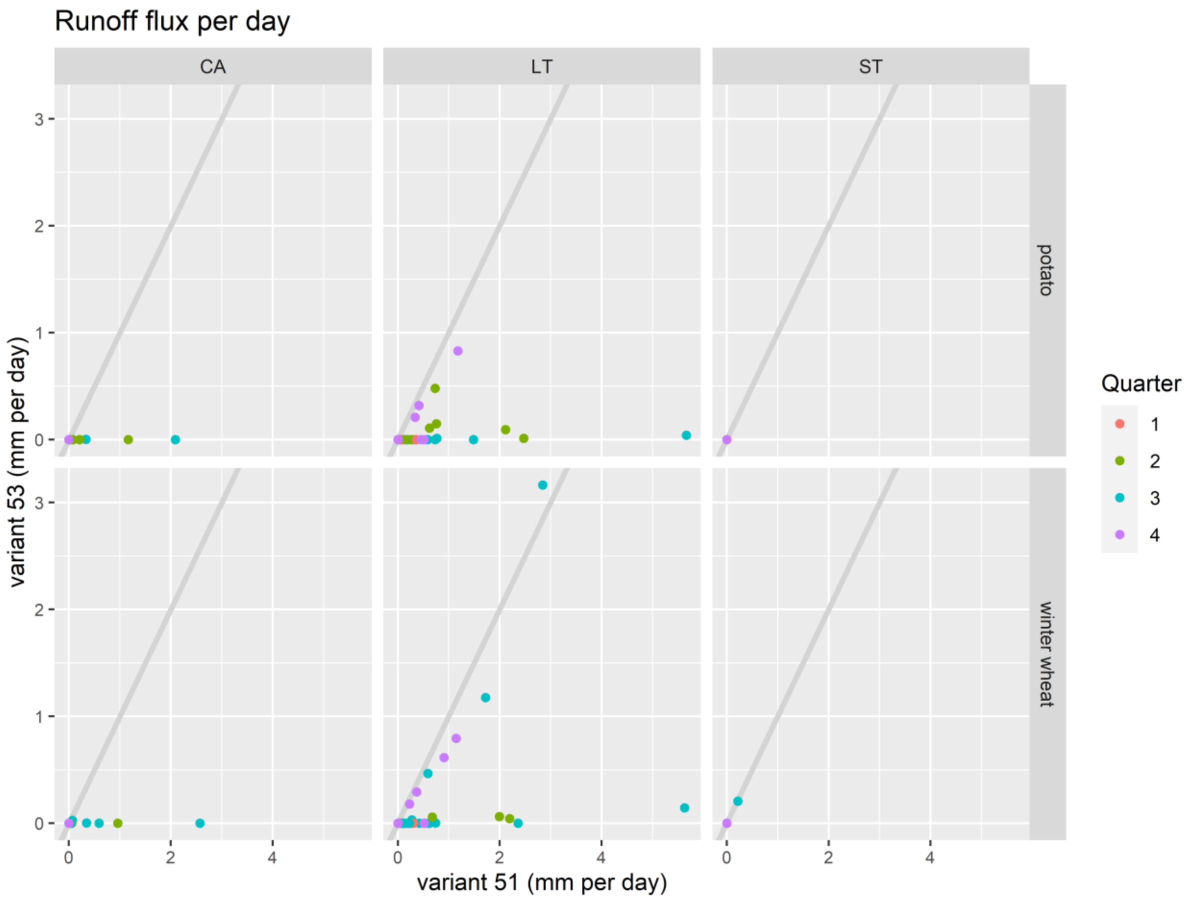


Figure 3-15 *Effect off infiltration capacity on the daily runoff quantities, presented as x-y plot (variant 51 - 10 cm/d, 53 -250 cm/d). With the quarter of the year indicated*

3.5.5 Increased permeability due to macro pores

Macropores influence the permeability at high moisture contents. To determine how this influences the water content and availability a simulation is made with a higher saturated permeability (Ksatexm) till a depth of 80 cm-ss (this depth worms can easily reach) till at least 50 cm/d (this is a moderately high infiltration rate for a clay soil). Also, the porosity can increase in this case with about 10-20 mm. For the sensitivity analysis the saturated water content is increased with 20 mm for the layers till 80 cm-ss.

Results
As is the case with the infiltration capacity, changes in macropores also results in small differences in the water balance. The transpiration increases a bit (about 1-2%). Also, the runoff is reduced for the CA and the ST field, as shown in Figure 3-16.

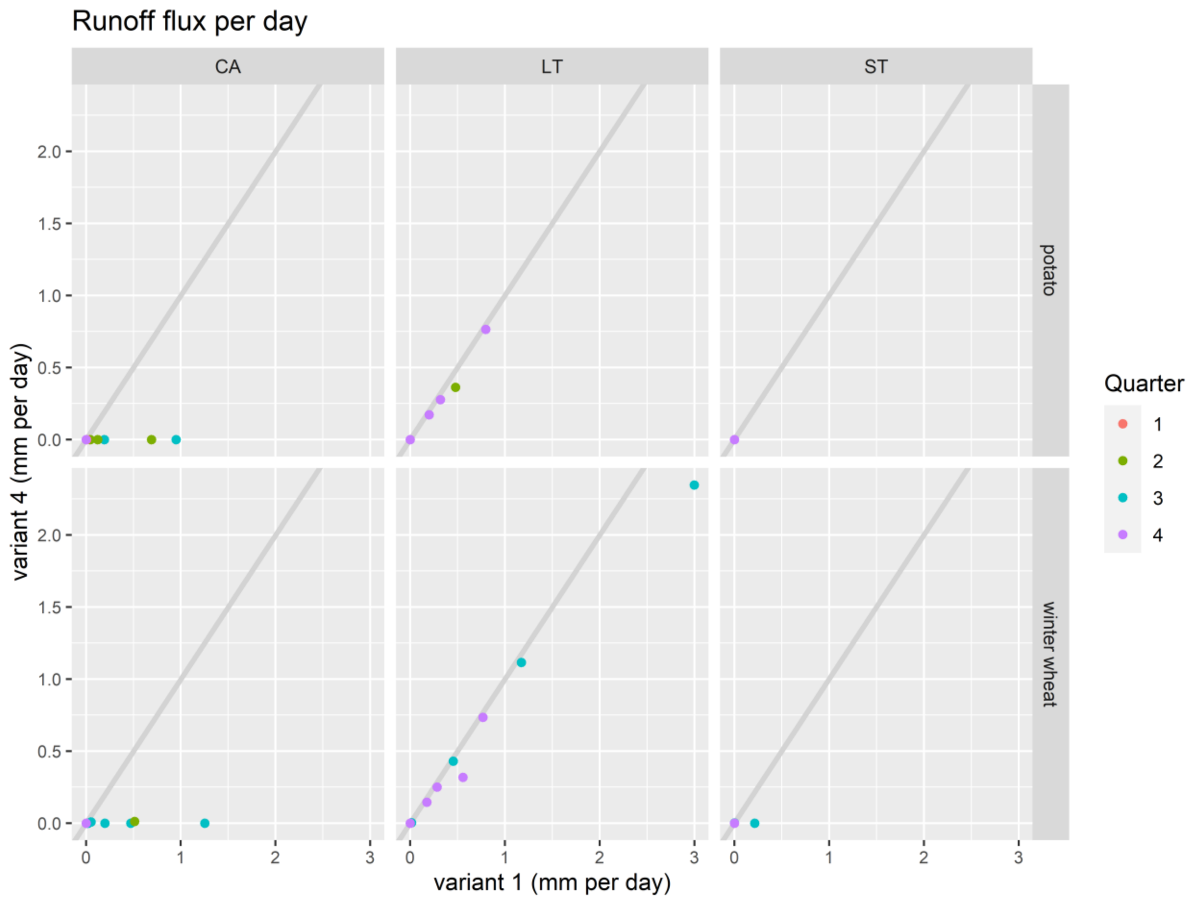


Figure 3-16 *Runoff for the current situation (**variant 1**) and for the variant with a higher saturated permeability (**variant 4**). With the quarter of the year indicated*

3.5.6 Bulk density

The water conductivity also depends on the bulk density: a higher density leads to lower permeabilities. The local properties are based on the samples taken, the properties with a lower density can be approximated via the relations given in Appendix 1.

As can be seen from the measurements of the bulk density on the CA site, the layer from 45 till 55 cm-ss is moderately compacted (the border lies on 1600 kg/m^3). To approximate the soil properties of a non-compacted layer for the bulk density, the mean values of Staring building blocks are used (Table 3-5). It is assumed that these values represent uncompacted soils: this is also motivated by the fact that the commonly accepted value for compacted soil lays at 1600 kg/m^3 and above (van den Akker & de Groot, 2008).

Table 3-5 *Mean bulk densities (kg/m3) of the Staring building blocks*

Bulk densities (mean values, kg/m3)			
	on 20 cm -sl		**on 60 cm -sl**
		O09 (medium light loam)	1530
B09 (heavy loam)	1360	O10 (heavy loam)	1480
B10 (light clay)	1280	O11 (light clay)	1400
B11 (medium clay)	1200	O12 (medium clay)	1270

This results in the SHP's as given in Table 3-6. As can be seen from the table the SHP of 3LG2 will not change because the bulk density of this layer will not change.

Table 3-6 *Van Genuchten-parameters, for CA layer 2, compacted and non-compacted, indicated with the suffix "_new" (Ks: fitted Ksat-value for the MvG-equation, Ksatex: in lab measured Ksat-value) and characteristic values critical Z-height and available water content (pF2 minus pF4.2). Green means a better water availability and red worse*

Id	**thetaS**	**thetaR**	**Alpha**	**Npar**	**Ksat**	**Lpar**	**Rho**	**Silt**	**Clay**	**critZ_1mmd**	**dWC**
	-	**-**	**-**	**-**	**Cm/d**	**-**	**Kg/m3**	**%**	**%**	**cm**	**%**
3LG1	0.4400	0.0000	0.0123	1.1360	3.05	-3.0794	1547	50	24	64	18.5
3LG1_new	0.5114	0.0000	0.0205	1.1093	7.04	-3.0794	1360	50	24	**51**	18.4
3LG2	0.4067	0.0000	0.0099	1.2634	11.57	5.0236	1488	30	16	121	24.5
3LG2_new	0.4067	0.0000	0.0099	1.2634	11.57	5.0236	1488	30	16	121	24.5
26LG1	0.3960	0.0000	0.0405	1.1037	77.05	6.0951	1631	40	24	48	13.4
26LG1_new	0.4964	0.0000	0.0833	1.0839	261.75	6.0951	1360	40	24	**37**	**14.1**
26LG2	0.3900	0.0344	0.0103	1.5240	16.49	4.1595	1601	25	16	142	25.4
26LG2_new	0.4152	0.0329	0.0123	1.5001	22.79	4.1595	1530	25	16	**131**	**26.0**
12LG1	0.4296	0.0000	0.0228	1.1938	14.19	1.6137	1388	30	19	72	21.1
12LG1_new	0.4388	0.0000	0.0247	1.1897	16.08	1.6137	1360	30	19	**69**	**21.2**
12LG2	0.3647	0.0325	0.0096	2.8569	32.32	1.8135	1589	20	12	169	22.0
12LG2_new	0.3841	0.0313	0.0112	2.7769	42.29	1.8135	1530	20	12	**153**	**20.4**

For the sensitivity analysis it is assumed that the SHP's of layer 2 are changed in the noncompacted SHP's. This means that for the ST and CA-sites the SHP's will change. For the LT-site the contemporary bulk density is approximately the same as the non-compacted value.
In the table some characteristics are given:

- critZ_1mmd - the critical Z-value: the depth water due to capillary rise of 1 mm/d will cross. The higher the critical Z-value the higher the capillary rise.
- dWC – water availability: water storage between field capacity (pF2) and wilting point (pF4.2).

For the site CA (12LG2) both critZ1 and WC pF2-4.2 become lower. For the site ST (26LG2) the capillary rise becomes lower and the available water content rises slightly.

Results

Figure 3-17 shows that the effects on the transpiration differ per location: less transpiration at the CA-site and more transpiration at the ST-site. The conversion of the SHP according to the formulas from Annex 1 is still uncertain, research is still going on. Therefore, not too much value should be attributed to the results of this analysis concerning the change of the bulk density.

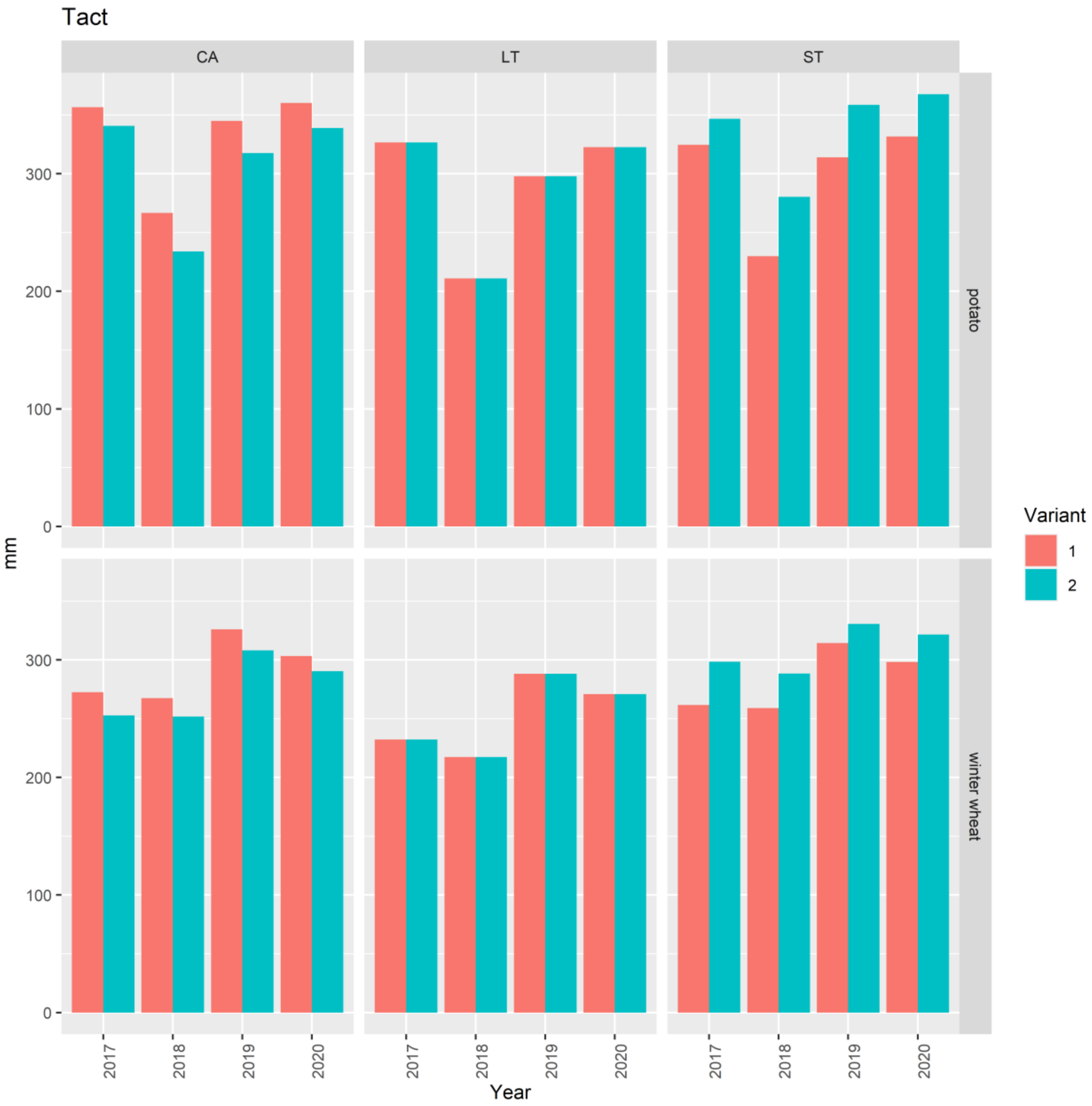


Figure 3-17 *Effect on the transpiration (Variant 1: reference, Variant 3: uncompacted plough layer)*

3.5.7 Variation in soil hydraulic properties

The BOFEK map shows several soil units (paragraph 2.4.1), resulting in a variation in water retention and permeability relations for the prevalent soil types. Therefore, the water availability varies per sample. Table 3-7 shows the differences in available water for the most common BOFEK profiles at the Soil Heroes fields and the fields itself. BOFEK 4018 is a lighter soil than 4012 and 4014 with a better capillary rise and more available water in the rootzone. Within one BOFEK soil several soil profiles are clustered. In Figure 3-18 the characteristics of the soil profiles belonging to BOFEK 4018 are given. The available water in the rootzone is about the same for all the soil profiles, but there is a great variation in capillary rise (see also Figure 3-19). The total available water ranges from 210 till 340 mm. In Figure 2-13 the available water for the sites is given (based on the measured soil hydraulic properties). For the measured plots the available water ranges from 160 till 270 mm.

Table 3-7 *Characteristics of the BOFEK-profiles and the plots, thickness rootzone 50 cm (RZ: rootzone, SS: subsoil both easily and hard available water)*

BOFEK2020	Soil code	RZeasy (mm)	RZhard (mm)	SSeasy (cm)	SShard (cm)
4012	Mn82A	30	65	70	41
4014	Mn35A	30	65	1	1
4018	Mn25A	48	94	61	118
LT		32	68	22	32
CA		60	59	119	32
ST		43	56	46	27

Table 3-8 *Variation of characteristics for the soil profile consisting to BOFEK 4018, thickness rootzone 50 cm (RZ: rootzone, SS: subsoil, both easily and hard available water)*
(in blue the dominant soil profile)

Profile	Soil code	RZeasy (mm)	RZhard (mm)	SSeasy (cm)	SShard (cm)
13020	MOo05	50	93	73	124
15080	pMn55C	47	94	16	77
15300	bMn25A	46	94	30	97
15311	eMn25Av	48	94	17	86
90115050	pMn55A	46	94	11	61
90115270	Mn25A	48	94	61	118
90116240	Rd90A	48	94	11	68

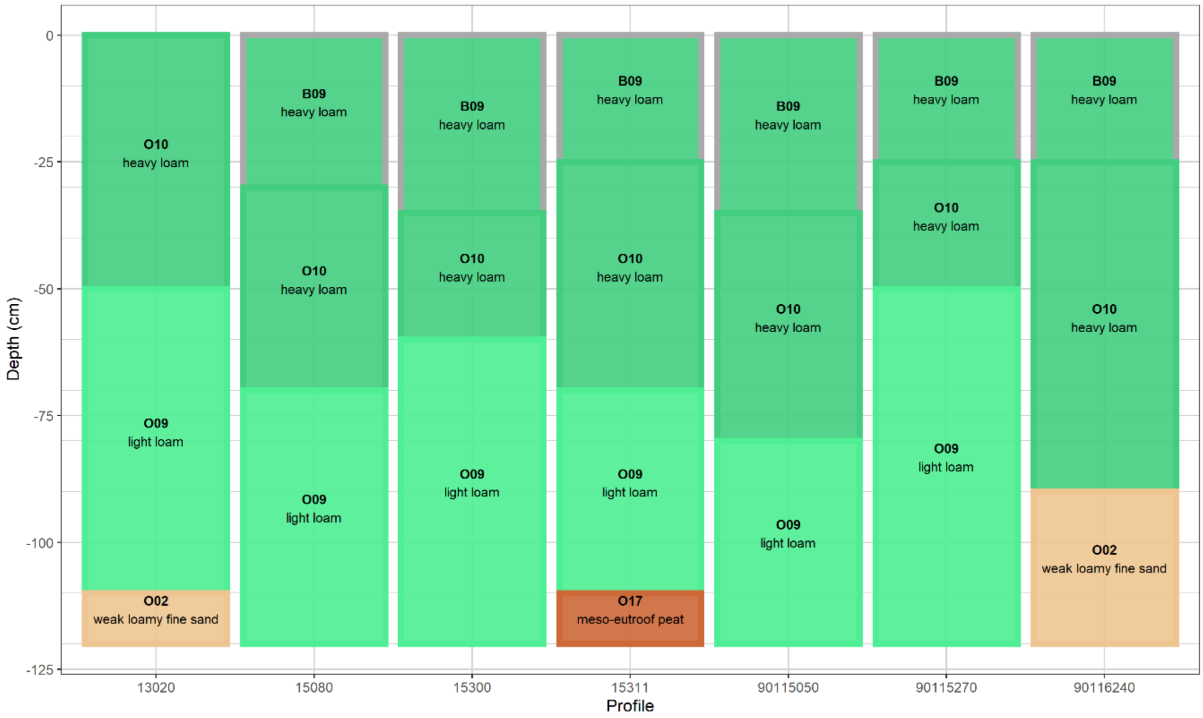
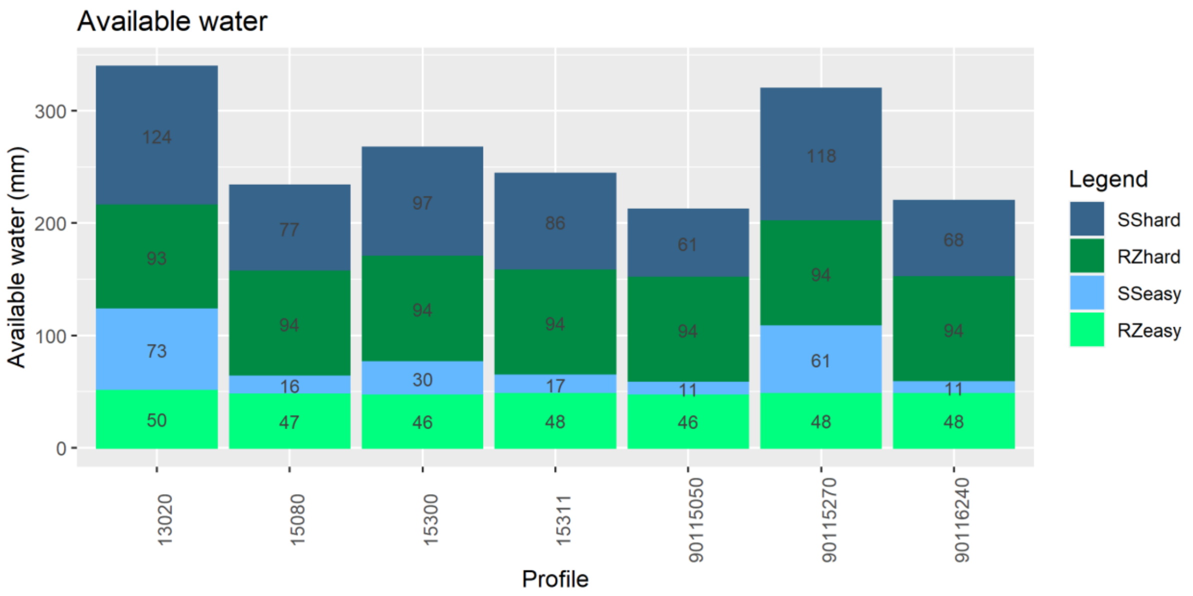


Figure 3-18 *Soil profiles belonging to BOFEK 4018 (dominant soil profile: 90115270)*



SShard: Hardly available capillary water, flux 2 till 1 mm/d (dark blue)
RZhard: Hardly available water root zone, pF 1.85 till 2.6 (dark green)
SSeasy: Easily available capillary water, field capacity till a flux of 2 mm/d (light blue)
RZeasy: Easily available water root zone, pF 2.6 till 4.2 (light green)

Figure 3-19 *Available water for soil profiles belonging to BOFEK 4018 (dominant soil profile: 90115270)*

Another consideration is that there is a variation in water retention and permeability relation for each single building block of the Staring series. The SHP's are based on several samples (Appendix 3 Heinen et al., 2020). The SHP of one building block is the average of several samples. This variation also effects the water availability and the runoff.
Therefore, as the BOFEK-map shows and also the Staring building blocks, there will be a variation in the SHP's within a field and also one field compared to another. To evaluate the effect of Regen Ag on the measured soil properties a greater number of SHP's per site should be measured and in different periods: before Regen Ag starts and after a couple of years.

A scenario with other soil hydraulic properties has not been set up, because this study focusses on properties influenced by Regen Ag and not on the natural variation in a field or between plots.

4 Synthesis and conclusions

4.1 Synthesis

The scenario analyses give insight in the effects on several metrics.
For the farmers the metric Transpiration is chosen. Transpiration is linked to the yield: the higher the transpiration the higher the yield, also leaves are greener and less irrigation is necessary.
For the waterboard the metrics Drainage and Runoff are crucial: especially during high rainfall events.
Drainage and Runoff determine the amount of water that flows to the canals.

Table 4-1 *Effects of measures on Transpiration and Runoff*

Measure	Effect on Transpiration	Effect on Runoff	Effect on Drainage
Extra organic matter	+	+[1] ?	0/+[1] ?
Enlarged rooting depth by less soil compaction	++	0[2]	0/+[2]
Higher infiltration capacity	0	0/+[2]	0
Increased permeability (till 80 cm-ss)	0	0	0
Lower bulk density	-/+ ?	0 ?	0/+ ?

? uncertain: due to uncertainties in the method

[1] not calculated

[2] dependent on the soil

Table 4-2 *Quantification to a 5 points scale of the effect on Transpiration and Runoff*

Classification	Effect on Transpiration (mm/y)	Effect on Runoff (mm/d)	Effect on Drainage (mm/d)
++	> 15	<-5	<-5
+	5 till 15	-5 till -2	-5 till -2
0	-5 till 5	-2 till 2	-2 till 2
-	-15 till -5	2 till 5	2 till 5
--	<-15	> 5	> 5

For transpiration (linked to the yield) the most sensitive parameter is the rooting depth. The effective rooting depth depends on soil compaction, the presence of macropores and the presence of fungi. Fungi can help crops to get more water: it increases the depth to which the roots can extract water. Regen Ag influences all these dependencies in a positive way.

For runoff the most sensitive parameters are soil texture and structure and as a result of that the infiltration capacity. The soil texture and structure determine the air-filled porosity at different degrees of wetness. This determines the water storage capacity. This parameter determines in combination with the infiltration capacity the amount of runoff. The simulations show a low runoff in the reference situation. As a result the decrease of runoff at higher infiltration capacities is quite low.

For drainage fluxes to the canals the scenario's show a varied picture. There can be a positive effect due to regenerative agriculture, but it depends on the circumstances (wet or dry soil).

Overall extra organic matter, enlarged rooting depth, less soil compaction, higher infiltration capacity, and increased permeability will have a neutral or positive effect on transpiration, runoff and drainage. All the effects of Regen Ag will occur at the same time. So overall it is expected that regenerative agriculture will have positive effects on 1) water availability for the crops and 2) reduction of runoff and drainage fluxes to the canals.

4.2 Conclusions and recommendations

The objective is to explore the possibilities of SWAP for modelling the differences that may occur as a result of regenerative or conventional management:

What is the effect of Regen Ag in comparison to Conventional Agriculture, CA (moisture supply capacity and runoff)?

- Roots: the rootable depth is quite important for the transpiration and the yield. This means that less soil compaction and more macropores enhances the available water and as a result the transpiration and crop yield.
- Fungi: Roots in collaboration with fungi can probably help the crop to get more water (especially in dry summers). A literature study is advisable.
- Infiltration capacity: Runoff is determined by the infiltration capacity and the air-filled porosity. Regen Ag can enhance the amount of worms in the soil and as a result the infiltration capacity. A higher infiltration capacity usually leads to less runoff.
- Macropores: more macropores lead to more air in the soil, and a higher infiltration capacity. And as a result, less runoff.

Can we distinguish in effects of management and site-specific characteristics?

- Initially the studied fields differ in soil type, compaction and surface water level. This makes it hard to attribute the effects of Regen Ag when comparing the different fields (CA in comparison to LT). Therefore in this research some scenarios were simulated to determine the effects of Regen Ag.

Can SWAP simulate the effect of Regen Ag?

Regen Ag influences several parameters which are of importance for the crop development:

- Rooting depth:
  Rooting depth is of importance for the crop development. It is not only dependent on the penetration resistance but also on the occurrence of macropores. For the parameterization both dependencies should be considered. But there is not a single formula with a clear relationship. So, scenario analysis can be performed.
- Fungi:
  Fungi can be simulated using an extended rooting depth. Sensitivity analysis can be performed to get an idea of the importance of the effect.
  A literature study in combination with expert knowledge can help.
- Organic matter content:
  Some relations on the effect of organic matter content exists. This is elaborated very well in other studies and therefore not a part of this study.
- Worms:
  Worms contribute to macropores and therefore a higher infiltration capacity. SWAP is able to simulate this.

Can a SWAP simulation help with the analysis/interpretation of measurement data?

Comparisons between measured values and model leads to the following conclusions:

- Water balance: the components of the water balance are plausible.
- Soil moisture content: several measurement data are available, which are used in a relative way. The simulations correspond reasonably well with the measurements.
- Groundwater level: there are not a lot of piezometers, only one and it is outdated. The seasonal dynamics correspond quite well with the simulations.

There are still several discrepancies between measurements and simulation. For the use in the scenario analysis the discrepancies between simulation and measurements are a smaller problem because a sensitivity analysis will focus on the relative effects.

Measured data: was it sufficient?
Some groundwater level measurements are available, but more are desirable. The available data were well simulated. The measured soil water contents were used in a relative way and the dynamics were simulated reasonably well. It would have been desirable to obtain:

- Groundwater level: field measurements (not too close to canals and drains!).
- Soil moisture: measurements with calibrated devices.
- SHP: relations were measured in the lab and were input for the model. These are important, but these are also costly. It is probably advisable to acquire more SHP-relations (several per field, also in time), but degree of representation has to be considered because of spatial variation.
- Infiltration capacity measurements.
  This depends very much on the period (wet or dry, summer or winter).
- Rooting depth: rooting depth is partly derived from penetration depth but can also be measured in the field.
- Fungi: a big uncertainty is the influence of fungi for the plants. Measurements would be highly relevant.
- Aggregate stability: Aggregate stability is of importance for the infiltration capacity and the aeration of the soil. At the end of 2022 new samples will be taken. This will be included in the report with the analysis of the field data.

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Annex 1 Density-dependent water retention and hydraulic conductivity

In SWAP the water retention and hydraulic conductivity relationships are given by the well-known Mualem (1976) and Van Genuchten (1980) equations (MvG model). The water retention characteristic is given by (Van Genuchten, 1980):

$$\theta(h) = \theta_r + \frac{(\theta_s - \theta_r)}{(1+|\alpha h|^n)^m} \tag{0-1}$$

where θ is the volumetric water content (cm^3 cm^{-3}), h is the pressure head (cm), θ_r is a (asymptotic) residual water content (cm^3 cm^{-3}), θ_s is the water content at saturation (cm^3 cm^{-3}), α is a curve shape parameter (cm^{-1}), and n and m are dimensionless curve shape parameters.
The hydraulic conductivity characteristic is given by (Mualem, 1976; Van Genuchten, 1980), with the restriction that $m = 1 - 1/n$:

$$K(h) = K_s \frac{\left((1+|\alpha h|^n)^m - |\alpha h|^{\text{n-1}}\right)^2}{(1+|\alpha h|^n)^{m(2+\lambda)}} \tag{0-2}$$

where K is the hydraulic conductivity (cm d-1), Ks is K at saturation (cm d-1), and l is a dimensionless curve shape parameter related to the pore size distribution.

Density-dependent parameters in MvG model
Tian et al. (2018) and Kool et al. (2019) showed that with changing dry bulk density the water retention curves and hydraulic conductivity at saturation change, so that it is likely that all (or most) of the parameters in the MvG model change accordingly. These changes are accounted for by the relative change in dry bulk density. In line with the approach of Assouline (2006a, b), Tian et al. (2018) and Kool et al. (2019) stated that

$$\theta_r^* = \theta_r \left(\frac{\rho^*}{\rho}\right) \tag{0-3}$$

$$\theta_s^* = \theta_s \left(\frac{\rho_s - \rho^*}{\rho_s - \rho}\right) \tag{0-4}$$

$$\alpha^* = \alpha \left(\frac{\rho^*}{\rho}\right)^{-\omega} \tag{0-5}$$

where ρ_s is the density of the solid phase of the soil (g cm^{-3}; typical value for mineral soils is 2.65 g cm^{-3} and 2.7-2.75 g cm^{-3} for clay soils) and the coefficient ω was empirically determined to be equal to 3.82 (later: 3.97, see below). Assouline (2006a, b) did not use the MvG model, but he used slightly different expressions. His parameter that resembles the n parameter in the MvG model was assumed not to be affected by a change in dry bulk density ($n^t = n^{t-1}$ = constant). However, based on their observations Tian et al. (2018) and Kool et al. (2019) concluded that also n should be adapted. They first proposed to change n according to

$$n^* = 1 + (n-1)\left(\frac{\rho^*}{\rho}\right)^{\varepsilon} \tag{0-6}$$

The coefficient ε is dependent on soil type (texture) and was calibrated as follows

$$\varepsilon = -0.97 + 1.28 \frac{f_{\text{silt}}}{f_{\text{clay}}} \tag{0-7}$$

where f_{silt} and f_{clay} are the weight fractions silt (2-50 μm) and clay (< 2 μm), respectively. At the same time they recalibrated ω in Eq. (0-5) as ω = 3.97. Later they provided a second method to change the n

parameter, which, however, requires additional input information. The alternative expression for how *n* changes is given by

$$n^* = n + (\rho^* - \rho)\left(\frac{n_{\text{ref}} - n_{\text{match}}}{\rho_{\text{ref}} - \rho_{\text{match}}}\right) \tag{0-8}$$

This relationship states that *n* changes linearly from its value belonging to the reference (ref) curve (likely the curve referring to the initial situation for which all other parameters are also given) to a value that was determined from a single measurement in a more dense or more lose situation (the matching situation). This thus requires additionally measured information (the matching point); Figure A1-3 visualizes this approach.

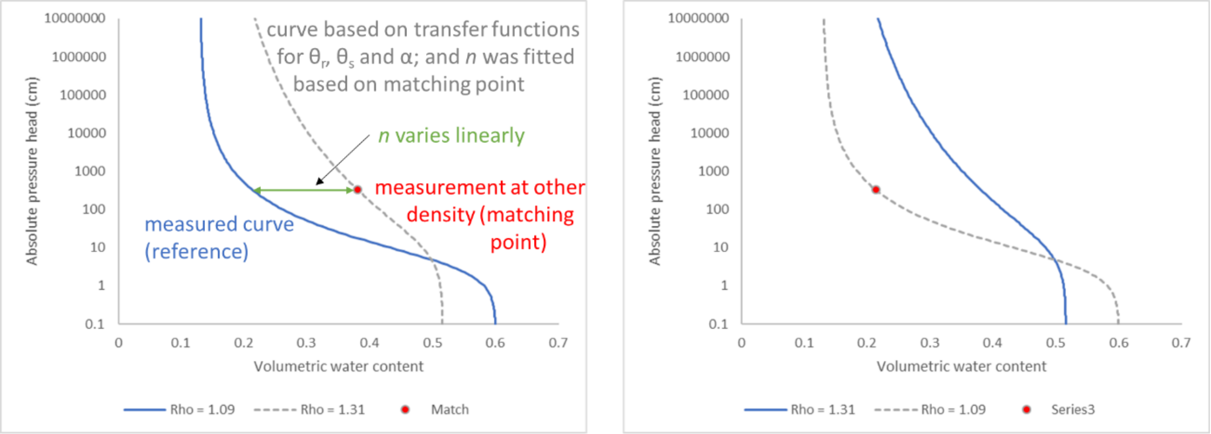

Figure A1-3 *The link between reference curve and matching point in-between the n-parameter varies linearly (based on Kool et al., 2019)*

Density-dependent hydraulic conductivity parameters in MvG-model

For the hydraulic conductivity at saturation, several models have been proposed in literature; see, e.g., the discussion in Assouline (2006b). Assouline (2006b) proposed the following transformation:

$$K_s^* = K_s\left(\frac{\theta_s^*}{\theta_s}\right)^3\left(\frac{\rho^*}{\rho}\right)^{\delta-7} \tag{0-9}$$

where K_s is a function of θ_s (or better: porosity), the dry bulk density ρ and a parameter δ. Assouline (2006b) concluded that for δ = 4 the similarity between measured and calculated K_s for all his soils proved to be good. Kool et al. (2019) indicated that δ should be in the range 2-4 for loam and clay soils, and δ should be in the range 4-6 for sandy soils; Assouline proposed to use δ = 6 for coarse sand. For the shape parameter λ no relationship with dry bulk density is given, such that

$$\lambda^* = \lambda \tag{0-10}$$

Assouline (2005) stated that there exists a strong relationship (correlation) between the coefficient of variation of the pore size distribution and this shape parameter λ. If we assume that this coefficient of variation before and after a change in dry bulk density remans about the same, then it seems fair to keep λ unchanged. This may be true for moderately changing dry bulk densities (as studied by Assouline), but this has not been verified for large changes in ρ, e.g., due to soil tillage. For the time being, however, we can only keep λ constant.

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Annex 2 Measurements moisture content

Several moisture sensors are installed to determine their usability. The sensors are placed at several locations. The figures below show the moisture measurements of Sensoterra and Dacom.

In Figure A2-1 Dacom data is displayed. A number of comments can be posted:

1. Negative water contents: the water content becomes negative in certain cases. Of course, this is not possible and indicates that the sensor is not calibrated.
2. Units: it is not clear what the unit mm means.
3. Synchroneity: The different lines are generally in sync.
   The purple line (50 cm-ss) shows a sharp decrease on June 17th and then a stronger increase on August 16th, 2019 and is therefore out of sync with the WC at the other depths.
4. Plausibility: Remarkably high are the values measured at a depth of 10 cm-ss in comparison with the deeper sensors. In comparison with the lower values at a greater depth this is not plausible.
5. Legend: it seems that the measurements at a depth of 10 cm and 50 cm have been changed.

In view of the above assessment, the data are used in a relative sense to determine the relatively dry and wet periods for soil moisture.

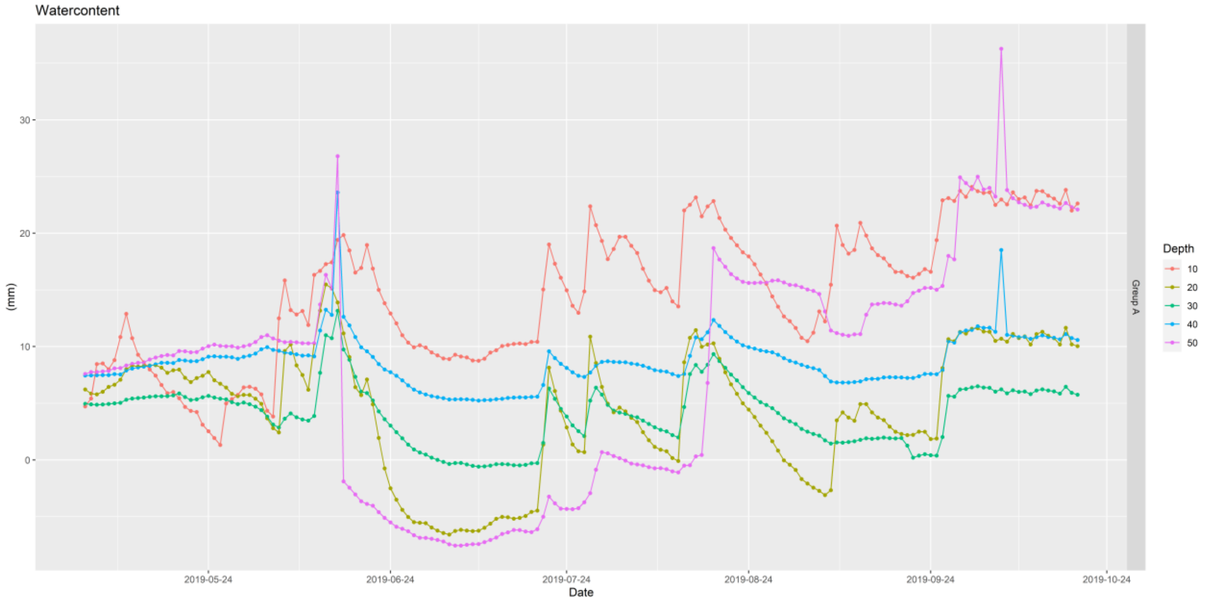

Figure A2-1 *Measurement data moisture content Dacom at different depths (location LT.2)*

In Figure A2-2 t/m Figure A2-4 Sensoterra data are displayed. Several comments can be posted:

1. Calibration: it appears that the measurements are not calibrated. The dynamics of many measurements cannot be related to the expected dynamics.
2. Synchroneity: The different lines are often out of sync with steps at certain times. E.g., for LT.2 around 20 June there is a sharp decrease.

In view of the above comments, the measurements are not usable for the validation of the model results.

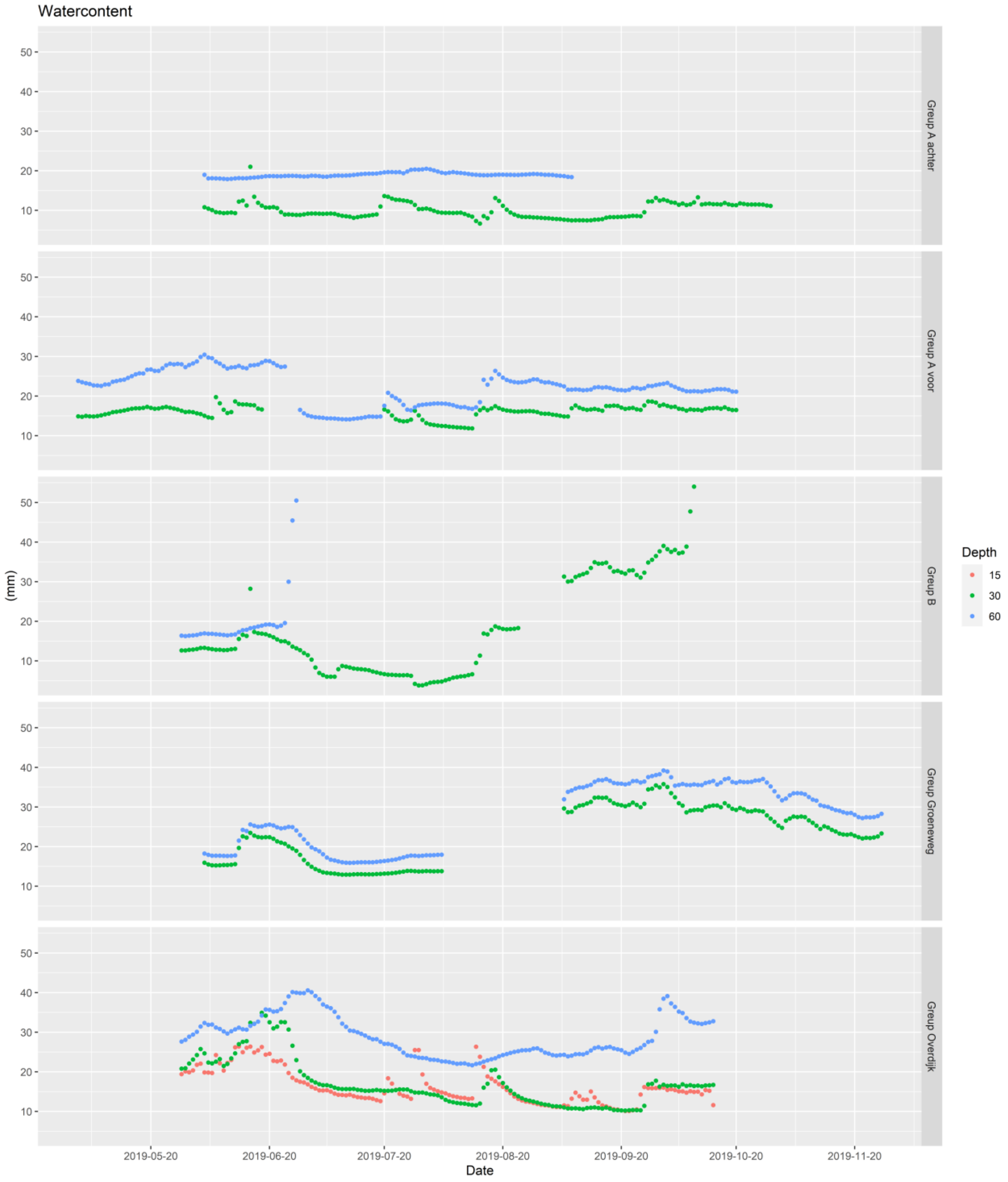

Figure A2-2 *Measured moisture content Sensoterra at different depths (location LT)*

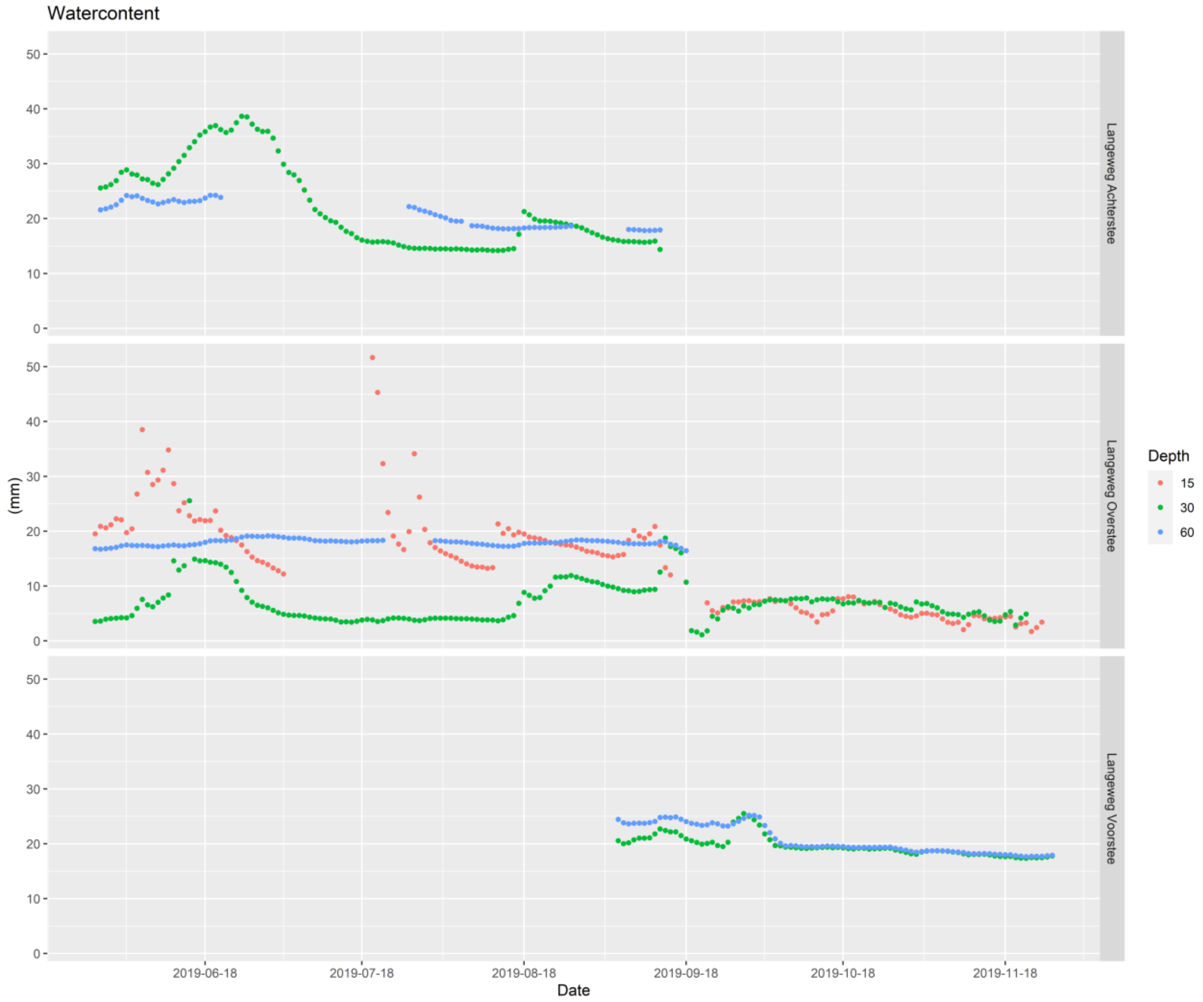

Figure A2-3 *Measured moisture content Sensoterra at different depths (location ST)*

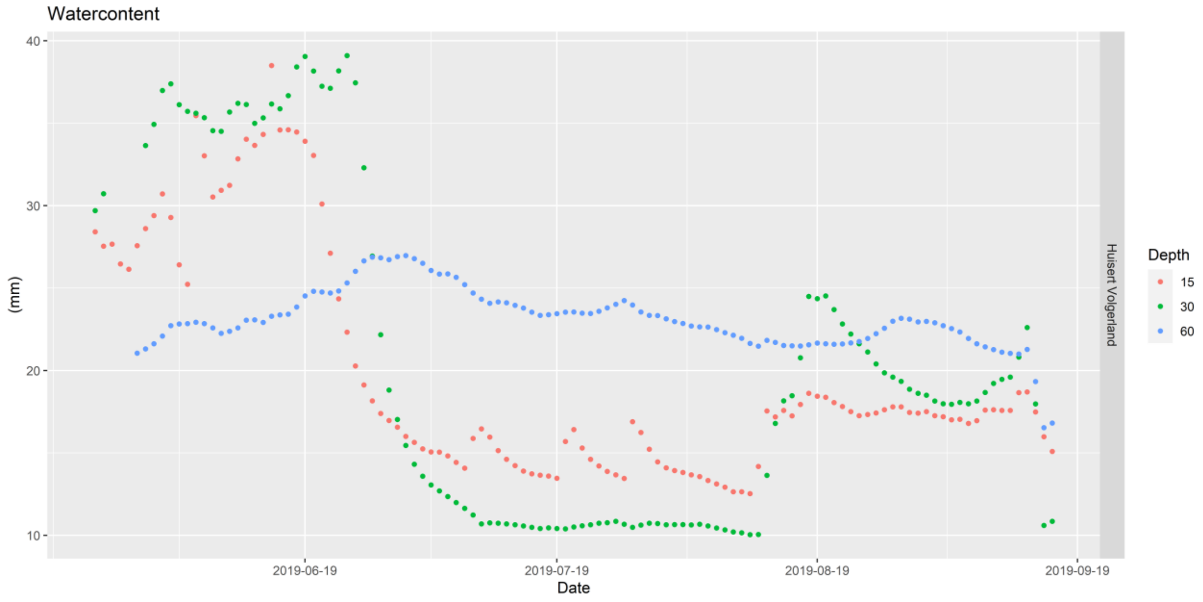

Figure A2-4 *Measured moisture content Sensoterra at different depths (location CA)*

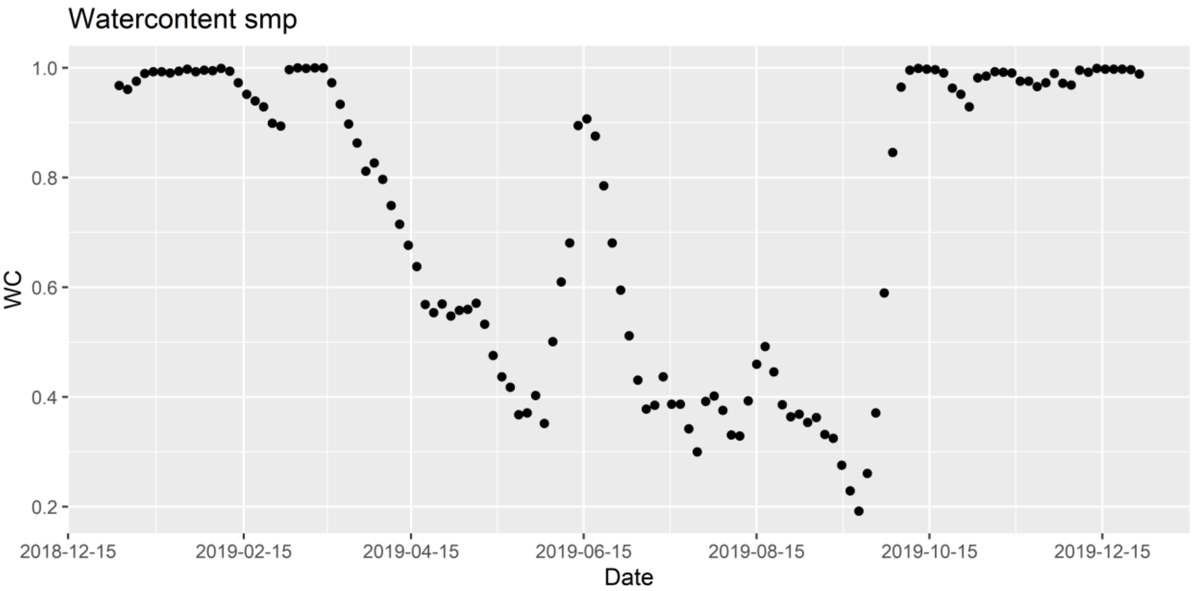

Figure A2-5 *Measured moisture content SMAP (fraction: 1.0 = saturated)*

In Figure A2-5 measurement data from the "NASA-USDA Enhanced SMAP Global soil moisture data" satellite are presented. They provide soil moisture information all over the world with a spatial resolution of 10 km. The figure shows the soil profile data for 2019. Given the resolution, it gives an indication of the dynamics in soil moisture in the top 10 cm. Locally, the dynamics can vary considerably depending on crop, soil, surface water levels and other local conditions.[5]

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[5] https://developers.google.com/earth-engine/datasets/catalog/ NASA_USDA_HSL_SMAP10KM_soil_moisture

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