

Chapter 1 NOBV year report 2022

Effects of subsurface water infiltration systems on phreatic groundwater levels in peat meadows



Effects of subsurface water infiltration systems on phreatic groundwater levels in peat meadows

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Photo on cover by Mariet Hefting: NOBV experimental plot at Zegveld (high water farm) with monitoring wells installed next the automatic flux chambers.

Abstract

Worldwide, drainage of peatlands has resulted in increased peat decomposition causing CO₂ emission and land subsidence. To stop or reduce this process, measures are being developed and tested, many of which aim to raise the summer phreatic groundwater level, which is considered an important factor reducing peat decomposition and its consequences. In this study, the effect of different water infiltrations systems (WIS) on phreatic groundwater level dynamics are tested at five locations in the Dutch peat meadow area. WIS are designed to limit lowering of the phreatic groundwater level in summer and lower phreatic groundwater levels in winter, but the actual effect presumably depends on multiple factors, like drain depth, drain spacing and geohydrological conditions, but also operational management like ditch and drain water level and system maintenance. All these factors may vary between the study locations. Results demonstrate that at three of the five locations, the average phreatic summer groundwater level was substantially less deep in the WIS parcel compared to the reference parcel, with differences of up to 27 cm. The deepest (summer) phreatic groundwater level at the different locations was up to 44 cm higher in the WIS parcel compared to the reference parcel. At one location, only a minor effect was observed for one (dry) summer. At the fifth location, which is located in an area with upward seepage, the WIS stimulated drainage of groundwater which resulted in a deeper lowering of the phreatic groundwater level compared to the reference parcel. The effect on winter drainage is less pronounced, based on calculated average winter groundwater levels. Still, in most situations, the average highest groundwater level is lower in the WIS parcel than in the reference parcel, indicating additional drainage does take place in winter. The effect of the WIS on phreatic groundwater levels was especially notable in the dry summer of 2022. Furthermore, our findings demonstrate that ditch water management (especially keep summer ditch water levels sufficiently higher than drain depth) and drain maintenance are of utmost importance for attaining the most optimal and desired effect of a subsurface water infiltration system.

Highlights

- Subsurface water infiltration systems, if correctly applied, generally limit lowering of summer phreatic groundwater levels in peat meadow areas.
- For the most optimal effect of WIS, water levels in the ditch or reservoir should be kept sufficiently high in summer, at least 20 cm above drain depth, and drains should be free of air and mud.
- Other factors affecting the effectiveness of WIS are soil composition, drain spacing and hydrological conditions (| e.g. the seepage / infiltration situation, depending especially on local and regional geology and morphology, and on soil characteristics including hydraulic conductivity).

1 Introduction

Worldwide, peatlands have been drained over the last decades to centuries to create and maintain arable land and pastures for dairy farming (e.g., Joosten and Clarke, 2002; Erkens *et al.*, 2016). Drainage of peatlands leads to increased aeration of the organic soils, which stimulates peat decomposition by biogeochemical processes (redox processes; e.g., Leifeld and Menchetti, 2018; Freeman *et al.*, 2022). Consequently, carbon that has been stored in peat soils for millennia (Yu *et al.*, 2010) is released as CO₂ into the atmosphere, contributing to global warming (e.g., Leifeld *et al.*, 2019; Evans *et al.*, 2021; Huang *et al.*, 2021). Besides CO₂ emission, peat decomposition following drainage leads to land subsidence, and ultimately complete loss of the peat layer.

To limit global warming, the Paris Agreement was established at the UN Climate Change Conference in 2015. It includes commitments from all countries that have joined the agreement to reduce their greenhouse gas emissions and work together to adapt to the impacts of climate change. In the Netherlands, goals for greenhouse gas emission reduction are laid down in a Climate Act¹, which states that greenhouse gas emission should be reduced by 49% in 2030 and by 95% reduction in 2050, compared to 1990 levels. The Dutch Climate Agreement (2019)² describes which measures need to be taken per sector to reach these goals. The goal envisaged for peat meadow areas, which are part of the sector agriculture and land use, is a reduction of 1Mton CO₂ equivalents per year in 2030, to be attained from ca 90.000 ha peat meadow areas (i.e., 11 tons CO₂ equivalents per year per ha reduction).

An important factor influencing greenhouse gas emission from peat soils is water table depth (Tiemeyer *et al.*, 2020; Evans *et al.*, 2020; Freeman *et al.*, 2022). With higher groundwater levels, (atmospheric) oxygen intrusion into the soil is reduced, such that less peat is susceptible to aerobic breakdown. Higher groundwater levels are therefore expected to reduce CO₂ emission by peat decomposition, especially in dry and warm summer periods, when phreatic groundwater levels are commonly low in the Dutch peat meadows. Therefore, most measures to reduce greenhouse gas emission from peatlands aim to prevent deep lowering of the (summer) phreatic groundwater level. This may be done by increasing ditch water levels or by installing subsurface water infiltration systems (WIS; e.g., Van den Akker *et al.*, 2010; Querner *et al.*, 2012; Hoekstra *et al.*, 2020; Kalinsky *et al.*, 2021). In some cases, the land use changes because of the wetter conditions, for example, peat meadows may be transformed into natural peatlands or paludiculture systems. A WIS consists of submerged horizontal drainpipes that are placed in the peat soil at least 15 – 20 cm below ditch water level (Figure 1). In dry summer periods, ditch water infiltrates through the drains into the soil to compensate the evapotranspiration and so prevents deep lowering of the phreatic groundwater level in the parcel. Theoretically, the groundwater level above the infiltration drain is close to the ditchwater level. In between the infiltration drains the groundwater level will be hollow, creating a gradient to the middle in between the drains. The amount of groundwater level lowering in between the drains depends on the infiltration capacity of the WIS, the actual evapotranspiration, eventual upward or downward seepage, soil water conductivity and drain spacing. For most situations, a drain spacing of 4 m is advised for peat soils (KOMO, 2021), but if the hydraulic conductivity is high, drain spacing may be enlarged to 6 m. In wet periods the drains may drain groundwater towards the drains and ditches, thereby lowering the phreatic groundwater level. In this situation, the groundwater level is highest in between the drains and groundwater flows towards the drains, thereby creating a gradient opposite of the summer situation.

¹ <https://www.government.nl/topics/climate-change/climate-policy>

² <https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/national-climate-agreement-the-netherlands>

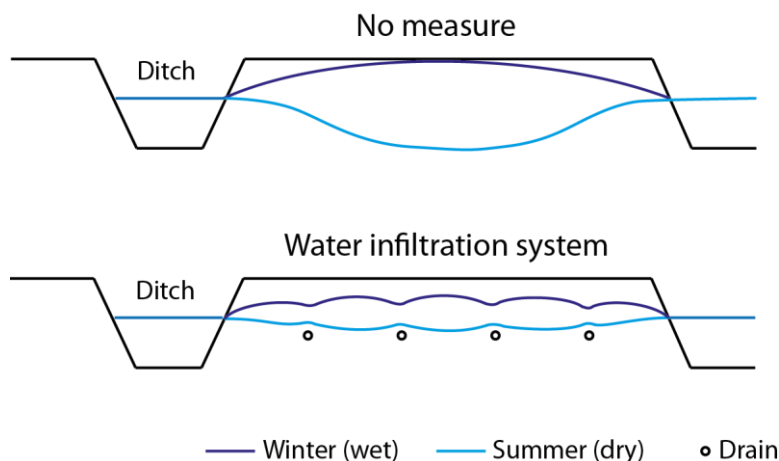


Figure 1. Conceptual figure illustrating the functioning of a water infiltration system.

The drains can be connected to the ditch directly, or indirectly via a small reservoir. The water level in the reservoir is actively managed by a pump to enhance either infiltration of water during dry conditions, or drainage of water during wet conditions. This practice is referred to as active WIS (AWIS), as opposed to passive WIS (PWIS) for the situation without a reservoir.

In this study, the effect of WIS on phreatic groundwater level dynamics in peat meadows has been investigated based on field data from five locations in the Netherlands. The study is part of the Dutch National Research Programme on Greenhouse Gases in Peatlands (NOBV; www.nobveenweiden.nl). Environmental conditions, like subsurface composition and hydrologic circumstances resulting from both natural hydrologic processes and water management, vary between the NOBV study locations. Moreover, the setup of the WIS varies among locations, i.e., there are variations in drain spacing, drain direction, drain depth, and the way of connection to the ditch; either direct, via a collector drain or indirect, via a reservoir with pump. Outcomes of this study give insight into the effectiveness of WIS on groundwater level dynamics at the different locations, including a quantification of these effects. Such information is vital to interpret and quantify effects of WIS on other factors such as land subsidence and greenhouse gas emission, through both field data analysis and modelling studies. In the end, derived insights may be used by policy makers for designing effective measures to reduce greenhouse gas emission in peat meadow areas, in order to reach climate goals.

2 Study sites and methods

2.1 Methods

Five NOBV study sites have been installed in the spring and summer of 2020, in peat meadows used for grass production and grazing by cows (Figure 2). At each of these locations two field plots have been installed, one in a parcel with a WIS and another in a nearby reference parcel without a measure.



Figure 2. Locations of paired field plots.

Phreatic groundwater levels have been measured at varying distances to the ditches and submerged drains. In the field plot with submerged drains, the phreatic groundwater level has been measured at 0.5 m distance to the drain, at $\frac{1}{4}$ drain spacing and at $\frac{1}{2}$ drain spacing. At some locations extra phreatic monitoring wells have been installed in or close to trenches, if present. In addition, at all locations, the water levels of the ditch(es) bordering the parcels, and at most locations also the hydraulic head in the Pleistocene sandy deposits underlying the Holocene peat and clay layers, have been monitored. At some locations also the hydraulic head at a few meters depth in the Holocene sequence was measured.

In soft soils, well casings are subject to friction by vertically deforming ground, which may cause vertical movement of the monitoring well up to centimetres in both an upward and downward direction. Hence, the reference level for water level measurements, for which commonly the top of the well casing is used, is not stable, which results in uncertain water level measurements. To overcome this problem, loggers (type Ellitrack-D), and connected water pressure sensors, were fixed to a steel tube founded in the stable sandy deposits underlying the Holocene soft soil sequence, to ensure water pressures have been measured relative to a stable reference level (Figure 3).

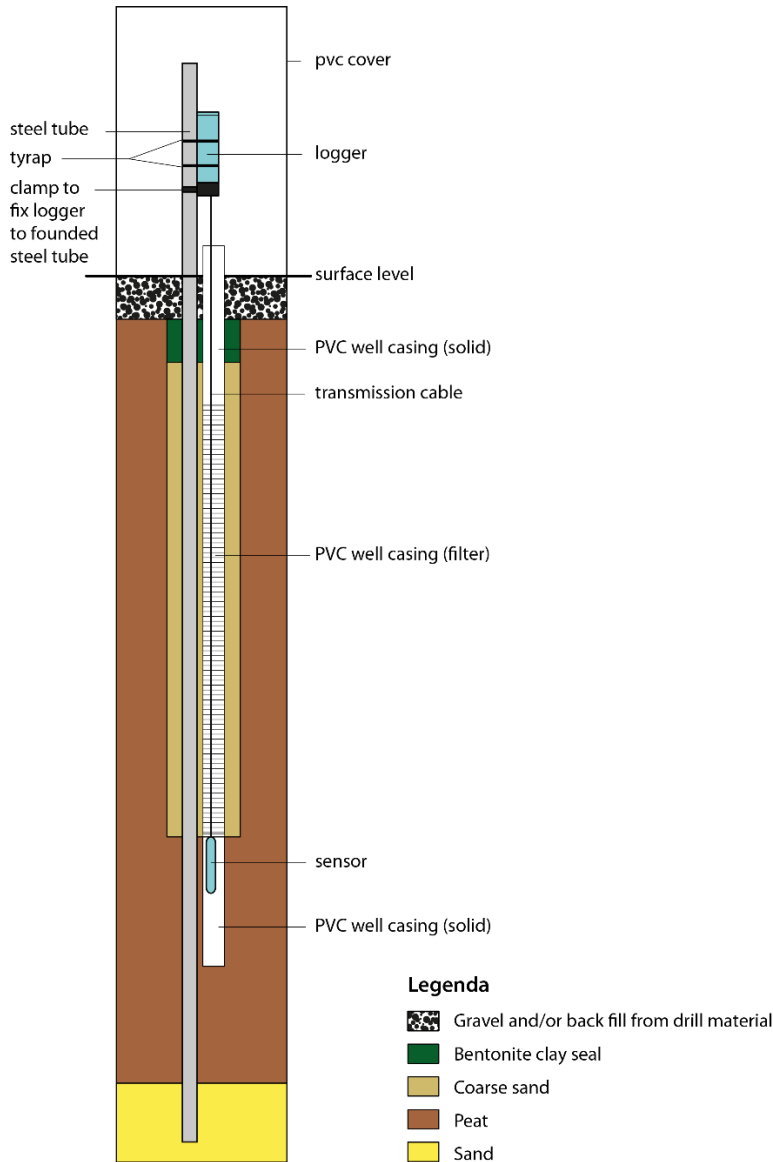


Figure 3. Schematic representation of a monitoring well. In Aldeboarn the well itself was fixed to the steel tube. In Zegveld and Vlist, the steel tube was positioned outside the coarse sand fill, at about 15 cm from the PVC well casing.

Based on the water pressure measured by the sensor, the groundwater level has been calculated relative to a reference level at the top of the logger. The height of this reference level, relative to the Dutch Ordnance Datum ('Normaal Amsterdams Peil'; NAP), was measured in the field by spirit levelling relative to a reference steel tube that is founded in Pleistocene sand. The elevation of this benchmark relative to NAP was determined based on a 15-minute measurement by an RTK-GNSS device.

At ditch water level monitoring wells, the PVC well casing itself has been pushed into stable soil below the ditch, on top of which the logger is fixed, protected by a PVC casing. For water pressure measurements in the drain a special construction has been designed, which also allows camera inspection of the drains (Figure 4).



Figure 4. Above: construction used at most sites for measuring water pressure in a drain (vertical pipe connected to the drain) and for camera inspection in the drain (Y-shaped pipes). Below: in Aldeboarn a construction with one diagonal pipe connected to the horizontal drain is used for the in-drain measurement. About halfway of the diagonal pipe sits above the soil surface. The groundwater level logger is located at the top and its pressure sensor at the bottom of the diagonal pipe.

To calculate the groundwater level relative to soil surface level, a correction must be made for vertical movement of the surface level. This has been done based on the spirit levelling and extensometer measurements that were performed at each parcel (Van Asselen *et al.*, in prep). For most wells, the surface level relative to NAP has been measured next to each monitoring well once a year (usually 4 measurements per monitoring well), usually in spring. For this specific moment in time, the depth of the groundwater level relative to surface level was calculated by subtracting the groundwater water level relative to NAP from the average surface level relative to NAP, as determined by spirit levelling next to the wells. For the succeeding period, vertical elevation changes of the surface level were derived from extensometer measurements (using the

anchor level just below surface level) at the specific study site. This procedure was repeated each time a new surface levelling measurement has been done. For ditch water level measurements, the average of all levelling measurements of either the reference or WIS parcel was used to calculate the ditch water level relative to surface level of the reference or WIS ditch respectively. In situations with one ditch (Zegveld and Vlist), spirit levelling measurements of the reference parcel were used. The calculated ditch and groundwater level data series relative to surface level are shown in various plots presented in the results section. In a future report, relations between groundwater level dynamics and precipitation will be further analysed.

Water level statistics (in Results and Discussion sections) have been calculated for calendar years, meaning that average summer statistics are calculated for the period 1 April until 31 September, and average winter statistics are calculated for the months January, February, March, October, November and December of the year in question. The average highest and lowest groundwater levels are in this study defined as the average of the 12% highest and lowest groundwater level measurements respectively for a year.

For each study site, cross sections of the surface level of each parcel have been constructed, running from ditch to ditch, based on spirit levelling measurements of the surface elevation in a transect as close as possible to the monitoring wells (indicated in Figure 5 Figure 9). For each parcel and year (2021 and 2022), two cross sections were constructed, in which the phreatic groundwater and ditch water levels were plotted for the moment in the year when the phreatic groundwater level in the reference parcel was lowest (dry conditions) and highest (wet conditions), respectively. For these two moments plus and minus two weeks, the average, maximum and minimum phreatic groundwater and ditch water level were calculated and plotted.

At all locations, the subsurface has been investigated by hand corings and, at all locations except for Rouveen, also by a Cone Penetration Test (CPT; see Erkens *et al.*, 2020). In general, the subsurface at all study sites consists of Holocene peat and clay layers, overlying Pleistocene sandy deposits. Details of the subsurface composition of each study site are briefly described in the next sections. Estimates of the organic matter content mentioned in the results sections were derived from field observations from experienced geologists and soil scientists and sometimes supported by loss on ignition (LOI) laboratory tests (cf. Heiri *et al.*, 2001).

2.2 Aldeboarn

At location Aldeboarn submerged drains were installed in the longitudinal direction of the parcel, using a drain spacing of 6 m. The drains are directly connected to the ditch at the northern end of the parcel (Figure 5), making this a passive WIS. The drain depth is 70 to 80 cm below surface level. Note that in all locations the term drain depth refers to the depth to the top of the drain.

The ditch that is closest (12 m) to the reference plot is a main polder ditch, which used to have a relatively stable water level of 70–80 cm below surface level. However, during the dry summer of 2020, the water level was raised considerably to ca. 45 cm below surface level by the water authority. Since 2022, a HAKLAM (in Dutch: '*Hoog Als het Kan, Laag Als het Moet*', meaning 'high if possible, low if necessary') water level management has been applied in this polder. This means that the polder water level is set high (ca. 45 cm below surface level) during dry periods and low if necessary for agricultural practice, such as for early growing season fertilization and/or the harvest of the last grass cut, which requires sufficient load-bearing capacity of the peat soil.

The ditch water level of the WIS parcel has often been higher than the ditch water level of the reference parcel. Here, at least for the last six years, the farmer has managed this ditch water level using a weir, applying his own HAKLAM water level management. Since the growing season of 2022, however, the ditch water level is fixed at ca. 45 cm below surface. This was done to 1) have similar ditch water level management as in the western part of the Netherlands, where

farmers usually cannot control ditch water levels themselves; 2) exclude water infiltration via trenches that may confound effects of infiltration via the subsoil pipes.

Both reference and PWIS parcels contain few trenches. The closest trench in the reference parcel lies 27 m to the west of the experimental plot and will infiltrate water when the ditch water level exceeds ca. 25 cm below surface level. In the PWIS parcel, the closest trench to the experimental plot lies 10 m to the west and will infiltrate water when the ditch water level exceeds ca. 45 cm below surface.

The subsurface in the NOBV parcels in Aldeboarn is characterized by clay on peat on detritus on sand. The top clay layer is 0.25 to 0.65 m thick, deposited in a marine environment. The clay is often stiff and has an organic matter content of about 15%. Below the clay layer, until a maximum depth of 2.1 m below surface, the subsurface consists of oligotrophic peat, containing remains of *Sphagnum* mosses, *Eriophorum* and heather. Until a depth of about 0.95 m the peat is strongly decomposed and amorphous. At the transition to underlying Pleistocene sand, an amorphous sandy detritus layer of 0.05 to 0.20 m thick has formed. The top few meters of the Pleistocene deposits consist of alternating sandy and clayey layers. Firm sand is found at a depth of about 7 to 8 m below surface.



Figure 5. Overview of the study site Aldeboarn. Numbers of monitoring wells correspond with numbers in Table 1. The spirit levelling transect has been used to make cross sections (see Results section).

Table 1. Details of monitoring wells of Aldeboarn. bs=below surface level.

No.	Parcel	Filter depth (m bs)	Drain spacing (m)	Measurement type
1	PWIS	0.75-1.70	0.5	Phreatic level
2	PWIS	0.75-1.70	1.5	Phreatic level
3	PWIS	0.75-1.70	3.0	Phreatic level
4	PWIS	NA	NA	In drain measurement
5	PWIS	0.75-1.70	1.5	Phreatic level
6	Reference	0.75-1.55	NA	Phreatic level
7	Reference	0.75-1.55	NA	Phreatic level
8	Reference	0.75-1.55	NA	Phreatic level
9	Reference	1.70-2.20	NA	Hydraulic head
10	Reference	NA	NA	Ditch water level
11	PWIS	NA	NA	Ditch water level
12	Reference	NA	NA	Trench water level
13	PWIS	NA	NA	Trench water level
14	Reference/ WIS	NA	NA	Ditch level

2.3 Rouveen

At location Rouveen, submerged drains have been installed in the longitudinal direction of the parcel with a drain spacing of 8 m (Figure 6). The drains are connected to a submerged collector drain, which is directly connected to the ditch, such that a passive WIS is created. Drains are installed at about 65 to 70 cm below surface level. Intended summer and winter ditch water levels are -1.0 m Dutch Ordnance Datum (about 40 cm below surface level) and -1.2 m Dutch Ordnance Datum (about 60 cm below surface level), respectively.

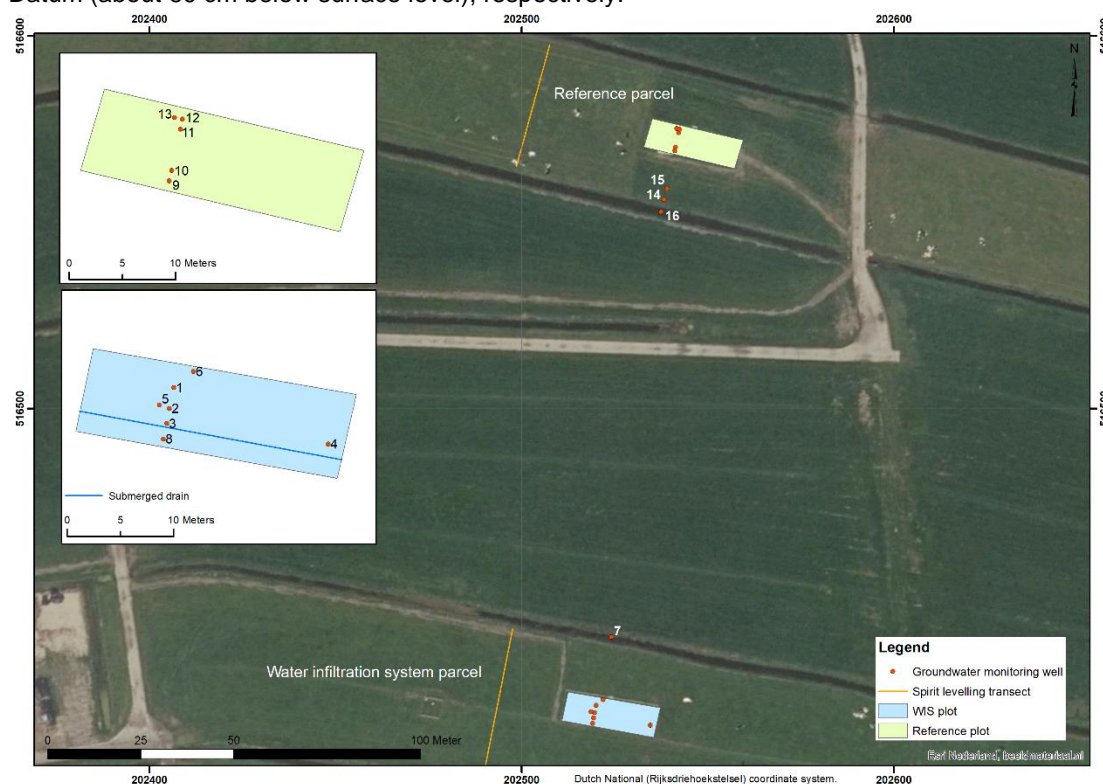


Figure 6. Overview of the study site Rouveen. The reference parcel is located at about 120 m distance from the PWIS parcel. The parcels have however similar dimensions and subsurface composition. The ditches are connected. Numbers of monitoring wells correspond with numbers in Table 2. The spirit levelling transect has been used to make cross sections (see Results section).

The subsurface in Rouveen is characterized by a clay layer on peat on sand. The top 0.05 to 0.10 m is mostly clayey peat with an organic matter content of about 30%. Underneath, a commonly stiff marine clay layer is found until about 0.30 to 0.40 m depth with an organic matter content of about 10%. Below the clay layer a peat layer occurs until a depth of 3.25 to 3.60 m below surface level. Underneath, sandy Pleistocene deposits are found. Until a depth of about 0.50 m, the peat layer is mostly strongly amorphous. At a depth of 0.70 to 0.80 m below surface level, the top of a moss peat layer is found, containing sedge and wood remains. This moss peat layer is up to 0.30 m thick. Underneath, a eutrophic sedge peat layer is found that may contain reed and wood remains. At some coring locations the peat is a bit clayey at a depth of 2.20 to 2.45 m below surface.

Table 2. Details of monitoring wells at Rouveen. bs=below surface level.

No.	Parcel	Filter depth (m bs)	Drain spacing (m)	Measurement type
1	PWIS	0.30-0.85	4	Phreatic level
2	PWIS	0.30-0.85	2	Phreatic level
3	PWIS	0.30-0.85	0.5	Phreatic level
4	PWIS	-	NA	In drain measurement
5	PWIS	2.50-2.75	2	Filter in peat layer
6	PWIS	3.44-4.44	NA	Hydraulic head
7	PWIS	-	NA	Ditch level
8	PWIS	0.30-0.85	1	Phreatic level
9	Reference	0.30-0.85	NA	Phreatic level
10	Reference	0.30-0.85	NA	Phreatic level
11	Reference	0.30-0.85	NA	Phreatic level
12	Reference	2.50-2.75	NA	Filter in peat layer
13	Reference	4.04-4.99	NA	Hydraulic head
14	Reference	-	NA	Phreatic level
15	Reference		NA	Phreatic level
16	Reference		NA	Ditch level

2.4 Assendelft

At location Assendelft submerged drains have been installed in the longitudinal direction of the parcel with a drain spacing of 4 m. The drains are connected to a pump-regulated reservoir via a collector drain, making this an active WIS. The aim of this AWIS is to maintain the phreatic groundwater level at about 25 to 30 cm below surface level. The drains are installed at circa 50 to 60 cm below surface level. In both the reference and the AWIS parcel 8 monitoring wells have been installed (Figure 7). Ditch water levels are kept at -2.4 m NAP, about 45 cm below surface level.

The Holocene sequence in Assendelft is about 16 m thick. In general, about 2 meters eutrophic reed-sedge peat is found on top of about 13 m marine clayey and sandy deposits. The organic content in the top 0.20 to 0.30 m of the peat layer varies between 10% and 40%. This layer has consequently been classified as either an organic clay or a clayey peat. The CPT results indicate that a 0.60 to 0.70 m thick peat layer occurs below the marine deposits. Underneath this basal peat layer, Pleistocene sandy deposits occur at a depth of 16 m below surface level.

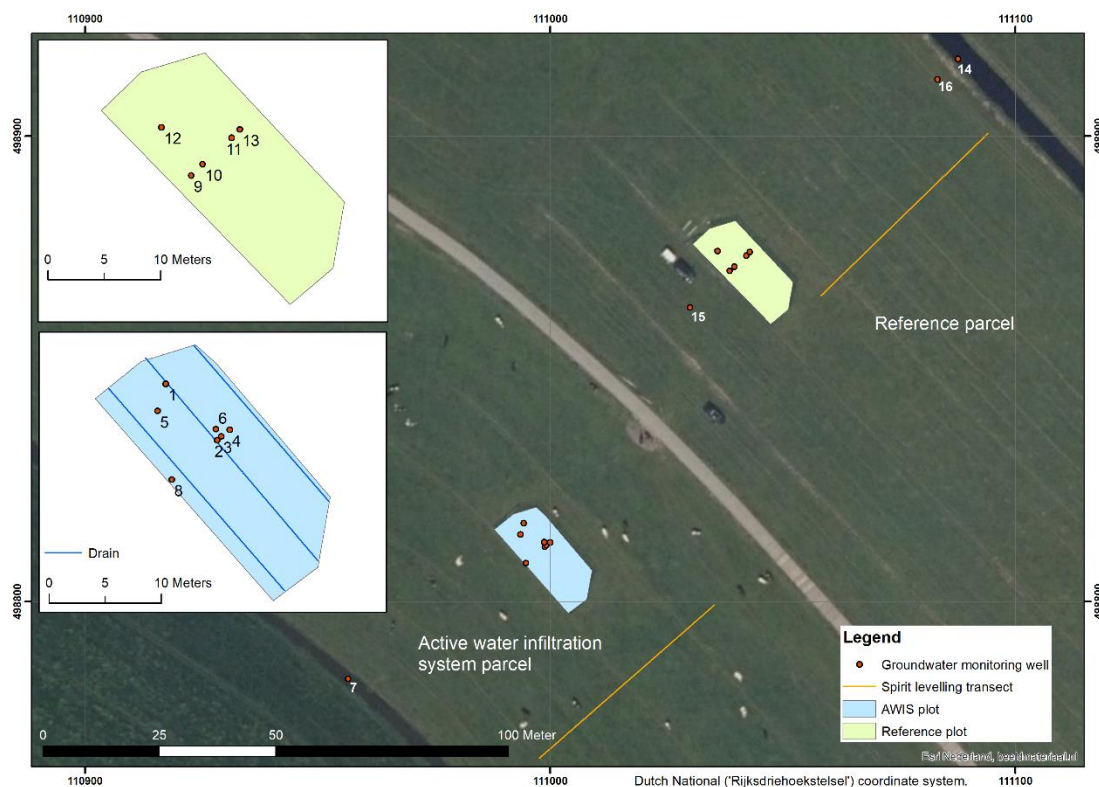


Figure 7. Overview of the study site Assendelft. Numbers of monitoring wells correspond to numbers in Table 3. The spirit levelling transect has been used to make cross sections (see Results section).

Table 3. Details of monitoring wells at Assendelft. bs = below surface level, AWIS = active water infiltration system.

No.	Parcel	Filter depth (m bs)	Drain spacing (m)	Measurement type
1	AWIS	NA	NA	In drain measurement
2	AWIS	0.30-1.30	0.5	Phreatic level
3	AWIS	0.30-1.30	1	Phreatic level
4	AWIS	0.30-1.30	2	Phreatic level
5	AWIS	16.90-17.10	NA	Hydraulic head
6	AWIS	1.60-1.85	1	Filter at medium depth
7	AWIS	NA	NA	Ditch level
8	AWIS	0.30-1.30	0.5	Phreatic level
9	Reference	0.30-1.30	NA	Phreatic level
10	Reference	0.30-1.30	NA	Phreatic level
11	Reference	0.30-1.30	NA	Phreatic level
12	Reference	16.90-17.10	NA	Hydraulic head
13	Reference	1.50-1.80	NA	Filter at medium depth
14	Reference	NA	NA	Ditch level
15	Reference	0.30-1.30	NA	Phreatic level
16	Reference	0.30-1.30	NA	Phreatic level

2.5 Zegveld

The NOBV plots in location Zegveld are situated in parcel 16 (Figure 8). Drains are installed in the longitudinal direction of the parcel with a drain spacing of 6 m, at a depth of about 70-75 cm below surface level. Drains are connected to a reservoir via a collector drain, making this an active WIS. In this way, the groundwater level can be managed to a constant target level. Both parcels 15 and 16 are connected to the same reservoir. The target groundwater depth is 40 cm in the middle in between two drains in parcel 15, which corresponds to 50 cm depth in parcel 16 which is about 10 cm higher. At parcel 16, ditch water levels are relatively low; 55 cm below surface level.

The Holocene soft soil sequence in Zegveld is 6.10 to 6.35 m thick and consists predominantly of peat. The top of the underlying Pleistocene deposits consists of eolian cover sands. The top 0.20 to 0.50 m of the peat layer consists of clayey amorphous peat, with an organic matter content gradually increasing from 30 - 40% to about 80%. Wood peat occurs until a depth of about 3 m, with eutrophic reed-sedge peat below, locally intercalated by thin reed peat layers. At a depth of 4.30 to 5.10 m below surface level a few cm thick clay layer occurs, surrounding peat may be a bit clayey as well. Below this clayey interval, the peat layer contains *Cladium mariscus* remains. At the transition to the Pleistocene sand wood peat may occur. Firm Pleistocene sand occurs at a depth of about 9 m below surface.

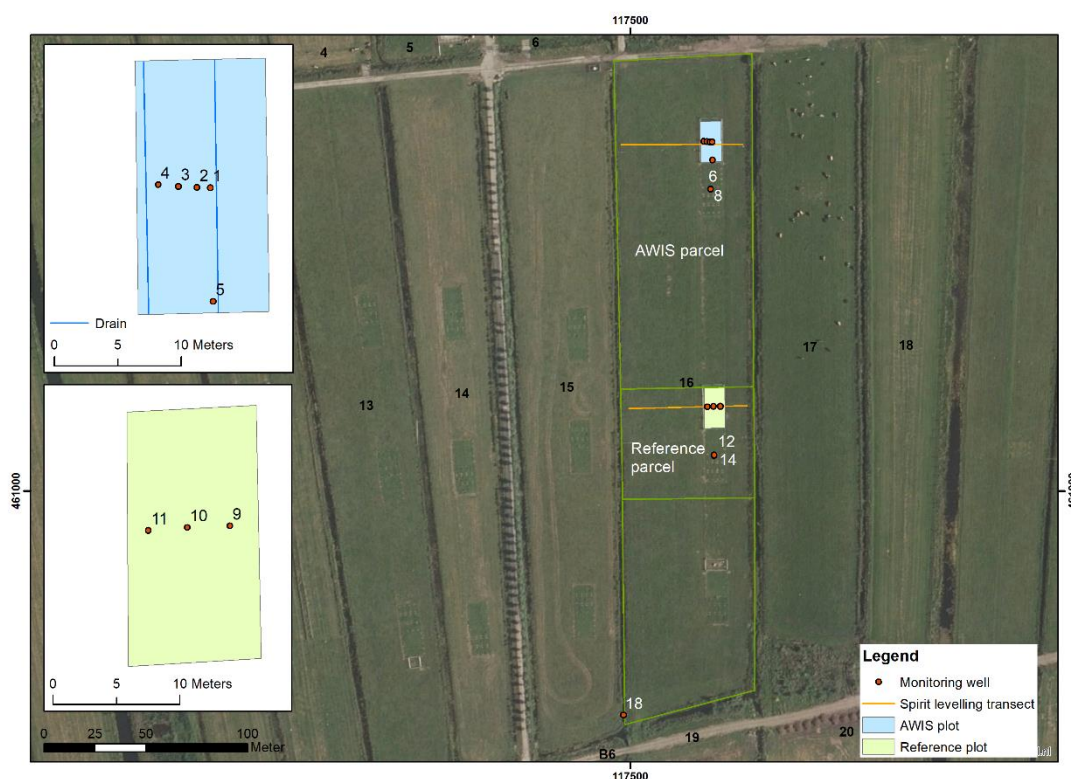


Figure 8. Overview of the study site Zegveld (parcel numbers indicated in black). Well numbers correspond to numbers in Table 4. The spirit levelling transect has been used to make cross sections (see Results section).

Table 4. Details of monitoring wells at Zegveld. bs = below surface level.

No.	Parcel	Filter depth (m bs)	Drain spacing (m)	Measurement type
1	AWIS	0.3-1.5	0.5	Phreatic level
2	AWIS	0.3-1.5	1.5	Phreatic level
3	AWIS	0.3-1.5	3	Phreatic level
4	AWIS	0.3-1.5	1.5	Phreatic level
5	AWIS	NA	NA	In drain measurement
6	AWIS	3.75-4.25	1.5	Filter at medium depth
8	AWIS	0.3-1.5	1.5	Phreatic level
9	Reference	0.3-1.5	NA	Phreatic level
10	Reference	0.3-1.5	NA	Phreatic level
11	Reference	0.3-1.5	NA	Phreatic level
12	Reference	3.5-4.0	NA	Filter at medium depth
14	Reference	0.3-1.5	NA	Phreatic level
18	Reference/AWIS	NA	NA	Ditch level

2.6 Vlist

At Vlist the drain spacing is 6 m and they have been installed in cross direction of the parcel, from ditch to ditch, at a depth of about 70 m below surface. Only the south end of the drain ends in the ditch; the north end of the drain is closed off (Figure 9). This makes the location a passive WIS site. Ditch water levels maintained by the waterboard are fixed at -2.15 m NAP (45 cm below surface level) in summer and -2.25 m NAP (55 cm below surface level) in winter. Measurements of the hydraulic head of the Pleistocene sand were available starting in autumn 2022.

The Holocene sequence in Vlist is 10 to 11 meters thick and consists of an alternation of (fluvial) clay and peat layers, on top of Pleistocene sandy deposits. Some clayey intervals in the Holocene sequence are sandy. The top circa 0.40 m consists of humic clay and/or strongly clayey peat, with an organic matter content ranging between roughly 15 and 35% (highest at the top). Below the clayey top layer, a wood peat layer occurs, which may be a bit clayey. At a depth of about 2 m below surface level, a few dm thick clay layer is found, below which eutrophic (sedge, reed and or wood) peat layers alternate with clay layers.

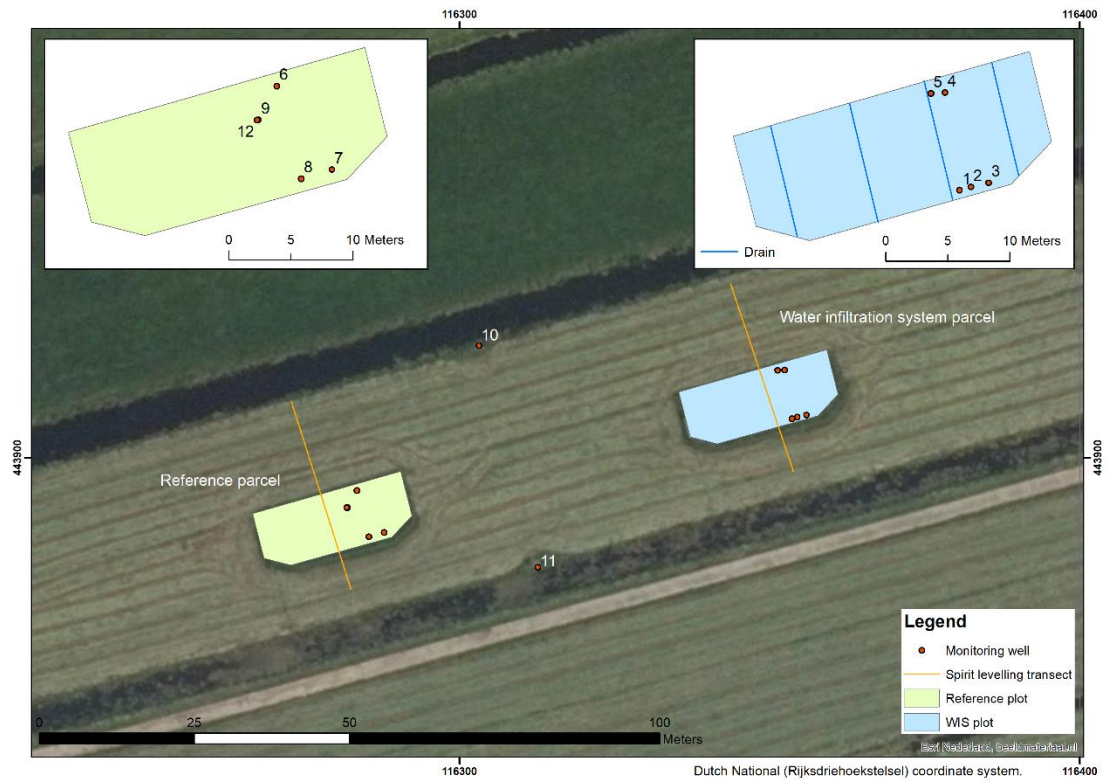


Figure 9. Overview of monitoring wells at Vlist. Numbers of monitoring wells correspond with numbers in Table 5. The spirit levelling transect has been used to make cross sections (see Results section).

Table 5. Details of monitoring wells at Vlist. bs = below surface.

No.	Parcel	Filter depth (m bs)	Drain spacing (m)	Measurement type
1	PWIS	0.5-1.5	0.5	Phreatic level
2	PWIS	0.5-1.5	1.5	Phreatic level
3	PWIS	0.5-1.5	3	Phreatic level
4	PWIS	0.5-1.5	1.5	Phreatic level
5	PWIS	NA	NA	In drain measurement
6	Reference	0.5-1.5	NA	Phreatic level
7	Reference	0.5-1.5	NA	Phreatic level
8	Reference	0.5-1.5	NA	Phreatic level
9	Reference	3.5-4.0	NA	Filter at medium depth
10	Reference/PWIS	NA	NA	Ditch level
11	Reference/PWIS	NA	NA	Ditch level
12	Reference	13.20-13.40	NA	Hydraulic head

3 Results

3.1 Aldeboarn

In the reference parcel of Aldeboarn, ditch water level has been variable as a result of the HAKLAM water management, fluctuating between ~45 cm below surface level in the summer of 2020 to ~90 cm below surface level in the first months of 2022 (Figure 10). Lowest ditch water levels usually occurred in winter, while summer ditch water levels were higher (but still relatively low compared to common ditch water levels in peat meadow areas in western Netherlands).

The phreatic groundwater level in the experimental plot in the reference parcel dropped to almost 125 cm depth in the relatively dry summers of 2020 and 2022 (Figure 10 and Table 6). In the relatively wet summer of 2021, the phreatic groundwater levels did not fall below 60 cm depth. In winter, the phreatic groundwater level fluctuated between surface level and 40 cm depth and was most of the time above 20 cm depth. The trench in the reference parcel only contained water in winter (Figure 10).

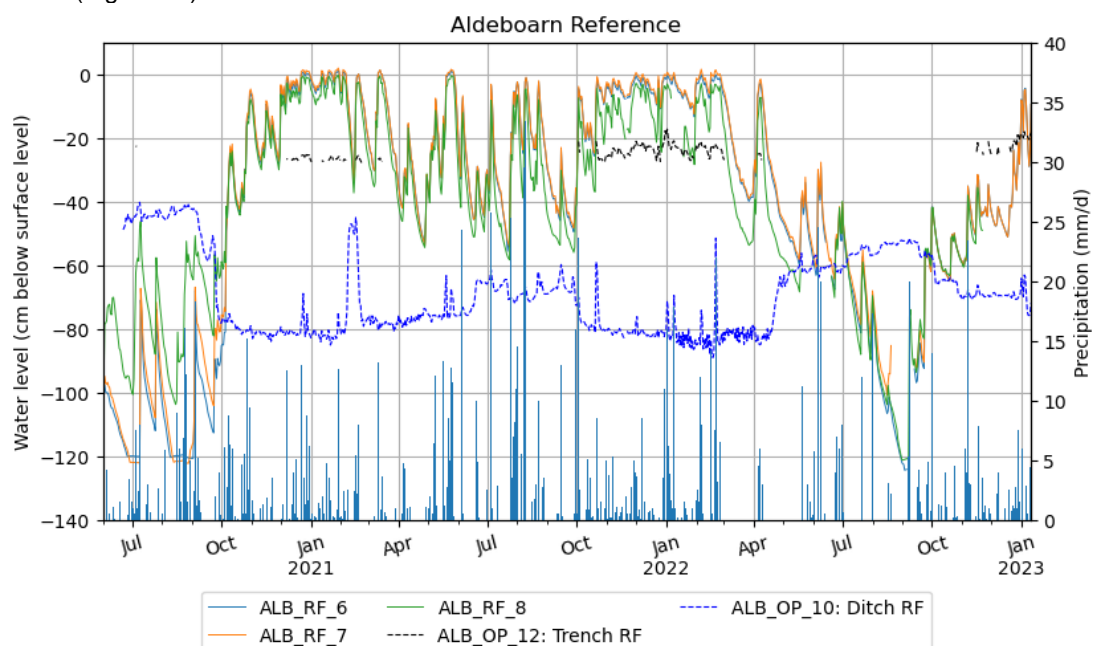


Figure 10. Phreatic groundwater level and ditch water level in the reference parcel in Aldeboarn, relative to surface level. Water levels in the trenches are only displayed when the trenches contained water.

In the PWIS parcel, the ditch water level mostly fluctuated between ~40 (in summer) to ~80 (in winter) cm below surface level (ALB_OP_11; Figure 11). In the autumn and winter of 2022, however, ditch water level remained relatively high (~45 cm below surface level).

The trench closest to the experimental plot in the WIS parcel was regularly filled with water, both during wet and dry periods as a consequence of precipitation or high ditch water levels, respectively (Trench MS; Figure 11). During the summer of 2022 this was mostly avoided due to altered ditch water level management, which was desirable for isolating the effects of only the drains on phreatic groundwater levels. The water pressure measured in the drain (for the periods this data series is available) generally closely followed the water level of the ditch with which the drains are connected. This demonstrates that the drain conducts water properly.

Measurements demonstrate that the PWIS has influenced phreatic groundwater levels. Summer deepest and average lowest phreatic groundwater levels in the PWIS parcel are in 2020 and 2022 generally higher compared to the reference parcel (Figures 10 to 13; Table 6). Close to the drain (0.5 m), the phreatic groundwater level generally fluctuated between 20 and 60 cm below surface level, seemingly most of the time following ditch water level dynamics (Figure 11). At 1.5 and 3.0 m from the drains, the phreatic groundwater level was more related to seasonal trends with lower groundwater levels in summer and higher levels in winter (Figure 11). The lowest phreatic groundwater level measured was 85 cm below surface level, at 3 m from the drain during the dry summer of 2022, which is substantially higher compared to the lowest phreatic groundwater level in the same period in the reference parcel (~125 cm below surface level). In the same summer, the groundwater level at 1.5 m from the same drain (western, number 2 in Figure 5) dropped to 68 cm below surface level. In the summer of 2020, the groundwater level at 3 m from the drain dropped to 76 cm below surface, while at 1.5 m from the drain groundwater level fell to 59 cm below surface. In the dry summers of 2020 and 2022, also the average summer phreatic groundwater levels are lower further away from the drain (Table 6). Hence, in general, a gradient exists between the drains, as expected, with deepest groundwater levels in between the drains, which is also seen in the cross section for the dry summer period of 2022 (Figure 12). The effect of PWIS on the phreatic groundwater level is also visualized in Figure 14, and statistics for individual monitoring wells are given in Table 6.

The phreatic groundwater level dynamics at 1.5 m from the other, eastern (ALB_MS_5), drain somewhat deviates from these observations. Here, it was generally drier in summer and wetter in winter, compared to measurements at 1.5 m from the western drain (Table 6). Trapped air was discovered in the eastern drain during inspection, which may have hindered water infiltration, and therewith, may have reduced efficiency.

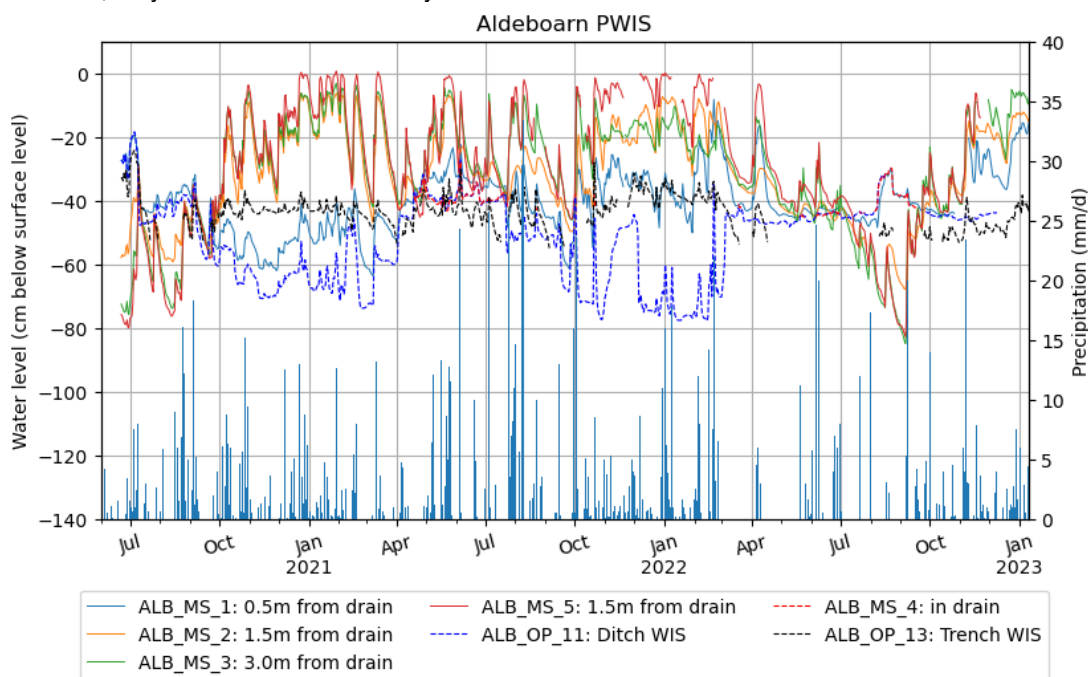


Figure 11. Phreatic groundwater level and ditch water level in the PWIS parcel in Aldeboarn, relative to surface level. Water levels in the trenches are only displayed when the trenches contained water.

In the period when highest phreatic groundwater levels occurred in the reference parcel, in January 2021 and January 2022, cross sections show that for the same period, lower phreatic groundwater levels occurred in the PWIS parcel, especially close to the drain (Figure 13, Figure 14 and Appendix Information A.1). This indicates the drains stimulated drainage of groundwater in wet periods, also indicated by the generally lower average highest groundwater levels in the PWIS parcel compared to the reference parcel (Table 6).

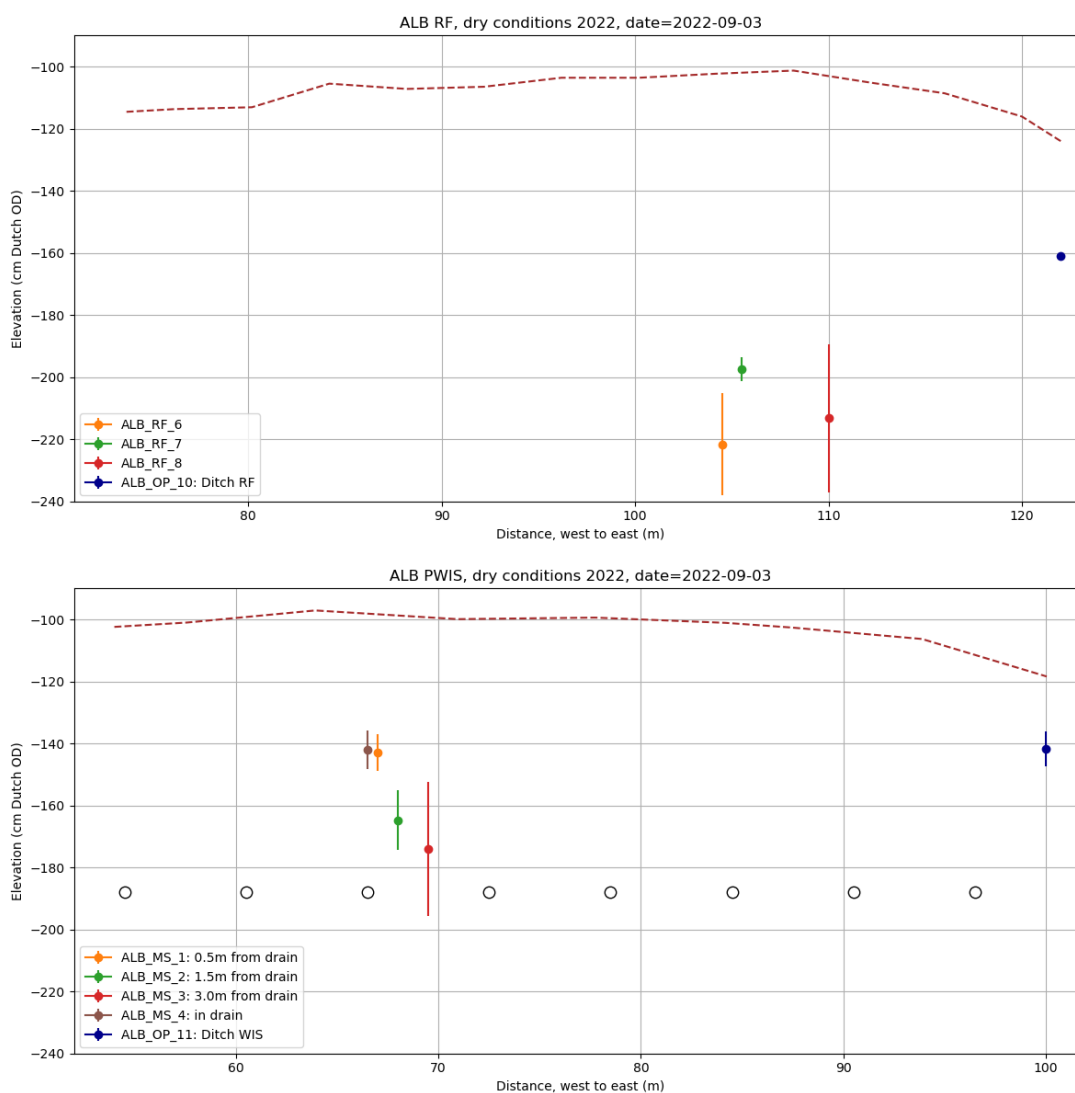


Figure 12. Cross section of surface level and ditch and phreatic groundwater levels in the reference and PWIS parcel (various distances from the drain) in Aldeboarn in dry (summer 2022) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated with circles.

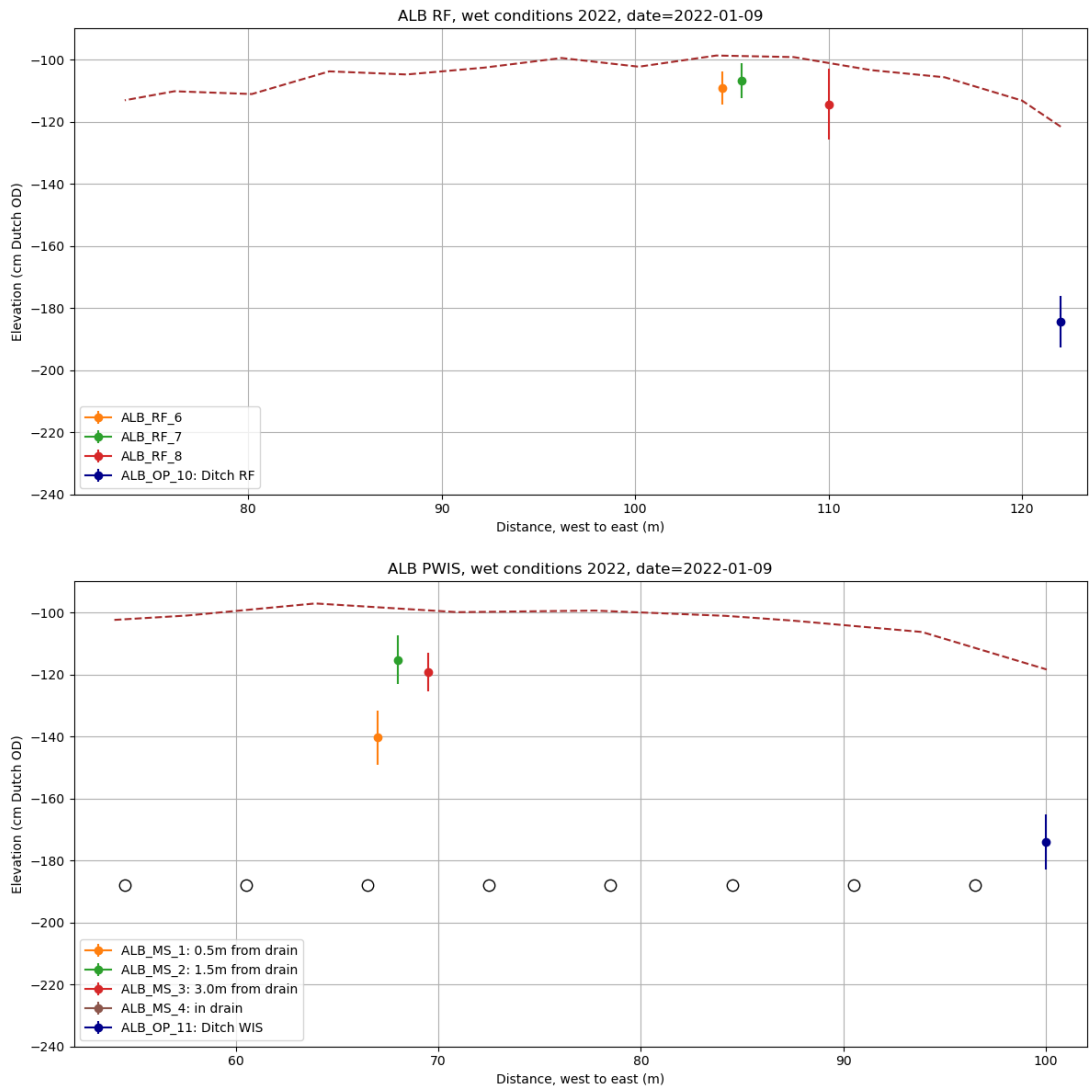


Figure 13. Cross section of the surface level and ditch and phreatic groundwater levels in the reference and PWIS parcel (various distances from the drain) in wet (winter 2022) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated with circles. The in-drain measurement was lacking for this period.

The hydraulic head in the sandy Pleistocene deposits underlying the Holocene peat sequence generally follows the phreatic groundwater level, which suggests there is no seepage or infiltration at this site (Figure 14). However, the top of the filter is at 170 cm depth while the top of the sand is at ~180 cm depth near the reference plot where the hydraulic head monitoring well is located (see Erkens *et al.*, 2020). Hence, the filter is partly connected to the Holocene organic layers, which explains the similar water pressures measured. Therefore, we cannot use this monitoring well for measuring the hydraulic head in the sandy Pleistocene deposits. We do expect a difference in hydraulic head because at most locations humic material has moved down from/through the peat layer and accumulated at the transition of the peat and underlying sand (forming a 'gliede' layer, which usually has a relatively low hydraulic conductivity).

For comparison, Figure 14 also shows the ditch water levels, the average phreatic groundwater level in the reference parcel, and the phreatic groundwater level at $\frac{1}{2}$ drain spacing (3.0 m in this case), also showing that the ditch water level in the PWIS parcel is generally higher than the ditch water level at the reference parcel.

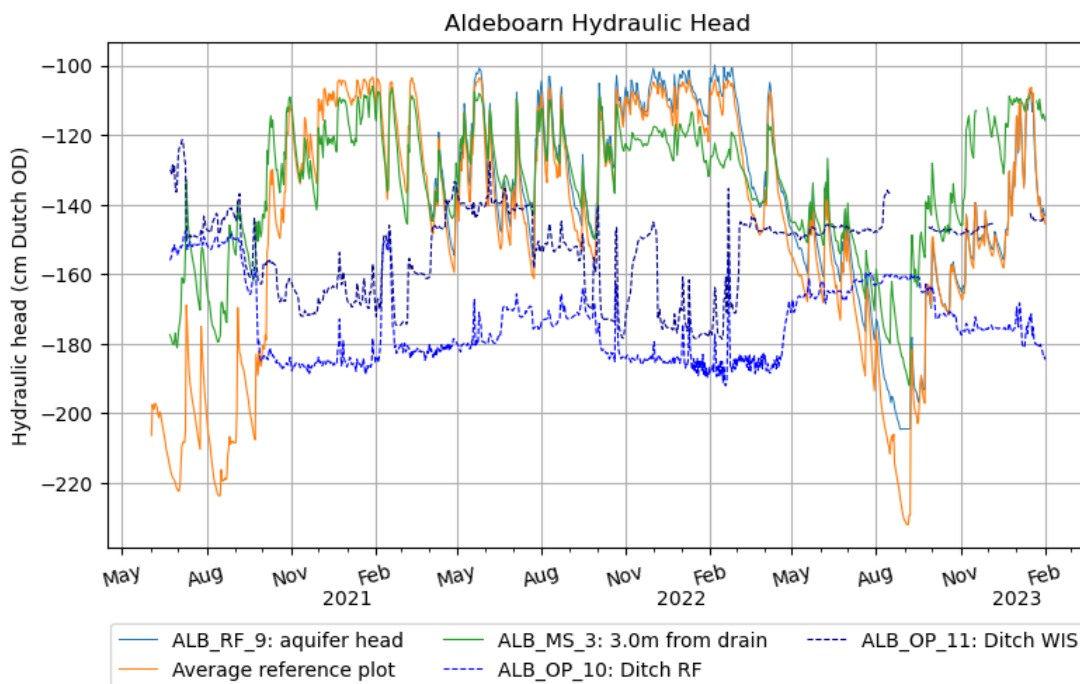


Figure 14. Hydraulic head in the top of the Pleistocene deposits underlying the Holocene peat sequence, ditch water levels, average phreatic groundwater level at the reference parcel, and phreatic groundwater level at ½ drain spacing in Aldeboarn.

Table 6. Statistics for water level monitoring wells in Aldeboarn (cm relative to surface level), av=average. Average lowest/highest water level is the average of the 12% lowest/highest measurements in a year.

monitoring well	year	av. water level	lowest water level	highest water level	av. lowest water level	av. highest water level	av. summer water level	av. winter water level
ALB_RF_6	2021	-18	-56	1	-46	0	-28	-8
	2022	-46	-124	0	-104	-2	-64	-30
ALB_RF_7	2021	-18	-54	2	-46	1	-28	-8
	2022	-42	-101	2	-84	-1	-56	-29
ALB_RF_8	2021	-24	-58	0	-52	-2	-35	-14
	2022	-55	-121	-3	-105	-8	-71	-35
ALB_MS_1: 0.5m from drain	2021	-40	-64	-22	-57	-29	-38	-42
	2022	-38	-50	-8	-46	-20	-41	-34
ALB_MS_2: 1.5m from drain	2021	-26	-50	-6	-43	-8	-31	-21
	2022	-34	-68	-7	-57	-11	-46	-23
ALB_MS_3: 3.0m from drain	2021	-22	-46	-3	-40	-6	-26	-18
	2022	-36	-85	-5	-69	-12	-48	-24
ALB_MS_5: 1.5m from drain	2021	-19	-46	1	-41	-1	-26	-11
	2022	-35	-83	0	-69	-4	-44	-22
ALB_OP_10: Ditch RF	2021	-78	-88	-48	-86	-64	-74	-81
	2022	-71	-92	-55	-88	-56	-64	-78
ALB_OP_11: Ditch MS	2021	-54	-77	-27	-74	-37	-45	-64
	2022	-50	-78	-32	-75	-41	-45	-55
ALB_OP_14: Ditch RF/MS	2021	-67	-81	-32	-79	-44	-60	-74
	2022	-66	-82	-40	-81	-48	-59	-73

3.2 Rouveen

In the reference parcel of Rouveen, the ditch water levels have fluctuated between ~40 to 50 cm below surface level in summer and ~50 to 60 cm below surface in winter (Figure 15). In dry summer periods, phreatic groundwater levels have lowered to a maximum depth of 66 cm below surface level (

Table 7). Average summer phreatic groundwater levels in the field plot in the reference parcel are 40 to 48 cm below surface level, and higher closer to the ditch (

Table 7; see also cross sections in

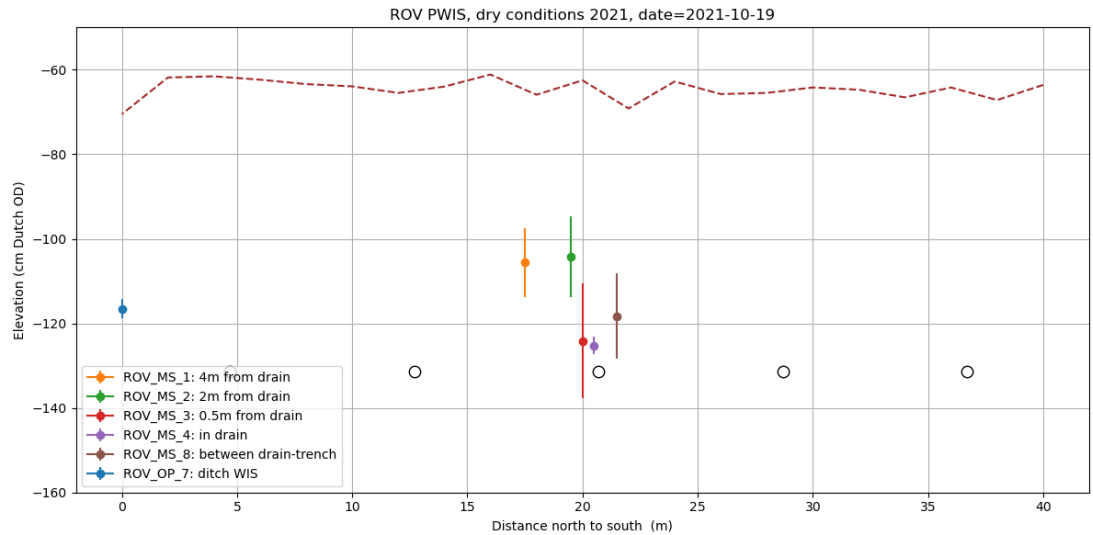


Figure 17 and Figure 18; Appendix Information A.2).

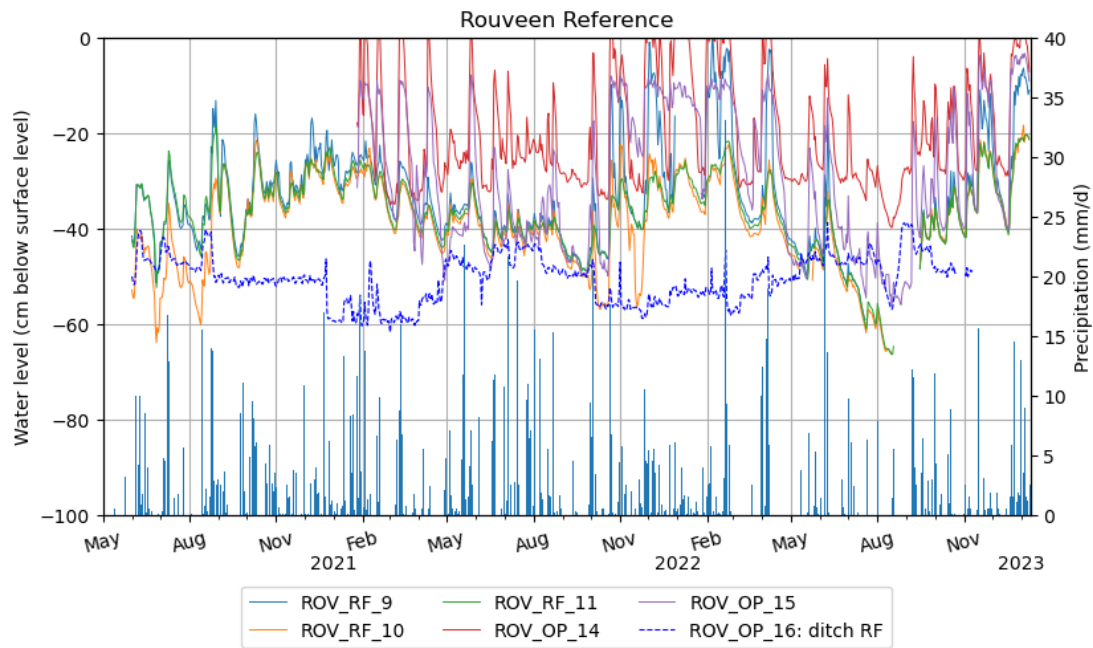


Figure 15. Phreatic groundwater level and ditch water level in the reference parcel in Rouveen, relative to surface level.

Also in the PWIS parcel ditch water levels fluctuated between ~40 and 50 cm below surface level in summer periods, and between ~50 and 60 cm below surface level in winters. The in-drain measurement (ROV_MS_4; Figure 16) closely follows ditch water level fluctuations, as expected since the drains are directly connected to the ditch. However, the in-drain measurements are

structurally lower than the ditch water level. This may be caused by loss of water pressure in the drain, which may be the result of the rather long distance (~100 m) from the drain in the plot to the ditch, where water flows also pass a connection to a collector drain. Also, air and/or mud in the drain, which was observed at some places in the drain during camera inspection (see Erkens *et al.*, 2020), might hamper water flow. Lastly, the automatic loggers might need a recalibration, which must be checked by manual water level measurements (of the ditch and in-drain water levels).

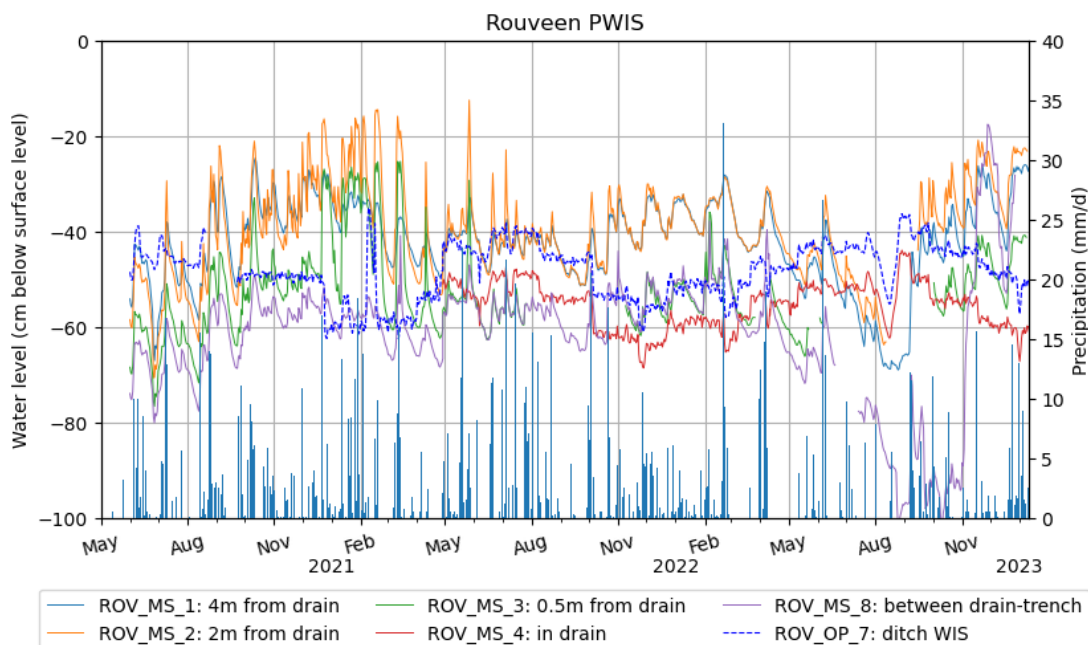


Figure 16. Phreatic groundwater level and ditch water level in the PWIS parcel in Rouveen, relative to surface level. From 21-8-2022 to 10-11-2022 extensometer (top anchor) measurements were missing. To calculate the water levels relative to surface level, the measurements have been linearly interpolated for this period.

In general, phreatic groundwater levels in the PWIS parcel are lower than in the reference parcel (Figure 16 and Figure 19). Deepest groundwater levels have been registered close to the drain (0.5 m distance) and in between the drain and the trench that is located just south of the field plot (ROV_MS_8; Figure 6). In the summer of 2022, the groundwater level in between the drain and trench dropped to about 100 cm below surface. This is supposedly an erroneous measurement, since measured groundwater levels are suddenly much deeper (than expected, considering the ditch water levels and seepage situation) after a data gap in the time series. Most of the time, the groundwater level close to the drain fluctuated around 60 cm below surface (ROV_MS_3 and ROV_MS_8; Figure 16). The phreatic groundwater level dynamics at 2 and 4 m distance from the drain are similar for most of the time, reaching depths of about 70 cm in the dry summers of 2020 and 2022. The groundwater level close to the drain was almost always lower than the water levels at 2 and 4 m distance from the drain. These observations indicate that at Rouveen, which is located in an area with upward seepage, ground/seepage water is drained by the drains year-round, thereby lowering the phreatic groundwater level (Figure 15 to Figure 19). Water infiltration through the drains, in order to limit groundwater level lowering in summer periods, is mostly not taking place.

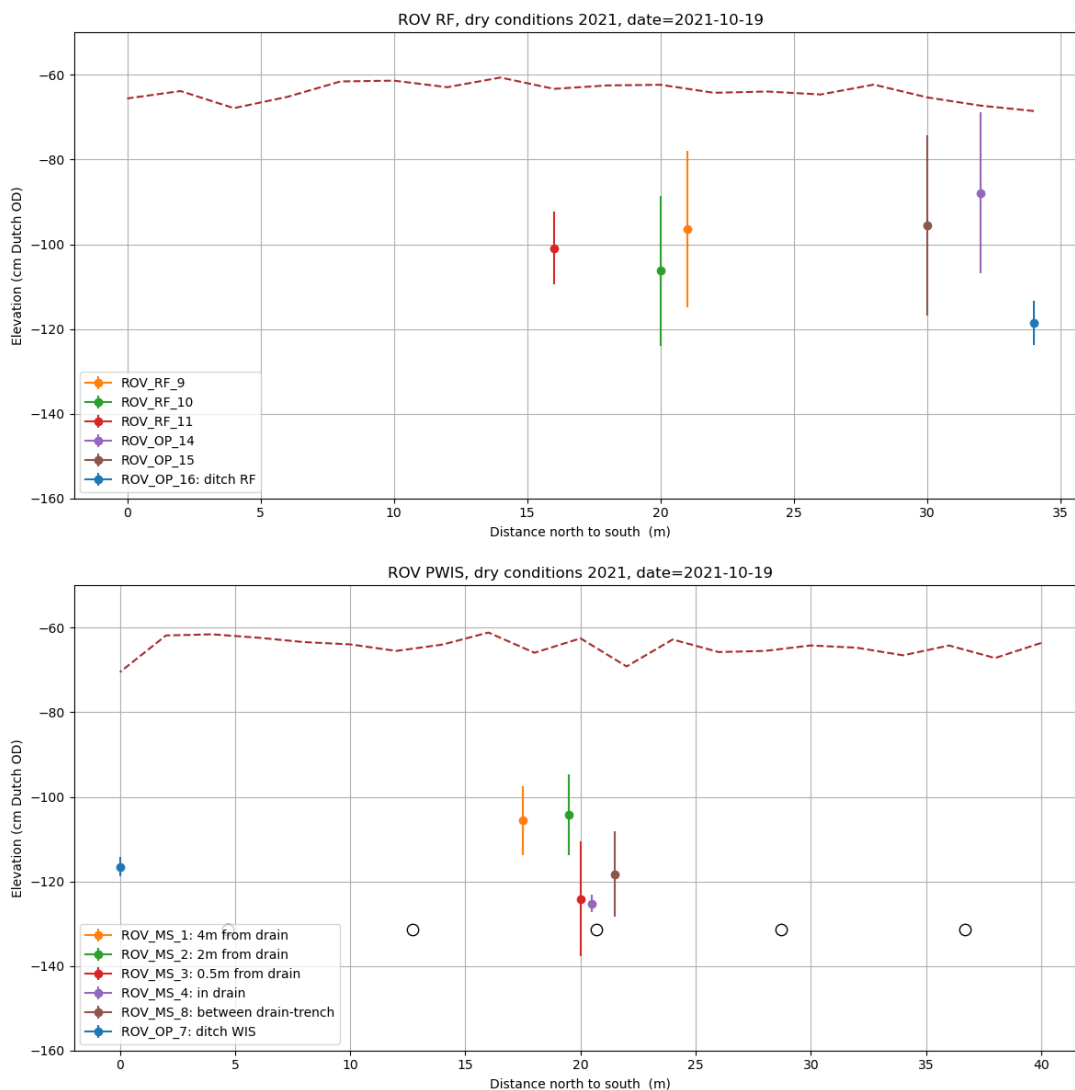


Figure 17. Cross section of surface level and ditch and phreatic groundwater levels in the reference (RF) and PWIS parcel (various distances from the drain) in Rouveen in dry (summer 2021) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated with circles. For this location, cross sections are presented for the year 2021, because of missing data for the summer period of the year 2022.

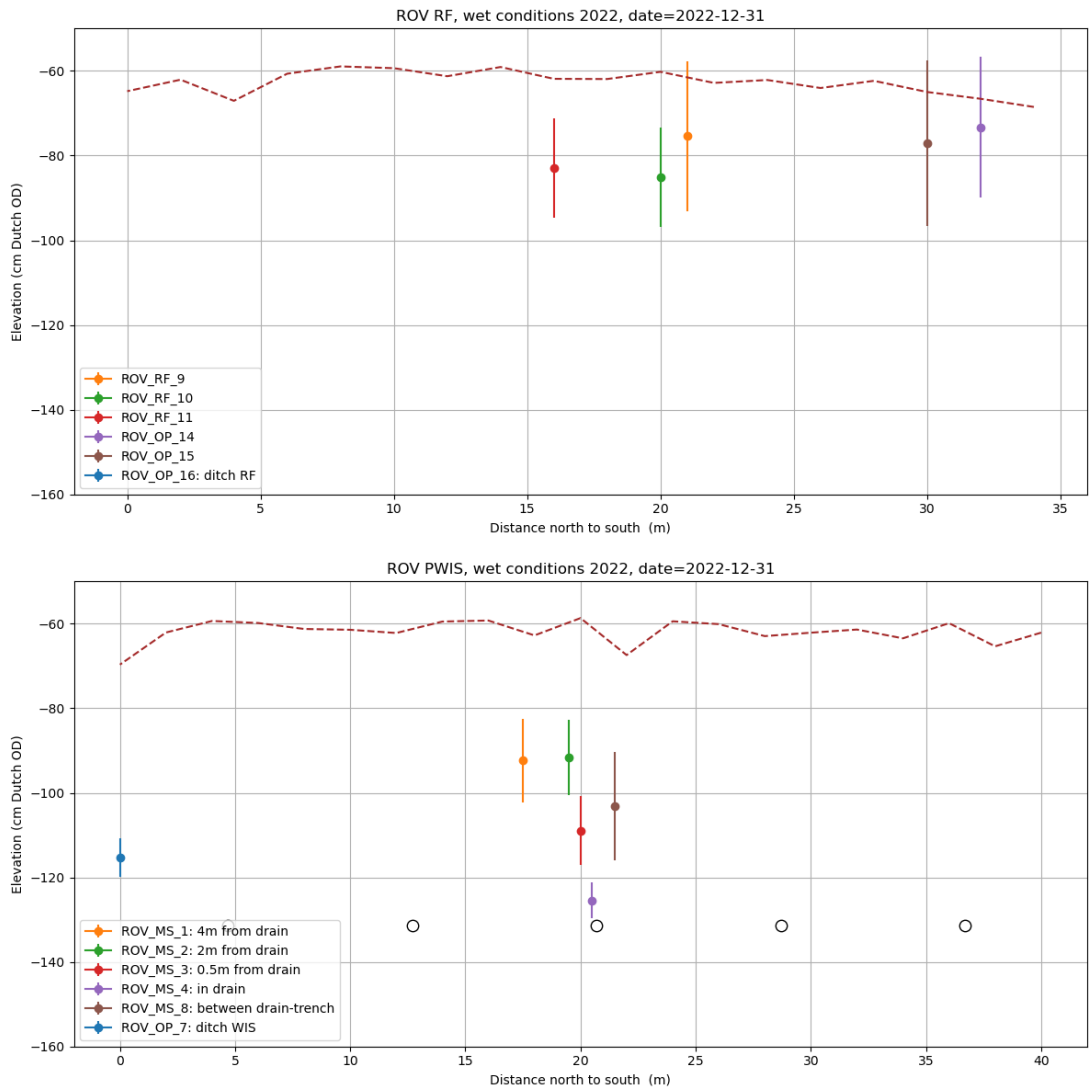


Figure 18. Cross section of surface level and ditch and phreatic groundwater levels in the reference and PWIS parcel (various distances from the drain) in Rouveen in wet (winter 2022) conditions, averaged over averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated with circles.

The hydraulic head in the sandy deposits below the peat layer is in general higher than the average of the phreatic groundwater levels in the reference plot (Figure 19), indicating that Rouveen is an upward seepage site. The peaks in 2022 coincide with high water levels of the river 'Zwarte Water', located at the other (higher) side of the dike westwards of the monitoring plots. This implies seepage is coming at least partly from this river, and the amount of upward seepage is variable in time. The monitoring well with filter at 2.50 to 2.75 m below surface level is generally similar to the phreatic groundwater level, indicating a relatively high vertical permeability in the peat layer, but a rather large resistance between this filter depth and the Pleistocene subsurface, which may be caused by the existence of clayey, peaty and/or loamy intervals at the transition from Pleistocene deposits to Holocene peat (Erkens *et al.*, 2020).

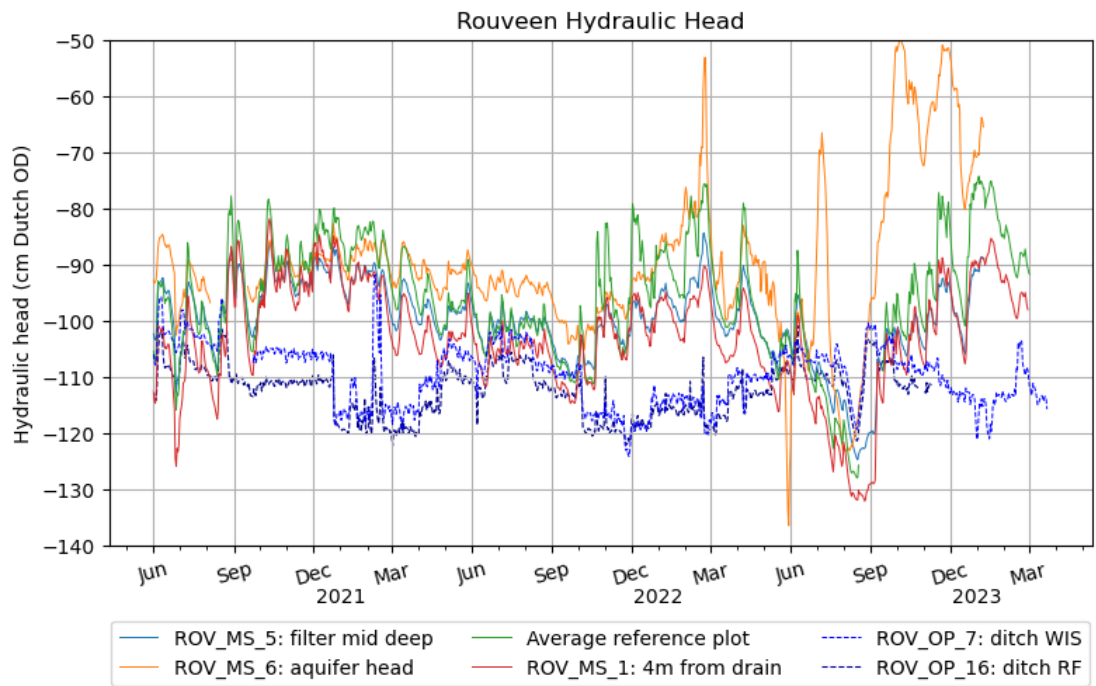


Figure 19. Hydraulic head in sandy Pleistocene deposits underlying the Holocene sequence and at ca 2.50 m depth in Rouveen. Also plotted are the average of the phreatic groundwater level in the reference parcel, the phreatic groundwater level at ½ m drain spacing, and the ditch water levels.

Table 7. Statistics for ground and ditch water monitoring wells in Rouveen, in cm relative to surface level. av. = average, GW = phreatic groundwater level. Average lowest/highest groundwater level is the average of the 12% lowest/highest measurements for a year. Numbers are colored orange if >25% of data was missing (i.e., >45 days for the summer or winter statistics, >91 days for yearly statistics).

monitoring well	year	av. water level	lowest water level	highest water level	av. lowest water level	av. highest water level	av. summer water level	av. winter water level
ROV_RF_9	2021	-35	-49	-1	-46	-18	-40	-30
	2022	-33	-59	2	-50	-8	-41	-27
ROV_RF_10	2021	-39	-57	-22	-52	-27	-42	-36
	2022	-39	-66	-21	-60	-25	-48	-33
ROV_RF_11	2021	-37	-49	-26	-46	-28	-40	-34
	2022	-39	-66	-21	-59	-24	-47	-32
ROV_OP_14	2021	-20	-35	6	-33	2	-23	-16
	2022	-20	-40	5	-35	2	-24	-14
ROV_OP_15	2021	-30	-51	-8	-48	-9	-38	-20
	2022	-31	-56	-8	-53	-10	-39	-19
ROV_MS_1: 4m from drain	2021	-41	-51	-32	-49	-33	-44	-39
	2022	-46	-69	-28	-66	-33	-52	-38
ROV_MS_2: 2m from drain	2021	-39	-53	-13	-50	-21	-43	-35
	2022	-41	-64	-25	-56	-31	-46	-36
ROV_MS_3: 0.5m from drain	2021	-51	-63	-25	-61	-30	-56	-47
	2022	-54	-66	-36	-61	-48	-60	-53
ROV_MS_4: in drain	2021	-56	-69	-47	-64	-49	-52	-62
	2022	-55	-65	-44	-61	-48	-53	-58
ROV_MS_8: drain-trench	2021	-58	-68	-41	-66	-51	-59	-57
	2022	-70	-102	-38	-96	-48	-74	-64
ROV_OP_16: ditch RF	2021	-52	-62	-42	-60	-44	-48	-57
	2022	-49	-58	-39	-56	-42	-47	-52
ROV_OP_7: ditch MS	2021	-50	-63	-35	-60	-40	-45	-55
	2022	-47	-58	-36	-54	-40	-44	-49

3.3 Assendelft

In the relatively dry summers of 2020 and 2022, the phreatic groundwater level in the reference parcel of Assendelft has lowered to a maximum depth of ~100 cm below surface level (Figure 20). The average summer phreatic groundwater level in 2022 is ~60 cm below surface level, in the wet summer of 2021 ~30 cm below surface level (Table 8). In winter periods, the average phreatic groundwater level is 12 to 25 cm below surface level (Table 8). The average ditch water level in summer was ~35 cm below surface level, in winter this was ~45 cm below surface level (Figure 20, Table 8).

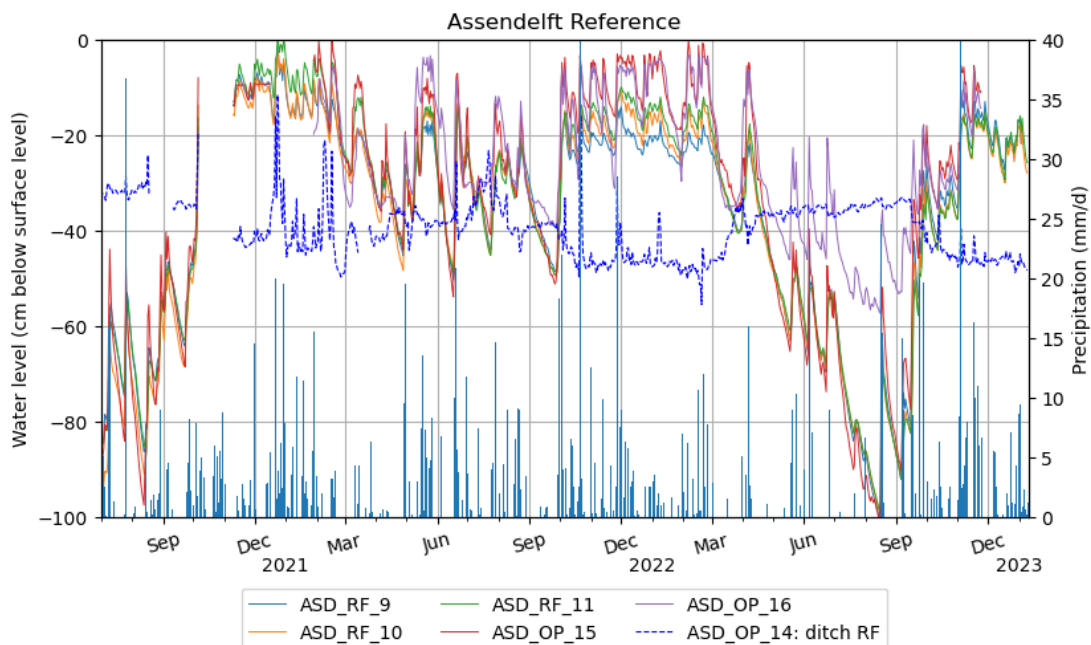


Figure 20. Phreatic groundwater level and ditch water level in the reference parcel in Assendelft, relative to surface level. In April 2022, the ditch water level monitoring well was disturbed. Consequently, the measurements for the period April to December 2022 are not reliable and are therefore for this period replaced by water level measurements of the ditch at the AWIS parcel.

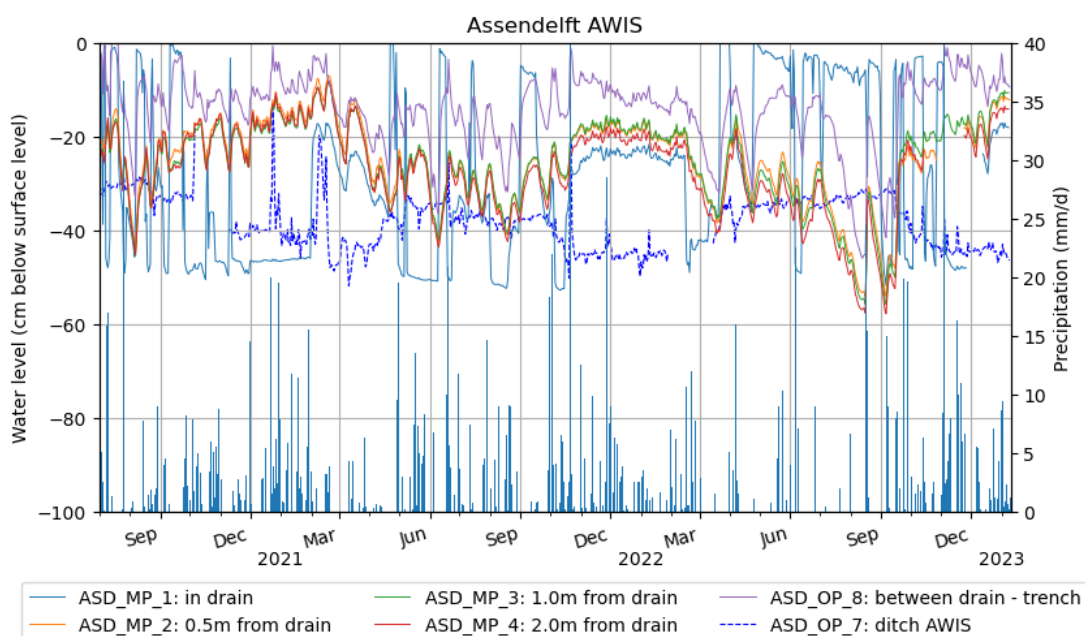


Figure 21. Phreatic groundwater level and ditch water level in the AWIS parcel in Assendelft, relative to surface level.

In the AWIS parcel, active pumping of water into the drains has resulted in average phreatic summer groundwater levels of 18 to 38 cm below surface level (Table 8), considerably higher than in the reference parcel (see also Figure 22, cross sections for the year 2021 are in Appendix Information A.3). Also, average lowest groundwater levels are higher in the AWIS parcel (Table 8). However, the phreatic groundwater level dropped below the target groundwater level of 35 cm depth several times (Figure 21). This is, especially in the relatively wet summer of 2021, caused by a periodically too low hydraulic head in the drains. Possibly, the farmer wanted to keep the land a bit drier in this wet period. In the dry summer of 2022, the AWIS seemingly could not always prevent groundwater level lowering below 35 cm depth, which is presumably due to very high evapotranspiration in this period (see also Appendix Information B). Average winter phreatic groundwater levels are in general similar in both parcels (Table 8), however, Figure 20Figure 21 and Figure 24 do show that in the wettest months (November, December, January) the phreatic groundwater level in the AWIS parcel is often 10 to 20 cm lower than the groundwater level in the reference parcel in the same period, indicating additional winter drainage is taking place. Statistics of all individual monitoring wells are given in Table 8.

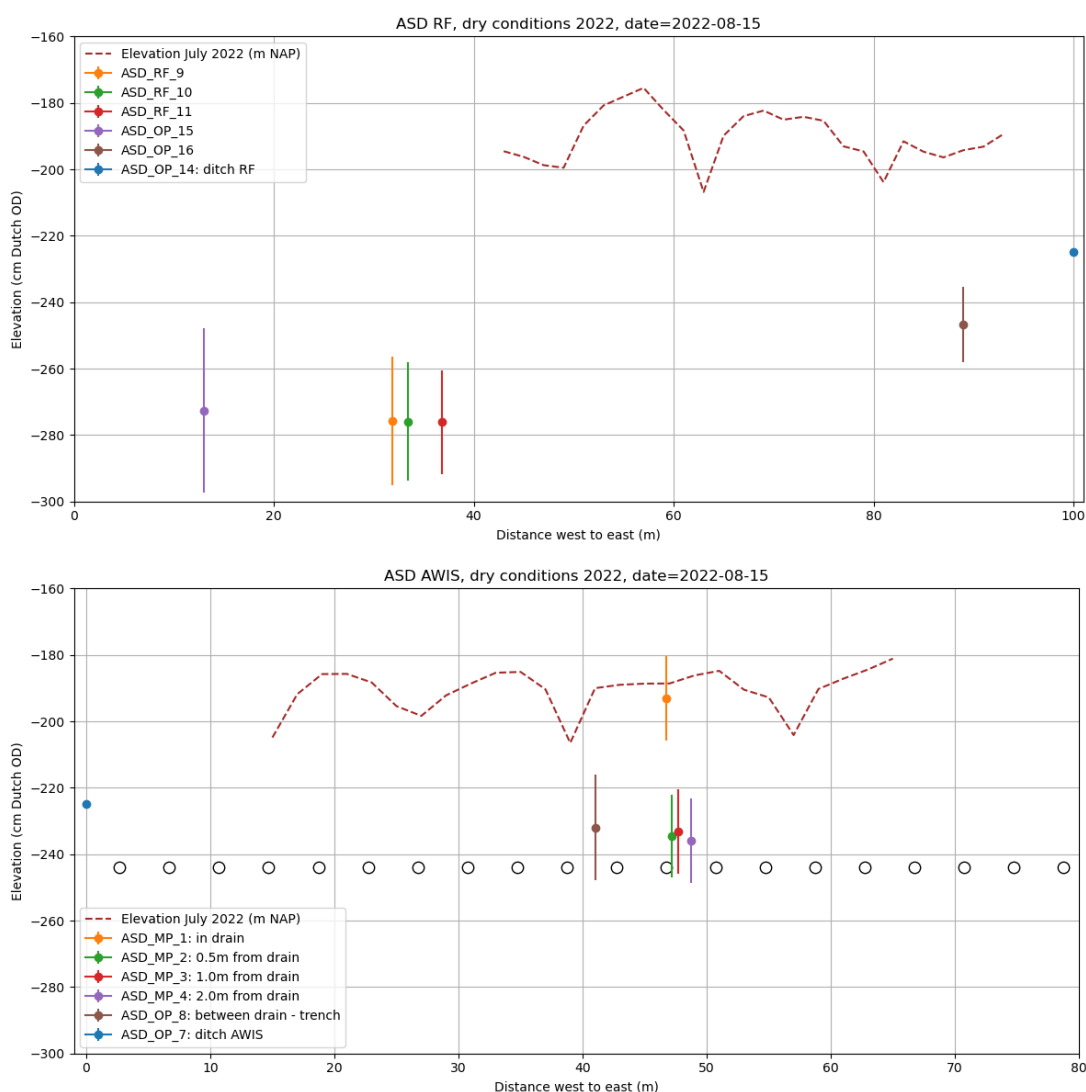


Figure 22. Cross section of surface level and ditch and phreatic groundwater levels in the reference and AWIS parcel (various distances from the drain) in Assendelft in dry (summer 2022) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated with circles. There is no levelling data available in the reference parcel at the position of the monitoring wells.

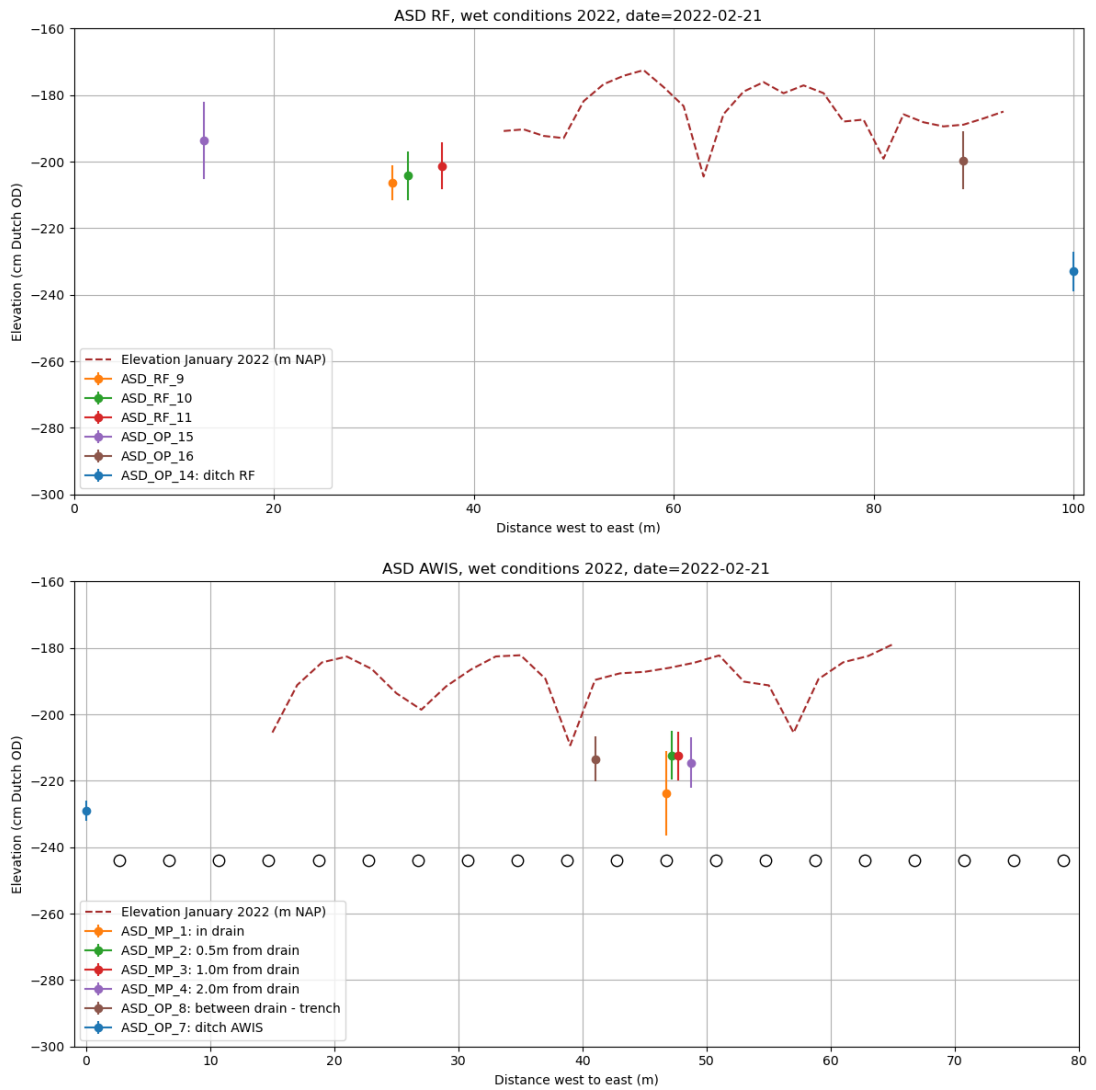


Figure 23. Cross section of surface level and ditch and phreatic groundwater levels in the reference and AWIS parcel (various distances from the drain) in Assendelft in wet (winter 2022) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated with circles. There is no levelling data available in the reference parcel at the position of the monitoring wells.

The hydraulic head in Assendelft (water pressure in sandy deposits at 17 m depth) is higher than the phreatic groundwater levels in the reference parcel (Figure 24). Upward seepage from this depth to the peat layer is however impeded by the thick (~10 m) marine deposits in between the peat and Pleistocene sand layers. This is supported by the monitoring well with filter just above the marine deposits, where the monitored hydraulic head is in general similar to the phreatic groundwater level (Figure 24). Only in the summers of 2020 and 2022 higher water pressures have been measured at this well with mid-deep filter, indicating some upward seepage at this depth (1.60-1.85 m below surface level) in dry periods, and the existence of a confining layer between this level and the phreatic groundwater level.

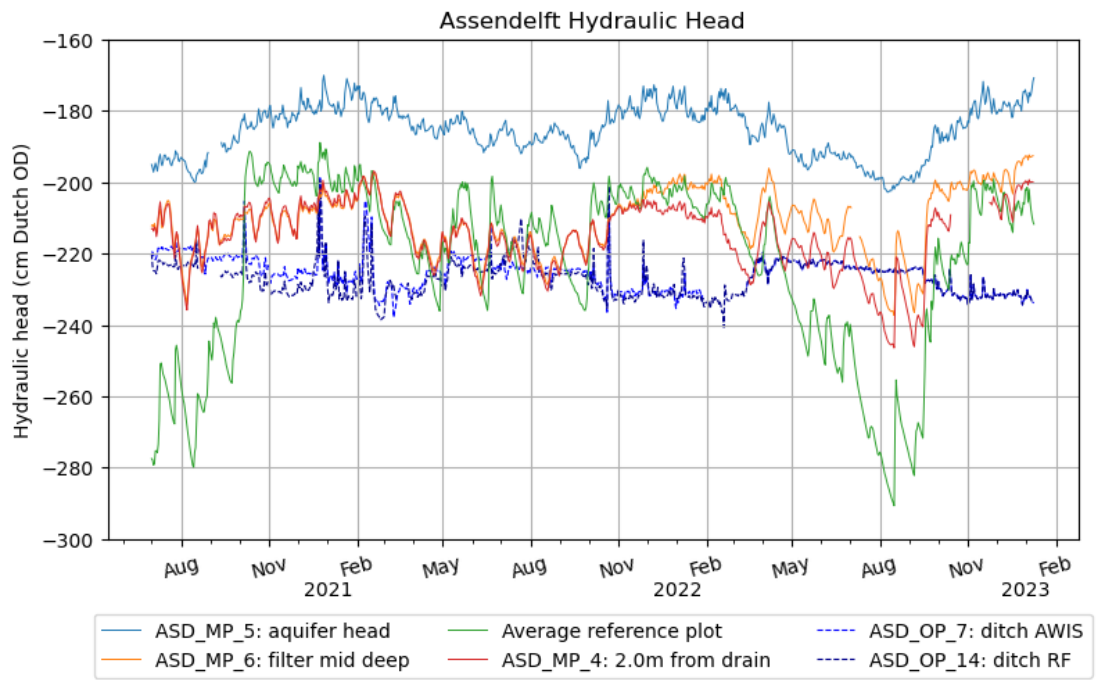


Figure 24. The hydraulic head in the Pleistocene sandy deposits at 17 m depth (ASD_MP_5), the hydraulic head at 1.60 m depth (ASD_MP_6), the average of the phreatic groundwater level, the phreatic groundwater level at $\frac{1}{2}$ drain spacing, and ditch water levels in Assendelft.

Table 8. Statistics for ground and ditch water monitoring wells in Assendelft, in cm relative to surface level. av. = average. Average lowest/highest groundwater level is the average of the 12% lowest/highest measurements for a year.

monitoring well	year	av. water level	lowest water level	highest water level	av. lowest water level	av. highest water level	av. summer water level	av. winter water level
ASD_RF_9	2021	-26	-50	-9	-44	-13	-32	-20
	2022	-44	-101	-12	-88	-17	-62	-25
ASD_RF_10	2021	-26	-50	-8	-45	-12	-33	-19
	2022	-44	-100	-13	-88	-16	-63	-25
ASD_RF_11	2021	-24	-49	-4	-45	-8	-33	-15
	2022	-44	-99	-12	-88	-15	-62	-24
ASD_OP_15	2021	-22	-54	1	-44	-4	-31	-12
	2022	-16	-36	0	-91	-5	-15	-16
ASD_OP_16	2021	-22	-39	-3	-36	-6	-26	-16
	2022	-16	-36	-3	-54	-5	-10	-17
ASD_MP_1: in drain	2021	-32	-53	0	-51	-8	-34	-30
	2022	-21	-52	3	-48	-1	-15	-28
ASD_MP_2: 0.5m from drain	2021	-24	-43	-7	-37	-11	-30	-17
	2022	-29	-54	-12	-48	-16	-34	-23
ASD_MP_3: 1.0m from drain	2021	-24	-42	-8	-37	-13	-30	-18
	2022	-28	-56	-11	-50	-15	-35	-21
ASD_MP_4: 2.0m from drain	2021	-25	-44	-8	-38	-13	-32	-19
	2022	-32	-58	-14	-52	-18	-38	-25
ASD_OP_8: drain - trench	2021	-14	-37	-1	-26	-6	-18	-10
	2022	-16	-46	-1	-37	-5	-20	-12
ASD_OP_14: ditch RF	2021	-40	-50	-16	-48	-30	-38	-43
	2022	-41	-56	-33	-48	-34	-36	-45
ASD_OP_7: ditch AWIS	2021	-36	-47	-15	-43	-28	-34	-39
	2022	-38	-46	-30	-44	-33	-35	-42

3.4 Zegveld

In the reference parcel, the phreatic groundwater level has lowered to about 80 (2021) and 105 (2022) cm below surface in summer times (Figure 25). In winter, the phreatic groundwater level generally fluctuated between 5 to 35 cm below surface.

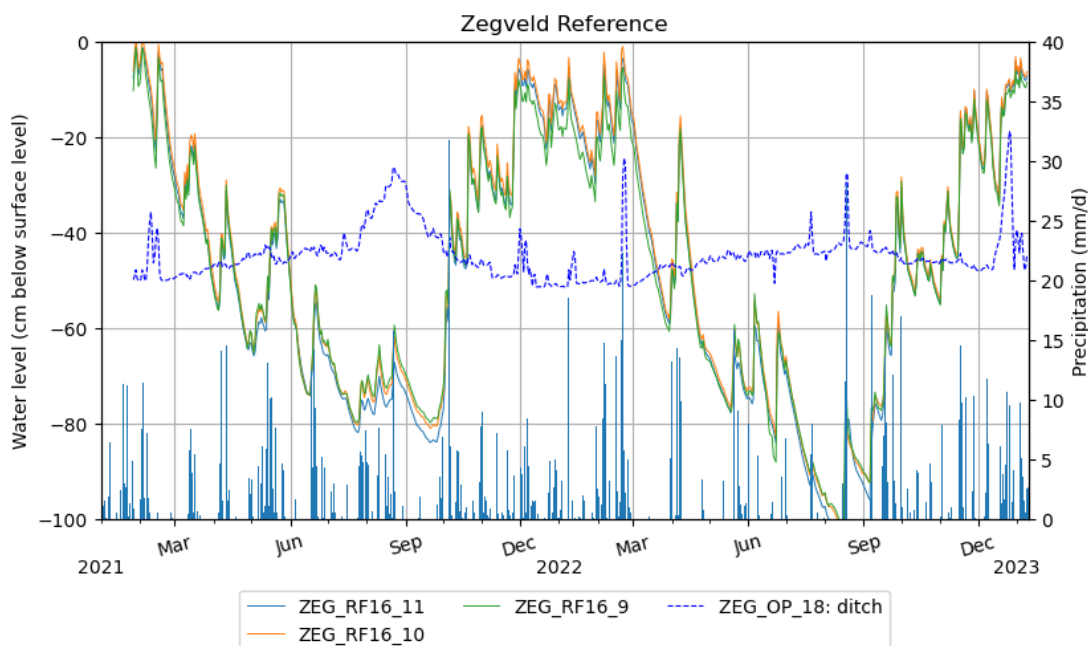


Figure 25. Phreatic groundwater level and ditch water level in the reference parcel in Zegveld, relative to surface level.

In the AWIS parcel, the phreatic groundwater level has lowered up to about 85 cm below surface level at 3 m from the drain (half the drain spacing) in the relatively dry summer of 2022, which is about 20 cm higher compared to the lowest phreatic groundwater level in the reference parcel in the same period (Figure 26, Figure 27, Appendix Information A.4; also average lowest groundwater levels are higher in the AWIS parcel; Table 9). Manual groundwater measurements from the same parcels demonstrate the difference between reference and AWIS phreatic groundwater levels can be up to about 35 cm (personal communication K. van Houwelingen, KTC Zegveld). Statistics of all individual monitoring wells are given in Table 9. Statistics for ground and ditch water monitoring wells in Zegveld, in cm relative to surface level. av. = average. Average lowest/highest groundwater level is the average of the 12% lowest/highest measurements for a year. Table 9.

The relatively low minimum phreatic groundwater level in the AWIS parcel in the summer of 2022 is about 35-45 cm lower than the target groundwater level depth of 40-50 cm. Despite maintaining reservoir water levels at or above 10 cm below surface level during (almost) the entire summer period of 2022 (personal communication K. van Houwelingen, KTC Zegveld; analyzed reservoir levels were not available yet during the time of writing this document, and hence, could not yet be included), the hydraulic heads in the drain at the parcel showed a decreasing trend as summer progressed. An inspection of the drains showed severe clogging of the drains with detritus and mud, probably originating from the ditch. Upon cleaning the drains (around August 15th), hydraulic heads in the drain were easily maintained at their target position. Also, groundwater level measurements show an upward trend, as opposed to measurements in the reference parcel in the same period. This indicates that water infiltration through the AWIS has improved after cleaning. Nonetheless, maintaining the groundwater levels at the target level depth of 50 cm likely requires higher reservoir and/or ditch water levels, similar as in Assendelft. In addition, in August 2021 and March 2022, the water level in the reservoir was raised too late, making it impossible to maintain a

groundwater level above 50 cm. The AWIS system in Zegveld will be optimized in the year 2023, by installing a new reservoir at parcel 16 (instead of the reservoir in parcel 15 to which the system is currently connected; this is especially desirable because of the ~10 cm higher surface elevation of parcel 16 compared to parcel 15, and hence, different reservoir levels are needed to keep groundwater levels at the same depth below surface level).

Cross sections and average winter phreatic groundwater levels imply that in wet winter periods, the phreatic groundwater level tends to be lower in the AWIS parcel compared to the reference parcel, as a result of drainage (Figure 28 and Appendix Information A.4). Furthermore, we observe the expected gradient with distance to drain; closest to the drain (0.5 m) the phreatic groundwater level tends to be higher in summer, and lower in winter, compared to the phreatic groundwater level at 1.5 and 3.0 m distance to the drains (Figure 27 and Figure 28; Table 9).

Furthermore, it should be noted that manual measurements of the water pressure in the drain have deviated a couple of times from the automatic measurements over the years 2021 and 2022, and hence the automatic measurements presented in Figure 26 are not completely reliable. They are included here anyway, because the measurements do reflect general trends in reservoir water level management. Still, it is important to check whether the automatic measurements are functioning properly, and if needed adapt calibration parameters in the loggers.

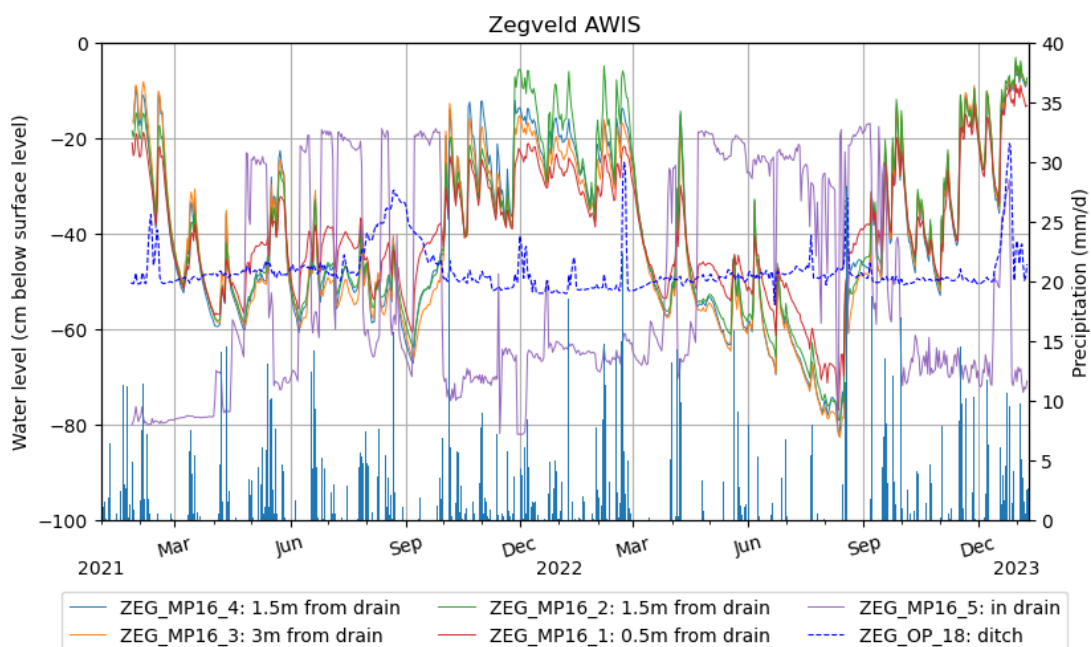


Figure 26. Phreatic groundwater level and ditch water level in the AWIS parcel in Zegveld, relative to surface level.

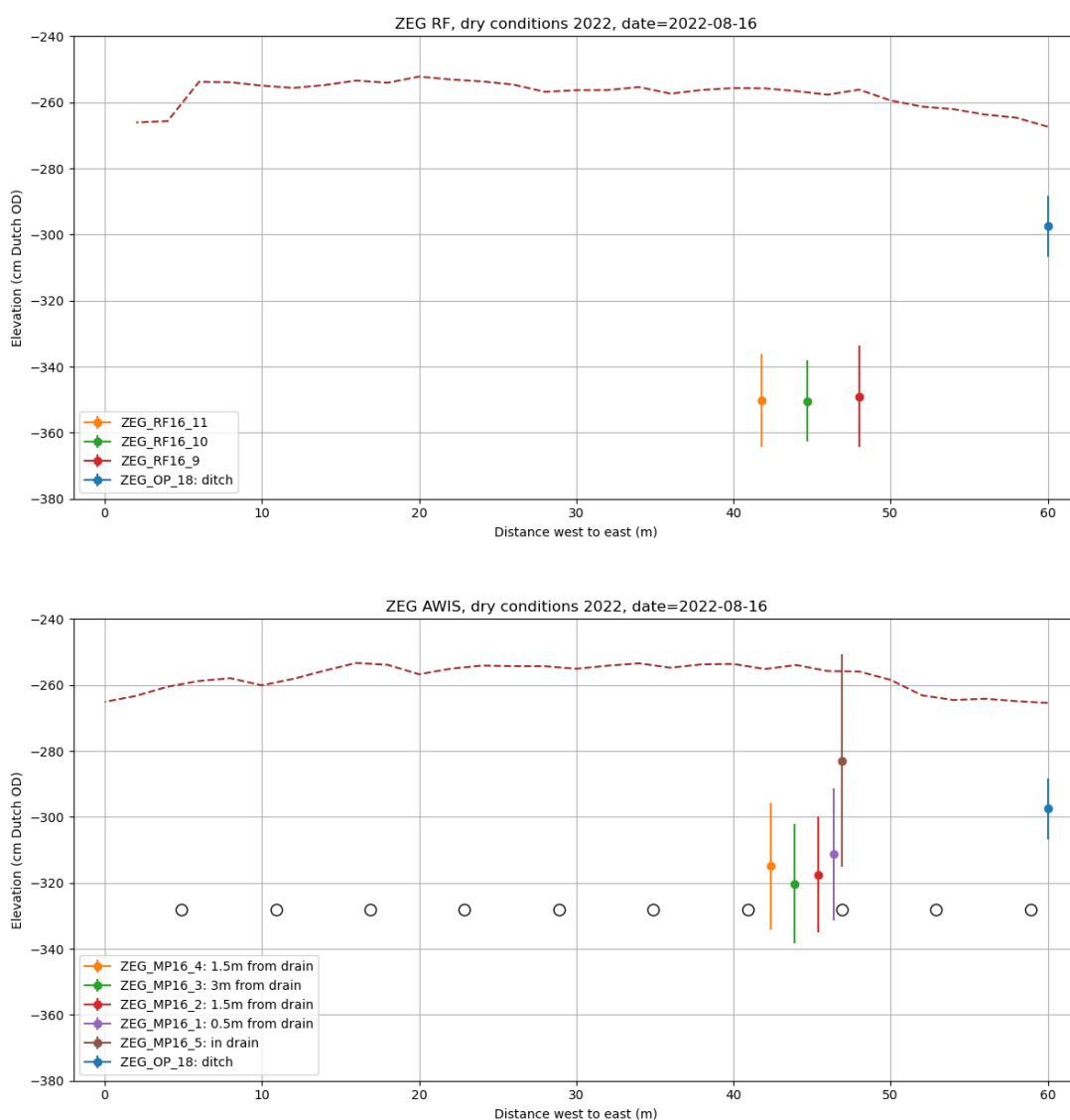


Figure 27. Cross sections of surface level and ditch and phreatic groundwater levels in the reference and AWIS parcel (various distances from the drain) in Zegveld in dry (summer 2022) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated with circles.

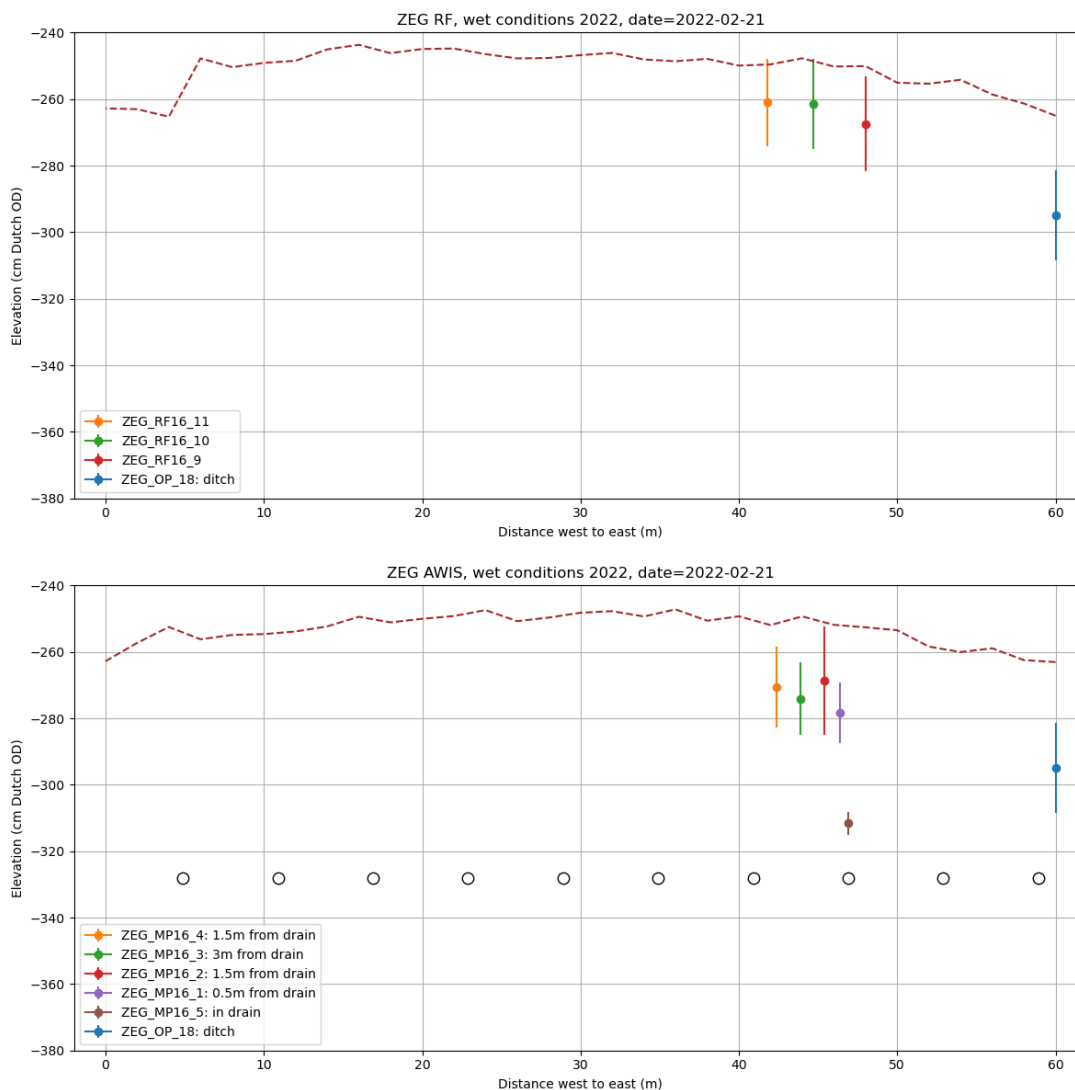


Figure 28. Cross sections of surface level and ditch and phreatic groundwater levels in the reference and AWIS parcel (various distances from the drain) in Zegveld in wet (winter 2022) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated with circles.

Table 9. Statistics for ground and ditch water monitoring wells in Zegveld, in cm relative to surface level. av. = average. Average lowest/highest groundwater level is the average of the 12% lowest/highest measurements for a year.

monitoring well	year	av. water level	lowest water level	highest water level	av. lowest water level	av. highest water level	av. summer water level	av. winter water level
ZEG_RF16_11	2021	-47	-84	-1	-81	-7	-66	-25
	2022	-51	-106	-4	-97	-10	-74	-28
ZEG_RF16_10	2021	-45	-81	1	-78	-6	-64	-23
	2022	-50	-103	-1	-94	-9	-72	-27
ZEG_RF16_9	2021	-46	-80	-1	-77	-10	-63	-26
	2022	-51	-101	-5	-93	-13	-72	-30
ZEG_MP16_4: 1.5m from drain	2021	-40	-67	-9	-60	-14	-51	-28
	2022	-42	-82	-4	-72	-14	-55	-29
ZEG_MP16_3: 3m from drain	2021	-41	-66	-8	-60	-16	-51	-29
	2022	-43	-83	-4	-74	-14	-56	-30
ZEG_MP16_2: 1.5m from drain	2021	-40	-64	-6	-58	-13	-50	-29
	2022	-41	-79	-3	-70	-11	-53	-28
ZEG_MP16_1: 0.5m from drain	2021	-40	-61	-19	-55	-23	-46	-33
	2022	-41	-77	-9	-64	-17	-49	-32
ZEG_MP16_5: in drain	2021	-58	-82	-18	-80	-19	-44	-73
	2022	-48	-80	-17	-70	-19	-32	-63
ZEG_OP_18: ditch	2021	-43	-51	-26	-50	-31	-40	-47
	2022	-45	-51	-18	-50	-36	-44	-46

In Zegveld two monitoring wells with a filter depth of 3.5-4.0 m below surface level and 3.75-4.25 m below surface level have been installed in the reference and AWIS parcel respectively. In general, in both parcels the measured hydraulic head at about 4 m depth is similar to the average phreatic groundwater level, though less spikey and sometimes a delayed response has been observed (Figure 29). These results indicate overall good vertical permeability of the peat layer.

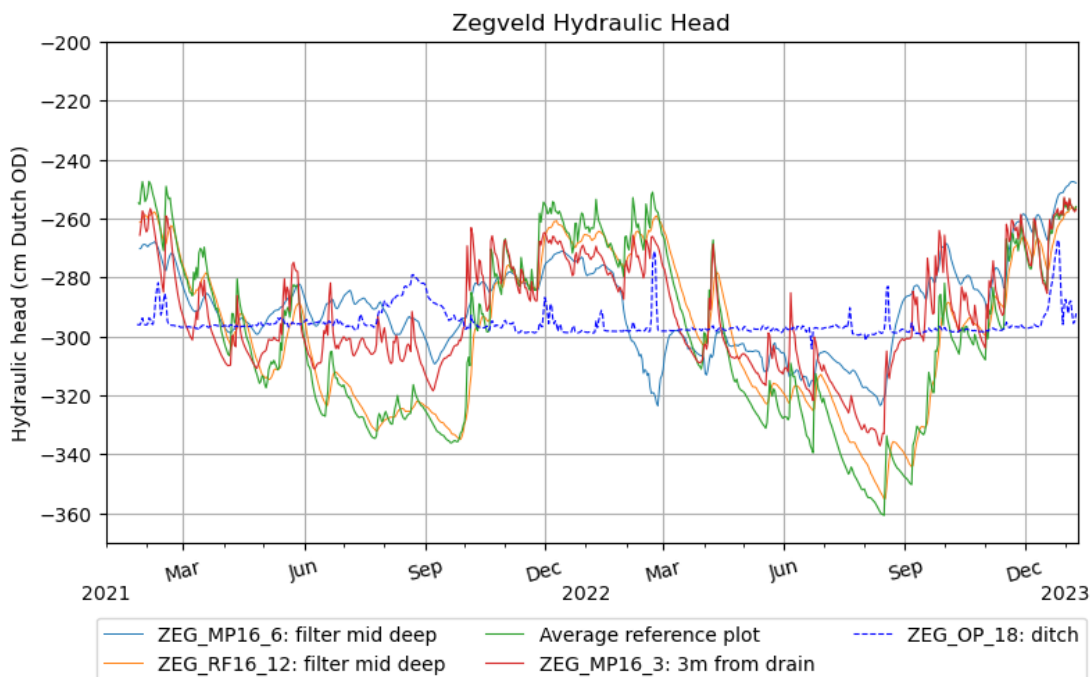


Figure 29. Hydraulic head at about 4 m depth, in the reference (ZEG_RF16_12) and AWIS (ZEG_MP16_6) parcel in Zegveld. Also, the average phreatic groundwater level in the reference parcel, the phreatic groundwater level at $\frac{1}{2}$ drain spacing, and ditch water level have been plotted.

3.5 Vlist

In the reference parcel in Vlist, the phreatic groundwater level has dropped to a maximum depth of about 70 and 95 cm below surface for the summers of 2021 and 2022 respectively (Figure 30). In winter, the phreatic groundwater level fluctuated roughly between 0 and 40 cm below surface level. The ditch water level has fluctuated between about 45 and 60 cm below surface level and is the same for the reference and PWIS parcel.

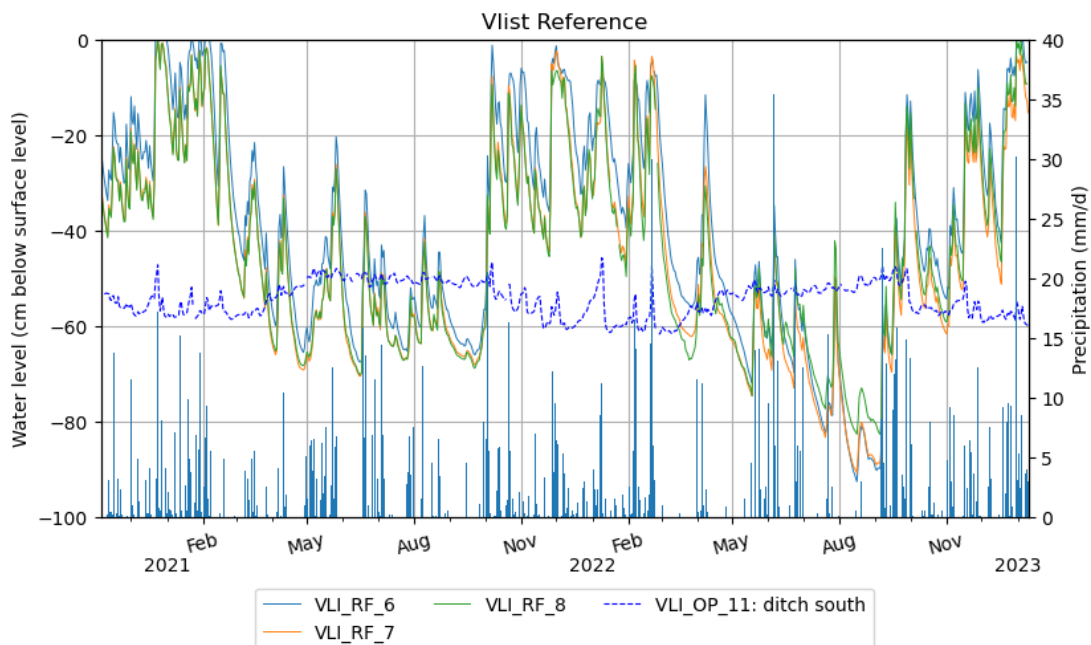


Figure 30. Phreatic groundwater level and ditch water level in the reference parcel in Vlist, relative to surface level.

In the PWIS parcel, the phreatic groundwater level has lowered to a maximum depth of 70 and 85 cm below surface in the summers of 2021 and 2022 respectively (Figure 31). Hence, only in the summer of 2022, we observed somewhat higher phreatic groundwater levels in the PWIS parcel, indicating infiltration through the drains (Figure 32; also somewhat higher average lowest groundwater levels in the summer of 2022; Table 10). Lowest phreatic groundwater levels occurred further away from the drain, at half drain spacing (3.0 m; Figure 31 and 32). In wet winter periods, phreatic groundwater levels tend to be somewhat lower in the PWIS parcel than in the reference parcel, indicating drainage in wet periods (Figure 33 Table 10. Statistics for ground and ditch water monitoring wells in Vlist, in cm relative to surface level. Appendix Information A.5; Table 10).

The in-drain measurement closely follows the ditch water level, which is expected at this location where the drains are directly connected to the ditch. However, the in-drain measurements unexpectedly plot higher than the ditch water level for most of the monitoring period. At the time of writing the reason for this is not clear and has to be sorted out. One explanation could be the use of incorrect calibration parameters in the logger, which should be checked, and if needed adapted, by manual water level measurements. Another explanation may be found in calculations of waters levels relative to surface level, for which levelling and extensometer measurements are used (see section 2.1). When plotting the ditch and in-drain water levels relative to Dutch Ordnance Datum (NAP) at this location (not presented in this report), the in-drain measurements plot a few centimetres below the ditch water level. Despite the in-drain measurements are not completely reliable, they are included in this report since they do show the general trend, which closely follows ditch water level fluctuations.

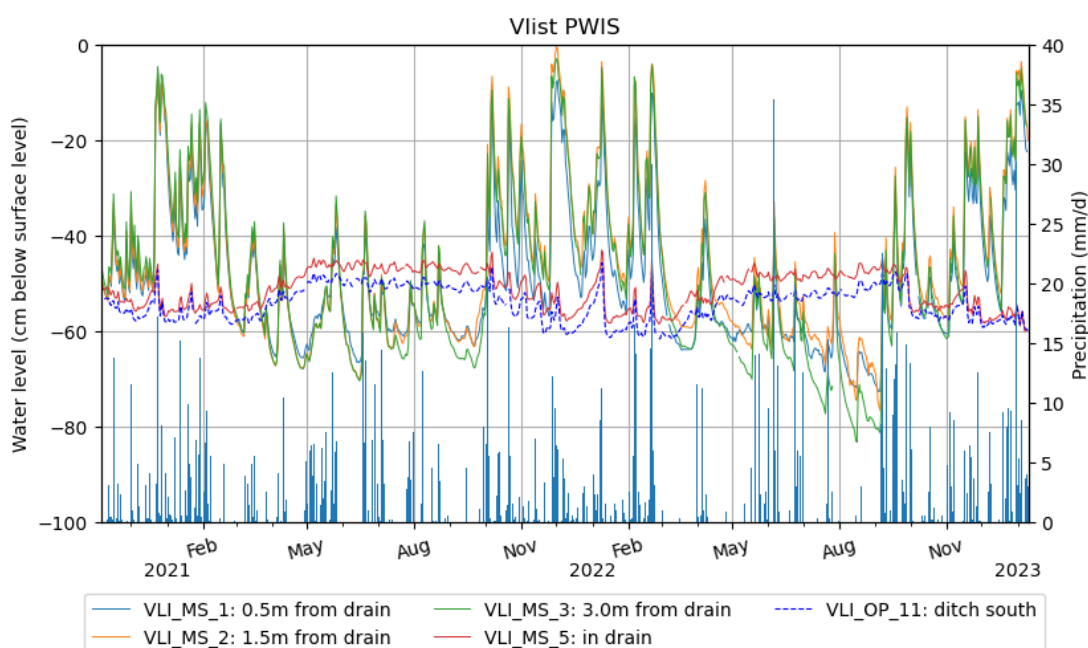


Figure 31. Phreatic groundwater level and ditch water level in the PWIS parcel in Vlist, relative to surface level.

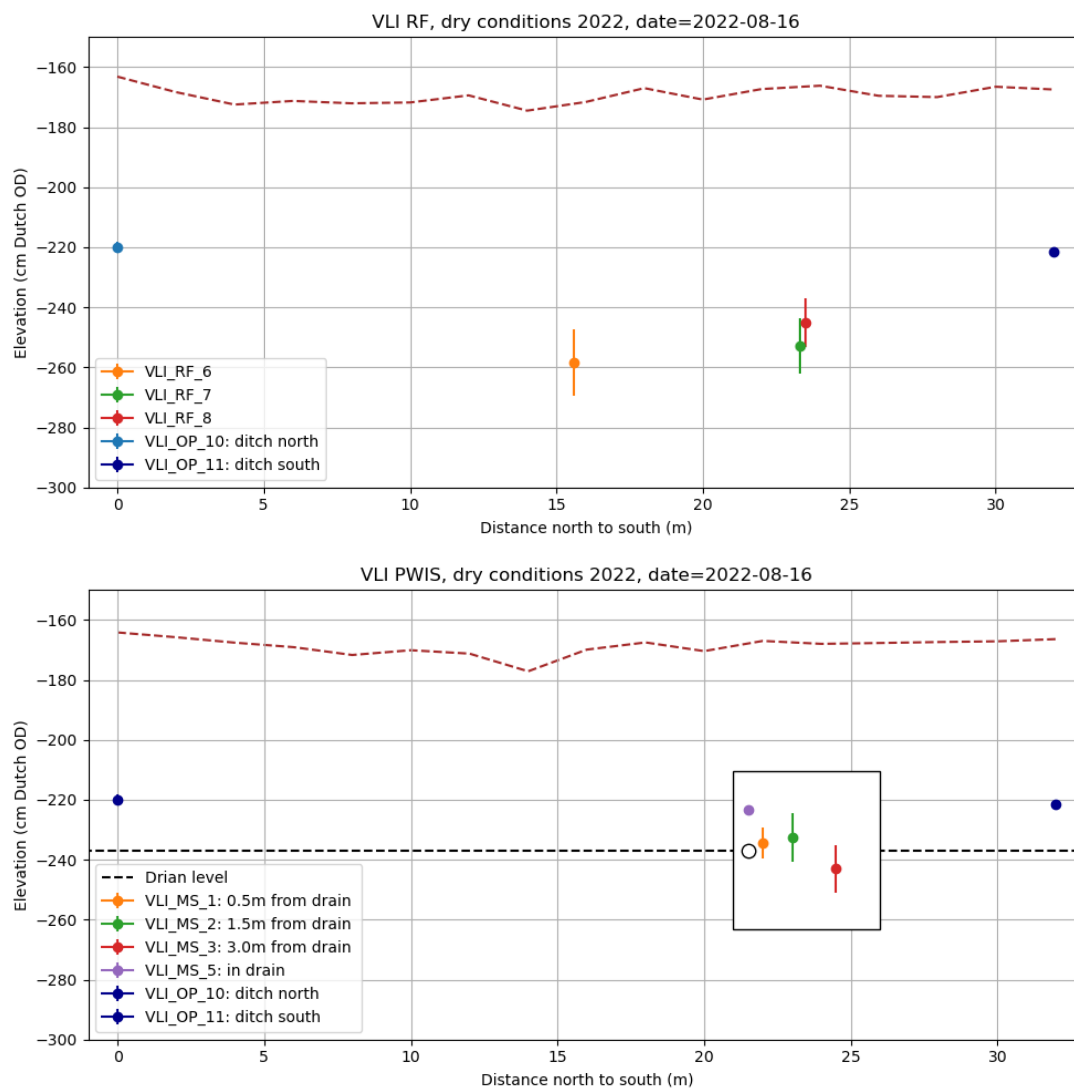


Figure 32. Cross sections of surface level and ditch and phreatic groundwater levels in the reference and PWIS parcel (various distances from the drain) in Vlist in dry (summer 2022) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated by the dotted horizontal black line. This representation is chosen as drains run from ditch to ditch. Within the white box the monitoring wells perpendicular to the drain are visualized, at scale.

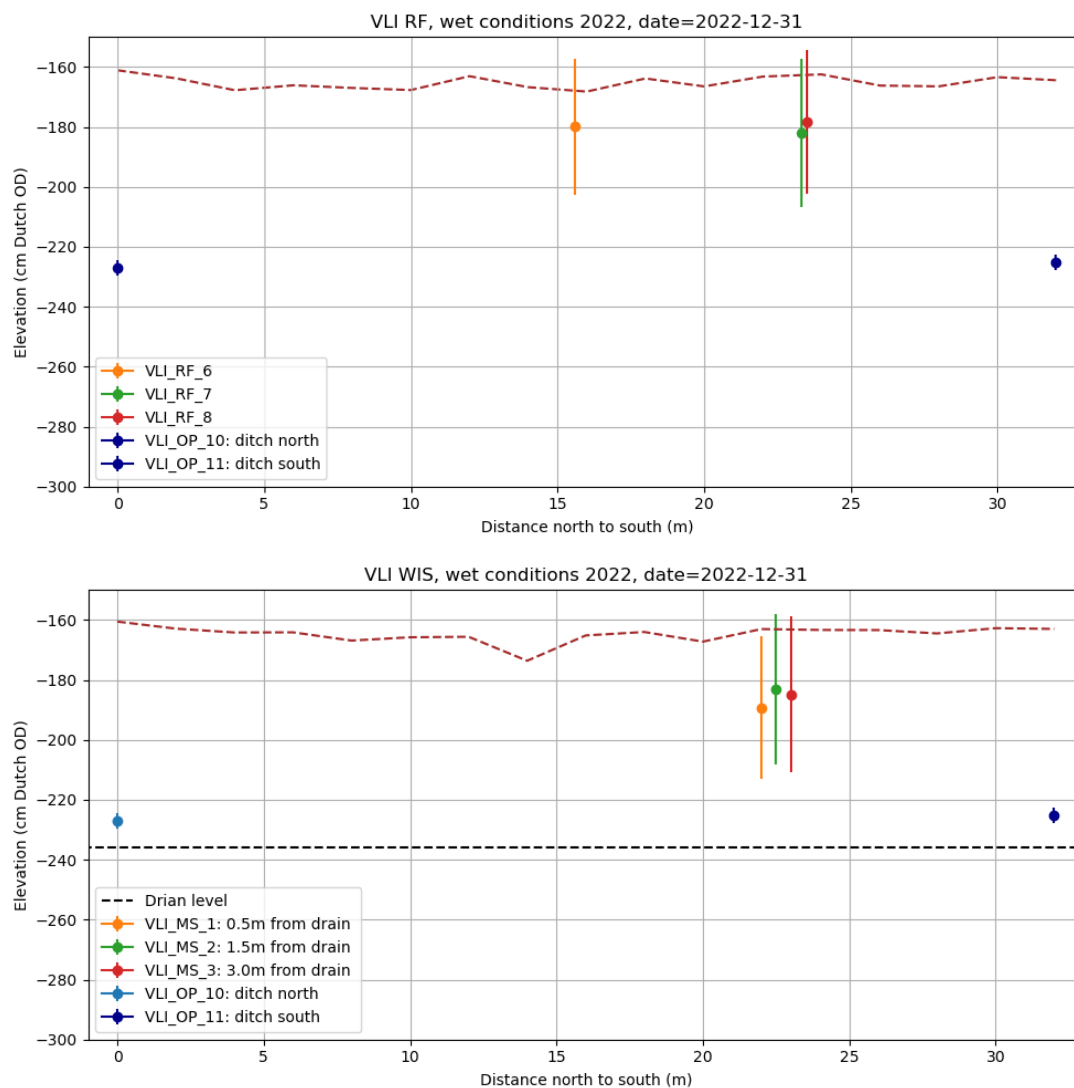


Figure 33. Cross sections of surface level and ditch and phreatic groundwater levels in the reference and PWIS parcel (various distances from the drain) in Vlist in wet (winter 2022) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated by the dotted horizontal black line.

Table 10. Statistics for ground and ditch water monitoring wells in Vlist, in cm relative to surface level. Av. = average, GW = phreatic groundwater level. The average lowest/highest groundwater level is the average of the 12% lowest/highest measurements for a year.

Monitoring well	year	av. GW level	lowest GW level	highest GW level	av. lowest GW level	av. highest GW level	av. summer GW level	av. winter GW level
VLI_RF_6	2021	-37	-68	3	-65	-3	-54	-19
	2022	-46	-93	0	-85	-9	-62	-30
VLI_RF_7	2021	-43	-71	-2	-68	-8	-59	-27
	2022	-52	-91	-3	-85	-15	-66	-37
VLI_RF_8	2021	-43	-70	-2	-67	-9	-59	-28
	2022	-50	-83	0	-78	-14	-62	-37
VLI_MS_1: 0.5m from drain	2021	-49	-67	-8	-64	-21	-57	-40
	2022	-52	-73	-10	-68	-24	-59	-45
VLI_MS_2: 1.5m from drain	2021	-47	-70	-1	-66	-16	-58	-36
	2022	-48	-77	-4	-67	-17	-56	-39
VLI_MS_3: 3.0m from drain	2021	-47	-70	-3	-67	-16	-59	-36
	2022	-52	-83	-4	-77	-19	-62	-41
VLI_MS_4: 1.5m from drain	2021	-40	-60	1	-56	-10	-50	-31
	2022	-54	-83	-3	-78	-18	-59	-49
VLI_MS_5: in drain	2021	-50	-58	-44	-56	-46	-47	-54
	2022	-52	-59	-43	-58	-47	-49	-55
VLI_OP_10: ditch north	2021	-53	-63	-46	-60	-47	-49	-57
	2022	-55	-63	-47	-61	-49	-51	-59
VLI_OP_11: ditch south	2021	-53	-61	-47	-59	-49	-51	-56
	2022	-55	-62	-46	-61	-50	-52	-58

The relatively short data series of the hydraulic head (measured since October 2022) in the Pleistocene sand in Vlist shows a decreasing trend if the phreatic groundwater level is relatively low and an increasing trend when phreatic groundwater levels are high. That is an indication of some seasonal seepage/infiltration, although on average it is probably quite neutral. This is expected because the sandy Pleistocene deposits are found at relatively great depth, and the Holocene sequences consists of an alternation of peat and clay layers (section 2.6), which will limit influence of the hydraulic pressure in the Pleistocene deposits on the phreatic groundwater level (and vice versa). Possibly, the Vlist river affects the hydraulic head in the Pleistocene sandy deposits (Figure 34).

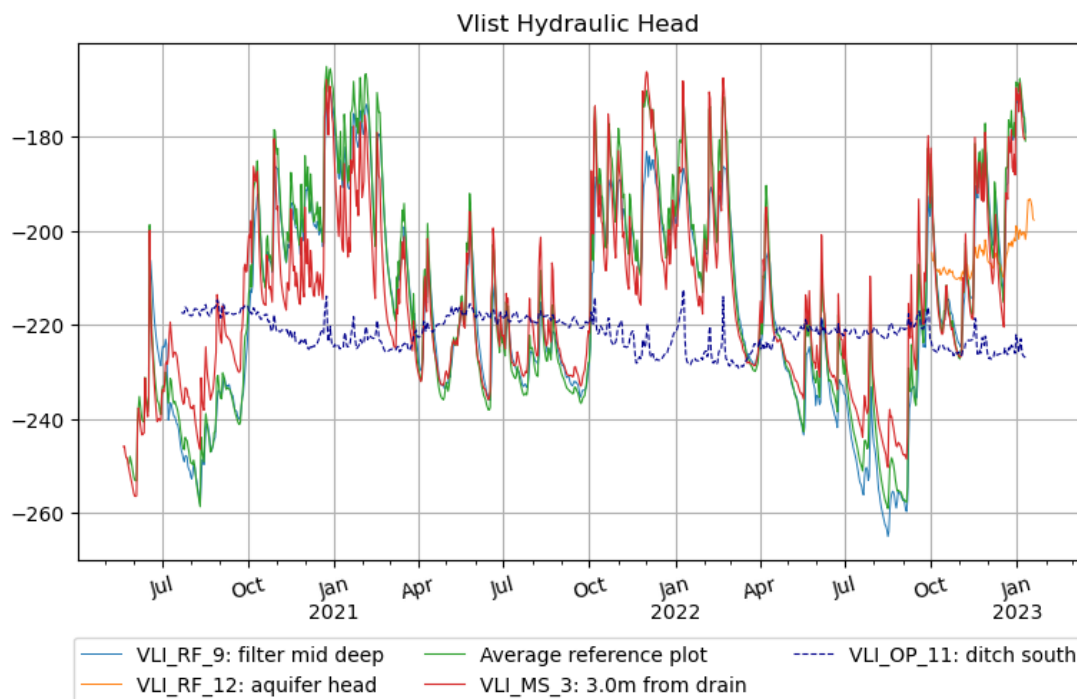


Figure 34. Hydraulic head at 3.5 to 4.0 and (from October 2022) at 13.2 to 13.4 m below surface level, in Vlist.

4 Discussion

To further discuss the monitoring results and evaluate the functioning and effectiveness of the WIS at the different locations, additional (ground)water level statistics have been calculated for the different study sites and years (Table 11).

Table 11. Overview of WIS type, ditch water and phreatic groundwater level characteristics and statistics for the five study sites. DW = ditch water, GW = phreatic groundwater, s = surface level, ds = drain spacing, PWIS = passive water infiltration system, AWIS = active water infiltration system, RF = reference parcel (averages of the phreatic monitoring wells in the reference parcel are given in the table), ALB = Aldeboarn, ROV = Rouveen, ASD = Assendelft, ZEG = Zegveld, VLI = Vlist. Average and deepest water levels are indicated in cm relative to surface level. Differences between RF and WIS parcel are indicated in cm (positive value = average GW level is higher in WIS parcel, negative value = average GW level is lower in WIS parcel). Differences exceeding ± 2 cm are indicated in green if the effect is as expected (higher summer or lower winter GW level in WIS parcel), in red if the effect is opposite of the expected (lower summer or higher winter GW level in WIS parcel). Differences less than ± 2 cm are indicated in orange (minor/no difference).

		ALB		ROV		ASD		ZEG		VLI	
Drain spacing (m)		6		8		4		6		6 ^a	
System type		PWIS		PWIS		AWIS		AWIS		PWIS	
Drain depth (cm-s)		70 - 80		65 - 70		50 - 70		70-75		70	
		2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Deepest DW level	RF ^b	-88	-92	-62	-58	-50	-56	-51	-51	-63	-63
	WIS ^b	-77	-78	-63	-58	-47	-46	-51	-51	-61	-62
Average summer	RF ^b	-74	-64	-48	-47	-38	-36	-40	-44	-49	-51
DW level	WIS ^b	-45	-45	-45	-44	-34	-35	-40	-44	-51	-52
Average winter DW	RF ^b	-81	-78	-57	-52	-43	-36	-47	-46	-57	-59
level	WIS ^b	-64	-55	-55	-49	-39	-42	-47	-46	-56	-58
Average highest	RF	-1	-4	-24	-19	-11	-16	-7	-11	-7	-12
GW level	WIS-1/4 ds	-8	-11	-21	-56	-13	-15	-13	-11	-16	-17
	WIS-1/2 ds	-6	-12	-33	-33	-13	-18	-16	-14	-16	-19
Average lowest	RF	-48	-98	-48	-56	-44	-88	-79	-95	-66	-82
GW level	WIS-1/4 ds	-43	-57	-50	-56	-37	-50	-58	-70	-66	-67
	WIS-1/2 ds	-40	-69	-49	-66	-38	-52	-60	-74	-67	-77
Deepest GW level (cm-s)	RF	-56	-115	-52	-64	-50	-100	-82	-103	-69	-89
	WIS-1/4 ds	-46	-83	-53	-64	-42	-56	-64	-79	-70	-77
	WIS-1/2 ds	-46	-85	-51	-69	-44	-58	-66	-83	-70	-83
Average summer	RF	-30	-64	-40	-45	-32	-62	-64	-73	-57	-63
GW level	WIS-1/4 ds	-26	-44	-43	-46	-30	-35	-50	-53	-58	-56
	WIS-1/2 ds	-26	-48	-44	-52	-32	-38	-51	-56	-59	-62
Average winter GW level	RF	-10	-31	-33	-31	-18	-25	-24	-28	-25	-35
	WIS-1/4 ds	-21	-23	-35	-36	-18	-21	-29	-28	-36	-39
	WIS-1/2 ds	-18	-24	-39	-38	-19	-25	-29	-30	-36	-41
Average summer	WIS-1/4 ds	4	19	-2	-1	2	27	14	19	0	7
GW level difference	WIS-1/2 ds	4	16	-3	-7	1	25	13	17	-1	2
Average winter GW	WIS-1/4 ds	-11	9	-2	-5	0	4	-4	1	-11	-5
level difference	WIS-1/2 ds	-8	7	-6	-7	-1	0	-4	-2	-11	-7
Average deepest	WIS-1/4 ds	10	33	-2	0	8	44	18	24	-1	12
GW level difference	WIS-1/2 ds	10	31	0	-5	6	42	15	21	-1	5

^aperpendicular to the parcel longitudinal direction.

^bfor Vlist values are given for the southern ditch.

Aldeboarn

In Aldeboarn, the presence of drains, combined with raised ditch water levels, in the PWIS plot, resulted in less deep average summer, and average lowest summer, phreatic groundwater levels compared to in the reference plot (section 3.1; Table 11). This was especially clear in the dry summer of 2022, when PWIS combined with a 19 cm higher average ditch water level, resulted in average summer phreatic groundwater levels that were 19 and 16 cm higher, and deepest phreatic groundwater levels that were 33 and 31 cm higher in the PWIS plot compared to the reference parcel, at 1.5 and 3.0 m from the drain, respectively (Table 11).

The monitoring well located at 1.5 m distance from the other drain running through the plot (ALB_MS_5) deviated from this general trend (section 3.1), which is presumably due to relatively much trapped air in this drain, as revealed by camera inspection at the start of the study. Another explanation might be the greater distance to the trench running west of the plot. Also in other drains trapped air was encountered. Air entrapment in drains may have originated when ditch water levels dropped below drain depth: the deepest measured ditch water levels in the PWIS parcel have been 78 cm below surface level, while the drains are located 70 to 80 cm below surface level (Table 11). To prevent intrusion of air in the drains, which likely affects their draining and infiltrating effectiveness, it is of utmost importance that ditch water levels remain at least 15 cm above drain depth. As ditch water management was changed during the growing season of 2022, further intrusion of air will be avoided.

In 2021, average winter phreatic groundwater levels at $\frac{1}{4}$ and $\frac{1}{2}$ drain spacing were 11 and 8 cm lower compared to the reference parcel, indicating drainage through the drains. In 2022, however, average winter phreatic groundwater levels were 9 and 7 cm higher at $\frac{1}{4}$ and $\frac{1}{2}$ drain spacing, compared to the reference parcel. This was presumably caused by the last three months of 2022, when (1) The average ditch water level of the PWIS parcel was ca. 20 cm higher, while that of the reference parcel was only 10 cm higher, compared to the same period in 2021. This resulted in an average ditch water level of the PWIS parcel that was ca. 28 cm higher than that of the reference parcel in this period in 2022 (Figure 14); (2) Groundwater levels in the reference parcel were still recovering from the 2022 summer drought (Figure 10). This caused a delayed return to the usual high winter groundwater levels. Figure 10 Average highest groundwater levels were however somewhat lower in the PWIS parcel compared to the reference parcel, indicating that overall, winter drainage is taking place (Table 11).

Rouveen

Phreatic groundwater levels in Rouveen are generally lower in the PWIS parcel than in the reference parcel (Table 11 and section 3.2). Hence, under the current circumstances (amongst others, ditch water levels) in Rouveen, an area with upward seepage, the PWIS was not effective in limiting phreatic groundwater level lowering in summer, but instead, stimulated drainage of groundwater year-round. In the PWIS parcel, the phreatic groundwater level was lowered most both close to the drain and close to the trench just outside the experimental plot. Reducing the rather large drain spacing of 8 m to for example 4 m will probably only increase the draining effect under current conditions.

Because this location is an upward seepage area, phreatic groundwater levels do not drop extremely low, even in very dry summers like that of 2022, when the deepest average phreatic groundwater level in the reference parcel was 64 cm below surface level (Table 11; for comparison, at the other study locations the phreatic groundwater level in the reference parcels dropped to ~90 to ~120 cm below surface level in the same period). If higher phreatic groundwater levels are desired, solutions (i.e., measures that cause a higher effectiveness of the WIS) may be sought in raising the ditch water level and/or connecting the drains to a reservoir with a pump to actively pump water into the parcels. In this case, it could be effective to reduce the drain spacing as well.

Assendelft

Active pumping in Assendelft has clearly prevented excessive lowering of summer phreatic groundwater levels; average phreatic groundwater levels were 27 and 25 cm higher in the summer of 2022, at $\frac{1}{4}$ and $\frac{1}{2}$ drain spacing respectively (Table 11). Deepest phreatic groundwater levels in the same period were 44 and 42 cm higher at $\frac{1}{4}$ and $\frac{1}{2}$ drain spacing respectively. Also, average lowest summer groundwater levels are substantially higher in the AWIS parcel compared to the reference parcel (Table 11). In the wet summer of 2021, the deepest phreatic groundwater levels were also higher in the AWIS parcel compared to in the reference parcel (~7 cm), although average phreatic groundwater levels were similar in both parcels (Table 11). In the summer of 2021, the phreatic groundwater levels in the reference parcel were already relatively high (32 cm below surface level on average): the AWIS could not further raise the phreatic groundwater level. In winter no clear effect of the AWIS has been observed.

Zegveld

Also in Zegveld, active pumping has clearly prevented excessive lowering of summer phreatic groundwater levels, both in the summer of 2021 and 2022 (Table 11 and section 0). Average phreatic groundwater levels were raised with 14 and 13 cm in 2021 and with 19 and 17 cm in 2022, at $\frac{1}{4}$ and $\frac{1}{2}$ drain spacing respectively. Deepest phreatic groundwater levels were raised with 18 and 15 cm in 2021 and with 24 and 21 cm in 2022, at $\frac{1}{4}$ and $\frac{1}{2}$ drain spacing respectively. In winter, average phreatic groundwater levels tend to be a few centimeters lower in the AWIS parcel compared to the reference parcel (Table 11).

The beneficial effect of the AWIS in Zegveld may be further increased if the hydraulic head in the drains is raised further. Also, proper management and maintenance of the AWIS system has proven to be very important in maintaining groundwater levels at the target levels. When the reservoir level is not raised in time (i.e., well before groundwater levels drop below the target level), they may only recover in very wet periods. Also, groundwater level development prior and after cleaning of the drains in August 2022 demonstrated that flow from the reservoir, through the drains and into the soil may be strongly impeded when drains are not checked and cleaned regularly. Moreover, to increase the efficiency of the AWIS system in Zegveld the ditch water level could be increased to 40 cm below surface level, and the drain spacing could be decreased to 4 m.

Vlist

In Vlist, we only observed an infiltrating effect of the PWIS in the dry summer of 2022 (section 3.5 and Table 11), which was very limited compared to other non-seepage locations. Measurements did indicate a draining effect in both winters (Table 11). A less clear effect of the PWIS at Vlist compared to the other study sites, may be partly caused by the relatively small parcel width of ca 30 m, by which infiltration of water from the ditches is likely much higher than at wider parcels, such as in Aldeboarn, and hence, beneficial effects of PWIS are harder to achieve. Presumably, the infiltrating effect in dry periods could be increased at Vlist if ditch water levels were raised.

General discussion

In this study, the AWIS system in Assendelft appeared to be most effective (i.e., greatest difference between WIS and reference parcel) in raising the phreatic groundwater level in the dry summer of 2022 (Table 11), which is presumably the result of a relatively high summer ditch water level (~30 cm below surface level), mostly effective water management by active pumping, a relatively small drain spacing of 4 m, and a good functioning of the drains. In the summer of 2021, however, no clear effect was observed, except for a somewhat less deep deepest groundwater level in the AWIS parcel. This could be explained by the relatively high average summer groundwater levels (about -30 cm below surface level in both parcels), which is already at about the target groundwater level, and by the relatively high amount of precipitation that year at this location (Appendix Information B). In general, differences in precipitation surplus or deficit (precipitation – potential evapotranspiration) among different locations and years, may also partly

explain differences in the effectiveness of the WIS. Hence, it is advisable to take such information into account in future analyses.

Also, in Aldeboarn and Zegveld, substantially higher summer phreatic groundwater levels have been measured in the WIS parcels as compared to their references, due to additional infiltration of water via the WIS. The effect is largest in the dry summer of 2022 (Table 11), when a high precipitation deficit caused very low phreatic groundwater levels in the reference parcels (Appendix Information B). In Aldeboarn, the measured effect (difference with the reference parcel) is probably not only the result of the PWIS, but also of the ditch water management: in both summers the average summer ditch water level is much higher (~20 to 30 cm) in the PWIS parcel compared to the reference parcel, where ditch water levels are relatively low compared to the other study sites (Table 11). These relatively low ditch water levels in the reference parcel, in combination with warm and dry conditions, are expected to partly explain the very low phreatic groundwater levels measured in Aldeboarn, of up to 125 cm below surface level. In Zegveld, the ditch water levels are equal for both parcels. It is likely that in Zegveld, a more precise management and maintenance of the system may result in a larger beneficial effect of the AWIS.

In Vlist, a small infiltration effect has been observed, only in the dry summer of 2022, which could be due to relatively low ditch water levels and the small parcel width. In Rouveen, the PWIS has resulted in lower phreatic groundwater levels due to drainage of upward seeping water. At most locations, measurements indicate similar or somewhat lower winter (average highest, average winter) phreatic groundwater levels in the WIS parcel, as a result of drainage through the drains (Table 11).

At first sight, these results imply that an AWIS system is more effective than a PWIS system, given the ditch water levels used at the study locations. The PWIS systems may however be just as effective if ditch water levels are raised further. Moreover, results of the different locations are affected by (ditch and reservoir) water management, which varies among locations and among parcels at one location, and by drain maintenance. In Aldeboarn, for example, the PWIS is combined with raised ditch water levels (different for the WIS and reference parcel), making it difficult to compare this PWIS with for example the AWIS in Zegveld. Future harmonization and optimization of water management and removing air and mud from drains should lead to better comparisons between AWIS and PWIS.

Overall, our results demonstrate that ditch water management and drain maintenance partly determines the effectiveness of the WIS. In general, the performance of the considered WIS could presumably be improved substantially by raising the ditch water level, keeping drains free of trapped air and mud, and limit the drain spacing to 4 m, which is in agreement with a recent certification procedure for WIS (KOMO, 2021). Mud and air in drain tubes may reduce the flux of water in the drain system seriously. Moreover, mud in infiltration drains may lead to accumulation of soil particles in and around the drain, which may affect the hydraulic conductivity of the soil surrounding the drain and therewith impede water flow. Also, air in infiltration drains might hinder water flow because it reduces the area available for water flow. Mud and/or air in drains may consequently lead to substantial differences between the in-drain water pressure measurement and the groundwater level measurement close to the drain (~0.5 m distance), which was observed at several locations in this study. However, these differences are not necessarily indicative of air and/or mud in the drain but are also expected because the radial resistance is often much higher than the vertical and horizontal conductivity of the soil surrounding the drains, as a result of water flowing at relatively high speed through a relatively small volume of soil around the drain (e.g., Van Beers, 1965; 1976). In an upward seepage area, WIS could presumably only be effective in raising phreatic groundwater levels if ditchwater levels and/or reservoir levels in an WIS are raised well above the water potential in the deeper soil layers (which might not always be possible, depending on the amount of upward seepage).

5 Conclusions

- In general, WIS limit phreatic groundwater level lowering in summer by additional infiltration of water into the soil through the drains, but only in areas without extensive upward seepage.
- The effect of WIS on winter drainage is less pronounced, though results of this study demonstrate that winter phreatic groundwater levels are frequently somewhat lower in the WIS parcels compared to the reference parcel.
- Important factors affecting the effectiveness of the WIS in raising summer phreatic groundwater levels are ditch water level management (water levels in ditch or reservoir should be sufficiently high in summer and should remain at least 15 cm above drain depth), drain maintenance (to ensure drains remain free of air and mud), drain spacing, the hydrological situation (upward seepage/infiltrating area, soil water conductivity), and meteorological conditions.

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Appendix

A Cross sections

A.1 Aldeboarn

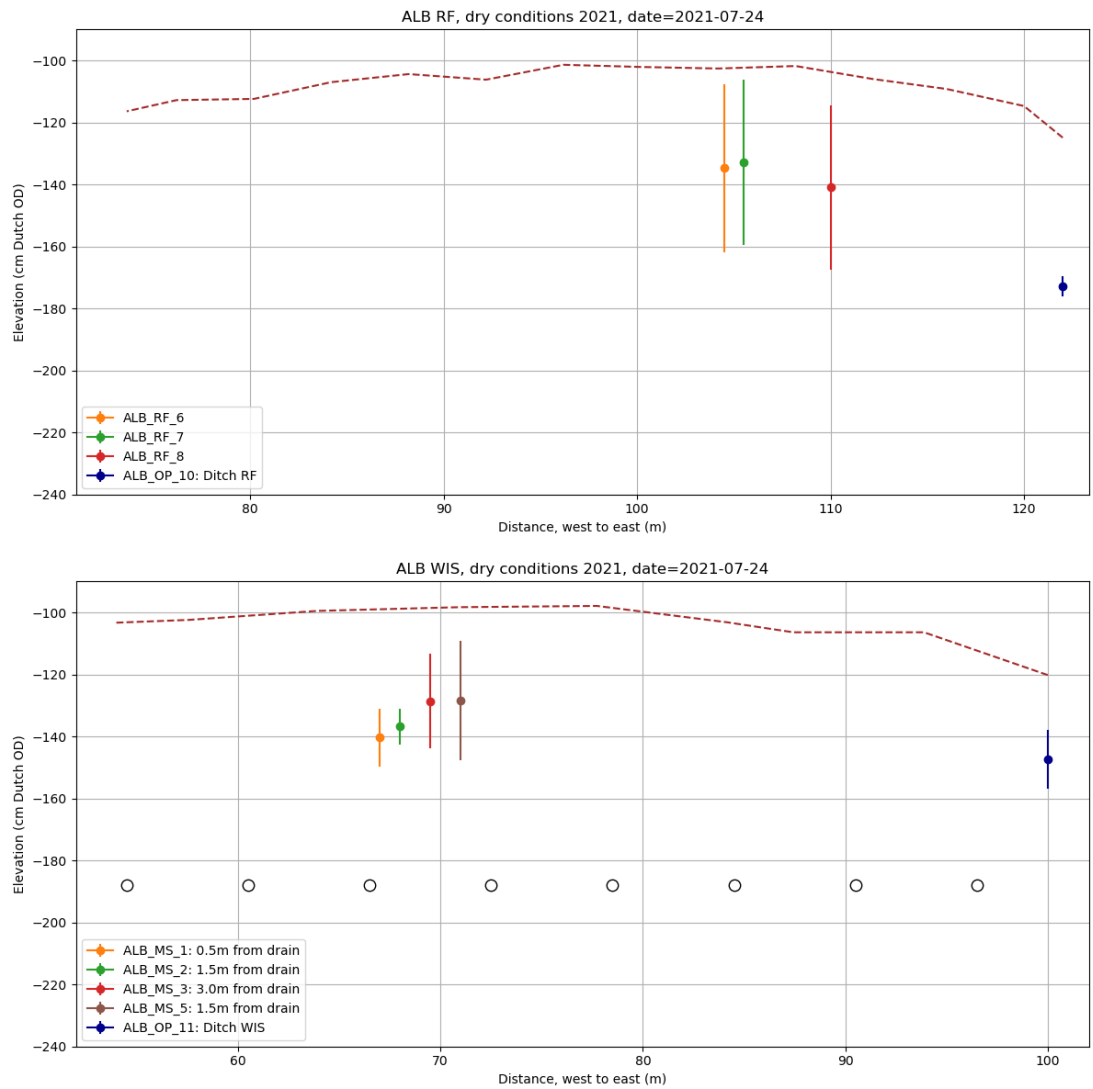


Figure A-1. Cross section of surface level and ditch and phreatic groundwater levels in the reference and WIS parcel (various distances from the drain) in Aldeboarn in dry (summer 2021) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated with circles.

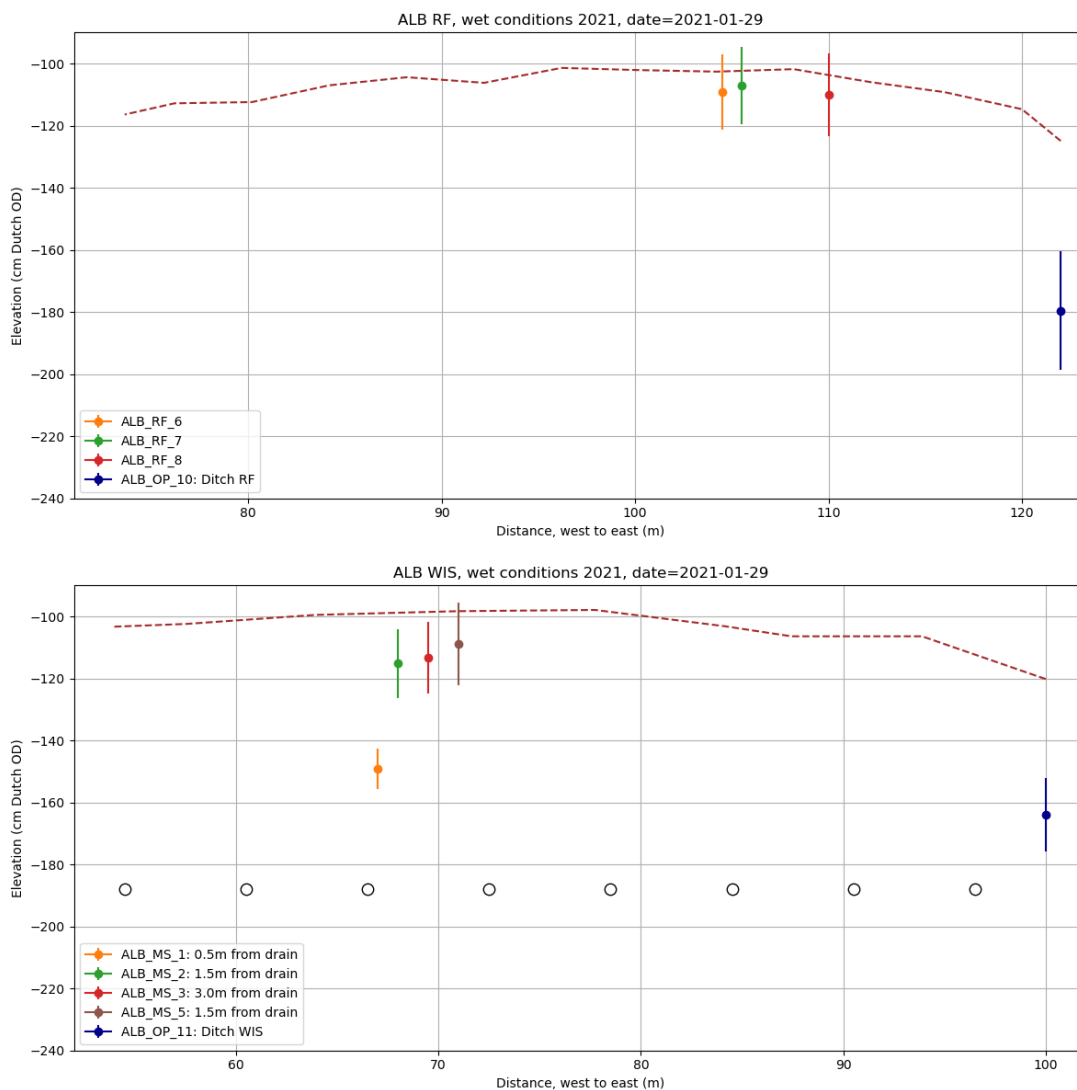


Figure A-2. Cross section of the surface level and ditch and phreatic groundwater levels in the reference and WIS parcel (various distances from the drain) in Aldeboarn in wet (winter 2021) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated with circles.

A.2 Rouveen

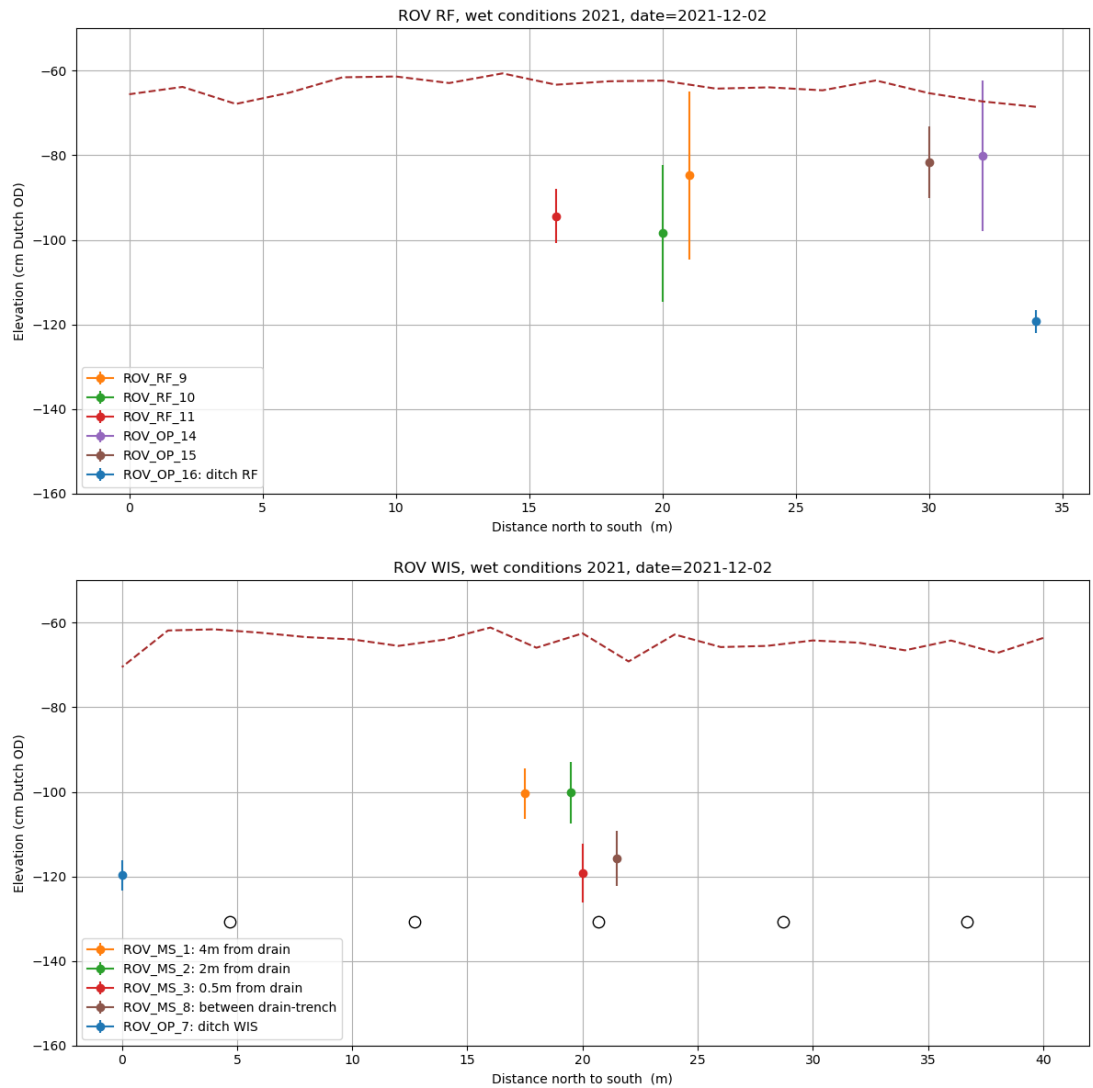


Figure A-3. Cross section of surface level and ditch and phreatic groundwater levels in the reference and WIS parcel (various distances from the drain) in Rouveen in wet (winter 2021) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated with circles.

A.3 Assendelft

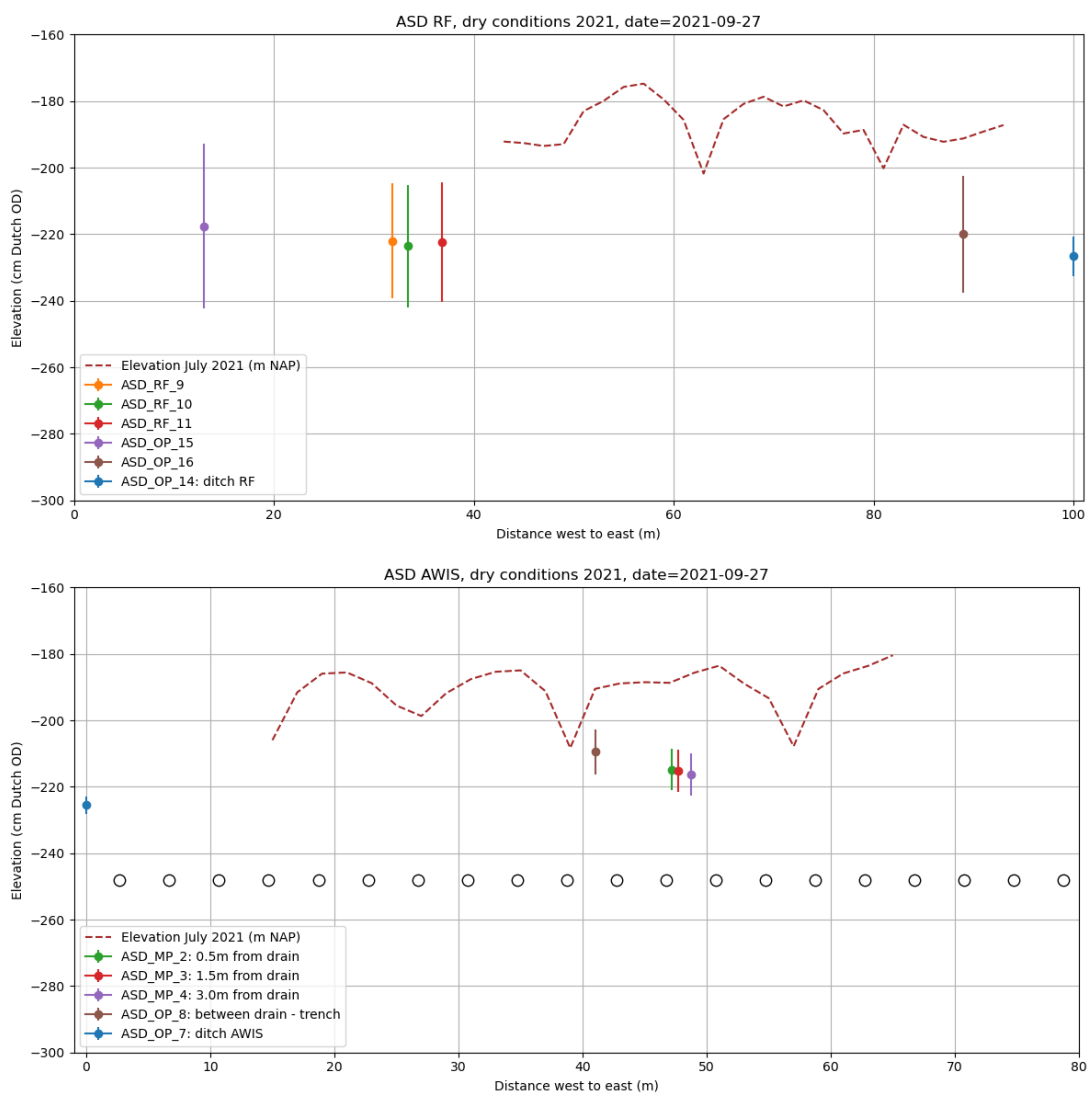


Figure A-4. Cross section of surface level and ditch and phreatic groundwater levels in the reference and AWIS parcel (various distances from the drain) in Assendelft in dry (summer 2021) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated with circles. There is no levelling data available in the reference parcel at the position of the monitoring wells.

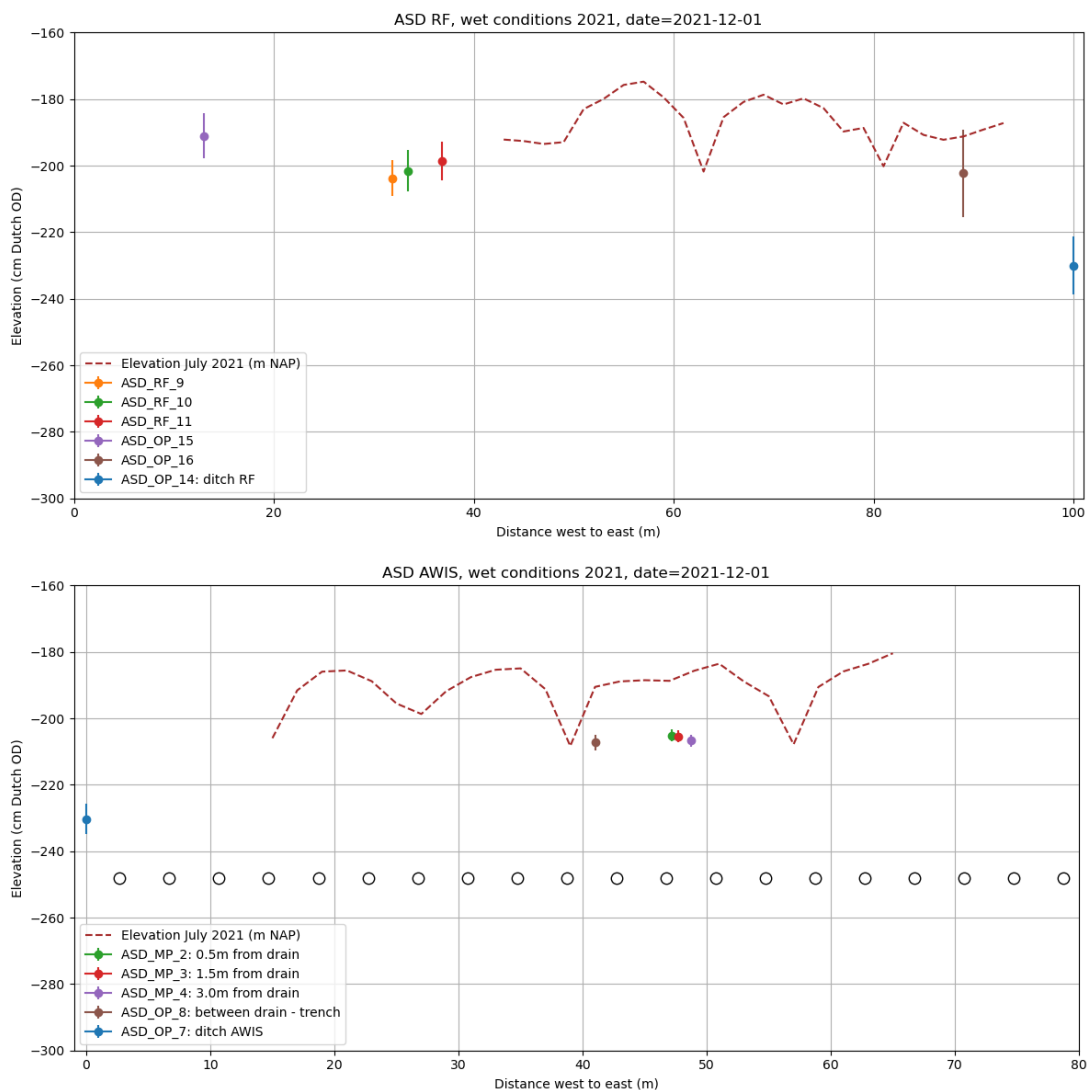


Figure A-5. Cross section of surface level and ditch and phreatic groundwater levels in the reference and AWIS parcel (various distances from the drain) in Assendelft in wet (winter 2021) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated with circles. There is no levelling data available in the reference parcel at the position of the monitoring wells.

A.4 Zegveld

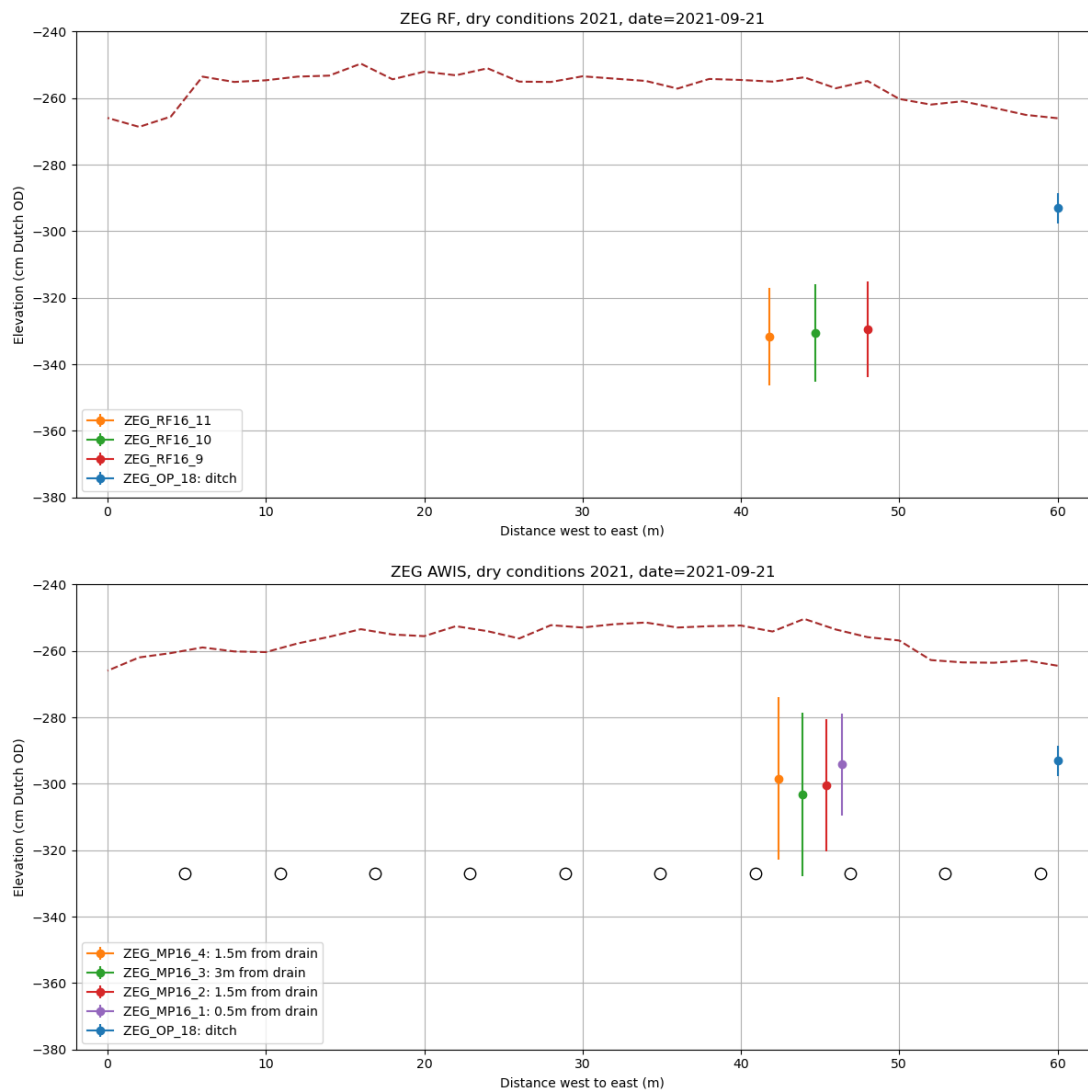


Figure A-6. Cross sections of surface level and ditch and phreatic groundwater levels in the reference and WIS parcel (various distances from the drain) in Zegveld in dry (summer 2021) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated with circles.

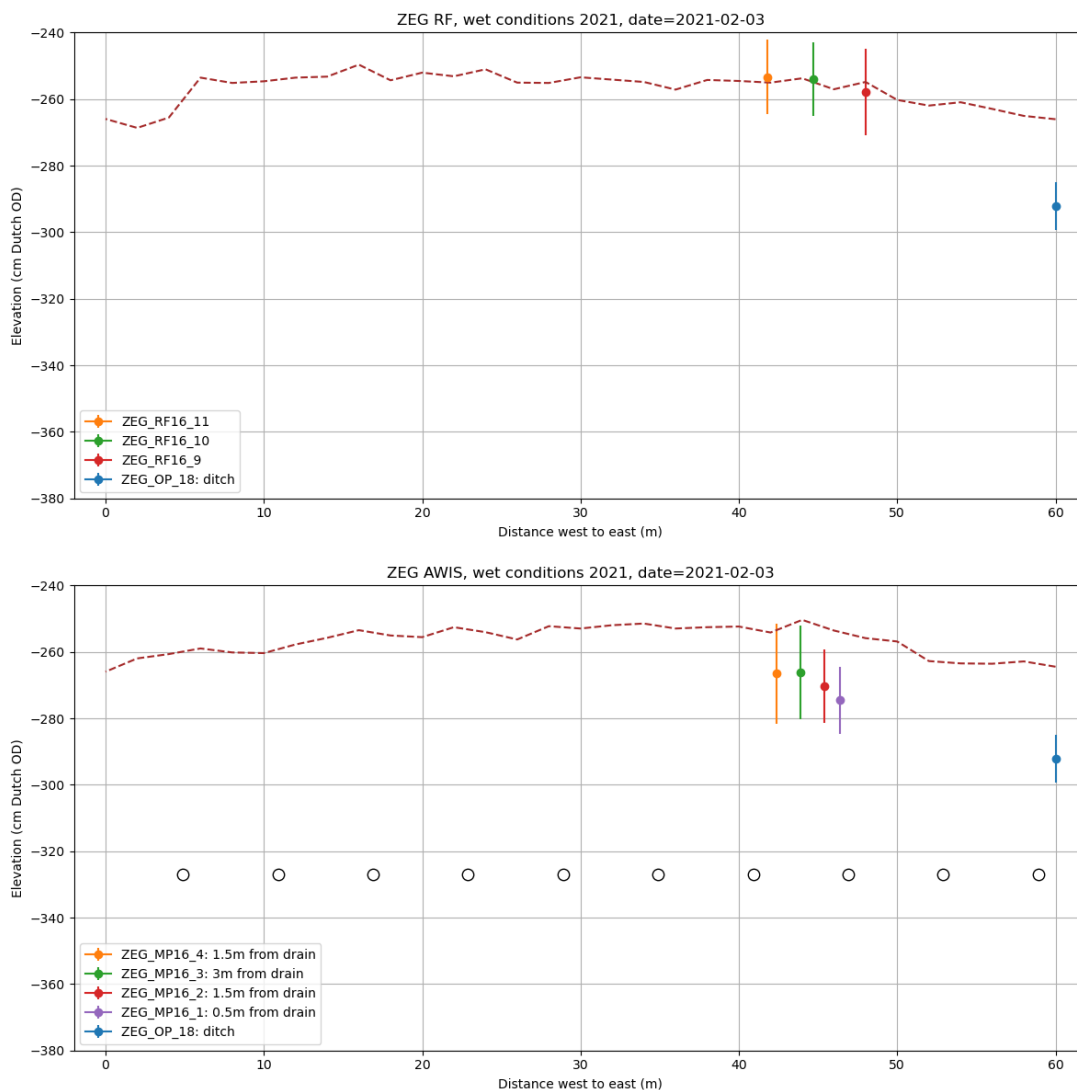


Figure A-7. Cross sections of surface level and ditch and phreatic groundwater levels in the reference and WIS parcel (various distances from the drain) in Zegveld in wet (winter 2021) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated with circles.

A.5 Vlist

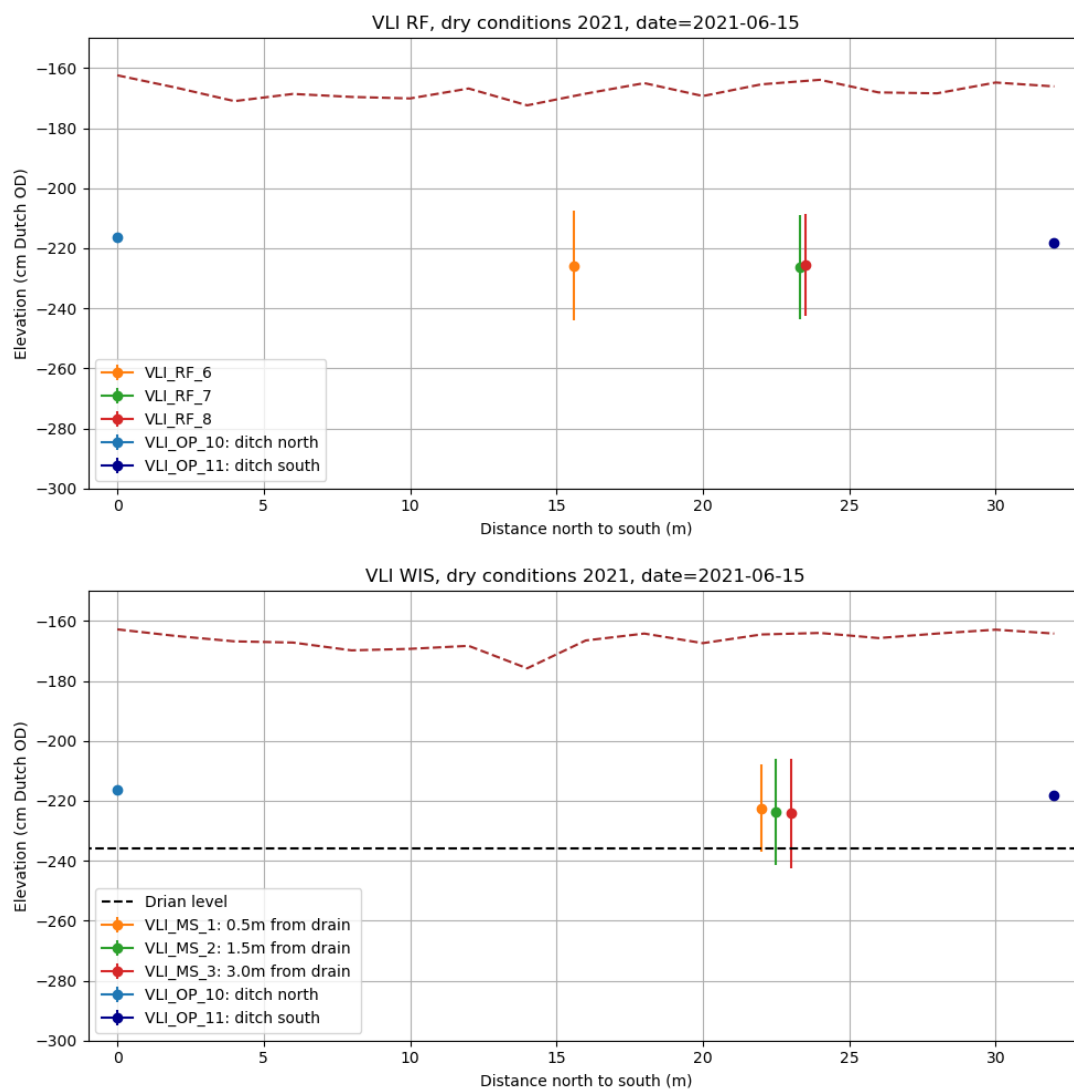


Figure A-8. Cross sections of surface level and ditch and phreatic groundwater levels in the reference and WIS parcel (various distances from the drain) in Vlist in dry (summer 2021) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated by the dotted horizontal black line.

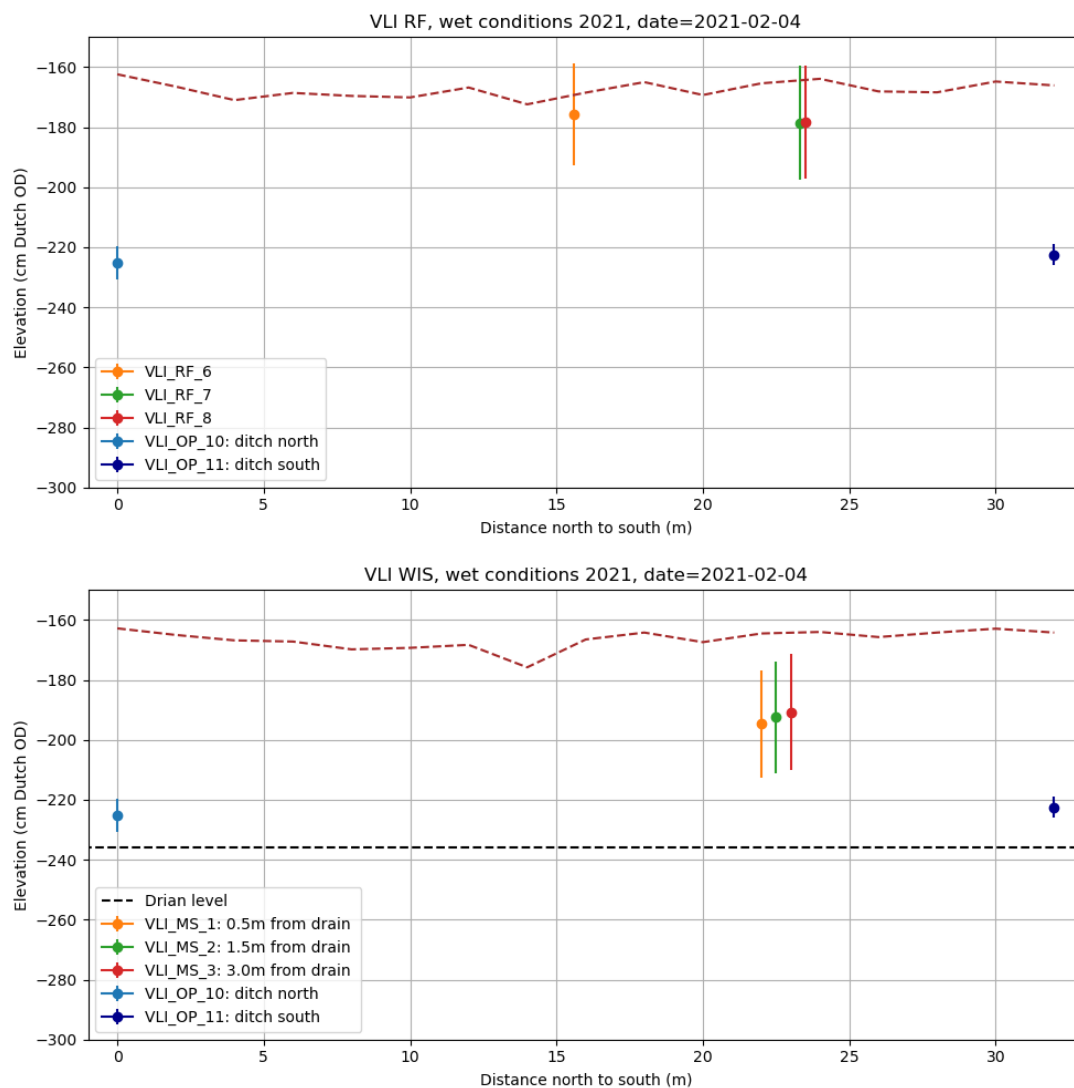


Figure A-9. Cross sections of surface level and ditch and phreatic groundwater levels in the reference and WIS parcel (various distances from the drain) in Vlist in wet (winter 2021) conditions, averaged over four weeks' time (deepest groundwater level +/- 2 weeks). Maximum and minimum groundwater levels in this period are indicated with vertical lines. Approximate positions of drains are indicated by the dotted horizontal black line.

B Precipitation and potential evapotranspiration

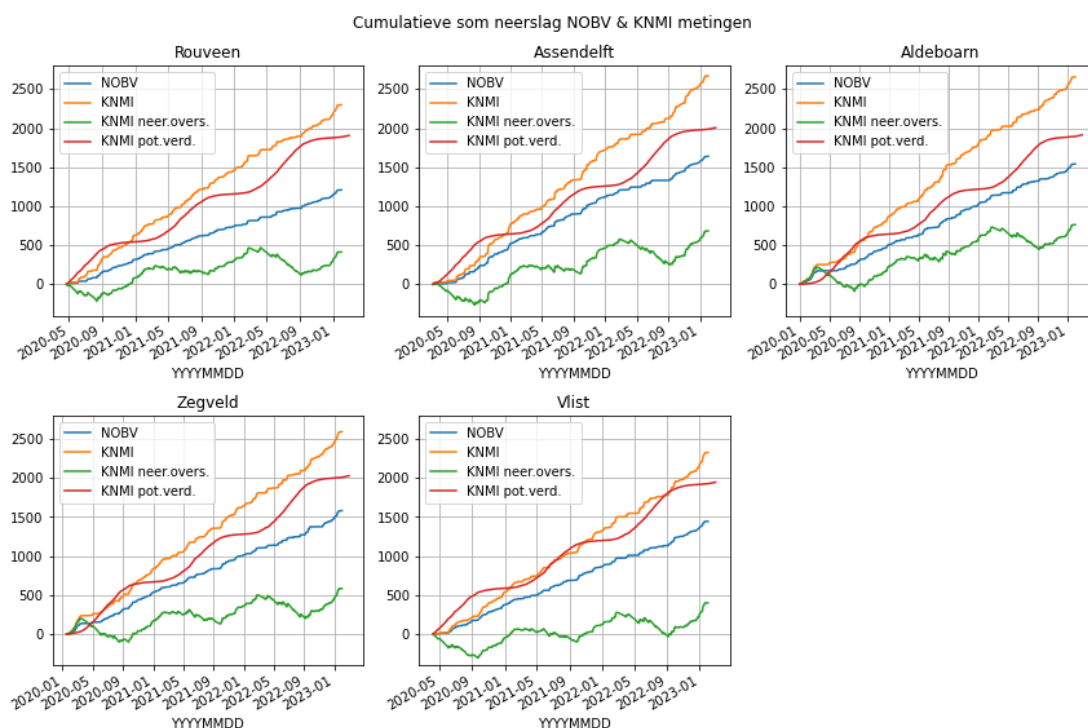


Figure B-1. Cumulative precipitation, potential evapotranspiration, and precipitation surplus/deficit for the five study sites. Source: KNMI.

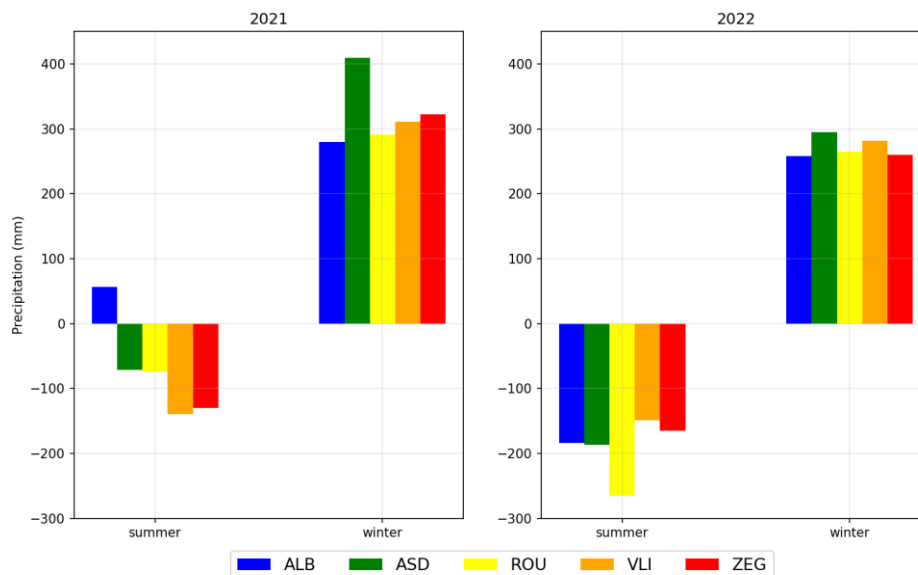


Figure B-2. Precipitation surplus or deficit for the summer (April, May, June, July, August, September) and winter (January, February, March, October, November, December) of the years 2021 and 2022 for the five study locations. Source: KNMI.