Research article

Functional Evaluation of Groundwater Level Decrease in Non-sloped Subsurface Drainage Systems in Upland Field on Peatland

NAHO NOHARA
Graduate School of Agriculture, Hokkaido University, Sapporo, Japan

MINORU YOKOCHI
Graduate School of Global Food Resources, Hokkaido University, Sapporo, Japan

TADAO YAMAMOTO*
Research Faculty of Agriculture, Hokkaido University, Sapporo, Japan
Email: tady@env.agr.hokudai.ac.jp

TAKASHI INOUE
Research Faculty of Agriculture, Hokkaido University, Sapporo, Japan

Received 1 February 2019 Accepted 20 October 2019 (*Corresponding Author)

Abstract In lowland farmland, the maintenance cost of conventional inclined subsurface drainage systems is high because the drainage pipes must be laid at depth, or the tile deepens as the farm field enlarges. To reduce the maintenance cost, the Hokkaido Provincial Government of Japan has introduced a subsurface drainage system with a smaller inclination angle than the conventional method. However, the drainage effects of non-sloped subsurface drainage systems have been rarely reported, and insufficient evidence has prevented their widespread acceptance. The present study investigates how the slope of the drainage pipe influences the groundwater-level decrease in poorly drained fields. The survey was conducted in the upland field on peatland located in the Ishikari River Basin, Hokkaido. In 2015, two types of subsurface drainage systems were constructed in the same lot: a conventional subsurface drainage (sloped area) system, and a subsurface drainage system with low inclination (non-sloped area). After measuring the groundwater level at 12 points and the precipitation from 2016 to 2017, we found that: i) the groundwater level was higher in the non-sloped area than in the sloped area, ii) between 2016 and 2017, the groundwater level decreased in the sloped area and rose in the non-sloped area. The above results suggest that the efficiency of decreasing the groundwater level during 3 years after the construction was lower in non-sloped subsurface drainage than in sloped subsurface drainage, which is different from that observed in the previous study.

Keywords subsurface drainage, groundwater level, large-scale field, peatland

INTRODUCTION

In some developed countries, including Japan, the economic growth of the agricultural industry has declined while that of the secondary and tertiary industries has increased. This problem has severely affected rural communities in Japan. Maintaining agricultural production and enhancing the competitiveness of agriculture are urgent demands in Japan’s agricultural policy. As the farming population decreases, agricultural production must be maintained by astute agricultural business, improvement of work efficiency, and labor-saving measures. As a precondition of arresting this decline, the enlargement of farm fields has been promoted. Subsurface drainage has been widely implemented for improving the yield and quality of farm products. In the future, the competitiveness of agriculture must be bolstered by lowering the installation cost of facilities and constructing irrigation and drainage systems, including subsurface drainage systems.

In Hokkaido, northern Japan, lowland farmlands developed from peatland are widespread, and subsurface drainage is employed to improve the soil condition. Recently, the average field size has progressively enlarged to enhance the productivity. Deeper pipes and ditches are needed to install conventionally sloped subsurface drainage pipes in large fields, which increases the implementation cost. In an attempt to alleviate this problem, subsurface drainage pipes with no inclination (<1/600) have been trialed in a suitable geographical feature (Koshiba et al., 2005). However, as very few studies have evaluated the function of non-sloped subsurface drainage, the practicality of this approach is currently unknown. Non-sloped subsurface drainage reduces over time as the drainpipes become uneven and accumulate soil sediments. Koshiba et al. (2005) reported no significant malfunction caused by pipe sedimentation and unevenness after five years' implementation of non-sloped subsurface drainage in a farm field with sandy loam soil. They also reported the same drainage through non-sloped and sloped pipes. They concluded that non-sloped pipe drainage effectively reduces the installation cost (Koshiba et al., 2005).

However, the functioning of non-sloped subsurface drainage has not yet been investigated in Hokkaido, where peat layer is distributed. Peat is an organic-rich soil consisting mainly of undecomposed plant material, which accumulates in saturated environments. Such environments require intense drainage to reach suitable conditions for agriculture, but owing to their unique composition, inevitably subside under agricultural drainage and artificial loading. Armstrong and Castle (1999) stated that peat subsidence frequently misaligns the drainpipes and inverts the gradient along the pipes. They also mentioned that because peat is rich in iron, pipes laid in peatland are often clogged with deposits of iron ochre, an orange-colored mud made of iron compounds (Armstrong and Castle, 1999). The question remains whether non-sloped drainage performs well in peatlands, where the drainage conditions are difficult. Therefore, to evaluate the function of non-sloped subsurface drainage on peatland fields, this study compares the groundwater-level changes in conventional (sloped) and non-sloped pipe subsurface drainage systems installed in the same field.

METHODOLOGY

Overview of the Research Site

The study was carried out in an upland field in Iwamizawa (43°12′ N, 141°43′E), located in the east of the Ishikari plains in Hokkaido (Fig. 1). The mean annual temperature and precipitation are 7.6°C and 1,163 mm, respectively. In the research field, the peat layer underlies a 30 cm-thick upper artificial soil. In August of 2015, subsurface drainage pipes with low inclination were installed in one-half of the field (forming the non-sloped area), and conventional subsurface drainage was implemented in the other half (sloped area) (Fig. 2). This setup permits a performance comparison between the drainage experiment and a control experiment with a different drainpipe slope in the same lot. The field size is 1.1 ha, and onions were grown from May to August in 2016 and 2017. The drainpipes are buried 70 cm below the surface at 9-m intervals. In the sloped area, the drainpipes are inclined at 1/500, and their diameter is 60 mm (versus 80 mm in the non-sloped area). This difference in diameter is based on the design criteria. The drainpipes are filled with gravels. Prior to cultivation, the subsoil was broken to improve the drainage.

Survey Equipment

The precipitation in the field was measured hourly by a tipping-bucket rain gauge with a diameter of 20 cm (HOBO event, Climatec Incorporated, Tokyo, Japan) placed near the study field. Groundwater-level gauges for absolute pressure measurements (S & DL water level, Oyo Corporation, Tokyo, Japan) were set at six points (five between the drainpipes, and one just above the drainpipe) in both the sloped and the non-sloped areas, giving 12 observation points in total (Fig. 2). The groundwater level was measured every 30 minutes. The measured absolute pressures were converted to gauge pressures by a barometer installed near the field.

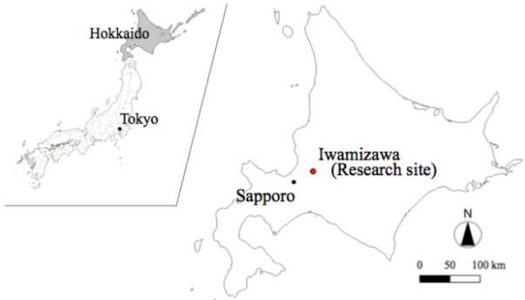


Fig. 1 Location of the research site

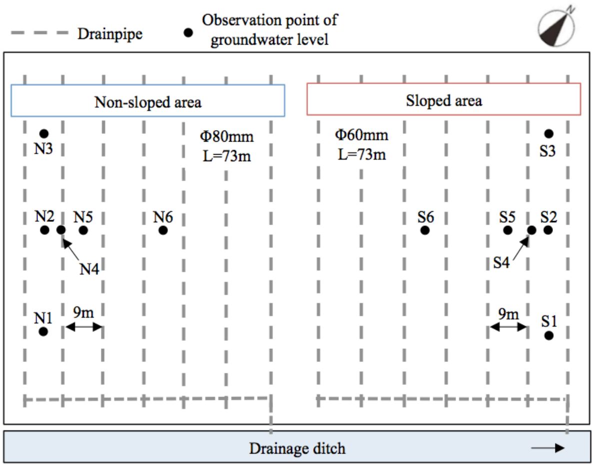


Fig. 2 Overview of the research site

Evaluation Method

The groundwater level generally rises immediately after rainfall, and gradually declines after the rain. The drop-down phase depends on the characteristics of the draining process. From the obtained rainfall data and the groundwater levels in the field investigations, we evaluated the following contents: i) groundwater-level dynamics, ii) groundwater-level drop response after a rainwater-induced rise in the groundwater level, and iii) achievement rate of the design target set by Hokkaido Prefecture Agricultural Administration Department. The subsurface drainage efficiency was evaluated by comparing the rainfall-related contents and groundwater table fluctuations in the sloped and non-sloped areas. We also evaluated the time-series changes in the function of each drainage system by comparing the results of 2016 and 2017. The observation data from June to mid-August in 2016 and 2017 were used for the drainage evaluation. For determining the drainage efficiency, we defined the following terms.

Groundwater level: Vertical distance from the ground surface to the groundwater table at each observation point.

Rain event: Rainfall within 24 hours of the rainfall start is regarded as a *rainfall series*. Rainfall of 1 mm/h or more within 24 hours after the rain stopped was included in the same event. Rain events with a total rainfall of 10 mm or more were used in the evaluation.

Amount of groundwater level increase: The groundwater-level difference between immediately before the rain event and the highest water level during the rain event.

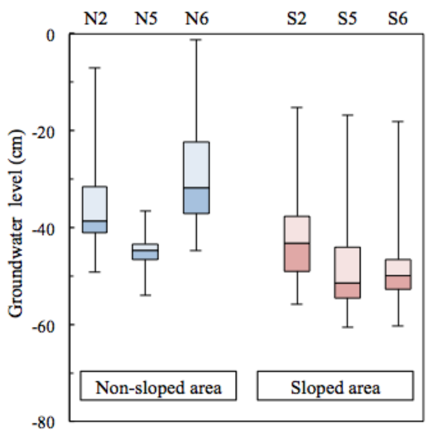
Amount of groundwater level drop: The groundwater-level difference between the highest water level during the rain event and the lowest water level after the rain event.

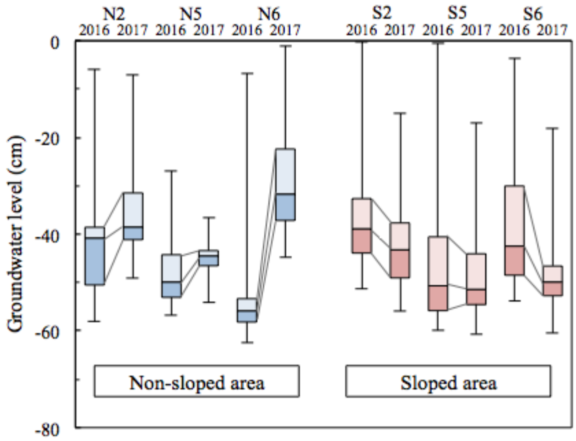
Groundwater level drop rate: The ratio of the amount of groundwater level drop to the amount of groundwater-level rise after the rain event.

RESULTS AND DISCUSSION

Fluctuation of Groundwater Level

The drainage was evaluated by comparing the fluctuations in the groundwater levels at each observation point. The results are presented as box plots. Fig. 3 shows the distribution of groundwater levels at six observation points located at the same distance from the drainage ditch (N2, N5, N6, S2, S5, S6) in 2017. Comparing the fluctuations in groundwater levels in 2017, the fluctuation range of groundwater levels at N5 tended to be narrower than other points. The groundwater fluctuations except N5 remained at a higher level in the non-sloped area than in the sloped area. Fig. 4 compares the distributions of groundwater level at the above-mentioned six observation points in 2016 and 2017. The 2016 survey result confirmed the high performance of the non-sloped subsurface drainage relative to the sloped system, similar to previous studies (e.g. Koshiba et.al., 2005). However, the groundwater distribution in the non-sloped area was higher in 2017 than in 2016. In contrast, the groundwater in the sloped area was lower in 2017 than in 2016, possibly because the subsoil was broken by subsoiler before tilling in 2017, and the precipitation was lower in that year than in 2016. However, despite the same climate conditions and the same farming method in both areas, subsoil breaking exerted no effect in the non-sloped area. This suggests that, for some reason, the subsurface drainage functioning (maintenance of low-level groundwater) was lower in the non-sloped area than in the sloped area.





The top and bottom extremes of the whiskers indicate the maximum and minimum groundwater levels, respectively, and the segment inside the box is the median groundwater level. The lower and upper base lines of the boxes indicate the first quartile (25th percentile) and third quartile (75th percentile), respectively.

Fig. 3 Groundwater level changes at 6 observation points in 2017

Fig. 4 Comparison of groundwater-level fluctuations between 2016 and 2017 at 6 observation points

Rain Response of Groundwater Level

In a properly functioning drainage system, the raised groundwater table quickly falls after the rainfall cessation. The drainage function was evaluated by relating the rises and falls in the groundwater level after several rain events. The evaluation was performed at 10 observation points (N1, N2, N3, N5, N6, S1, S2, S3, S5, S6) located between the drainage pipes. Points located above the drainage pipes (N4, S4) were excluded because their locations relative to the drainpipe differed from those of the other points. Figs. 5 and 6 plot the groundwater-level drop versus the groundwater-level rise at 24 and 72 hours, respectively, at all observation points after each rain event. The average groundwater-level drop rate over all rain events and observation points can be determined from the regression coefficient; when the regression line is steep, the soil is well drained after the rainfall-induced rise in groundwater level. The drainage efficiencies were compared by comparing the steepness of the regression lines between the sloped and the non-sloped areas, or between 2016 and 2017. The statistical significances of the groundwater-level drop rates were assessed by a 2-sample *t*-test at the 95% confidence level.

We first compared the drainages in the sloped and non-sloped areas in 2017. As shown in Fig. 5, the gradient of the regression line was smaller in the non-sloped area than in the sloped area. In the sloped area, 67% of the groundwater level raised by rainfall (on average) was withdrawn within 24 hours, versus 52% in the non-sloped area. The groundwater-level drop rate was significantly higher in the sloped than in the non-sloped area (2-sample *t*-test; $p < 0.01$). At 72 hours following the rain events, the groundwater drop rates were statistically the same (2-sample *t*-test; $p > 0.1$). The results imply that immediately after the rain events, the drainage system with sloped pipes better withdrew the groundwater level than the drainage system with level pipes.

Next, the time-series changes of drainage function in the non-sloped area were compared between 2016 and 2017. At 24 hours following the rain events, the groundwater-level drop rate was smaller in 2017 than in 2016, and the reduction was significant (2-sample *t*-test; p <0.01). The same result was obtained at 72 hours following the rain events (Fig. 6). Specifically, the groundwater level at 72 hours following the rain events dropped by 100% in 2016 (meaning that the groundwater level had recovered to its pre-rain level within 72 hours), but reduced by only 82% in 2017. In the sloped area, a reduction in the groundwater-level drop rate between 2016 and 2017 (from 96% to 85%) was found only at 72 hours following the rain events. If it is assumed that there are no differences in soil physical properties based on farming operations, the decline of the subsurface drainage function after rainfall was more conspicuous in the non-sloped area than in the sloped area, implying that inclining the drainpipes plays an important role in maintaining drainage function.

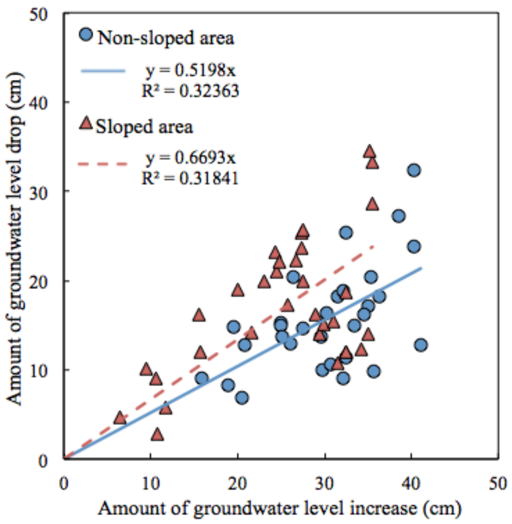


Fig. 5 Relationship between rise and fall in groundwater level at 24 hours after rain events in 2017

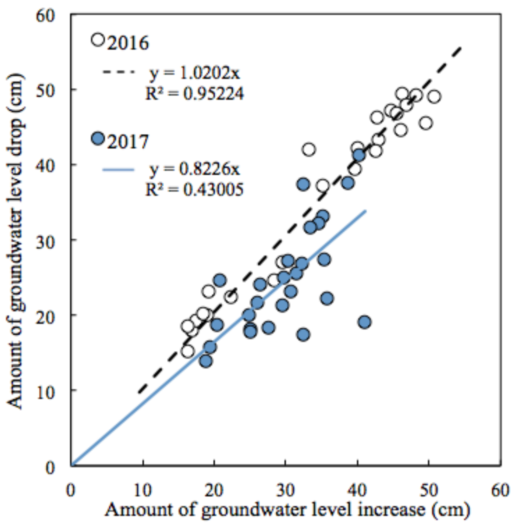


Fig. 6 Relationship between rise and fall in groundwater level at 72 hours after rain events in the non-sloped area

Achievement Rate of the Groundwater Level Standard

Table 1 Achievement rates of groundwater-level standard

		2016	2017
Non-sloped area	N1	100%	63%
	N2	86%	38%
	N3	100%	63%
	N4	100%	—
	N5	100%	100%
	N6	100%	0%
	Avg.	**97%**	**53%**
Sloped area	S1	100%	100%
	S2	43%	63%
	S3	71%	100%
	S4	100%	100%
	S5	100%	100%
	S6	86%	100%
	Avg.	**83%**	**94%**

The desired groundwater level has been set as a design target of subsurface drainage systems. According to the Hokkaido Prefecture Agricultural Administration Department (2010), a welldesigned groundwater level should be −60 to −50 cm under dry conditions, and −50 to −40 cm at two or three days after cessation of a rain event. However, during the observation period of the present study, the no-rainfall periods rarely continued for more than seven days; therefore, we decided to set the standard for a well-functioning groundwater level below −40 cm at 72 hours after cessation of a rain event. The achievement rate of this standard was calculated at each observation point, and used in the drainage-efficiency evaluation. Table 1 lists the achievement rates at all observation points in 2016 and 2017. The achievement rates and averages in the sloped area improved from 2016 to 2017. On the other hand, many points in the non-sloped area showed low achievement rates in 2017, and the average achievement rate was considerably decreased from that of 2016 in spite of subsoil breakage. Furthermore, the achievement rate was higher in non-slope area than in the sloped area in 2016; therefore, it seems that pipe inclination is not a direct cause of the decrease in the subsurface drainage function. From these results, we considered that some factors, except for soil physical changes, influencing drainage function decline may have occurred by the elapsed time since the construction. Thus, the cause of drainage function decline may be related to changes in conditions inside the pipe, similar to water pass prevention due to sediment accumulation.

CONCLUSION

The present study investigated how the slope of the drainage pipe influences the groundwater-level decrease in poorly drained fields on peatland located in the Ishikari River Basin, Hokkaido. After measuring the groundwater level at 12 points and the precipitation from 2016 to 2017, we found that: (i) the groundwater level was higher in the non-sloped area than in the sloped area; (ii) between 2016 and 2017, the groundwater level decreased in the sloped area and increased in the non-sloped area; and (iii) the drainage efficiency in the non-sloped area tended to decrease after 3 years of installation.

The 2017 findings revealed a large difference between the groundwater behavior in the sloped and non-sloped areas, although the same farming method was implemented in both areas, and the drainage function obviously declined in the non-sloped area. These results contradict a previous field study conducted on loam soil (Koshiba et al., 2005). Unlike loam soil, peatlands cause special problems in subsurface drainage, such as subsidence-associated misalignment of the pipes and deposition of iron ochre (*Thiobacillus ferrooxidans* colony) in the pipe interiors. Subsurface drainage through sloped pipes may tolerate these problems because the pipe gradient increases the flow velocity of the drainage water. At sufficiently high flow velocities, the deposit is easily washed away. The gradient might also prevent misalignment and inverse gradients of the pipes. On the other hand, the non-sloped drainage may be adversely affected by these peatland characteristics. Our results implied that inclining or periodic cleaning the drainpipes is important for maintaining the performance of the drainage system.

ACKNOWLEDGEMENTS

This research was conducted under the cooperation agreement between Hokkaido Prefecture Agricultural Administration Department, and Fishers and Forest Department, and Faculty/Graduation School/Research Faculty of Agriculture, Hokkaido University. The authors would like to thank the staffs of Hokkaido Prefecture Agricultural Administration Department and Sorachi Subprefecture, and Central Agricultural Experiment Station of Hokkaido Research Organization for their supports.

REFERENCES

Armstrong, A.C. and Castle, D.A. 1999. Drainage of organic soils. In Skaggs, R.W. and Schilfgaarde, J. van (Eds.) Agricultural Drainage, 1083-1105, Madison, Wisconsin, USA.

Hokkaido Prefecture Agricultural Administration Department. 2010. Design guidelines for subsurface drainage.

33-34, Retrived from http://www.pref.hokkaido.lg.jp/ns/jcs/grp/03/ankyosisin2206.pdf
Koshiba, N., Okuyama, T., Iwabuchi, Y. and Arihara, K. 2005. Drainage performance of a shallow pipe drain with no slope. Jour. JSIDRE, 73 (10), 917-918.