Effects of subsurface water infiltration systems on land movement dynamics in Dutch peat meadows

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Abstract. Large-scale drainage and cultivation of peat soils over the last centuries, occurring worldwide, has resulted in
10   substantial CO_2 emission and land subsidence caused by peat decomposition by microbial activity, shrinkage and soil compaction. In addition, seasonal reversible vertical soil movement is caused by shrink and swell in the unsaturated zone and by poroelastic deformation in the saturated zone. To reduce CO_2 emission and land subsidence in drained peat soils, subsurface water infiltration systems (WIS) are expected to be a suitable measure. In this study, effects of WIS on seasonal vertical soil movements are evaluated, based on field measurements from five locations in Dutch peat meadows, for the years 2021 to
15   2023. First estimates of long-term land subsidence have also been made. At each study location, vertical soil movement has been measured using spirit levelling and extensometers, both in a parcel with a WIS and in a nearby reference parcel without any measure. Phreatic groundwater level fluctuations are found to induce soil volume decreases and increases in both the saturated and the unsaturated zone, which cause vertical land movement dynamics of up to 10 cm in the dry summer of 2022 at a location with a relatively thick (6 m) peat layer. Poroelastic deformation processes in the deeper saturated soil contribute
20   substantially to surface level movement, and are largely reversible for the relatively short time period considered in this study. In peat meadows, subsurface water infiltration systems, if correctly applied, reduce seasonal vertical soil movements while (potentially) reducing soils' resilience to drought-induced volume losses. Seasonal vertical soil surface dynamics are about an order of magnitude higher than longer term (years to decades) land subsidence rates, which are commonly in the order of mm yr^{-1} in the Dutch drained peat areas as is supported by estimates of land subsidence from this study. Therefore, multi-year data
25   series are needed to filter out variations in seasonal dynamics, which are mainly introduced by annual variations in weather conditions, and more accurately estimate long-term land subsidence.

1 Introduction

Many coastal plains worldwide contain abundant peat in the subsurface that has formed over millennia under conditions of decelerating Holocene sea-level rise (e.g., Stanley and Warne, 1994; Törnqvist et al., 2008; Drexler et al., 2009; Van Asselen,

30   2011). At present, many coastal areas are densely populated (e.g., Neumann et al., 2015). Human activities, in particular drainage for land reclamation, have resulted in large-scale ending of peat formation in peat-rich coastal plains worldwide.

In the Dutch coastal peatlands, for example, drainage using ditches and artificial lowering of the phreatic groundwater table in peat soils already started about 1000 years ago, to make the land suitable for agriculture. This resulted in increased peat decomposition by biogeochemical (oxidation) processes, resulting in CO_2 emission and land subsidence due to loss of soil

35   volume (Erkens et al., 2016) and an increase of bulk density due to loss of the fibric structure by humification. Lowered phreatic groundwater levels may also lead to land subsidence by irreversible soil shrinkage above, and soil compaction below the phreatic groundwater level. Shrinkage is caused by suction forces that develop when the soil dries due to drainage and evapotranspiration and water extraction by roots. Soil compaction is induced by loading and/or structurally lowered pore water pressure following drainage, which increases the effective stress (Terzaghi, 1943; Van Asselen et al., 2009 and references

40   therein). In response to land subsidence following drainage, ditchwater levels and therewith phreatic groundwater levels were lowered repeatedly in historical times, to prevent the soil from becoming too wet for agricultural activities. This caused additional and (still) ongoing land subsidence. Despite drainage, most reclaimed peatlands have become too wet for crop growth and are therefore at present used as pastures for dairy farming.

45   Land subsidence due to peat compaction and decomposition is a slow and complex process taking place over long periods (many years, e.g., Van Asselen et al., 2009). On shorter (days to months) timescales, reversible soil vertical movements commonly take place. In the unsaturated soil zone, these movements are especially caused by shrinkage and swelling of the soil as a result of periodic changes in soil suction forces driven by annual variations in evapotranspiration and precipitation causing soil moisture changes. In the saturated soil, periodic variations in pore water pressures may cause seasonal poroelastic

50   deformation causing vertical soil movements. At one of the study sites of this research, preliminary results indicated short-term vertical surface level movements of up to ~4 cm (Van Asselen et al., 2020). Irreversible land subsidence may also be affected by changes in rainfall patterns, which can significantly impact the water table levels and soil moisture profiles within peatlands. Changes in temperature may affect the rate of peat decomposition. Warmer temperatures accelerate the decomposition process, leading to a loss of peat's ability to support itself and contribute to subsidence. Conversely, cooler

55   temperatures will slow down decomposition, potentially stabilizing the peatland temporarily. Climate change also influences vegetation cover, which impacts through plant evapotranspiration moisture levels of the soil.

Land subsidence in low-lying coastal areas may significantly contribute to relative sea level rise and increase the risk and impact of flooding (e.g., Ericson et al., 2006; Syvitski, 2008; Nicholls et al., 2021). Land subsidence also leads to (high costs related to) damage to buildings and infrastructure and may cause salinization (e.g., Van de Born et al., 2016). Also short-term

60   (seasonal) vertical movements may lead to damage and increased flood/inundation risks. In addition, land subsidence due to peat decomposition is linked to CO_2 emissions. Over the last years, measures have been implemented that aim at reducing CO_2 emissions from peatlands. It is not widely studied how these measures change land subsidence processes. It is needed to

quantify seasonal vertical movements and land subsidence in different environmental settings, determine the relative
contribution of different processes to total deformations and assess the proportions of vertical movements that are reversible
and irreversible. This will lead to increased understanding of soil deformation processes and their main drivers, which is needed
to be able to take effective measures to reduce land subsidence and CO_2 emission in drains peat meadows.

Peat decomposition and compaction may be reduced by rewetting peat soils; increased anaerobic conditions reduce
microbiological activity, while higher pore water pressures in more saturated soils reduce the effective stress thereby reducing
or halting compaction processes. Cultivated peat soils could be completely rewetted and transformed into natural peatland,
thereby losing their agricultural function. To maintain the agricultural land use function, which is often desirable for economic
and cultural reasons, excessive lowering of the phreatic groundwater level in summer may be limited by installing subsurface
water infiltration systems (WIS; Van den Akker et al., 2010; Querner et al., 2012). Drainpipes are brought into the soil, at a
depth of about 20 cm below ditch water level, which stimulates water infiltration from the ditch into the peat soils in dry
periods with high evapotranspiration. To actively maintain and steer the phreatic groundwater level at a desired depth,
independent of the ditch water level, drains may be connected to a reservoir with a pumping system (in this paper referred to
as an active WIS, i.e., AWIS). Systems that are directly connected to a ditch, without a reservoir, are referred to as a passive
WIS (PWIS).

The main aim of this paper is to assess effects of WIS on seasonal vertical soil movement in drained peat soils, based on
analysis of elevation changes obtained by spirit levelling and extensometers, groundwater level measurements, and subsurface
lithological composition. In this study we focus on seasonal vertical soil movements since the time series are relatively short
to make reliable estimates of longer term (multiyear) land subsidence. Still, we include first estimates of long-term subsidence
rates and evaluate effects of WIS on longer term land subsidence. The research is part of the Netherlands Research Programme
on Greenhouse Gas Dynamics in Peatlands and Organic Soils (NOBV). Data was collected in the period mid-2020 to 2023
from five study sites distributed over the Dutch peatland area. For one of these locations data from 2019 was available. Field
measurements are vital to monitor the efficiency and applicability of WIS under different environmental circumstances, and
possibly optimize these systems in order to stop or reduce land subsidence and CO_2 emission from drained peat soils (Aben et
al., 2024).

2 Methods and study sites description

The five study sites are presented in Fig. 1. At these locations, one field plot is situated in a WIS parcel and another field plot
is situated in a nearby reference parcel without such a system, but with similar environmental conditions.

Figure 1. Map of organic soils in the Netherlands and locations of paired field plots, each consisting of a WIS parcel and a nearby reference parcel. Source topographical map: TNO (2019). Peat and peaty soil map is derived from Brouwer et al. (2021).

At each study location, elevation changes have been monitored in both the WIS and reference parcel using two methods: spirit levelling and extensometry (see sections 2.1 and 2.2 respectively). In addition, groundwater and ditch water levels are monitored at each location (Van Asselen et al., 2023). Also, the subsurface has been investigated by hand corings using Edelman and gouge augers, and, at all locations except for Rouveen, also by a Cone Penetration Test (CPT; Erkens et al., 2019). In general, the subsurface at all study sites consists of Holocene peat and clay layers, overlying Pleistocene sandy deposits. Details of the groundwater system and subsurface composition at each study location are described in section 2.3. In this study, estimates of the organic matter content mentioned in the results sections are derived from field observations from experienced geologists and soil scientists and from Loss On Ignition laboratory tests (LOI = ((dry weight − ashed weight) / dry weight) ∗ 100%); cf. Heiri et al., 2001).

2.1 Spirit levelling

Spirit levelling is performed four times a year along fixed transects perpendicular to and in the longitudinal direction of a parcel, relative to a local benchmark (a steel tube) that has been founded in firm Pleistocene sand underlying the soft Holocene peat and clay sequence. The elevation of this benchmark, relative to the Dutch Ordnance Datum (NAP), has been measured by spirit levelling to a nearby official NAP benchmark, which are regularly checked for stability. At each location, three to five transects of several tens of meters in length are measured per parcel, commonly using a measuring interval of 2 meters. Measurements in ditches and on ditch banks are excluded from analyses in this study. The locations (XY coordinates) of the begin and endpoints of the transects are determined each field campaign using an RTK-GNSS device to ensure levelling measurements are performed at the same locations. In Aldeboarn, the distance between two measurement points ranges from 2 to 7.5 m and measuring points were marked belowground to allow for replication in time. The configuration of transects at the five study areas is presented in section 2.3. Surface elevation is measured in winter (January), spring (April), summer (July) and autumn (October). This technique measures surface elevation with mm-scale accuracy. It should be taken into account that levelling results presented in this study are averages of ~100 surface level measurements on a parcel. Moreover, the surface level of a peat meadow is irregular due to e.g. vegetation growth and trampling by cattle, and vertical soil movement may be spatially variable due to e.g. variations in subsurface composition and local hydrology. Consequently, the standard deviation of calculated average elevation changes (relative to the first measurement; see section 2.4) is commonly in the order of a 10 to 20 millimetres.

2.2 Extensometry

The extensometers used in this study are specifically designed for high-resolution measurement of vertical movement of multiple subsurface levels in soft peat and clay soils at mm accuracy. At each of the five study sites, an extensometer has been installed in both the WIS and the reference parcel. Each extensometer measures the vertical displacement at five anchor levels, relative to a reference (massive cone) anchor fixed in a firm and stable sandy layer below the soft soil sequence (Fig. 2). The reference anchor is assumed to be stable. The depth of the firm sand has at most locations been determined based on the results of the CPT, which shows at what depth the resistance and friction of the soil significantly increases, indicating the occurrence of firm sand. By calculating the deformation of the soil layer between two anchors, based on their vertical displacements, the contribution of different soil layers to total surface deformation in time may be determined (Fig. 2).
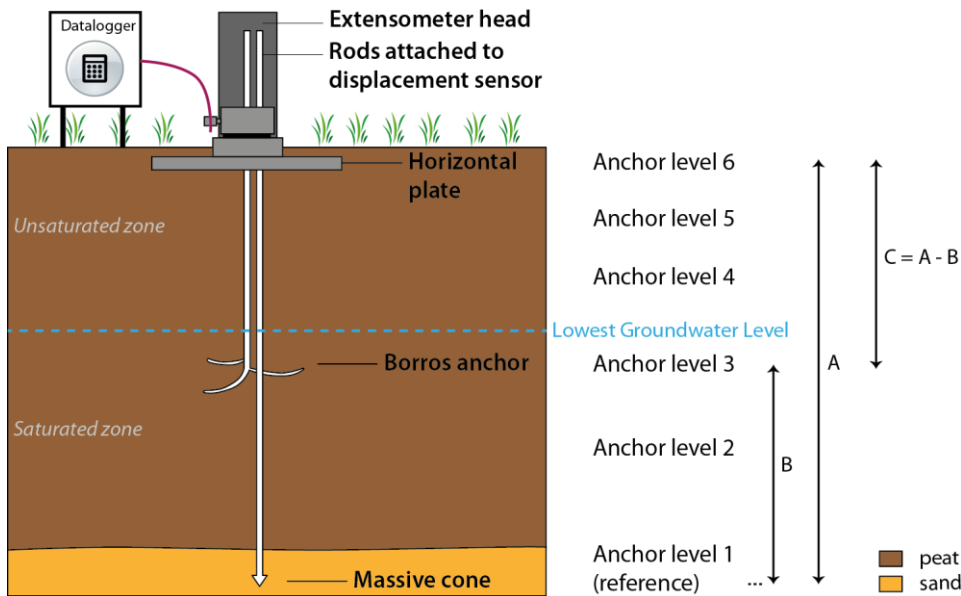
Figure 2. Schematic representation of an extensometer set-up. Deformation of soil layers may be calculated based on elevation changes of individual anchor levels, e.g., in the example above, the deformation of layer C = elevation change of anchor level 6 (=A; relative to the reference anchor 1) – elevation change of anchor level 3 (=B; relative to the reference anchor 1).

Different types of anchors are used (Fig. 2):

- Anchor level 1 is a massive cone, this is the reference level. The anchor is installed using a cone penetration test vehicle. The bottom of the borehole that was made to install this anchor has been filled with a grout. This was done to prevent a connection is created between the groundwater in the Holocene and the Pleistocene sequences, which may have different hydraulic heads. In Rouveen, the reference anchor has been installed by driving the (massive cone) anchor into the soil using a manual pile driver.

- Anchor levels 2 to 4 are Borros type anchors, consisting of 3 prongs that are firmly embedded in the soft soil. First, a small borehole is drilled using a gouge auger. Next, the Borros anchor is brought to the desired depth, after which the prongs are extended using hydraulic pressure. Fully extended, the prongs extend circa 150 mm into the soil.

- Anchor level 5 is installed at a depth of circa 40 cm below surface, which is too shallow for a Borros anchor. Instead, a horizontal steel strip is used as anchor, which is brought into the undisturbed ground via a small trench.

- Anchor level 6 is a square perforated stainless-steel plate (0.5 x 0.5 m, 8 mm perforation, about 40% open area) that is dug into the soil at a depth of circa 5 cm, thereby largely representing surface level vertical dynamics. The top cm soil are removed before installation and put back on top of the plate after installation. The plate is installed at ca 5 cm depth to prevent measuring vertical movement caused by especially vegetation growth, and to ensure that the vertical movement measured can be attributed to soil deformation.

All anchors are connected to the extensometer head, which is fixed to the perforated stainless-steel plate (anchor level 6), with screwed stainless-steel rods (Fig. 3). The rods are protected by a ribbed tube, limiting friction of the (deforming) soil on the rods. In the extensometer head each rod is connected to the displacement sensor, which are either vibrating wire displacement transducers or linear potentiometers. Because of limited available space in the extensometer head, this setup has a maximum of five anchor levels. The displacement sensors are connected to a datalogger next to the extensometer (Fig. 3). In this study, measurements are recorded hourly. In the WIS parcel, the extensometer is installed halfway between two drains, in the reference parcel the extensometer is installed at about one third of the parcel width.

Figure 3. Left: extensometer head and stainless-steel plate a few centimetres below surface level. Right: extensometer protected by a PVC cover and connected to the datalogger with solar panels.

2.3 Study sites

2.3.1 Aldeboarn

In Aldeboarn, a PWIS has been installed in 2016. In the summer following the installation of PWIS, ditch water levels were raised from 80 cm to about 40 cm below surface level of the field site (Weideveld et al. 2021; Fritz et al. 2021). Vertical elevation (changes) has been measured using levelling and extensometry since mid-2020 (Figure 4). Drains are installed between 70 to 80 cm depth, in the longitudinal direction of the parcel. The distance between drains is ~6 m. In Aldeboarn, a HAKLAM (in Dutch: '*Hoog Als het Kan, Laag Als het Moet*', translating into 'high if possible, low if necessary') water level management has been applied. This means that the polder water level (and therefore the ditch water level of the reference plot) is set high (~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 require sufficient load-bearing capacity of the peat soil. The ditch water level in the reference parcel has fluctuated between ~45 cm below surface level in the summer of 2020 and ~90 cm below surface level in the first months of 2022 (Van Asselen et al., 2023). In the PWIS parcel, the ditch water level is fixed at ~45 cm below surface level since the growing season of 2022. Before that time, the ditch water level fluctuated between ~40 cm and ~80 cm below surface level (Van Asselen et al., 2023). Unfortunately, a reliable measurement of the hydraulic head in the sand layer below the peat layer is lacking at Aldeboarn, but the hydrological model LHM4.1 (LHM, 2023) indicates that on average this site is neutral (no significant seepage or infiltration). Further information about the

groundwater measurements and the PWIS system, and how it is connected to the ditches, is provided by Van Asselen et al. (2023).

The subsurface in Aldeboarn is generally characterized by clay on peat on detritus on sand (see also soil profiles at extensometer locations in Table 1 and Erkens et al., 2019). The top clay layer is 0.25 to 0.65 m thick, deposited in a marine environment. The marine clay is often stiff and has an organic matter content (i.e., LOI) of about 15%. Peat fragments may occur in the clay layer due to ploughing (Fritz et al., 2021). Below the clay layer, to a maximum depth of 2.1 m below surface, the subsurface consists of oligotrophic peat, containing remains of *Sphagnum* mosses, *Eriophorum* and heather. The drained peat is strongly decomposed and amorphous, usually down to 65 cm depth, and up to a depth of at maximum 0.95 m. At the transition to underlying Pleistocene sand, an amorphous sandy detritus layer of 0.05 to 0.20 m thick is present. The top few meters of the Pleistocene deposits consist of an alternation of sandy and clayey layers. Firm sand, in which the reference anchor of the extensometer is installed, is encountered at a depth of about 7 to 8 m below surface.
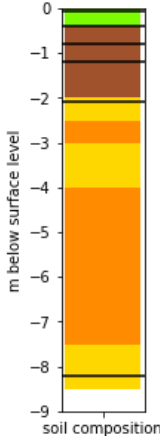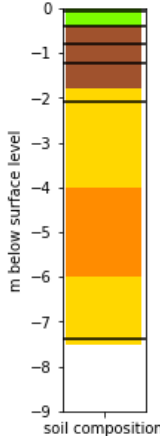
Figure 4. Position of field plots, spirit levelling transects and extensometers in the reference and PWIS parcel at Aldeboarn.

X, Y and Z coordinates and anchor depths of the extensometers in Aldeboarn are given in Table 1.

Table 1. Positions and anchor depths of the extensometers in Aldeboarn. X and Y coordinates are given in the Dutch National Grid (Rijksdriehoekstelsel). Z (surface elevation) relative to Dutch Ordnance Datum (NAP). The anchor level positions are also indicated in the soil profile (black horizontal lines; green=clay, brown=peat, yellow=sand, orange=sand and/or loam).

Description	PWIS parcel		Reference parcel	
X-coordinate [m]	189537		189689	
Y-coordinate [m]	563080		563061	
Surface elevation [m NAP]	-1.02		-1.02	
Thickness top clay layer (m)	0.4		0.4	
Thickness peat layers (m)	1.6		1.4	
Anchor depth [m below surface level]:				
Anchor 1	-8.20		-7.40	
Anchor 2	-2.10		-2.10	
Anchor 3	-1.20		-1.21	
Anchor 4	-0.81		-0.80	
Anchor 5	-0.40		-0.40	
Anchor 6	-0.06		-0.06	

2.3.2 Rouveen

In Rouveen, drains are installed at circa 65 to 70 cm depth, in the longitudinal direction of the parcel. The drain spacing is ~8 m. The drains are connected to a submerged collector drain, which is directly connected to the ditch, making this a PWIS. Vertical soil movement has been measured by spirit levelling and extensometry since end 2018 (Figure 5). During the measuring period, ditch water levels for both the reference and PWIS parcel have fluctuated roughly between 40 to 50 cm below surface level in summer and 50 to 60 cm below surface in winter (Van Asselen et al., 2023). Rouveen is an upward seepage location (see Van Asselen et al., 2023), output of the hydrological model LHM4.1 indicates average upward seepage for the period 2011-2018 of about 0.4 mm day^{-1} at this location; LHM, 2023).
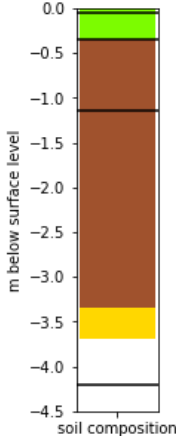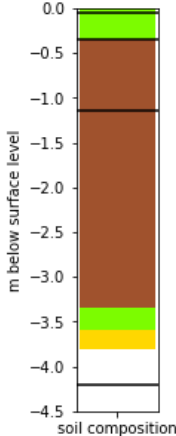
Figure 5. Position of field plots, spirit levelling transects and extensometers in the reference and PWIS parcel at Rouveen.

The subsurface in Rouveen is characterized by clay on peat on sand (see also soil profile figures at extensometer locations in Table 2 and Erkens et al., 2019). The top 0.05 to 0.10 m is composed of clayey peat with an organic matter content of ~30 %,

215 below this layer a generally stiff marine clay is found until ~0.30 to ~0.40 m depth with an organic matter content of ~10 %. Below this clay layer peat occurs until a depth of 3.25 to 3.60 m below surface, the depth at which sandy Pleistocene deposits occur. The top of the peat layer is strongly amorphous. Within 0.80 m below surface a moss peat layer occurs of up to 0.20 m thick, containing sedge and wood remains. Below this layer a eutrophic sedge peat layer is found, that may contain reed and wood remains. At some locations within the parcels, the peat is a bit clayey at a depth of 2.20 to 2.45 m below surface.

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Table 2. Positions and anchor depths of the extensometers in Rouveen. X and Y coordinates are given in the Dutch National Grid (Rijksdriehoekstelsel). Z (surface elevation) relative to Dutch Ordnance Datum (NAP). The anchor level positions are also indicated in the soil profile (black horizontal lines; green=clay, brown=peat, yellow=sand, orange=sand and/or loam).

Description	PWIS parcel		Reference parcel	
X-coordinate [m]	202476		202537	
Y-coordinate [m]	516419		516574	
Surface elevation [m NAP]	-0.56		-0.60	
Thickness top clay layer (m)	0.35		0.35	
Thickness peat layer (m)	3.0		3.0	
Anchor depth [m below surface level]:				
Anchor 1	-4.2		-4.2	
Anchor 2	-1.15		-1.15	
Anchor 3	-0.35		-0.35	
Anchor 4	-0.05		-0.05	

2.3.3 Assendelft

In Assendelft an active WIS has been installed in 2017, aiming to keep the groundwater level at about 35 cm below surface level. Drains are installed at circa 50 to 60 cm depth, in the longitudinal direction of the parcel. The drain spacing is 4 m. Soil vertical movement has been measured using spirit levelling and extensometry since mid-2020 (Figure 6). Ditch water levels for both the reference and AWIS parcels are mostly 20 to 45 cm below surface level (Van Asselen et al., 2023).

The hydraulic head in Assendelft (water pressure in sandy Pleistocene deposits at 17 m depth) is higher than the phreatic groundwater levels in the reference parcel (Van Asselen et al., 2023). Upward seepage from this depth to the peat layer is however impeded by the thick (~10 m) marine (clay, loam and sand) deposits in between the peat and Pleistocene sand layers. Groundwater level measurements do indicate some upward seepage in dry periods at this location (Van Asselen et al., 2023). Also, the hydrological model LHM4.1 (LHM, 2023) indicates some upward seepage at this location (~0.1 mm day^{-1} on average, for the period 2011-2018).
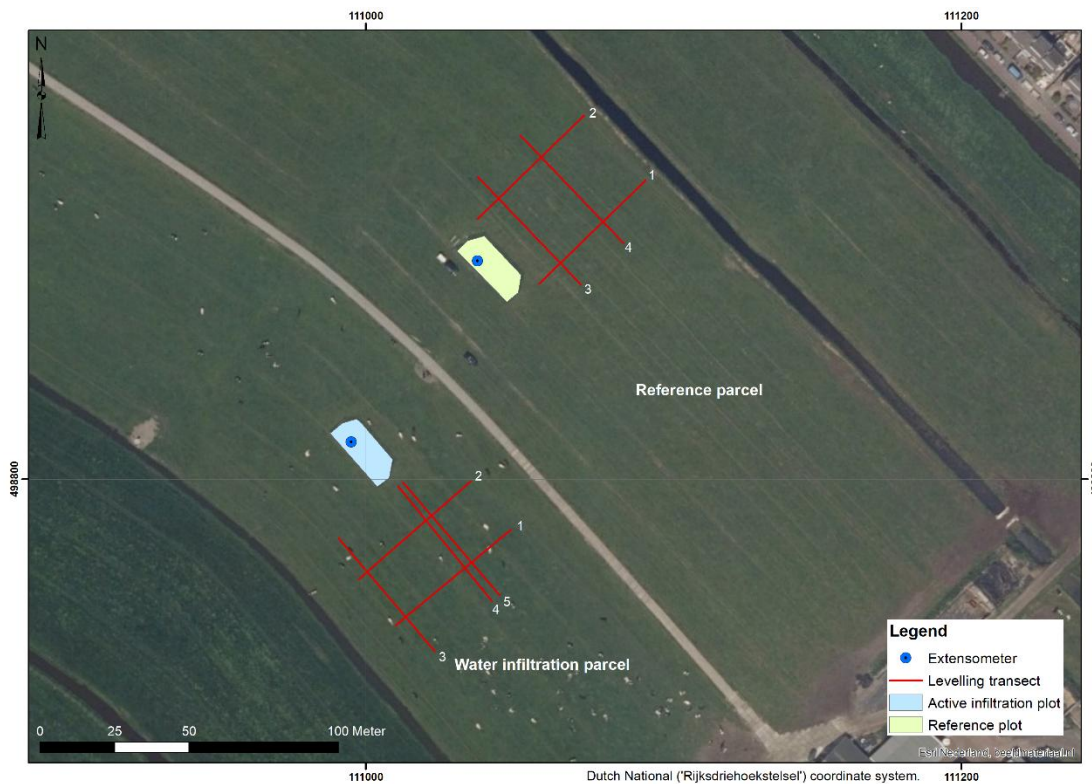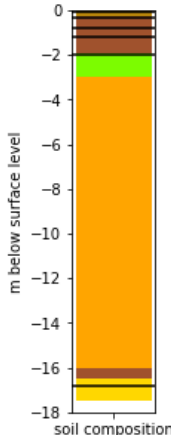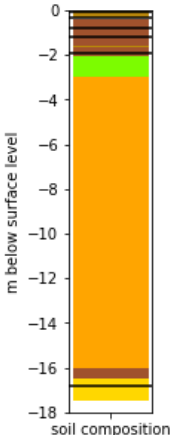
Figure 6. Position of field plots, spirit levelling transects and extensometers in the reference and AWIS parcel at Assendelft.

The Holocene sequence in Assendelft is about 16.5 m thick. In general, about 2 meters eutrophic reed-sedge peat is found on
245 top of about ~14 m marine clayey and sandy deposits on ~0.5 m of basal peat (see also soil profiles at extensometer locations
in Table 3 and Erkens et al., 2019). The organic matter content (LOI) in the top 20 to 30 cm roughly varies between 10 % and
40 %. This layer has consequently been classified as either an organic clay or a clayey peat. Below the basal peat layer,
Pleistocene sandy deposits occur at a depth of 16.5 m below surface.

250 For X, Y and Z coordinates and anchor depths of the extensometers in Assendelft see Table 3.

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Table 3. Positions and anchor depths of the extensometers in Assendelft. X and Y coordinates are in the Dutch National Grid (Rijksdriehoekstelsel). Z (surface elevation) relative to Dutch Ordnance Datum (NAP). The anchor level positions are also indicated in the soil profile (black horizontal lines; green=clay, brown=peat, yellow=sand, orange=sand and loam).

Description	AWIS parcel		Reference parcel	
X [m]	110995		111038	
Y [m]	498812		498873	
Surface elevation [m NAP]	-1.95		-1.88	
Thickness top clayey peat layer (m)	0.25		0.30	
Thickness peat layer (m)	1.75		1.75	
Anchor depth [m below surface level]:				
Anchor 1	-16.80		-16.80	
Anchor 2	-1.99		-1.90	
Anchor 3	-1.22		-1.21	
Anchor 4	-0.81		-0.79	
Anchor 5	-0.34		-0.33	
Anchor 6	-0.06		-0.06	

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2.3.4 Zegveld

In Zegveld multiple measures are investigated: both active and passive water infiltration systems in combination with either relatively high or low ditch water levels (Figure 7). Drains have been installed in 2016 at about 70-75 cm depth in the longitudinal direction of the parcels. The drain spacing is 6 m. At parcel 16, ditch water levels are relatively low; ~55 cm

265 below surface level. The target groundwater level of AWIS 16 is 40 cm below surface level. At parcels 11 and 13 ditch water levels are kept relatively high at ~25 to 30 cm below surface level. The target groundwater level of AWIS 11 is 25 to 30 cm below surface level in summer and 35 to 40 cm below surface level in winter.

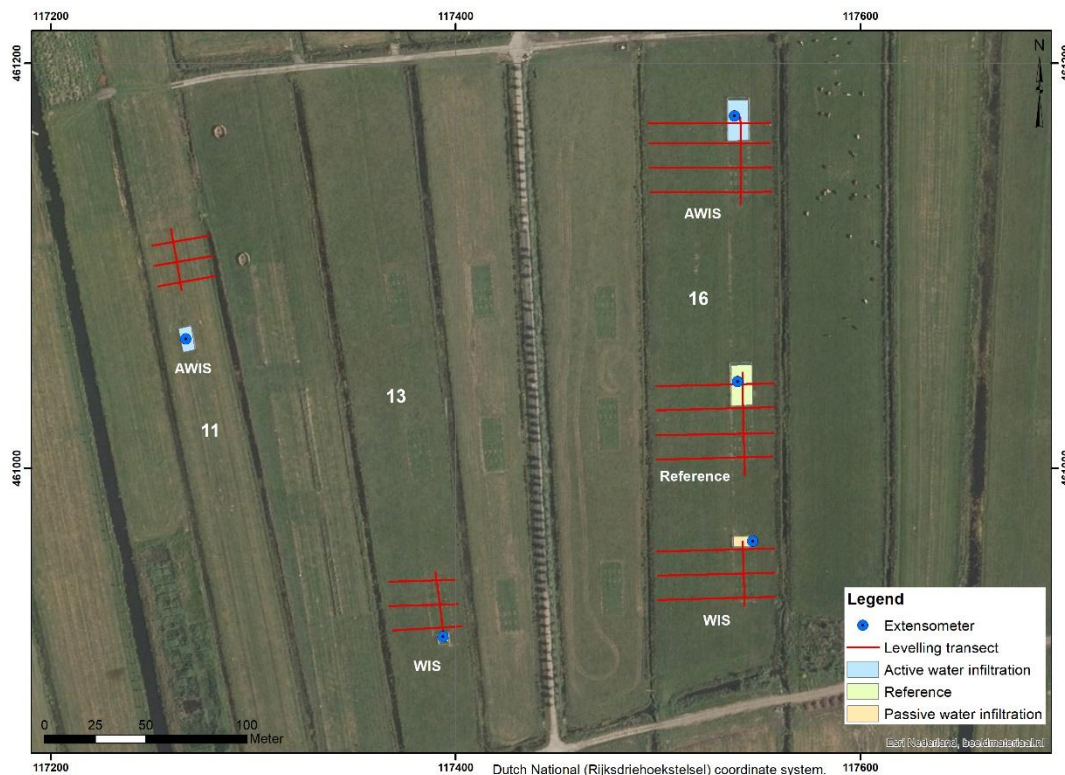
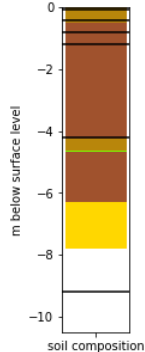
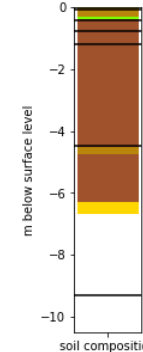
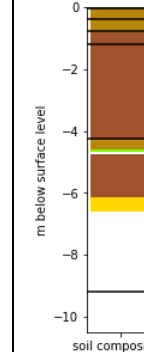
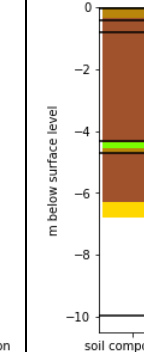
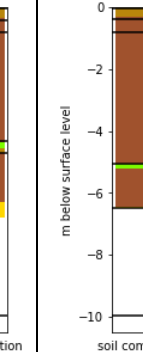



Figure 7. Position of field plots, spirit levelling transects and extensometers in the reference and water infiltration parcels at Zegveld.
270 **In parcel number 16 ditch water levels are relatively low (around 55 cm below surface) and in parcel numbers 11 and 13 ditch water levels are relatively high (around 25 cm below surface).**

In Zegveld, a reliable automatic monitoring well for measuring the hydraulic head in the sandy Pleistocene subsurface was lacking during the monitoring period. The hydrological LHM model indicates a near neutral situation at this location, with on average for the period 2011-2018 minor infiltration of -0,06 mm day^{-1} (LHM, 2023).

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The Holocene soft soil sequence in Zegveld is 6.10 to 6.35 m thick and consists predominantly of peat (see also soil profiles at extensometer location in Table 4 and Erkens et al., 2019). The top of 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 varying roughly between 30 and 40 %, further down gradually increasing to about 80 %. In parcel 16, a 10 to 15 cm thick
280 anthropogenic organic layer may occur at the surface consisting of historically applied cow manure and material dredged from the ditches, with variable sand admixture and/or pottery and brick remains (waste materials). To a depth of about 3 m predominantly wood peat occurs, below, eutrophic reed-sedge peat dominates, locally intercalated by thin reed peat layers. At a depth of 4.30 to 5.10 m below surface a few cm thick clayey interval occurs. Below this layer, 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
285 about 9 m below surface.

X, Y and Z coordinates and anchor depths of the extensometers in Zegveld are given in Table 4.

Table 4. Positions and anchor depths of the extensometers in Zegveld. X and Y coordinates are given in the Dutch National Grid (Rijksdriehoekstelsel). Z (surface elevation) relative to Dutch Ordnance Datum (NAP). The anchor level positions are also indicated in the soil profile (black horizontal lines; green=clay, greenish brown = clayey peat or peaty clay, brown=peat, yellow=sand, orange=sand and/or loam).

Description	AWIS parcel 16	Reference parcel 16	PWIS parcel 16	PWIS parcel 13	AWIS parcel 11
X [m]	117538	117539	117547	117394	117267
Y [m]	461174	461043	460964	460917	461064
Surface elevation [m NAP]	-2.48	-2.51	-2.60	-2.36	-2.33
Thickness top clayey peat layer (m)	0.5	0.4	0.8	0.35	0.30
Thickness peat layer* (m)	5.8	6.0	5.35	5.95	6.15
Anchor depth [m below surface level]:					
Anchor 1	-9.20	-9.30	-9.20	-9.95	-9.98
Anchor 2	-4.21	-4.49	-4.26	-4.72	-6.48
Anchor 3	-1.21	-1.20	-1.18	-4.31	-5.05
Anchor 4	-0.80	-0.79	-0.78	-0.82	-0.82
Anchor 5	-0.42	-0.41	-0.40	-0.41	-0.38
Anchor 6	-0.07	-0.06	-0.04	-0.05	-0.05

*including intercalated thin clayey intervals at about 4.5 m depth.

2.3.5 Vlist

In Vlist drains have been installed in 2011 at circa 70 cm depth, perpendicular to the longitudinal direction of the parcel, connected to one ditch, making this a passive WIS. The drain spacing is 6 m. For this study, elevation (changes) has been

measured by spirit levelling and extensometery since mid-2020 (Figure 8). The ditch water level at both sides of the parcel has fluctuated between ~45 and ~60 cm below surface level (Van Asselen et al., 2023).

300

The relatively short data series of the hydraulic head available for Vlist (measured since October 2022) shows a decreasing trend if the phreatic groundwater level is relatively low and an increasing trend when phreatic groundwater levels are high (Van Asselen et al., 2023). This is an indication of some seasonal seepage/infiltration, although on average it is probably quite neutral, which is also indicated by the hydrological LHM model (~-0.03 mm day^{-1} on average for the period 2011-2018; LHM,

305   2023).

The Holocene soft soil sequence in Vlist is 10 to 11 meters thick and consists of an alternation of (fluvial) clay and peat layers of in general several decimeters thick (see also soil profiles at extensometer locations in Table 5 and Erkens et al., 2019). Some of the clay layers contain sand. The top ~0.40 m consists of humic clay and/or strongly clayey peat, with an organic matter

310   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, a few dm thick clay layer is found, below which eutrophic (sedge, reed and or wood) peat layers alternate with clay layers.
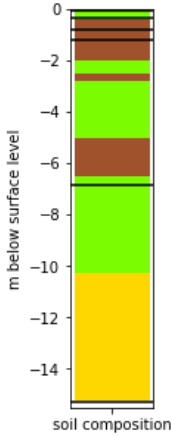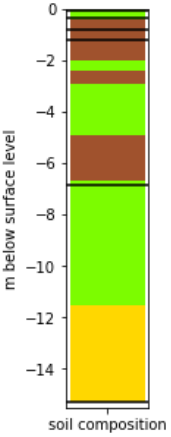
Figure 8. Position of field plots, spirit levelling transects and extensometers in the reference and PWIS parcel at Vlist.

X, Y and Z coordinates and anchor depths of the extensometers in Vlist are given in Table 5.

Table 5. Positions and anchor depths of the extensometers in Vlist. X and Y coordinates are given in the Dutch National Grid (Rijksdriehoekstelsel). Z (surface elevation) relative to Dutch Ordnance Datum (NAP). The anchor level positions are also indicated
320 **in the soil profile (black horizontal lines; green=clay, brown=peat, yellow=sand, orange=sand and/or loam).**

Description	PWIS parcel		Reference parcel	
X [m]	116349		116280	
Y [m]	443911		443891	
Surface elevation [m NAP]	-1.70		-1.69	
Thickness top clay layer (m)	0.4		0.4	
Thickness first peat layer (m)	1.6		1.6	
Anchor depth [m below surface level]:				
Anchor 1	-15.20		-15.30	
Anchor 2	-6.74		-6.85	
Anchor 3	-1.18		-1.20	
Anchor 4	-0.79		-0.78	
Anchor 5	-0.39		-0.37	
Anchor 6	-0.05		-0.05	

2.4 Data analysis

To get insight into seasonal vertical soil movement and long-term land subsidence, changes in elevation are calculated for each study site, for both spirit levelling and extensometer data, relative to the spirit levelling measurement day in January 2021
325 (time 0:00 for the hourly extensometer measurements). This reference was chosen because from this date onward, field measurements are available for all five locations. If available, measurements before this date are included, also relative to the levelling measurement in January 2021.

Spirit levelling data analysis

330 For each spirit levelling field campaign (four times a year), measured surface elevations relative to the Dutch Ordnance Datum ('*Normaal Amsterdams Peil*'; NAP) are averaged for both the WIS and reference parcel. After calculating the elevation changes, the yearly (2021 and 2022) vertical movement dynamics (D) for year X have been derived from the maximum (H_{max}) and minimum (H_{min}) elevation (relative to January 2021) within one year, calculated for the period 1 November year X-1 until 31 October year X using:

335

$$D = H_{max} - H_{min} \tag{1}$$

In this way, the yearly vertical movement dynamics will in most cases represent seasonal subsidence going from the wet period during which the surface elevation is commonly highest (autumn and winter) to the dry period (spring and summer), when the surface elevation is commonly lowest.

Extensometer data analysis

In this study, extensometer anchors at approximately 0.05 and 0.80 m depth are included in the analysis as we focus on effects of water infiltration systems on land movement dynamics and the contribution of the permanently saturated and unsaturated zone, respectively below and above ca 0.80 cm depth. For Rouveen, an anchor at 0.80 m depth was not available, hence, the anchor at 1.15 m depth was used instead. The current paper focuses on effects of water infiltration systems on land movement dynamics, for which it is not necessary to include all anchors. In a separate paper focusing more on different processes contributing to land movement and subsidence and the relation to groundwater level dynamics and lithology, all anchor levels will be included. The (top) 0.05 m depth anchor is included because it best represents surface level, i.e., total deformation of the soft soil sequence, and therefore best compares with spirit levelling measurements of the surface level. The ~0.80 m depth anchor was chosen to gain first insights into the relative contribution of the (predominantly) saturated soil below this level to vertical land surface movement. Elevation changes per anchor (hourly measurements) are calculated relative to the levelling field campaign day in January 2021 (at time 0:00). For each year, the relative contribution of the 0.80 or 1.15 m anchor to the 0.05 m (surface) anchor level was estimated based on the ratio of the dynamics of the 0.80 or 1.15 m anchor to the dynamics of the surface anchor level (*100 %).

In addition, for each levelling field measurement day, the average elevation changes of the 0.05 and 0.80 m depth anchors have been calculated, also relative to the levelling field campaign day in January 2021. These daily extensometer averages are used to compare measurements from both techniques.

The land movement data are plotted together with local high-resolution phreatic groundwater level measurements (for details see Van Asselen et al., 2023). At WIS parcels, vertical land movement is compared with the phreatic groundwater dynamics from a monitoring well halfway between two drains (similar position as the extensometer). For the reference parcel, the phreatic groundwater level monitoring well closest to the extensometer has been used. At all sites, the dich water level management has not changed over the measuring period. The years considered in this study show different precipitation deficits: 70 mm in 2021, 233 in 2022, and 133 mm in 2023 (national averages), so one relatively wet year (2021), one dry year(2022) and one relatively standard year (2023).

To make first assessments of the long-term land subsidence rates, linear trendlines have been fitted on the yearly highest (winter) elevations (measurements in January and February) of the successive years of the extensometer surface anchor (at

about -0.05 m depth) and the anchor at ~80 or 115 cm depth. Note that these are first estimates and longer time series will result in more reliable estimates in the sense of higher R^2. Hence, derived subsidence rates should be regarded with caution. Linear trendlines were used because we intend to estimate average subsidence rates for a specific time period, and moreover, the measurement period is still too short for investigating other types of fits. Also, another subsidence study that did have
375 longer time series (a few decades) for the Zegveld site showed that a linear trend is adequate for assessing an average subsidence rate (Massop et al., 2024).

3 Soil vertical movement measurement results

3.1 Aldeboarn

Both levelling and extensometer measurements demonstrate less vertical dynamics in the PWIS parcel compared to the
380 reference parcel (3 to 20 mm less seasonal subsidence; Table 6; Figure 9). In general, PWIS also resulted in less deep (maximum and average) groundwater levels in summer at this location (Van Asselen et al., 2023; Fig. 9). The summer levelling measurement in 2021 is lacking but the extensometer data series shows relatively low summer subsidence for this period (21 mm; Table 6; Fig. 9), presumably related to the relatively wet summer of 2021 with relatively high phreatic groundwater levels. Results demonstrate a clear relation between vertical soil movement and groundwater dynamics (Fig. 9). For example, in the
385 dry and warm summer of 2022, the phreatic groundwater level lowered substantially, which coincides with a relatively strong seasonal subsidence. The highest yearly vertical soil dynamics has been measured in the reference parcel in 2022 (58 mm). Based on the extensometer data, we see a higher absolute effect on vertical dynamics of the PWIS in a dry year with relatively low groundwater levels (2022) compared to a wetter year with less deep groundwater levels (2021/2023). Furthermore, the extensometer data indicates that the contribution of the -0.80 m anchor to seasonal subsidence of the -0.06 m anchor is higher
390 in the reference parcel than in the PWIS parcel. In general, changes in layer thickness relative to January 2021 have been a bit higher in the unsaturated layer (-0.06 to -0,80 m below surface) compared to the saturated layer (> -0.80 cm below surface), with less soil deformation of both layers in the WIS parcel compared to the reference parcel, and an until now largely reversible movement in the saturated soil layer as can be seen from the fact that change in thickness of the saturated layer returns to approximately 0 each year, while change in thickness of the unsaturated layer does not (Fig. A1). This suggests land subsidence
395 is so far mainly caused by peat decomposition and irreversible shrinkage in the top layer, and not by peat compaction in the saturated layer. Fitted trendlines indicate average long-term land subsidence 6 mm/yr in the reference parcel and 4 mm/yr in the PWIS parcel (0.06 anchor; Fig. 6).
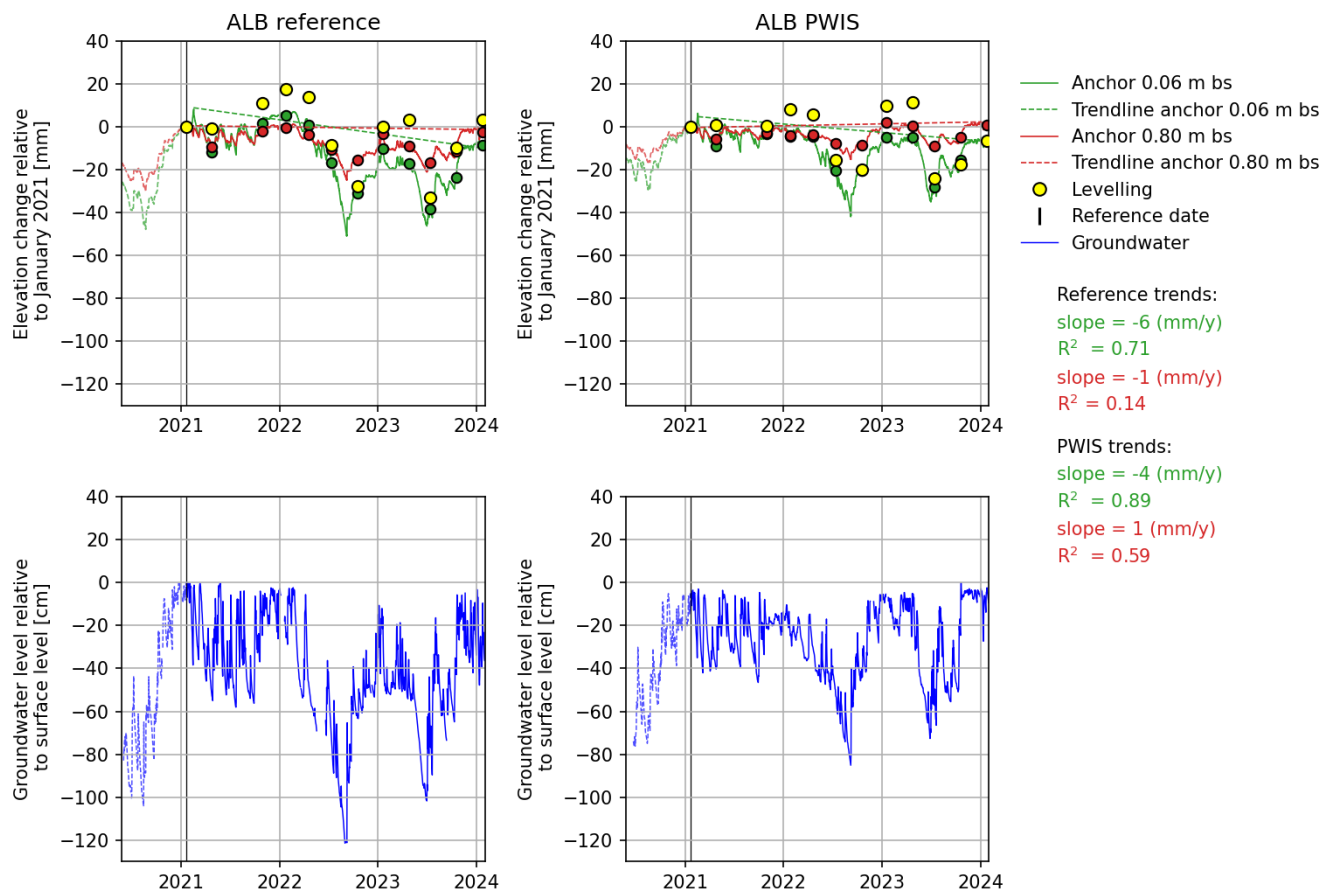
Figure 9. Elevation changes relative to the levelling day in January 2021, indicated with the black vertical line, for the reference (ALB RF; left) and WIS (ALB WIS; right) parcel in Aldeboarn, based on spirit levelling (average of all measurements points per parcel) and extensometer measurements (surface anchor at 0.06 m depth in green and anchor at ~0.80 m depth in red; daily averages for the levelling days are indicated with green and red dots respectively). In blue the phreatic groundwater level is shown. Bs = below surface. Data before the reference date are indicated with dotted lines.

Table 6. Yearly vertical soil dynamics in mm for Aldeboarn, based on levelling and extensometer measurements (anchors at 0.06 and 0.80 m depth). For levelling, the summer measurement is lacking for 2021, therefore the spring measurement (end of April) has been used instead for calculating D. RF=reference parcel, Dif.=difference. Extensometer daily averages have been calculated for the days of the levelling measurements. The contribution of the 0.80 m anchor to the surface anchor (0.06 m depth) is given in the last column.

Yearly vertical soil dynamics (mm):		Levelling	Extensometer; Anchor depth 0.06 m		Extensometer; Anchor depth 0.80 m		Contribution -0.80 anchor to -0.06 anchor
			Average on levelling day	*Full data series*	*Average on levelling day*	*Full data series*	
2021	RF	5	14	21	9	10	48%
	WIS	1	9	18	6	7	36%
	Dif. to RF	*-4 (=- 83%)*	*-5 (=- 34%)*	*-3 (=- 15%)*	*-4 (=- 39%)*	*-4 (=-36 %)*	
2022	RF	46	36	58	15	26	45%
	WIS	28	16	42	5	15	36%
	Dif. to RF	*-18 (=- 38%)*	*-20 (=-55 %)*	*-16 (=-28 %)*	*-10 (=-67 %)*	*-11 (=-42 %)*	
2023	RF	41	*28*	*36*	*13*	*18*	50%
	WIS	36	*23*	*31*	*11*	*13*	42%
	Dif. to RF	*-5 (=-12%)*	*-5 (=-14%)*	*-5 (-28%)*	*-2 (=-15%)*	*-5 (=-18%)*	

3.2 Rouveen

In general, the PWIS in Rouveen has resulted in lower phreatic groundwater levels compared to the reference parcel (Van Asselen et al., 2023; Figure 10). This undesired effect of the PWIS was attributed to substantial upward seepage in this area. Upward seepage causes relatively high phreatic groundwater levels, also in the summer season. The drains, that were installed at a depth close to the deepest annual phreatic groundwater level, have predominantly drained groundwater. Their role as infiltration drains has been minimal at this location. Field measurements do not show a clear effect of the PWIS on soil movement dynamics; in general, differences in dynamics between the reference and PWIS are relatively small and on several occasions in opposite direction of what was expected (Table 7). The highest amount of vertical dynamics recorded at this location is 53 mm, measured by spirit levelling in the WIS parcel in 2021.

The linear trendlines indicate average land subsidence of 3 mm yr^{-1} (R^2=0.73) for the reference parcel and 11 mm/yr (R^2=0.94) for the PWIS parcel (Figure 10). The linear trendline fitted on the 1.15 m anchor data indicates stable conditions (rising trend of 1 mm/yr with low R^2 of 0.37) in the reference parcel and 4 mm yr^{-1} (R^2=0.78) subsidence in the PWIS parcel. Hence, so far, the data suggest more subsidence in the PWIS parcel as compared to the reference parcel, which could be explained by the lower phreatic groundwater levels measured in this parcel, causing increased peat decomposition and shrinkage in the unsaturated layer and peat compaction in the saturated layer (Fig. A2). In the reference parcel, land subsidence is predominantly caused by processes acting in the unsaturated soil layer above 1.15 m depth (Fig. A2).
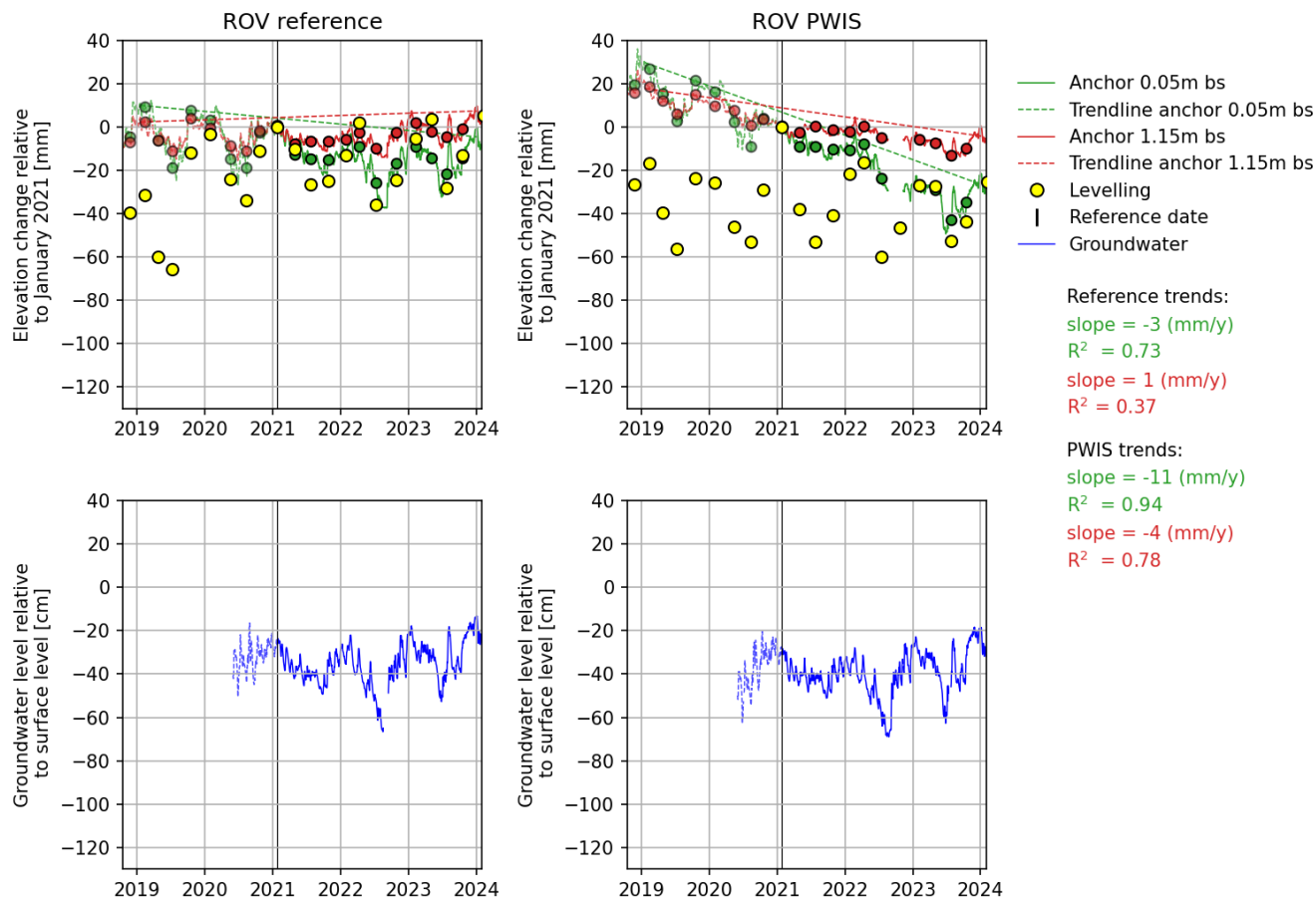
Figure 10. Elevation changes relative to the levelling day in January 2021, indicated with the black vertical line, for the reference (ROV RF; left) and WIS (ROV WIS; right) parcels in Rouveen, based on spirit levelling and extensometer measurements (surface anchor at 0.05 m depth in green and anchor at 1.15 m depth in red; daily averages for the levelling days are indicated with green and red dots respectively). In blue the phreatic groundwater level is shown. Data before the reference date are indicated with dotted lines or lighter colors.

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445

450 **Table 7. Yearly vertical dynamics in mm for Rouveen, based on levelling and extensometer measurements. RF=reference parcel, Dif.=difference. Extensometer daily average has been calculated for the day of the levelling measurement. The contribution of the 1.15 m anchor to the surface anchor (0.05 m depth) is given in the last column.**

Vertical soil dynamics (mm):		Levelling	Extensometer; Anchor depth 0.05 m		Extensometer; Anchor depth 1.15 m		Contribution of -1.15 anchor to -0.05 anchor
			Average on levelling day	*Full data series*	*Average on levelling day*	*Full data series*	
2019	RF	34	28	37	15	20	53%
	WIS	40	24	35	12	23	65%
	Dif. to RF	*+5 (+16 %)*	*-4 (-16 %)*	*-2 (-5 %)*	*-3 (-19 %)*	*+3 (+15 %)*	
2020	RF	31	23	37	11	20	54%
	WIS	27	25	32	9	15	45%
	Dif. to RF	*-3 (-11 %)*	*+3 (+12 %)*	*-5 (-13 %)*	*-2 (-15 %)*	*-6 (-28 %)*	
2021	RF	26	15	26	8	15	57%
	WIS	53	10	20	3	9	45%
	Dif. to RF	*+27 (+101 %)*	*-5 (-32 %)*	*-6 (-23 %)*	*-5 (-68 %)*	*-6 (-39 %)*	
2022	RF	38	17	34	7	17	48%
	WIS	44	16	27	5	11	40%
	Dif. to RF	*+6 (+15 %)*	*-1 (-4 %)*	*-7 (-21 %)*	*-2 (-26 %)*	*-6 (-35 %)*	
2023	RF	32	13	29	7	17	49%
	WIS	26	16	27	7	11	42%
	Dif. to RF	*-6 (=-20%)*	*+3 (=+26%)*	*-3 (=-9%)*	*+1 (=+7%)*	*-6 (-35 %)*	

3.3 Assendelft

The AWIS in Assendelft has resulted in higher summer phreatic groundwater levels (Figure 11; see also Van Asselen et al.,
455 2023) and lower vertical soil dynamics in the AWIS parcel compared to the reference parcel. In general, periods with dropping groundwater levels coincide with soil subsidence, while periods with rising groundwater levels coincide with soil uplift. The effect of AWIS on both groundwater level and vertical soil dynamics (i.e., seasonal subsidence) is especially notable in the summers of 2022 and 2023 (Figure 11; Table 8). The highest vertical dynamics recorded is 79 mm, based on the extensometer data series (-0.06 m anchor in 2022) in the reference parcel. The contribution of the -0.80 m anchor is relatively high (>50 %),
460 especially in the wet year of 2021. In the reference parcel, soil deformation of the saturated soil layer below -0.80 m depth is higher than the unsaturated top soil (Fig. A3). In the AWIS parcel, soil deformation is similar in both layers and is less than in the reference parcel. Soil deformation in the saturated layer is reversible so far, indicating that land subsidence (only in the reference parcel) is mainly caused by peat decomposition and shrinkage of the top soil. Fitted trendlines indicate average long-term land subsidence 7 mm/yr in the reference parcel and 1 mm/yr in the AWIS parcel (0.06 m anchor; Fig. 11).

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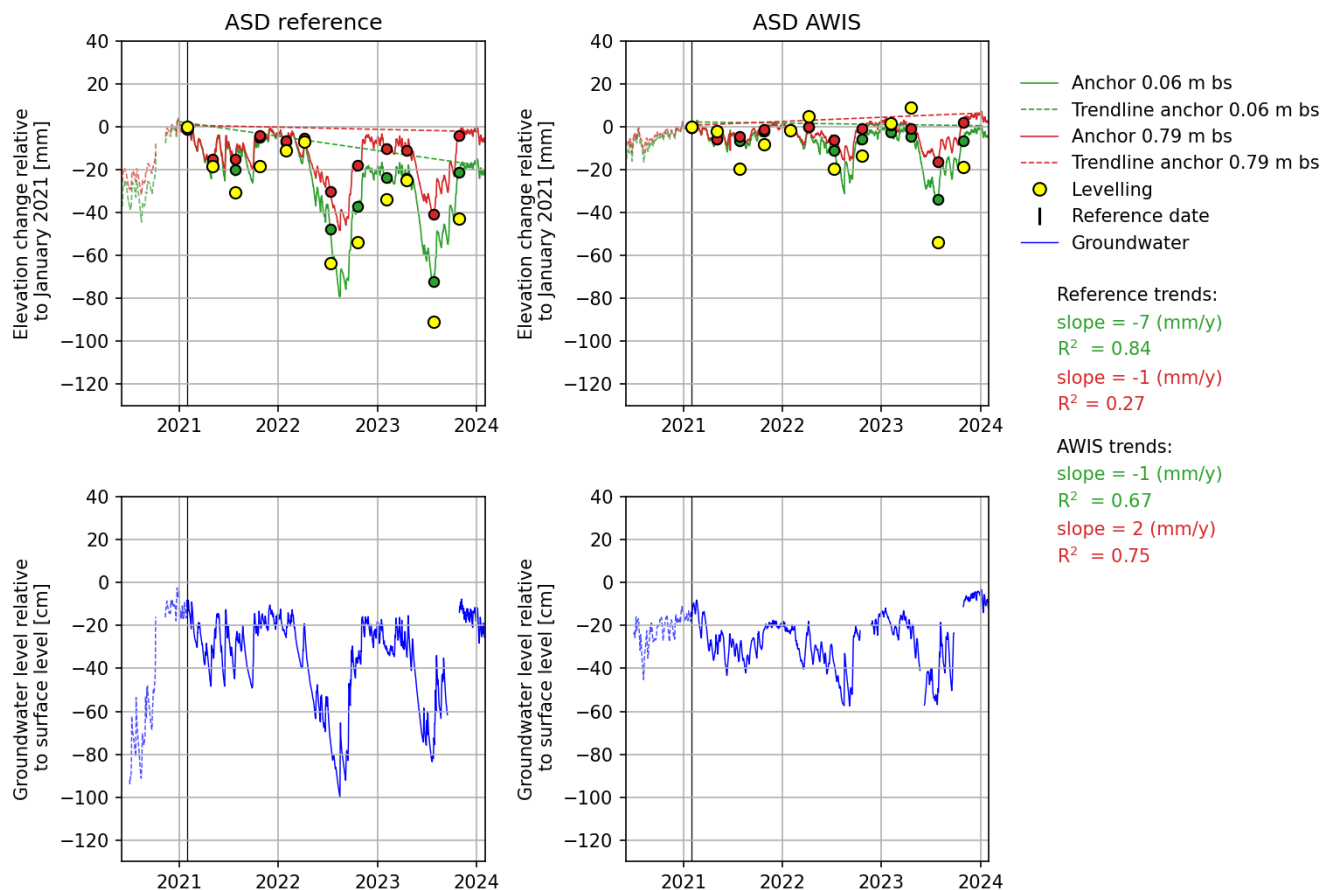
Figure 11. Elevation changes relative to the levelling day in January 2021, indicated by the black vertical line, for the reference (ASD RF; left) and AWIS (ASD AWIS; right) parcels in Assendelft, based on spirit levelling and extensometer measurements (surface anchor at 0.06 m depth in green and anchor at ~0.80 m depth in red; daily averages for the levelling days are indicated with green and red dots respectively). In blue the phreatic groundwater level is shown. Data before the reference date are indicated with dotted

470 **lines. bs=below surface.**

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Table 8. Yearly vertical soil dynamics in mm for Assendelft, based on levelling and extensometer measurements. RF=reference parcel, Dif.=difference. Extensometer daily averages have been calculated for the days of the levelling measurements. The contribution of the 0.80 m anchor to the surface anchor (0.06 m depth) is given in the last column.

Vertical soil dynamics (mm):		Levelling	Extensometer; anchor depth 0.06 m		Extensometer; Anchor depth 0.80 m		Contribution -0.80 anchor to -0.06 anchor
			Average on levelling day	*Full data series*	*Average on levelling day*	*Full data series*	
2021	RF	31	19	30	15	25	85%
	AWIS	20	6	15	6	13	92%
	Dif. to RF	*-11 (=-36 %)*	*-13 (=-67 %)*	*-15 (=-51 %)*	*-10 (=-63 %)*	*-12 (=-74 %)*	
2022	RF	57	42	79	25	48	61%
	AWIS	24	11	33	6	18	54%
	Dif. to RF	*-32 (=-57 %)*	*-31 (=-74 %)*	*-45 (=-58 %)*	*-19 (=-77 %)*	*-31 (=-6 3%)*	
2023	RF	66	50	56	36	37	67%
	AWIS	63	30	35	18	21	59%
	Dif. to RF	*-3 (+-5%)*	*-19 (=-39%)*	*-20 (=-37%)*	*-18 (=-51%)*	*-17 (=-45%)*	

3.4 Zegveld

In Zegveld, measurements took place in five fields in which different measures have been applied. In general, the different measures, i.e., type of WIS and high or low ditch water level, have resulted in less deep summer phreatic groundwater levels and less yearly vertical soil dynamics compared to the reference parcel, as demonstrated by all types of elevation measurements applied at this study site (Table 9; Figure 12; Fig. B1; Table B1; Van Asselen et al., 2023). Again, results show a clear relation between vertical soil movement and groundwater dynamics (Fig. 12). The contribution of the -0.80 cm anchor is relatively high at Zegveld (> ~60 %) and is highest in the reference parcel. Lower vertical soil movement dynamics in the AWIS parcel compared to the reference parcel seems to be largely caused by less (poroelastic) deformation in the saturated soil below 0.80 m depth (Fig. A4). Fitted trendlines indicate average long-term land subsidence of 8 mm/yr in the reference parcel and 2 mm/yr in the PWIS parcel so far, and subsidence is mainly due to irreversible peat decomposition and shrinkage in the unsaturated zone at this location (Fig. A4).

Yearly vertical soil dynamics is highest in the reference parcel. In the summer of 2022, the extensometer full data series recorded total dynamics of 98 mm in this parcel relative to the preceding winter. For most of the study sites, vertical dynamics was highest in the dry year of 2022. No clear relation between the type of measure and the calculated (reductions in) dynamics has been observed, but all measures showed different vertical dynamics as compared to the reference parcel. Manual phreatic

groundwater level measurements in 2019 and 2020 did show that summer phreatic groundwater levels were highest in the AWIS parcel, followed by the PWIS parcel, and were lowest in the reference parcel (Erkens et al., 2021).

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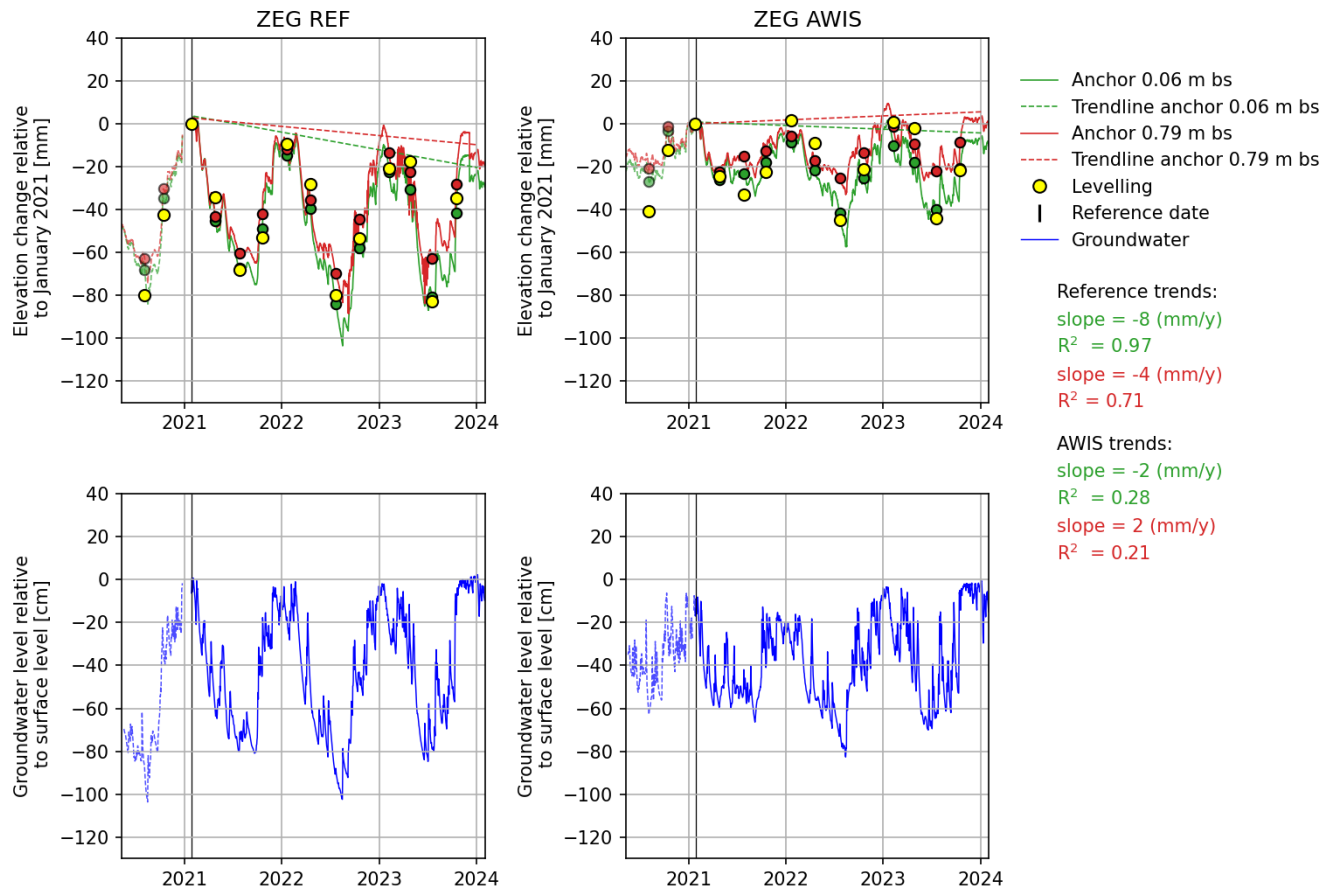
Figure 12. Elevation changes relative to the levelling day in January 2021, indicated by the black vertical line, for two parcels in Zegveld (in parcel 16 with low ditch water level: ZEG REF = reference parcel, and ZEG AWIS), based on spirit levelling and extensometer measurements (surface anchor at ~0.05 m depth in green and anchor at ~0.80 m depth in red; daily averages for the levelling days are indicated with green and red dots respectively). In blue the phreatic groundwater level is shown. Data before the
505 **reference date are indicated with dotted lines. bs= below surface.**

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Table 9. Yearly vertical soil dynamics in mm for Zegveld, based on levelling and extensometer measurements. RF=reference parcel, Dif.=Difference. Extensometer daily averages have been calculated for the days of the levelling measurements. The contribution of the 0.80 m anchor to the surface anchor (0.05 m depth) is given in the last column. In 2023 the vertical soil dynamics measured at 0.80 cm depth is larger than at 0.05 m depth, which indicates measurements uncertainties in the order of millimeters.

Vertical soil dynamics (mm):		Levelling	Extensometer; Anchor depth 0.05 m		Extensometer; Anchor depth 0.80 m		Contribution -0.80 anchor to -0.05 anchor
			Average on levelling day	*Full data series*	*Average on levelling day*	*Full data series*	
2021	p16-RF	68	66	78	59	68	86%
	p16-AWIS	33	26	36	22	27	75%
	Dif. to RF	*-35 (-51 %)*	*-40 (-61 %)*	*-43 (-54 %)*	*-37 (-63 %)*	*-41 (-61 %)*	
2022	p16-RF	71	69	98	57	84	86%
	p16-AWIS	47	33	53	19	31	59%
	Dif. to RF	*-24 (-34 %)*	*-36 (-52 %)*	*-45 (-46 %)*	*-38 (-67 %)*	*-53 (-63 %)*	
2023	p16-RF	65	58	77	49	83	100%
	p16-AWIS	45	29	46	20	36	78%
	Dif. to RF	*-20 (-31 %)*	*-29 (-50 %)*	*-31 (-40 %)*	*-29 (-59 %)*	*-47 (-57 %)*	

3.5 Vlist

In general, measurements from Vlist indicate slightly higher summer phreatic groundwater levels (Van Asselen et al., 2023) and slightly lower vertical dynamics in the PWIS parcel compared to the reference parcel (up to 10 mm less vertical dynamics; Table 10; Figure 13). Most pronounced effects are measured based on surface levelling. The highest amount of vertical dynamics at this location is 47 mm, which has been measured by spirit levelling in the reference parcel in 2022. The contribution of the -0.80 m anchor to the surface anchor is lowest in the dry year of 2022. The amount of soil deformation is fairly similar in the saturated and unsaturated layer of both the reference and PWIS parcels, where irreversible deformation mainly occurs in the unsaturated layer above ~0.80 m depth (Fig. A5). Fitted trendlines indicate average long-term land subsidence 2 mm/yr in the reference parcel and 0 mm/yr in the PWIS parcel (Fig. 13).
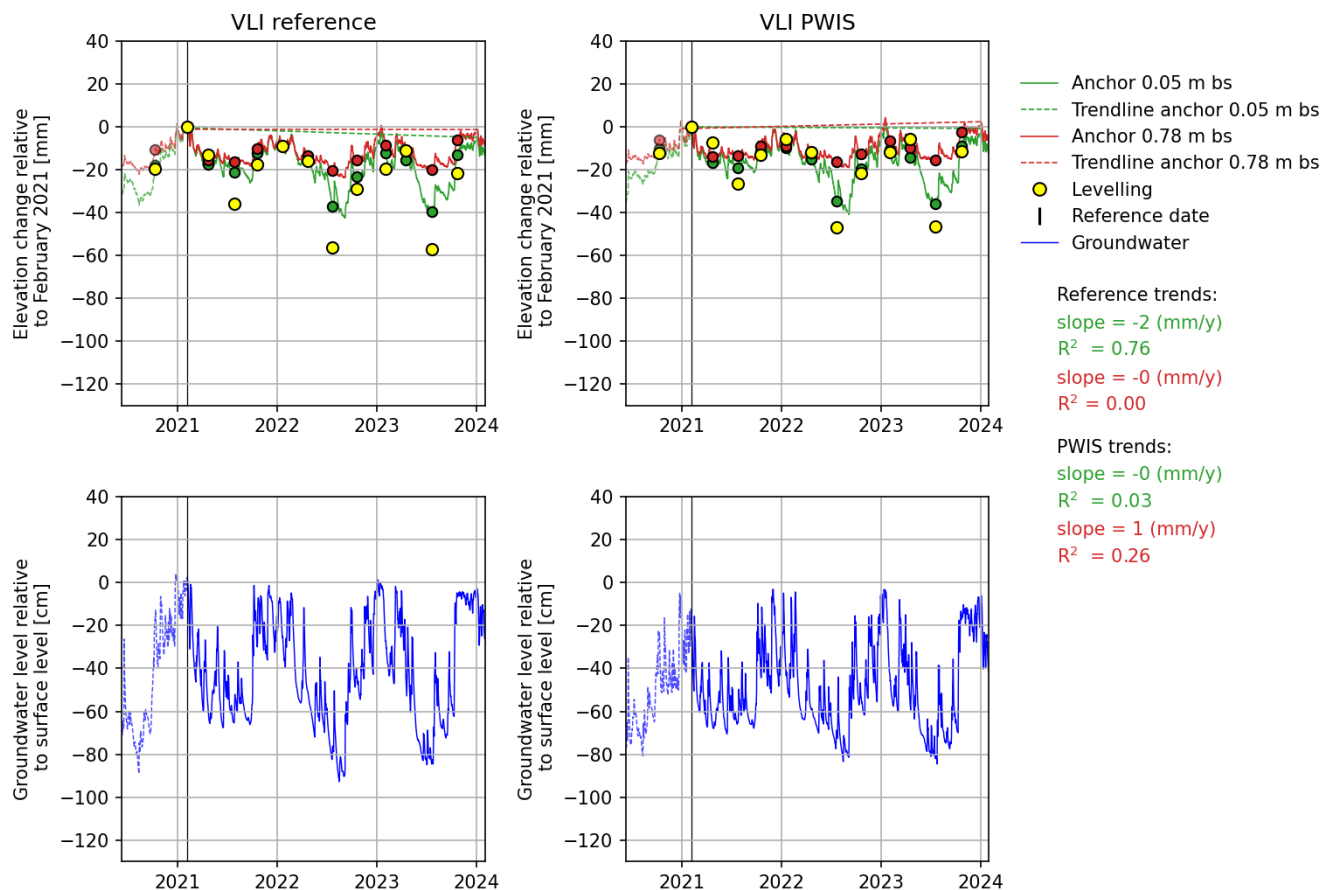
Figure 13. Elevation changes relative to the levelling day in January 2021, indicated by the black vertical line, for the reference (VLI RF; left) and PWIS (VLI WIS; right) parcels in Vlist, based on spirit levelling and extensometer measurements (surface anchor at 0.05 m depth in green and anchor at ~0.80 m depth in red; daily averages for the levelling days are indicated with green and red dots respectively). In blue the phreatic groundwater level is shown. Data before the reference date are indicated with dotted lines. bs=below surface.

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Table 10. Yearly vertical soil dynamics in mm for Vlist, based on levelling and extensometer measurements. RF=reference parcel, Dif.=difference. Extensometer daily averages have been calculated for the days of the levelling measurements. Standard deviation for elevation changes based on levelling is on the order of 10 to 20 mm. The contribution of the 0.80 m anchor to the surface anchor (0.05 m depth) is given in the last column.

Vertical soil dynamics (mm):		Levelling	Extensometer; Anchor depth 0.05 m		Extensometer; Anchor depth 0.80 m		Contribution -0.80 anchor to -0.05 anchor
			Average on levelling day	*Full data series*	*Average on levelling day*	*Full data series*	
2021	RF	36	22	28	17	20	70%
	WIS	27	19	27	15	19	69%
	Dif. to RF	*-10 (-27 %)*	*-2 (-10 %)*	*-1 (-4 %)*	*-2 (-13 %)*	*-1 (-5 %)*	
2022	RF	47	28	39	11	20	51%
	WIS	42	24	40	7	18	45%
	Dif. to RF	*-6 (-12 %)*	*-4 (-13 %)*	*+1 (+2 %)*	*-4 (-33 %)*	*-2 (-10 %)*	
2023	RF	46	27	38	14	21	55%
	WIS	41	27	38	13	20	52%
	Dif. to RF	*-5 (-12 %)*	*0 (0 %)*	*+1 (+2 %)*	*-1 (-6 %)*	*-1 (-4 %)*	

3.6 Main findings of vertical land movement measurements

- At all locations except for Rouveen, the WIS has resulted in less lowering of the phreatic groundwater level in summer and as a result of that, in reduced yearly vertical dynamics, i.e., seasonal soil subsidence. Compared to the reference parcels, the reduction of the yearly vertical soil dynamics is up to 74 % (measured at Assendelft in the summer of 2022 at the anchor level of ~80 cm depth; Assendelft is also the location where strongest effects on summer phreatic groundwater levels were measured (Van Asselen et al., 2023)). In absolute numbers, the AWIS in Assendelft resulted in up to 45 mm less yearly vertical soil dynamics compared to the reference parcel. In Zegveld, AWIS resulted in up to 53 mm less yearly vertical soil dynamics.

- The high resolution data series of vertical soil movement and phreatic groundwater level demonstrate that these two factors are strongly related, at different timescales, in the sense that a rise of the groundwater level results in upward soil movement, and a drop of the groundwater level results in downward soil movement.

- The highest yearly vertical soil dynamics, i.e., seasonal subsidence, is 98 mm, which has been recorded by the extensometer full data series in the summer of 2022 in the reference parcel of Zegveld.

- Zegveld is also the location with the thickest peat layer (ca 6 m thick) of all sites considered in this study. Firm sandy deposits are found at a depth of ca 9 to 10 m. It is likely that a thicker peat layer results in larger vertical soil dynamics, because a thicker layer is available especially for poroelastic deformation. But, also in Assendelft relatively high vertical soil dynamics have been observed. Here, the peat layer is less thick, ca 2 m thick, but below this layer a ca 10 m layer consisting of predominantly marine clay and sand is present. This thick Holocene layer is also subject to

poroelastic deformation (see Fig. A3). The relation between lithology and soil dynamics will be further investigated in a follow-up paper.

- Deformation of the saturated subsurface (i.e., soil below ~0.80 m depth, or in case of Rouveen below ~1.15 m depth) contributes considerably to surface level vertical movement. The contribution of deformation of the soil below this anchor level to surface subsidence is about 30 to 95 % (based on extensometer measurements, Table 6 to 10). At all study sites except for Rouveen, deformation of the saturated soil below 0.80 m depth is largely reversible so far, which suggests that long-term (irreversible) land subsidence is mainly caused by soil deformation processes in the unsaturated top layer (peat decomposition and irreversible shrinkage; see also Appendix A). However, longer time series are needed to exclude a contribution of deformation processes in the saturated peat in long-term subsidence. At the extensometer location in the PWIS parcel of Rouveen, where upward seepage water is drained, also irreversible deformation of the saturated soil below 1.15 m depth has taken place (Fig. A2).

- The yearly vertical dynamics derived from the daily averaged extensometer data are usually lower than the dynamics calculated from corresponding spirit levelling data (Table 6, Table 8 - Table 910). A likely explanation of this structural difference is deformation of the top ~5 cm by shrinkage and swell, which is not measured by the extensometer. With spirit levelling, the surface level is measured.

- The full extensometer data series, however, often yield higher vertical dynamics than those inferred from the spirit levelling (e.g., Aldeboarn, Assendelft, Zegveld). This suggests that quarterly measurements often miss most extreme elevations (minima and maxima) occurring within a year, which is indeed clearly noticeable when comparing the levelling data points (yellow) and the extensometer full data series in Figures Figure 9 to Figure 13.

- Differences between levelling and extensometer surface level measurements may also be caused by spatial variations in surface level movement: the levelling data are spatial averages, while the extensometer measures at one location.

- First estimates of long-term average land subsidence (top anchor) are in the range of 0 to –11 mm/yr. Rates are lower in WIS parcels, except for Rouveen, where a multiyear subsidence rate of 3 mm yr^{-1} was estimated for the reference parcel and 11 mm yr^{-1} for the PWIS parcel. The unexpected higher subsidence rate estimated for the PWIS parcel at this upward seepage area is likely the result of lower summer groundwater levels due to increased drainage of seepage water.

The spirit levelling and extensometer techniques measure elevations at millimetre scale accuracy. Uncertainties in the measured soil/surface elevation (changes) may especially arise from unstable reference levels, although these are all fixed in the firm sandy subsurface, making it unlikely that they have moved over the study period (which is only a couple of years). The accuracy of the pressure sensor used to measure groundwater level is on the order of 1 centimetre, which has been tested in the laboratory. Additional uncertainties arise from deviations of the de water level in a monitoring well compared to the actual phreatic groundwater level in the surrounding soil. However, because the measured groundwater level fluctuations are

on the order of tens of centimetres, and measured soil vertical movement are on the order of centimetres, it is unlikely that
600 mentioned uncertainties will affect the results and main findings of this study.

4. Evaluation and discussion

4.1 Effects of water infiltration systems on vertical soil movement

4.1.1 The relation between the phreatic groundwater level and soil deformation

The yearly groundwater level dynamics (range) and the deepest groundwater level are two hydrological characteristics that
605 affect vertical soil movement, by their influence on reversible and irreversible soil deformation processes. Our observations
indeed indicate that phreatic groundwater level dynamics is a key factor controlling vertical movement, e.g. deformation, of
peat soils (Figures 9 to 13). Furthermore, for the five investigated study locations except for Rouveen, WIS have resulted in
less deep phreatic groundwater levels in summer periods (Figure 9 to 13; Van Asselen et al., 2023), and therewith in less
yearly vertical soil movement.
610

The relation between the phreatic groundwater level and vertical soil movement is further indicated by the relation between
the yearly deepest phreatic groundwater level and vertical dynamics of the shallowest extensometer anchor (Fig. 14). For most
parcels, except for those in Rouveen, a positive relation between the deepest groundwater level and vertical dynamics, i.e.
seasonal subsidence, is observed. Results of this study also demonstrate that phreatic groundwater level fluctuations at shorter
615 (daily/weekly) timescales also affect vertical soil movement; a rise or drop of the groundwater level leads to an almost
immediate response of soil deformation processes resulting in respectively upward or downward soil movement (Figure 9 to
13).
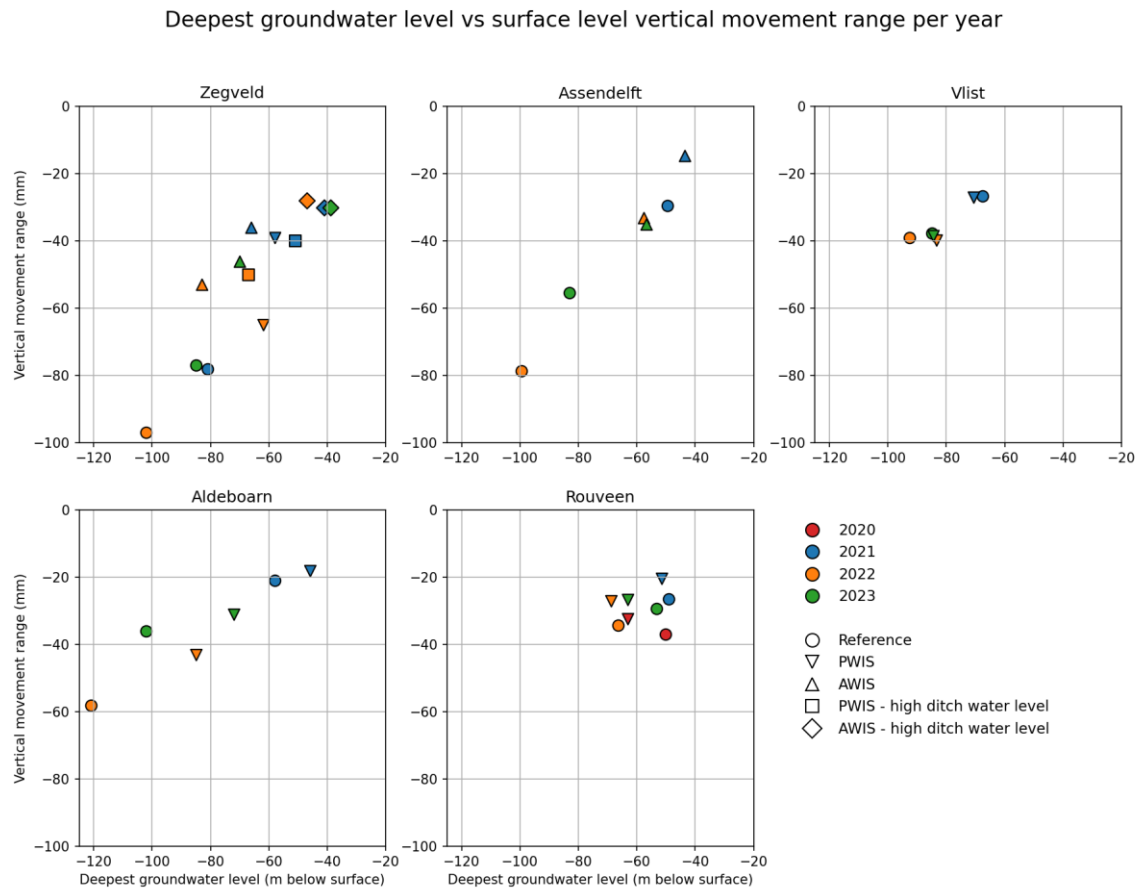
Figure 14. Relation between the yearly vertical dynamics and deepest groundwater level for all parcels at all five locations.

620 In Rouveen, which is located in an area with upward seepage, the drains have unintendedly increased drainage, resulting in lower phreatic groundwater levels as compared to the reference situation. Extensometer measurements indicate that this has resulted in more long-term subsidence in the PWIS parcel as compared to the reference parcel, which also shows that the phreatic groundwater level dynamics is a key factor controlling vertical land movement.

4.1.2. Suppression of both unsaturated zone shrink-swell and saturated poroelastic deformation

625 The measurements presented in this study show that phreatic groundwater level dynamics affect reversible vertical soil movement, i.e. deformation, of the soil both above and below ~0.80 m depth. Above this depth the soil is variably saturated and reversible soil deformation is for an important part caused by shrink and swell processes, as a result of variations in pore suction forces resulting from soil drying and wetting cycles. Less deep lowering of the phreatic groundwater level in summer as a result of WIS is expected to limit shrinkage of the unsaturated top soil because, overall, the top soil layer remains wetter

630   and therewith suction forces remain lower compared to soils with lower summer groundwater levels. This especially seen at Aldeboarn and Assendelft (see results section and Appendix A).

Less deformation of the soil in the commonly saturated zone below ~0.80 m depth may be explained by effects of groundwater level dynamics on the effective stress in the subsurface. The effective stress, changes of which causes deformation of soil, is

635   defined as the total stress (i.e., weight) minus the pore water pressure (Terzaghi, 1943). Fluctuations in the phreatic groundwater level cause temporal variations in pore water pressure and therewith effective stress, which causes (poroelastic) soil volume increases and decreases. Less deep summer groundwater levels, as a result of WIS, results in smaller variations of the pore water pressure, and hence less soil deformation. This is especially clearly seen at Aldeboarn, Assendelft and Zegveld (Appendix A). Reversible deformation in the saturated soil is referred to as poroelastic deformation (e.g., Kümpel, 1991). In

640   Zegveld, the contribution of poroelastic deformation to surface level vertical movement is relatively large, presumably due to the relatively thick (~6 m) peat layer that is prone to deformation at this location. The total thickness of soil layers in which poroelastic deformation occurs often is much larger than the thickness of the unsaturated zone. So far, results suggest that soil deformation in the saturated soil layer is largely reversible (observed at all sites except the Rouveen PWIS plot).

645   Thus, results of this study demonstrate, as expected, that phreatic groundwater level dynamics and vertical soil movement dynamics are strongly related (Figures 9 to 14). Commonly, a lowering of the groundwater level leads to downward soil movement (soil subsidence by shrinkage and poroelastic deformation) while a rise of the groundwater level leads to upward soil movement (by swell and poroelastic deformation). It is expected that this relation applies to all organic soils. Poroelastic deformation is commonly larger in organic soils than in clay soils. Shrinkage and swell properties may vary among different

650   peat and clay soils (Peng et al., 2006).

4.1.3 Suppression of subsidence

It is expected that WIS will also reduce long-term subsidence, through its effect on groundwater level dynamics which affect multiple soil deformation processes. Firstly, if deep summer phreatic groundwater levels can be prevented by WIS and groundwater level dynamics are reduced, there will be less variations in pore water pressures and therewith effective stresses.

655   This reduces the risk of irreversible soil compaction. In addition, the risk for irreversible shrinkage is expected to be lower because generally wetter soil conditions will lower the risk of severe drying of the soil. Moreover, soil moisture and temperature are main drivers of peat decomposition (Boonman et al., 2022). Less deep phreatic groundwater levels in warm summer are expected to lead to less loss of soil volume due to aerobic peat decomposition by microbial activity, because oxygen can intrude less deep into the soil creating suboptimal (soil moisture) conditions for peat decomposition.

660

First estimates of long-term average subsidence rates vary between 2 and 8 mm/yr in the reference field sites and between 0 and 4 mm/yr in WIS field sites where WIS resulted in the desired effect of less deep groundwater levels in summer. For all

sites except Rouveen, the estimated rate is lower in the WIS parcel compared to the reference parcel. In Rouveen, WIS resulted in deeper groundwater levels, and a higher long-term average subsidence rate of 11 mm/yr (opposed to 3 mm/yr in the Rouveen reference site). Reduced land subsidence rates in WIS parcels are seemingly largely caused by reduced peat decomposition and/or irreversible shrinkage in the unsaturated top soil (Appendix A), though longer time series are needed to assess the long-term contribution of different subsidence processes more accurately. Estimated rates are in the same order of magnitude as subsidence rates in similar peat areas found in other Dutch (e.g., Schothorst, 1977, Beuving and Van den Akker, 1997, Massop et al., 2024) and international (Bloom, 1964; Haslett et al. 1998; Edwards, 2006; Fritz, 2006; Long et al., 2006; Törnqvist et al., 2008; Horton and Shennan, 2009) studies. Variations in both time and space in subsidence rates may be caused by variations thickness of the peat layer, peat type, peat decomposition rate, peat density, intensity of drainage, and climatic conditions (Egglesmann, 1976; Asselen et al, 2009).

The higher subsidence rate in the PWIS parcel of Rouveen is presumably related to (unintendedly) deeper average phreatic groundwater levels in this parcel causing increased peat decomposition and compaction. This observation supports the existence of a positive relation between phreatic groundwater level depth and long-term land subsidence The effect of groundwater levels on long term subsidence is also shown by Massop et al. (2024), who demonstrate that, based on long-term (circa 50 years) spirit level measurements of surface level and soil markers at different depths, long-term subsidence in a field with relatively high ditch water levels (and related higher phreatic groundwater levels) was less than in a field with relatively low ditch water levels (and related lower phreatic groundwater levels).

4.2 Spirit levelling versus extensometer technique

In this study, spirit levelling and extensometery have been used to assess vertical soil movement dynamics and multiyear land subsidence in peat meadow areas. Both field techniques can measure elevation changes at mm-scale precision. An important difference between these two techniques relates to their temporal and spatial applicability. An extensometer measures vertical soil movement at one location, and, therefore, does not provide information on spatial variability of vertical soil movement within a parcel. The temporal resolution is high however (hourly measurements), and soil movement is measured at various depths. This allows detailed analysis of land movement dynamics and subsurface deformation and relate these to other conditions like groundwater level dynamics and variations in subsurface composition. This is vital to understand and unravel different processes contributing to land movement dynamics and long-term subsidence. Spirit levelling has a higher spatial coverage, measuring along multiple transects, but the temporal resolution is commonly low (four times a year in this study, often less), which brings the risk of missing vertical dynamics (see also figures in the results section). Consequently, in particular in the case of spirit levelling, long timeseries are essential, as demonstrated by for example the levelling timeseries of Rouveen that do not yet indicate a clear long-term trend with a low R^2, while the extensometer measurements at this location do result in a subsiding trend with fairly high R^2).

695 Indeed, our measurements demonstrate that the range derived from the high-resolution extensometer measurements is often higher than the range derived from spatially averaged spirit levelling data (see result section). Dynamics derived from extensometer measurements averaged for the day of spirit levelling are, however, often lower compared to dynamics derived from spirit levelling, which may be due to deformation of the top ~5 cm soil between surface level and the topmost extensometer anchor, which is not registered by the extensometer surface anchor. These differences should be carefully

700 considered and taken into account when using these methods for measuring vertical soil movement.

5. Conclusions

The levelling and extensometer data series presented in this study show that yearly vertical soil dynamics, i.e., seasonal subsidence, of the surface is in the order of centimetres. The largest vertical dynamics of almost 10 cm has been measured in an area with a relatively thick (6 m) peat layer, in the dry and warm summer of 2022. This study also demonstrated that seasonal

705 vertical soil movement is about an order of magnitude higher than long-term subsidence rates in drained peatlands (commonly mm yr^{-1}). Therefore, multiyear data series are needed to filter out seasonal (variable) dynamics and estimate long-term subsidence. In this study, first estimates of long-term average subsidence rates based on linear fits on extensometer data series indicate subsidence rates of 2 to 8 mm/yr in the reference field sites and 0 to 4 mm/yr in WIS field sites, with variable R^2 values. In Rouveen, where WIS resulted in deeper phreatic groundwater levels, a long-term average subsidence rate of 11

710 mm/yr was estimated. Longer data series are needed to make (more) reliable (with higher R^2) estimates of land subsidence.

Results of this study demonstrate that short-term (daily to monthly) vertical soil movements are related to phreatic groundwater level fluctuations, which affect soil deformation processes in both the unsaturated and saturated zone. Water infiltration systems in peat meadows, if correctly applied, limit phreatic groundwater level lowering in summer periods, and therewith,

715 also limit seasonal subsidence. Less deep summer phreatic groundwater levels cause less shrinkage in the unsaturated zone, due to higher water content and lower suction forces. In the saturated zone, higher phreatic groundwater levels cause less poroelastic deformation because of reduced changes in pore water pressure, and therewith, effective stress. Poroelastic deformation of the saturated subsoil (below ~0.80 m depth) may contribute considerably to surface level movement, often more than processes in the unsaturated zone, especially if the subsurface is composed of a relatively thick peat layer. We found

720 that poroelastic deformation in the saturated zone is largely reversible for the relatively short time period considered in this study, while soil deformation processes in the unsaturated zone are partly irreversible, which leads to long-term land subsidence. At longer time-scales, irreversible deformation processes in the saturated soil could also contribute to total land subsidence (e.g. Massop et al., 2024).

725 Differences in the temporal and spatial resolution of the spirit levelling and extensometer techniques requires careful consideration for developing land movement monitoring plans. Spirit levelling measurements give insight into the spatial

variability of elevation and elevation changes within a parcel. This technique is especially useful for long-term (at least 10 years of measurements) application to determine average long-term subsidence of a parcel. Extensometer measurements are particularly useful for high-resolution monitoring of soil movement dynamics at different depths, which allows to quantify

730 both short and long-term soil movement, and to better understand soil deformation processes in different soil layers and their relative contribution to surface level movement.

Author contributions

S. van Asselen performed all analyses and prepared the manuscript, with contributions from all authors, and others (see Acknowledgements).

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Competing interests

The authors declare that they have no conflict of interest.

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