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Performance of subsurface drainage implemented with trencher and trenchless machineries

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ABSTRACT

The trenchless (T0) and trencher (T1) drainage installation methods are widely applied in Finland. There is an ongoing debate and a lack of science-based information about the performance differences between the methods. The objective was to assess drainage performance differences between T0 and T1 by analyzing groundwater table observations from field sections drained with the two methods. The differences were studied by using statistical analysis over a two-year period after the drainage installation. An experimental field in middle-Finland was divided into four T0 sections and four T1 sections. The groundwater level was manually measured about twice a week from seven locations in each section. Automatic recording was installed in one T0 section and one T1 section. The manual observations formed 56 time series, which were tested between the same-method plots (T0-T0 and T1-T1) and the different-method plots (T0-T1). Automatic data was used to validate the manual observations. In the T0 sections, 60–90% of the groundwater level observations were higher than those in the T1 sections. These observations had an average difference of 0.14–0.25 m. The variation in the groundwater level time series was larger between the T0 sections than between the T1 sections. Statistically significant differences between the same method field sections indicated that other factors also affected the groundwater table (soil type, etc.). However, the differences between T0 and T1 were stronger than those between the same-method sections, and the differences were clearest when the groundwater levels were above the drain depth (1.0 m). In the seasonal time series, the biggest differences were found during the autumn and winter periods. The average differences between T0 and T1 might not be significant in practice, but occasional larger (> 0.4 m) differences may have a short-term influence on field activities and crop growth.

1. Introduction

In Nordic conditions, field drainage is needed to avoid excessive soil wetness, ensure optimal root zone moisture conditions for crops and improve soil trafficability. Snow coverage in winter, a rapid snowmelt period in spring, and frequent rainfalls in autumn are typical in boreal climate areas. Therefore, drainage systems have to function efficiently at the start of the growing season and in autumn during the harvest. For cultivation activities, the bearing capacity of soil needs to be sufficient for heavy machinery without risking soil compaction (Mueller et al., 2003). Poor trafficability delays sowing and harvesting (e.g., Kornecki and Fouss, 2001; Kandel et al., 2013). In Finland, field drainage is mainly subsurface drainage implemented with trencher (T1) or trenchless (T0) machinery. In the T1 method, a drain pipe is laid at the bottom of the excavated trench and filled with envelope material, and the excavated soil (e.g., Ritzema et al., 2006). In the T0 method, the soil is lifted up or pushed aside while placing the drain pipe in the soil. Envelope material around the pipe is applied in both methods (e.g., Vakkilainen and Suortti-Suominen, 1982).

The drain installation methods transform the soil structure above the drain lines (FAO, 2005), but it is not clear how the soil transformation differs between the applied drainage machineries. The soil is disturbed during the installation, which has reported to improve drainage function (Chow et al., 1993), and to create soil compaction at the trench walls with the T0 method (Spoor and Fry, 1983). Kanwar et al. (1986) showed the water table was higher in the T0 plots than in the T1 plots, but the

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factors affecting the lower performance of T0 drainage remained uncertain. Mirjat and Kanwar (1992) reported that the increased drainage performance in the T0 method plots 10 years after the drainage installation was likely due to improvement of the soil structure that was disturbed during the installation. Chow et al. (1993) reported that there were no significant changes in soil properties with the T1 method over 30–40 years. It is not clearly reported if the selection between the T0 and T1 method is the main reason for the field drainage performance and has not been systematically tested in Nordic conditions.

Trenchless installation is faster and cheaper, which explains its popularity (e.g., Nijland et al., 2005; Zijlstra, 1986; Vakkilainen and Suortti-Suominen, 1982). With high-quality execution, both the T1 and T0 systems have similar lifetime (e.g., Nijland et al., 2005). However, a drainage design should take into account the differences in the drainage performance that depends on the soil properties and the installation conditions (e.g, Tuohy et al., 2015). In the selection of the drainage method, the limitations of the field and the installation equipment should be kept in mind (e.g., Tuohy et al., 2016b; Ritzema and Stuyt, 2015; Smedema et al., 2004). Fine textured soil types (clay and silt) are more sensitive than coarse soils for the moisture content to be low enough to bear the drainage machinery without causing severe damage to the soil structure. Vakkilainen and Suortti-Suominen (1982) noted that the T1 method resulted in a better drainage quality than the T0 method in fine texture soils with an unstable soil structure during wet installation conditions. In sandy soils, drainage capacity differences between the methods were not detected. According to drainage guidelines (Nijland et al., 2005), the installation conditions are more limited for the T0 than T1 method.

In field studies the performance of different drainage practices have been investigated with varying experimental setups. Mirjat and Kanwar (1992) found differences between T0 and T1 in the same field area, but did not study the differences between same method field sections. Even within the same field area there are other factors (e.g. surrounding areas, field topography, and heterogeneity in soil properties) affecting the performance of the installed drainage system, which can be evident from studying the differences within the same drainage method sections (e.g. Tuohy et al., 2016a). Vakkilainen et al. (2010) studied the drainage performance differences in T0 and T1, but had other differences in the drainage installations (drain spacing, depth, and envelope material). They identified no differences in the drainage performance between T0 and T1, but found the topography at the field boundaries affecting the hydrological behavior of the sections drained with the T1 and T0 methods. Tuohy et al. (2016a) studied conventional and mole drainage systems in terms of their response to short-term rain events and tested the effect of installation conditions to drainage performance. To understand the overall differences of the drainage methods there is a need to compare longer time series and to use drained field sections where the effects of other factors (e.g. installation conditions, drain spacing, drain depth, and backfill and filter material) to drainage performance are minimized.

Literature reveals varying hydrological effects of the drainage installation methods (T0 and T1), pointing out the need for a systematic comparison of the methods. The main objective of this study was to investigate the differences in the performance of subsurface drainage implemented with T1 and T0 machineries. A specific aim was to evaluate, how well the effect of factors other than the drainage method on the groundwater levels could be removed by the experimental design. The differences were evaluated using statistical and graphical analyses of groundwater table data in 2015–2017. Additional aims were to assess the applicability of statistical tests to quantify the magnitude of the differences, and discuss the limitations and sources of uncertainties in the data and experimental design.

2. Site description and data collection

The experimental site is located in Sievi in middle-Finland (Fig. 1c). In the region, the mean annual precipitation was 550–660 mm, and the mean annual temperature was 2–4 °C (Pirinen et al., 2012). The experimental field area was 2.34 ha, with a mean slope of < 0.2%. The surrounding areas of the field are flat, and their cultivation is mostly similar to the experimental field. Before the experimental study, the field was drained by open ditches that were spaced 30 m apart and had a depth of about 0.85 m.

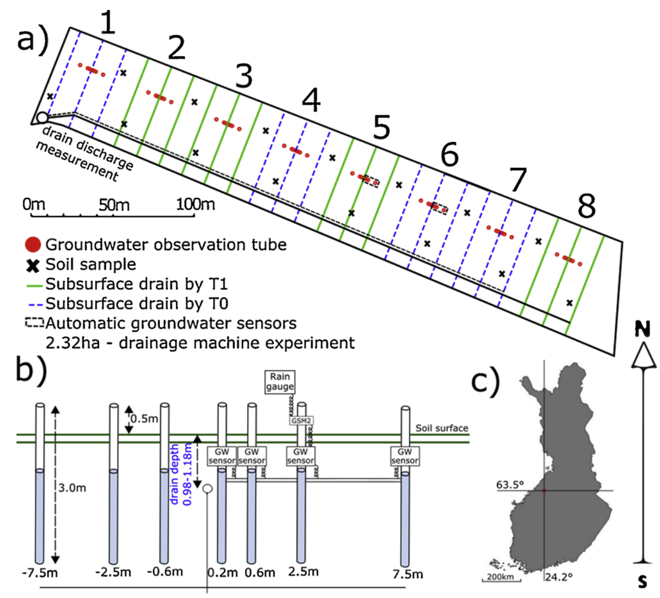

Fig. 1. (a) Eight field sections of the Sievi drainage installation experiment (Äijö et al., 2016). Subsurface drains were installed by trenchless (T0) (Sections 1, 4, 6, and 7 – blue dash lines) and trencher (T1) (Sections 2, 3, 5, and 8 – green lines) machineries. Collector drain pipes are at the southwest side of the field (continuous and dashed black lines), and groundwater observation tubes are marked with red dots. Soil sample locations are marked with black cross marks. (b) Setup for the groundwater observations (Äijö et al., 2017). (c) Field location in Finland (© NLS). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

For the drainage experiment, the field was equally divided into eight sections. Before the start of the experiment, groundwater levels in all sections were monitored at 22 groundwater observation tubes (PEH, polyethene, Ø50 mm) during March–May 2015. The tubes were installed to a depth of 2.5 m below the soil surface and perforated along a length of 1.5 m from the bottom.

Soil from the field sections was sampled from 15 locations using a spiral drill (see Fig. 1). The particle size distribution and the soil type were determined at depths of 0.5–0.8 m and 0.8–1.0 m (Table 1). According to the Finnish soil classification (Yli-Halla et al., 2000), topsoil was rich loamy sand, and the average depth of the topsoil layer was 0.3 m. The soil type above the drain layer (0.5–0.8 m) was more similar between the field sections. The soil type in the drain depth (0.8–1.0 m) was determined to be either loam, sandy loam or loamy sand (IUSS, 2014). In the outer sections (1, 2, 7 and 8), the soil type was loam; in the inner sections, it was sandy loam, except in section 6 it was loamy sand. Section 6 had the lowest clay percentage (5%). Sections 1, 7, and 8 had the highest clay percentage (20%). The sand percentage was over 60% in the inner sections (3 to 6) and 30–40% in the outer sections (1, 2, 7, and 8). For the outer sections (1, 2, 7, and 8), the silt percentage was between 40% and 50%, and clearly smaller (8–30%) for the inner sections (3 to 6). For all sections, organic matter content in the drain layer was small (0.5–1.5%).

During the growing seasons of 2015 and 2016, the crop in all sections was barley (“*Brage*”). Before the experiment, oats, grass, and rapeseed were cultivated in the field. Sowing was conducted in the end of May (2015) and in early June (2016), and harvesting was done in September in both years.

Table 1
Particle size distribution and soil texture class (IUSS, 2014) at the soil layers (0.5–0.8 m and 0.8–1.0 m) for T0 and T1 sections.

Layer depth		Field section							
		1 (T0)	2 (T1)	3 (T1)	4 (T0)	5 (T1)	6 (T0)	7 (T0)	8 (T1)
50–80 cm	Clay (%)	9	6	5	11	4	10	12	21
	Silt (%)	21	9	9	17	10	17	13	41
	Sand (%)	70	85	87	71	85	73	75	39
	Soil type	Sandy loam	Loamy sand	Loamy sand	Sandy loam	Loamy sand	Sandy loam	Sandy loam	Loam
80–100 cm	Clay (%)	22	10	9	10	9	5	21	23
	Silt (%)	42	47	24	10	30	8	43	47
	Sand (%)	36	43	67	80	61	87	36	30
	Soil type	Loam	Loam	Sandy loam	Sandy loam	Sandy loam	Loamy sand	Loam	Loam

2.1. Experimental setup

The area of the each monitored section was 0.27 ha. The sections were subsurface drained in May 2015 with equal drain spacing (15 m) and a drain depth of around 1.0 m. Before installing subsurface drains, the open ditches (spaced evenly across the field from northeast to southwest) were backfilled, and the field was leveled. It was assumed that the backfilled ditches had a similar effect on all sections, as the experimental plots were perpendicularly aligned against them (Fig. 1). The experimental setup was designed to minimize the differences between the field sections caused by factors other than the subsurface drainage methods.

Four section pairs (one T0 and one T1) were formed so that the order of the methods between the pair sections was randomly selected. Because of the field topography, sections were placed along the same line from northwest to southeast (Fig. 1a). Each section was drained by three perforated plastic pipes (Ø 50 mm), and the groundwater table was observed as a function of distance from the middle drain line to minimize the impact of neighboring field sections on the observed groundwater table. The field sections were not separated from each other by any artificial barrier.

Drains were installed with trencher (Inter-Drain 1824 T, the Netherlands) and trenchless (Hoes plow, Germany) machinery. Collector pipes (non-perforated pipes) were installed to facilitate gathering drain discharges from the T0 and T1 sections separately in two measurement devices (Hydrus DN50, Diehl Metering), which were located in the outlet of the drainage system at the western side of the field.

Before the drainage installation, a rainfall of 4 mm during the previous 3 days was recorded. During the day of the installation, a small rain event of < 1 mm occurred before the drainage works, and 6–8 mm of rain fell before the drainage was completed. Therefore, the field surface was partly waterlogged at the end of the installation period. Regardless of the rain during the field works, the installation was conducted according to the Finnish recommendations (RIL, 2016).

Groundwater observation tubes were installed after sowing in June 2015. A filter fabric was used around the perforated pipe 1.5 m from the bottom of the tube. Tubes were at distances of −7.5, −2.5, −0.6, 0.2, 0.6, 2.5, and 7.5 m across from the middle drain pipe (from northwest to southeast, with the drain location at 0.0 m in Fig. 1). Automatic sensors were installed in four observation tubes (0.2, 0.6, 2.5, and 7.5 m from the drain line) in sections 5 and 6.

The trenches were 24 cm wide in T1 and 22 cm wide in T0. Gravel was used as an envelope material about 10 cm above the drain. Topsoil was used for trench backfilling in both methods. The drain depth was continuously monitored during the installation; the variation in depth was found to be within 0.2 m. The field was leveled a few days after the installation.

2.2. Data collection

The depth to groundwater table was measured manually using a Little Dipper 0–22 m (Heron Instruments, Canada) about twice a week from spring to autumn and once a week during winter. The observations were started on 4 June 2015. Observations were preferably gathered on the same weekdays and at the same time of day. One monitoring round took 2–3 h, and it was always conducted in the same way. No randomization was applied in the monitoring.

The groundwater table depth was automatically recorded with 10-min time intervals using pressure sensors (PAA-36XW, Keller, Switzerland). The recording was started on 16 Jun 2015. Precipitation was measured every 10 min on site with a RainCatcher (Keller, The Netherlands). Manual weekly observations of rain and snowfall were recorded.

The collector pipe of the trencher method was clogged in November–December 2015, which affected the drain discharge and groundwater table near the discharge measurement location (field sections 2 and 3 in Fig. 1).

3. Methods and data description

3.1. Time series

Manual groundwater depth observations formed 56 time series (at seven locations per section–four T0 and four T1). Manual time series were recorded between 4 June 2015 and 30 June 2017, and each location contained 172 observations.

Because the drain installation depth varied between the eight sections (0.98–1.18 m below the soil surface), a reference elevation of 0 m was defined as the drain level in each section. Negative values indicated that the groundwater table was below the drain level, and positive values indicated that it was above the drain level.

In order to compare manually measured with automatically recorded groundwater depths, a new time series from automatic data was formed by selecting only the records that were obtained at the same time as the manual measurements in sections 5 and 6. Using this new time series, the validity of the manual data was assessed. The automatic measurements started 12 days later than the manual observations, and the automatic data was not recorded in T1 (section 5) from 11 to 31 December 2016.

3.2. Graphical analysis

The manual observations were plotted as a range of groundwater level variation to detect differences between the drainage methods by graphical analysis. The ranges for T1 and T0 were shown at four distances (0.2, 0.6, 2.5, and 7.5 m) from the middle drain (including both sides of the drain, Fig. 1b). The range was formed from the four sections by computing the minimum and maximum groundwater level at each time point (172 observation times). The minimum time series for the four distances for T0 and T1 are formed by Eqs. 1 and 2, respectively, and similarly for the maximum time series.

$$W_{T0}(min)_{i,d} = MIN(W(1)_i, W(4)_i, W(6)_i, W(7)_i)_d \quad \forall\, i \in \{1, ..., 172\}, \quad \forall\, d \in \{0.2, 0.6, 2.5, 7.5\} \tag{1}$$

$$W_{T1}(min)_{i,d} = MIN(W(2)_i, W(3)_i, W(5)_i, W(8)_i)_d \quad \forall\, i \in \{1, ..., 172\}, \quad \forall\, d \in \{0.2, 0.6, 2.5, 7.5\} \tag{2}$$

where *W(k)* is the groundwater level at section *k*, *i* is the observation time point, and *d* is the observation distance (including both sides of the drain, Fig. 1b).

Variability of the time series for T0 and T1 was assessed by computing the variance of each observation time (four field sections for both methods) and calculating the median value of variances over the whole time period.

3.3. Time series analysis and study setup

Time series were tested between the different-method and the same-method sections to assess whether the difference in groundwater level was caused by the drainage method (T0-T1 pairs) or by other factors (T0-T0 and T1-T1 pairs). After testing the full-length time series (172 observations), two types of filtering for the manual data were applied to form (i) high groundwater level series and (ii) seasonal series. Case (i) contained only values above the drain level to distinguish whether the differences occur due to the drainage method. The groundwater table beneath the drain depth was not affected by the drainage. Time series were created with data points where all observations were above the drainage depth (1.0 m). After filtering, 126 observations were left from the original 172 observations. Case (i) dataset was additionally studied to detect if the drain layer soil type (0.8–1.0 m) alone caused differences in groundwater levels. In case (ii), the strong seasonal differences in weather were taken into account by dividing the time series into four seasons: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February).

The applied tests with their requirements and null hypotheses are listed in Table 2. Sen's slope and cumulative sums allow for the time dependency of the observations. Sen's slope is a non-parametric statistic that shows the tendency of the magnitude and direction of the time series (Hirsch et al., 1982). The study relies on the results from the one sample *t*-test, the sign test, and the Wilcoxon signed-rank test for matched pairs, although they do not take into account the time dependency of the observations. This would be justified in the case of infrequent manual observations if the time dependency were less prominent with larger time lags (> 30 consecutive observations) in this case than in the case of more frequent automatic measurements. The parametric *t*-tests and the Pearson correlation require the observations to be normally distributed, and therefore the normality test (Shapiro-Wilk) and the correlation were calculated for the time series to assess the test assumption. The *t*-tests can be used for the non-normal data if the number of observations is large enough (e.g., more than 30).

There were two methods for comparing the test results: using A) means of the values of the test results as a function of observation location, or B) categorized test results. In case A, the mean test results were calculated from 6 T0-T0 pairs, 6 T1-T1 pairs, and 16 T0-T1 pairs. Each pair was tested at the seven observation locations. In case B, the test results were not labeled according to the observation location and the total number of categorized test results (the number of pairs was multiplied with the number of observation locations) were 42 for T0-T0, 42 for T1-T1 pairs, and 112 for T0-T1 pairs.

4. Results

4.1. Testing of performance of drainage using graphical analysis

The minimum and maximum time series for T0 and T1 (Fig. 2) showed a clear periodicity for groundwater level. During mid- and late winter (January and February), the groundwater level descended below the drain depth, down to a depth of 2.5 m below the soil surface (maximum observation depth). The winter descent is followed by a steep rise in the groundwater level due to snowmelt in spring (yellow areas in Fig. 2). During winter 2015–2016, the snow cover period lasted from December to March and was followed by a rapid snowmelt in April (öijö et al., 2017). During summer and autumn (green and orange areas in Fig. 2), the groundwater table varied quickly in response to rainfall events.

The percentage of the observation time points, when the trenchless curve was above the trencher curve, varied from 60 to 90% for the minimum curve and from 72 to 84% for the maximum curve (Fig. 2). These numbers imply that the groundwater level in T0 tends to be closer to the soil surface. The average differences between the minimum and maximum curves varied between T0 and T1 and were highest in spring (0.48 m for T0, 0.56 m for T1) and lowest in autumn (0.33 m for T0, 0.26 m for T1). However, in spring, the groundwater level was mainly below the drainage depth (Fig. 2), during which the variation was the highest. The variance of groundwater level was also higher for T0 (0.015–0.019 m^2) than for T1 (0.009–0.013 m^2).

At the time of the harvest in 2015 and 2016, the groundwater level range was higher for T0 (0.2–0.98 m in 2015 and 0.02–0.73 m in 2016) than for T1 (0.07–0.76 m in 2015 and −0.04 to 0.3 m in 2016). At sowing time, the ranges were clearly smaller for both T0 (−0.14 to 0.05 m) and T1 (−0.3 to 0.07 m).

4.2. Background tests for the manual data

The test results (Fig. 3) for T0 and T1 sections showed that only 18 of the 56 (7 observation locations in each of the 8 sections) time series passed the Shapiro-Wilk normality test (p-value > 0.05). However, the

Table 2
Characteristics of the applied statistical tests and statistics. (Newbold et al., 2007).

Test	Parametric/Non-parametric	Distribution	Samples	Observations	Null hypothesis
t-test for matched pairs	**Parametric**	**Normal**	**1**	**Independent**	**Sample of matched pairs comes from a population with zero mean**
Sign test for matched pairs	**Non-parametric**	**Any**	**1**	**Independent**	**Sample of matched pairs comes from a population with zero median**
Wilcoxon signed-rank test	**Non-**parametric	**Any**	**1**	**Independent**	**Sample of matched pairs comes from a population with zero median**
Shapiro-Wilk test	**Goodness of fit test**		**1**		**Data is normally distributed**
Statistic	Parametric/Non-parametric	Distribution	Samples		
Pearson correlation	**Parametric**	**Normal**	**2**		
Kendall correlation	**Non-parametric**	**Any**	**2**		
Spearman correlation	**Non-parametric**	**Any**	**2**		
Sen's slope	**Non-parametric**	**Any**	**2**		
Cumulative sum	**Non-parametric**	**Any**	**1**		

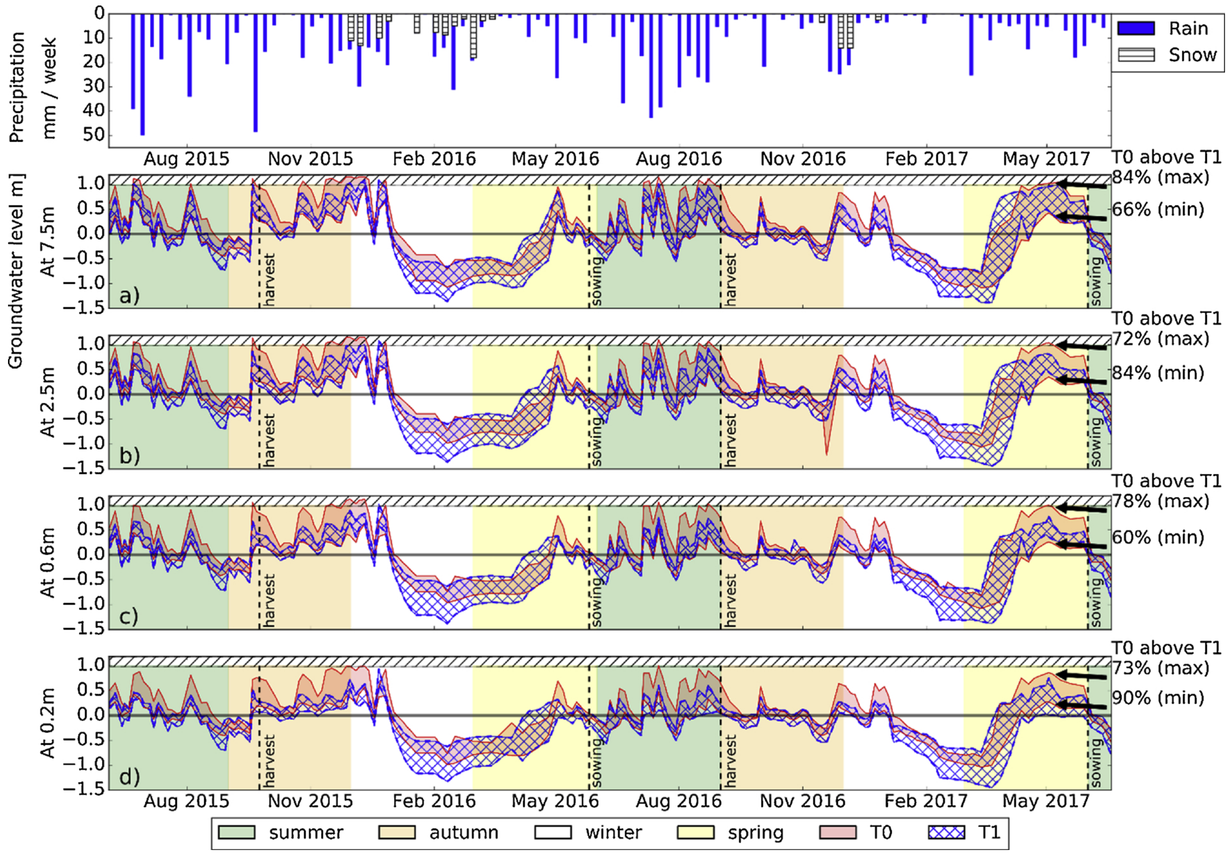

Fig. 2. Range of manually observed groundwater level time series for the trenchless (T0) and trencher (T1) methods. The black line represents the drain level, and the slash-line area the variation in the soil surface level. Summer, autumn, winter, and spring are indicated by green, orange, white, and yellow areas, respectively. Harvest and sowing dates are marked with dash vertical lines. The share of observations (%), in which the T0 curve is above the T1 curve, is calculated for the minimum and maximum curves. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

histograms were in most cases not excessively skewed or asymmetric. The kurtosis (excess) in the histograms varied, as they were in some cases flatter and in some cases more peaked than the normal distribution. To be more specific, the non-normal time series of T0 sections (1 and 7) and T1 sections (2 and 8) were more skewed to the left and at the same time rather flat. This phenomenon seemed to be the main reasons for the rejection of the Shapiro-Wilk test null hypothesis. The data distribution seemed to depend also on the order of the sections in the field. The histograms of the near-border sections (1, 7, and 8) were skewer and flatter than the sections in the middle of the field (see Fig. 1a)

All of the time series pairs (T0-T0, T1-T1, and T0-T1) had relatively high correlations (> 0.84) based on both the Pearson and Spearman correlation coefficients. Both correlation coefficients had almost similar values. Correlations for the same drainage method pairs (T0-T0 and T1-T1) and T0-T1 pairs were of the same order of magnitude. However, the correlation results seemed to be influenced by the soil type differences and the section position in the field. The correlations were highest (0.91–0.98) between neighboring sections (6 + 7, 4 + 3, 6 + 5) and between sections (3 + 5, 1 + 7, 1 + 2) that had a similar soil texture (in Table 1). The lowest correlations (0.84–0.88) were found between the sections (1 + 4, 1 + 5) that differed most in soil texture.

4.3. Testing of performance of drainage using time series

The test results in Fig. 4 imply that there were statistical differences in the groundwater level between the T0-T1 drainage pairs and the same drainage pairs (T0-T0 or T1-T1). Most of the cases tested with the parametric *t*-test and the non-parametric Wilcoxon and sign tests showed p-values < 0.01 (Table 3). The test results for the T0-T1 pairs suggest that the T1 method is preferred over the T0 method. The positive statistic indicated that the groundwater level in T0 is above T1. The Sen's slope (Fig. 4d) showed that the T0-T1 pairs differed from the same drainage method pairs. The slope was positive for the T0-T1 pairs, but around zero for the T0-T0 and T1-T1 pairs. The positive slope values implied that the groundwater level is deeper in T1 than T0, which is consistent with the graphical analysis in Fig. 2.

Cumulative sums of the groundwater level differences showed more variability for the T0-T0 pairs (Fig. 5a) compared to the T1-T1 pairs (Fig. 5b). The exception was at the locations −2.5 m and 0.2 m, where the cumulative sums of the T1-T1 pairs were spread through a wider range. The shape of the cumulative sums (the order of the lines) for T0-T0 was similar at each of the locations. The highest and lowest cumulative sums were between the inner (4 and 6) and outer (1 and 7) sections. The order was not as clear for the T1-T1 pairs (Fig. 5b).

The differences between the T0 and T1 sections (T1 is subtracted from T0) were detected as a rise in the cumulative sums (Fig. 5c). In almost all of the cases, the groundwater level was higher in the T0 section than in the T1 section. The same phenomenon was seen in the groundwater level range graphs (Fig. 2) and from the categorized test results (Table 3). The T0-T1 cases where the cumulative sums are negative (groundwater level in T1 above T0) were found with field section 4, which had clearly different soil particle size distribution compared to the T1sections (see Table 1).

4.4. Seasonally grouped time series

The sign test showed differences (p-value < 0.01) for T0-T0 and T0-T1 pairs during winter, summer, and autumn (Fig. 6a and c). For T1-T1 pairs, the differences were seen mainly during autumn and winter

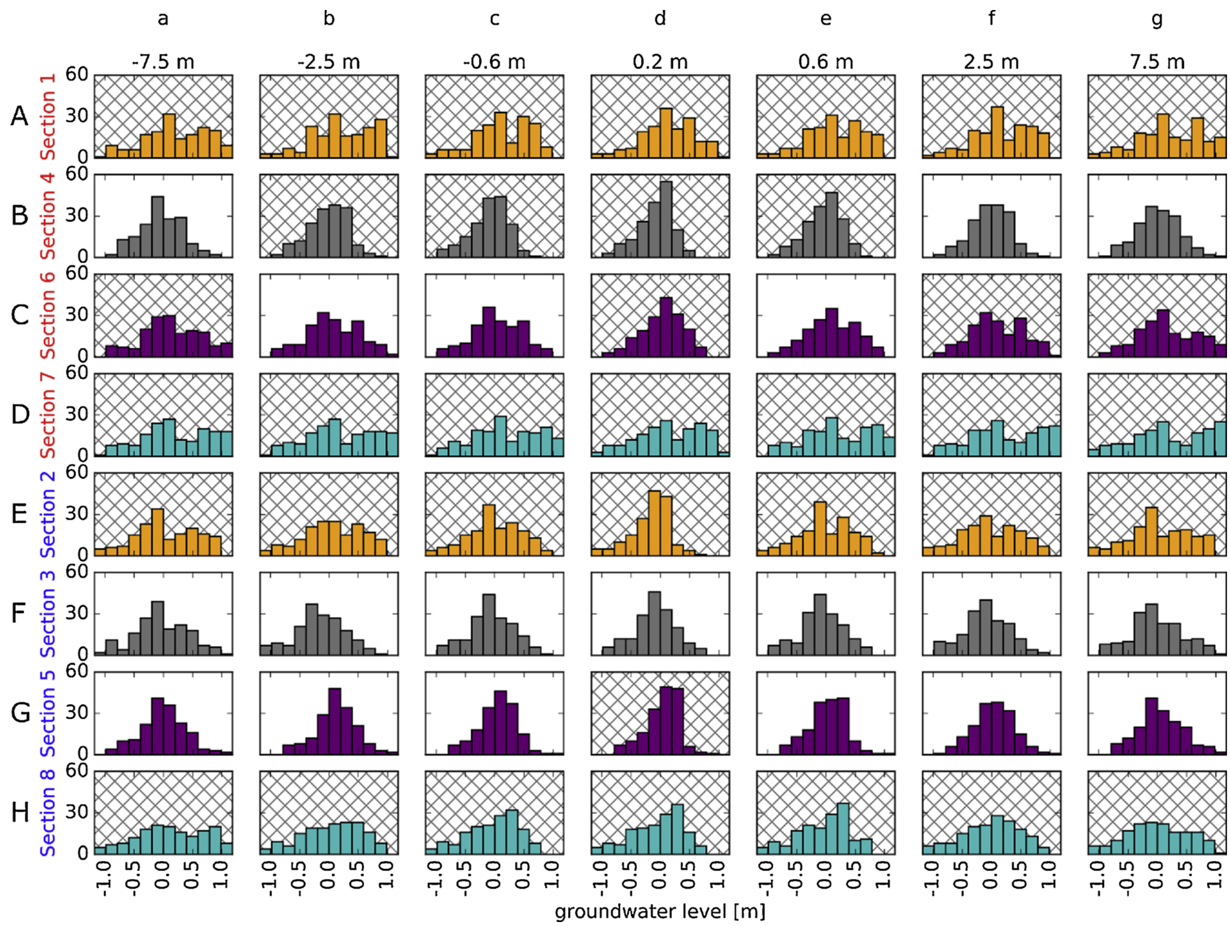

Fig. 3. Histograms of the groundwater level time series at different distances (columns a to g) from the drain location. Rows A to D are T0 sections, and rows E to H are T1 sections. The Shapiro-Wilk normality test results for the time series are presented with clear background (passed) and crossed background (rejected) at the seven observation locations (−7.5, −2.5, −0.6, 0.2, 0.6, 2.5, 7.5 m) using a bin interval of 12 for the range of -1.18–1.18. The null hypothesis that the data is normally distributed was rejected when the p-value was below 0.05.

(Fig. 6b). The seasonal variation in the test results seemed stronger than the differences between the T0-T1 pairs and the same-method pairs. However, the test results for T0-T1 pairs again showed that the T1 method was preferred over the T0 method: the share of positive statistics (dark bars in Fig. 6c) was higher than the share of negative statistics (light-shaded bars in Fig. 6c).

The categorized Sen's slope values (Fig. 6d–f) showed that in spring, T1-T1 pairs (slope < −0.01) differed from T0-T0 and T0-T1 pairs (slope > 0.01). In other seasons, T0-T1 pairs had positive slope values (i.e., the groundwater level for T0 was above T1), while the T0-T0 and T1-T1 pairs had slope values that were around zero or were negative (grey, yellow, and green bars in Fig. 6d and e). This is consistent with the sign test results: the test statistics of the same method pairs (Fig. 6a–b) were more evenly divided into positive and negative values.

4.5. Depth-filtered time series

The *t*-test and the sign test results for the depth-filtered time series of groundwater level were similar as those of the complete time series in Fig. 4 and Table 3. Most of the T0-T0, T1-T1, and T0-T1 cases showed

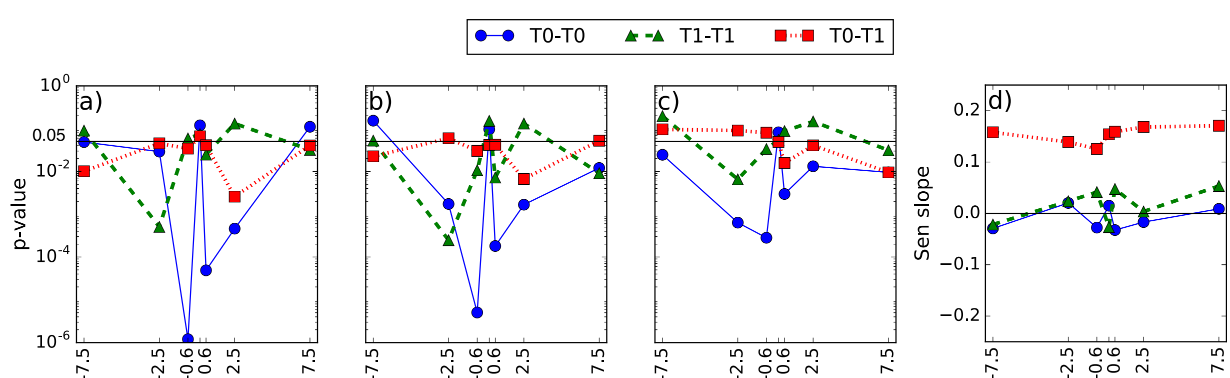

Fig. 4. Test results for differences between trenchless and trencher methods (T0-T1) and within the same method (T0-T0 and T1-T1): (a) One sample *t*-test, (b) Wilcoxon signed-rank test, (c) sign test, and (d) Sen's slope for full time series with T0-T0 (n = 6), T1-T1 (n = 6), and T0-T1 (n = 16) pairs, where n refers to the number of field section pairs.

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Table 3
Classification of the one sample t-test, Wilcoxon signed-rank test, and sign test results for T0-T0 pairs ($N = 42$), T1-T1 pairs ($N = 42$), and T0-T1 pairs ($N = 112$). N is the number of test cases (seven observation locations for each pair). W_{neg} is the sum of negative ranks, and W_{pos} is the sum of positive ranks. S^+ is the number of positive signs, and S^- is the number of negative signs.

Test	Pair	p < 0.01	0.01 ≤ p < 0.05	0.05 ≤ p < 0.1	0.1 ≤ p < 0.2	0.2 ≤ p
One sample t-test (positive statistic)	T0-T0	14	0	0	1	1
	T1-T1	14	1	0	2	4
	T0-T1	89	1	1	1	4
One sample t-test (negative statistic)	T0-T0	24	0	0	0	2
	T1-T1	18	1	0	1	1
	T0-T1	12	1	0	1	2
Wilcoxon $W_{pos} > W_{neg}$	T0-T0	14	1	1	0	2
	T1-T1	13	4	2	0	3
	T0-T1	86	1	1	0	3
Wilcoxon $W_{neg} > W_{pos}$	T0-T0	23	1	0	0	0
	T1-T1	16	3	1	0	0
	T0-T1	14	2	1	0	4
Sign $S^+ > S^-$	T0-T0	15	1	0	1	1
	T1-T1	14	2	0	2	2
	T0-T1	85	1	1	5	2
Sign $S^- > S^+$	T0-T0	21	2	1	0	0
	T1-T1	13	5	1	1	2
	T0-T0	9	1	1	0	7

p-values of < 0.01. For T0-T1 pairs, the tests clearly preferred T1 over T0 as the number of positive statistics was greater than the number of negative statistics. The positive Sen's slope values (Fig. 7a) for the T0-T1 pairs indicated that the groundwater level was higher in the T0 section than in the T1 section. Fig. 7b demonstrates the effect of drain layer soil type (Table 1) on groundwater level differences between the field sections. Comparison of loam sections (1, 2, 7, and 8) to sandy loam / loamy sand sections (3, 4, 5, and 6) showed positive slopes, which suggested that the groundwater level was closer to the soil surface in loam section than in sandy loam / loamy sand section. Notably, the effect of the drainage installation method (T0 or T1) on groundwater level time series was visible from the Sen's slope between the same soil type field sections (Fig. 7b): slope was not close to zero with the same soil type pairs (loam and sandy loam / loamy sand), which meant that there were differences between the tested time series. In both same soil type groups, there were two field sections drained with the T0 method and two with the T1 method.

Cumulative sums for the depth-filtered time series of the groundwater level differences (Fig. 8) showed more variability with the T0-T0 pairs (Fig. 8a): the total cumulative sums ranged between −50 and 40 m. The range for T1-T1 pairs (Fig. 8b) was between −20 and 20 m. The cumulative sums for the T0-T1 pairs (Fig. 8c–d) showed that the groundwater level in the T1 section was mainly lower than in the T0 section (rising cumulative sums). The differences were highest between the field sections that had different soil types (star-marks in Fig. 8). However, the difference between the soil types was markedly smaller for the T1 method (Fig. 8b). The clearest difference was when the soil type and the drainage method were different (Fig. 8d).

4.6. Comparison of automatic measurements and manual observations

In 14 out of 16 cases, the t-test and Wilcoxon signed-rank test (Table 4) revealed a difference between the automatic and manual groundwater level series (p-value < 0.05). The sign test shows that there was no clear pattern for the difference between the automatic and manual time series. At three T0 locations the groundwater level with automatic data was above the manual data, but at one location (7.5 m) the difference was the opposite. At the T1 locations, the automatic and manual data were closer to each other (test value close to 50%), except at one location (0.6 m). In absolute terms, the mean deviation of the time series pairs varied between −0.01–0.02 m for T1 and −0.02–0.01 m for T0, which is small compared to the absolute deviation between the manual time series (0.11–0.17 m).

5. Discussion

This study showed that there were differences in the groundwater levels between T0 and T1. On average, the maximum groundwater level was 0.1 to 0.15 m closer to the soil surface in the T0 sections compared to the T1 sections. Mirjat and Kanwar (1992) and Kanwar et al. (1986) also reported that the groundwater level was lower in trencher drainage than in trenchless drainage, but did not test differences between the same installation method plots. This study showed that the drainage method alone did not explain the statistically significant differences between the groundwater levels, as differences were also found between the same-method sections. However, the absolute mean differences were smaller between the same-method section pairs

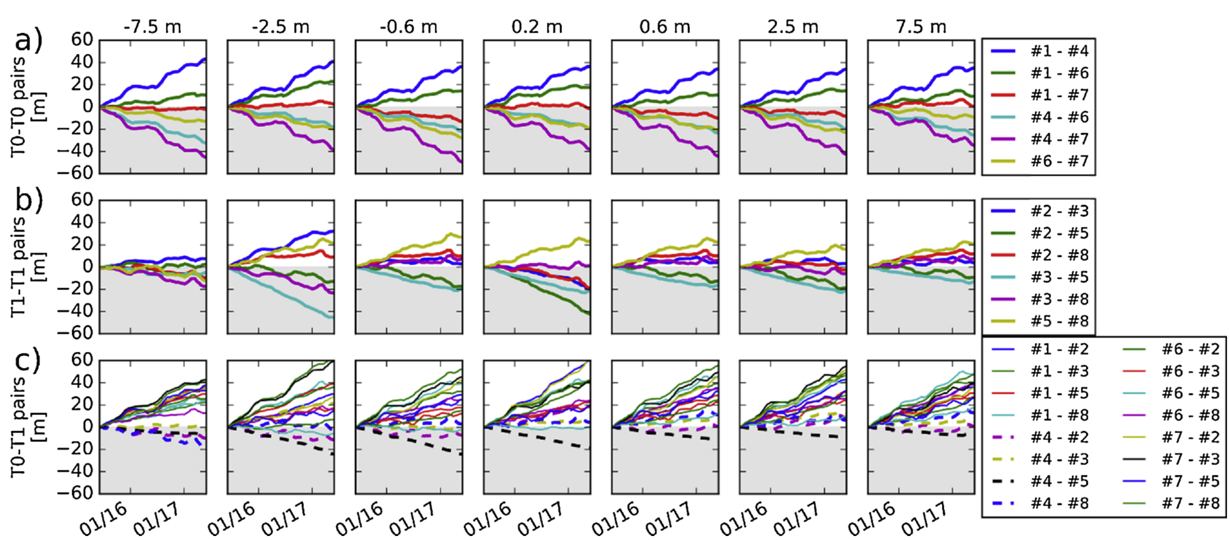

Fig. 5. Cumulative sums of the groundwater level differences for (a) T0-T0 pairs ($n = 6$), (b) T1-T1 pairs ($n = 6$), and (c) T0-T1 pairs ($n = 16$), where n is the number of field section pairs. The positive values mean that the groundwater level is higher in the T0 section than in the T1 section (row c).

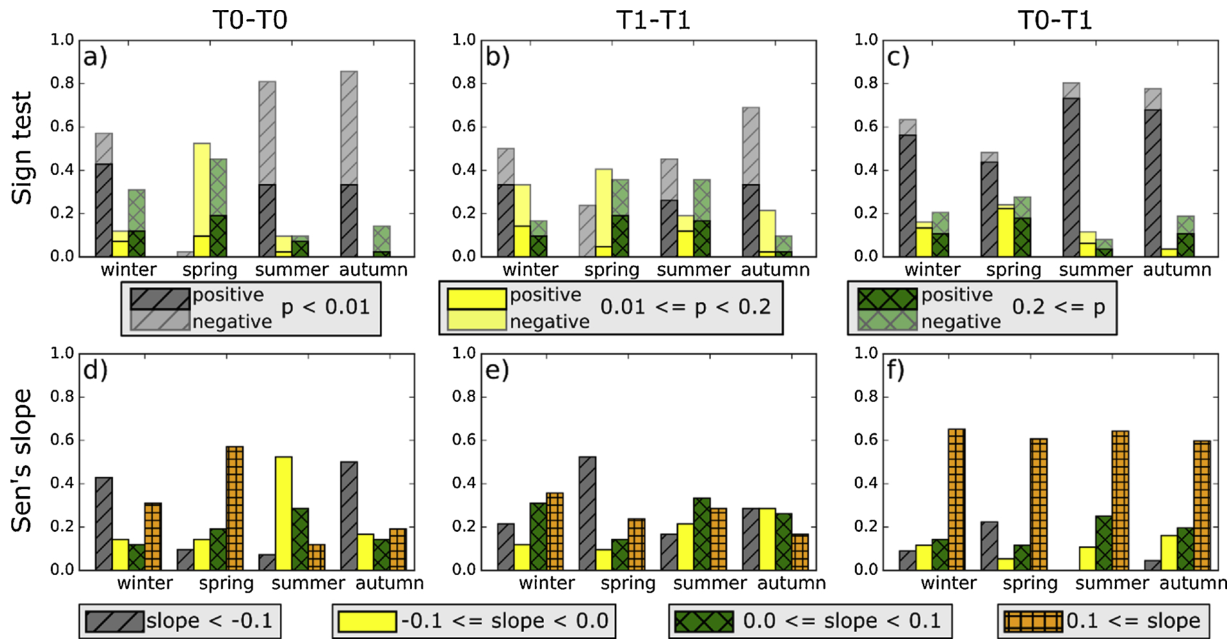

Fig. 6. Share of categorized test results for differences between trenchless and trencher methods (T0-T1) and within the same method (T0-T0, T1-T1): sign test (a–c), and Sen's slope (d–f) results for the seasonally grouped time series. The p-values (a–c) of 42 T0-T0, 42 T1-T1, and 112 T0-T1 test cases are categorized into three groups and Sen's slope into four groups. Negative (light-shaded bars) and positive (dark bars) statistics are marked separately for the categorization.

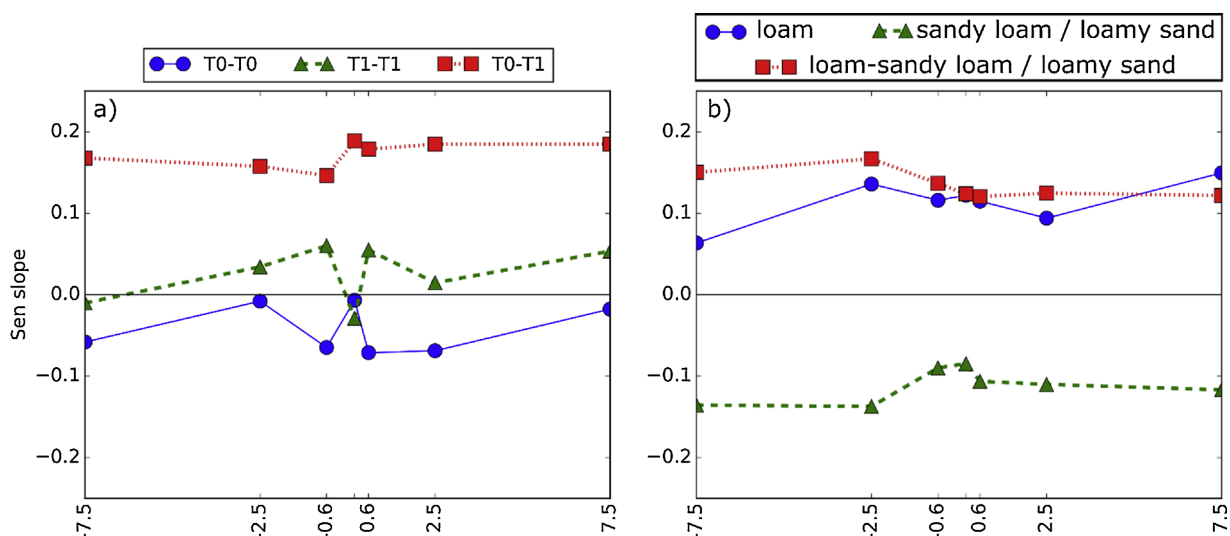

Fig. 7. Test results for differences between time series of depth-filtered data (groundwater level above 1.0 m) when testing the effect of (a) the drainage method or (b) the soil type. In (a) the field sections were divided into trenchless (1, 4, 6 and 7) and trencher (2, 3, 5 and 8) sections. In (b) the field sections were divided into loam sections (1, 2, 7 and 8) and sandy loam / loamy sand sections (3, 4, 5 and 6).

(0.01–0.08 m) than between the different-method section pairs (0.11–0.17 m). Mirjat and Kanwar (1992) also reported that the differences between the groundwater table for the T0 and T1 methods diminished after 10 years from the installation due to improvements in soil structure, which resulted in better performance with the T0 method. In this study, a longer monitoring period would be needed to reveal more permanent or long-term effects of the installation method.

Ayars and Evans (2015) listed the needs for sustainable drainage system design and pointed out the use of soil physical and hydrological properties as one key element. This study detected performance differences of drainage techniques shedding additional light on the role of soil transformation during the drainage installation. Chow et al. (1993) showed that the T0 and T1 methods resulted in differences regarding soil bulk density, macroporosity and hydraulic conductivity, but did not report soil variability as an affective factor to these differences. In Sievi, the cumulative sums within the same method showed that the differences in the groundwater levels were found between the loam and sandy loam / loamy sand sections. The differences between the T0 and T1 methods were more pronounced in the finer soil texture than the coarser soil texture. Tuohy et al. (2016b) showed that a site specific drainage solution (drain spacing and depth) was critical in the case of soils with low permeability (silty clay or silty clay loam). In Sievi, the drain spacing and depth did not vary, but effect of drainage machinery was visible regardless of the soil type as there were differences in the drainage performance within the same soil type field sections (Fig. 7b).

The test with the depth-filtered and seasonal time series showed that differences were mainly attributed to the drainage system and soil properties above the drain depth. The drainage installations in Sievi were conducted with an aim to minimize the differences between T0 and T1, using gravel as envelope material for both methods. The

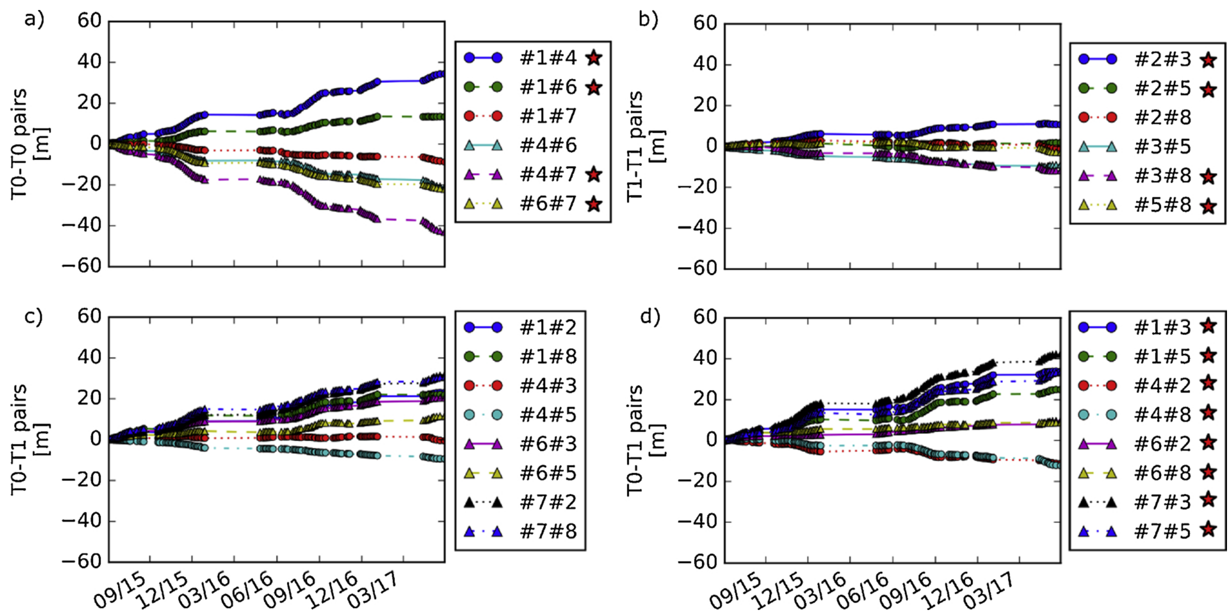

Fig. 8. Cumulative sums of groundwater level differences (average of the seven observation locations) for the depth-filtered time series of (a) T0-T0 (n = 6), (b) T1-T1 (n = 6), (c) T0-T1 with same soil type (n = 8), and (d) T0-T1 with different soil type (n = 8) pairs, where n is the number of pairs. The field section pairs that have different soil type are marked with a star.

Table 4
Test results for comparing automatic and manual groundwater level measurements in sections with the trencher (T1) and trenchless (T0) drainage methods. The acceptance of the test hypothesis (in Table 2) is marked in yellow (rejected) and blue (accepted). (For interpretation of the references to colour in this table legend, the reader is referred to the web version of this article.)

	One sample *t*-test				Wilcoxon signed rank test				Sign test (manual < auto)			
	7.5	2.5	0.6	0.2	7.5	2.5	0.6	0.2	7.5	2.5	0.6	0.2
Auto vs manual (T0)	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	84%	4%	38%	9%
Auto vs manual (T1)	0.01	0.61	$<10^{-3}$	$<10^{-3}$	0.014	0.50	$<10^{-3}$	$<10^{-3}$	38%	53%	89%	18%

graphical analysis and cumulative sums showed that the smallest absolute differences were at the furthest observation distance from the drain line, while the largest absolute differences were near the drain line (at the −0.6, 0.2, and 0.6 m locations). That is well in line with the findings that the trenchless and trencher machineries alter the soil above and near the drain line differently (FAO, 2005; Chow et al., 1993). The Sievi results suggested that the soil transformation depended on soil type with the T0 method, whereas soil transformation was more similar with the T1 method. Both methods had two loam sections and two sandy loam/loamy sand sections. The variability of the groundwater level was higher near the drain line for T0 than for T1.

In Sievi, the groundwater table reacted quickly to the rain events. Despite the quick response, the twice-a-week observation interval was found to be accurate enough to identify differences in the groundwater level between T0 and T1. Groundwater level was studied instead of drain discharge, because it is a common variable to assess field drainage capacity (e.g., Kornecki and Fouss, 2001; Mirjat and Kanwar, 1992) and trafficability (Kandel et al., 2013), and it enabled the spatial comparison between the field sections. Observation intervals used for manual data seemed to be accurate in detecting the changes in groundwater levels, which was seen in the similar autocorrelations (for the first 26 lags) both in automatic and in manual data. Even though there were statistically significant differences between the automatic and manual data, comparison of the absolute values revealed that the groundwater level varied between the sections more than between the automatic and manual measurements in sections 5 and 6. In Sievi, automatic data series were available only from one T0 section and one T1 section, while manually collected data series (four T0 and four T1 sections) enabled the comparison between T0-T0 and T1-T1 pairs. Automatic measurements were useful in verifying the manual observations and could be further used in calculating the response time of drainage after different rain events, as described by Tuohy et al. (2016a).

According to Helsel and Hirsch (2002), the nature of the hydrological time series (non-normal distributions, autocorrelation, outliers, and dependence on other uncontrolled variables) should be carefully considered to avoid misinterpreted test results. The main challenges in selecting the tests were met by applying multiple statistical tests and analysis methods (Table 5). Statistical tests for matched pairs (*t*-test, Wilcoxon signed rank test, and sign test) were selected to avoid the correlation between the field sections from affecting the test results. The study setup was designed to minimize the impact of the neighboring field sections. However, because field sections were not separated by plastic walls in the ground, lateral subsurface flow possibly occured. To study the differences caused by the drainage method, it was desirable that the only change between the field sections would be the drainage method. The time series had strong positive correlations, which was mainly caused by the same field conditions (temperature and precipitation). The matched pair test assumptions of independent observations were violated (Table 5), which is often common in hydrological studies (e.g., Kandel et al., 2013; Mirjat and Kanwar, 1992; Bakhsh and Kanwar, 2004). Still, the results from the matched pair tests gave similar indications as the results from time series analysis (Sen's slope and cumulative sums), which did not suffer from the time dependency of the observations.

Table 5
Summary of the used statistical methods and the study questions. The tested pairs (T0-T0, T1-T1, and T0-T1 pairs) are shown in the questions and the data used in the test is shown in the parenthesis (FS = full time series, SeS = seasonally selected time series, DFS = depth-filtered time series).

	Research questions							
	Were there differences in groundwater levels between the T0-T1 pairs?	Were there differences in groundwater levels between the T0-T0 or T1-T1 pairs?	Were there seasonal differences?	Were the differences caused by the drainage method (T0 or T1)?	Showed differences between T0-T0 pairs	Showed differences between T1-T1 pairs	Showed differences between T0-T1 pairs	Test assumptions violated
Graphical analysis (FS)	x	x	x					
Variance (FS)		x						
One sample t-test (FS, SeS, DFS)			x		x	x	x	Yes
Wilcoxon signed-rank test (FS)					x	x	x	Yes
Sign test (FS, SeS, DFS)			x		x	x	x	Yes
Sen's slope (FS, SeS, DFS)	x	x	x				x	
Cumulative sums (FS, DFS)	x	x		x				

Based on the results, it is necessary to study the variation between the same drainage method sections to distinguish the effect of the drainage machinery from other factors. Testing the same-method field sections has been missing in previous drainage method studies (Mirjat and Kanwar, 1992; Peyton et al., 2016), but was noted by Tuohy et al (2016a), who could not rule out the effect of sloping field topography and soil heterogeneity on their results. In this study, the field topography was taken into account in the experimental design, and the sections were placed to maximize their similarity in terms of soil type, slope, and water flow routes (including old open ditches). However, the drainage machinery effect was not completely isolated as statistical differences were found within the T0-T0 and T1-T1 pairs. The graphical analysis and the cumulative sums suggested that the experimental design did not fully exclude the effect of topography (e.g. natural flow direction) or soil type. In the winter, groundwater level dropped below the drain level, which was not solely caused by the installed drainage system. The low groundwater level (below the drain depth) could be due to (1) soil frost that causes capillary upflux lowering the water level (e.g. Sheng et al., 2013), or (2) groundwater outflow. During the low groundwater level period, there was high variation in the groundwater level within the field, which can indicate variability in soil properties or surrounding area controlling the water flow magnitude and direction in the field. Soil properties and regional water table gradient are the main features that control gravitational flow in the deep soil layers. Even though the effects of other factors on water table were not fully exposed, the statistical tests and cumulative sums for the T0-T1 pairs clearly preferred the T1 method over the T0 method.

The overall differences in groundwater levels might not have an impact on cultivation, as supported by the lack of distinct differences in crop yield between the sections in Sievi (Äijö et al., 2017). The graphical analysis showed some occasional larger (> 0.4 m) differences between the T0 and T1 sections, especially at the 0.2 m location (21 of the 172 observations). In July 2016 there were five such large differences in a row due to high rainfall volumes (Fig. 2). In November–December 2015 there were nine observations with a higher groundwater level (> 0.4 m) in the T0 section than in the T1 section during mild and wet early winter conditions.

The graphical analysis and the seasonally categorized time series revealed that larger differences between T0 and T1 occurred during late summer harvest (0.2 to 0.47 m) than during spring sowing (0.01 to 0.05 m) for the maximum groundwater levels.

6. Conclusions

Statistical analysis of the field measurements from a drainage machinery experiment in Sievi showed that the subsurface drainage method affected the groundwater level after the installation (0–2 years). However, statistically significant differences were found in the time series between the same-method field sections as well, indicating that the effect of soil type on groundwater level was not totally excluded by the experimental setup.

The T0 sections were found to have a lower drainage performance than the T1 sections. The absolute differences did not seem to affect cultivation at the time of the sowing, but the differences were most pronounced during harvest. The cumulative sums and time series variances showed more variability in the groundwater levels between the T0 sections compared to the T1 sections. In finer soil texture, the effect of the drainage machinery was greater on drainage performance, compared to coarser soil texture. The drainage performance (groundwater levels above the drain level) was more similar between T0 and T1 in the sandy loam / loamy sand sections compared to loam sections. The impact of T1 on groundwater levels was more consistent in loam and sandy loam / loamy sand sections compared to T0.

Among the groundwater level differences found at all observation locations, the largest absolute differences were found at the locations near the drain. The effect of the drainage machinery on water table diminished as the observation distance from the drain increased.

The Sen's slope and the cumulative sum proved to be the most efficient tools for identifying differences between the groundwater level time series. Even though the matched pair tests showed differences between the same (T0-T0 and T1-T1) and different (T0-T1) drainage method groups, the Sen's slope identified clearer differences in T0-T1 group, and the cumulative sums showed the magnitude of groundwater level differences between the tested groups.

The practical value of the study is in answering the question about the performance of the T0 and T1 methods in Nordic conditions. There has been a lack of scientific information about the differences the methods may have. The results showed that there were detectable differences between T0 and T1, but the practical implications to the field drainage performance were small.

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