2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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Potential of controlled drainage and sub-irrigation to manipulate groundwater table for mitigating acid loadings in Finnish acid sulfate soils

Seija Virtanen[1], Jaana Uusi-Kämppä [2], Peter Österholm [3], Anna Bonde[4], Markku Yli-Halla[5]

[1]Drainage Foundation sr, Simonkatu 12 B 25, 00100 Helsinki, Finland; [2]Natural Resources Institute Finland (Luke), Natural resources and bioproduction, Tietotie 4, 31600 Jokioinen, Finland; [3]Department of Geology and Mineralogy, Åbo Akademi University, Domkyrkotorget 1, 20500 Åbo, Finland; [4]ELY Centre, South Ostrobothnia, Vaasa, Finland; [5]Department of Food and Environmental Sciences, University of Helsinki, P.O. Box 27, 00014 Helsinki, Finland

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ABSTRACT. *Acid sulfate (AS) soils are located worldwide mainly on coastal and floodplain areas. In Europe, the largest cultivated AS soil areas are on the coasts of Baltic Sea in Finland. The oxidation of sulfidic materials in AS soils results in formation of sulfuric acid and consequent dissolution of toxic metals and deterioration of aquatic ecosystems. Their reclamation for cultivation by field drainage, dredging of main drains and poldering exposes soils for oxidation and once initiated the negative impacts may last for decades. Practical water protection measures to mitigate acid loads from cultivated AS fields are urgently needed. In this study, the impact of controlled drainage (CD) and sub-irrigation (CDI) on water quality was compared with a field that has normal subsurface drainage (ND). In CD and CDI groundwater depth was regulated by control wells and in CDI additional water was pumped into drains when groundwater dropped below the critical level. The groundwater could be kept higher in CD and in CDI than in ND and the higher groundwater slightly decreased acidity of discharge water. After dredging, the main drain groundwater level dropped deeper than earlier and consequently the acidity of discharge water increased. In CDI, the acid leaching was on average 22% less than in ND. However, ever more reduction in acid loadings is needed to reach the target of good quality of surface waters in AS soil areas till 2027, as aimed in the EU Water Framework Directive regulation.*

Keywords *acid sulfate soils, acidity of drain water, controlled drainage, EC, environmental protection, sulfate, subsurface drainage*

Introduction

Acid sulfate (AS) soils are located worldwide mainly on coastal and floodplain areas, assumed to cover over 17 million ha (Andriesse & van Mensvoort, 2006). They are called the “nasties” soils in the world because they contain surplus of sulfidic materials in relation to neutralizing agents (Dent & Pons, 1995). The oxidation of sulfidic materials, e.g. pyrite (Equation 1) or monosulfides (Equation 2) results in the formation of sulfuric acid (van Breemen, 1973).

$$FeS_2 + 3\frac{1}{4}\,O_2 + 3\frac{1}{2}\,H_2O \text{ -> } Fe(OH)_3 + 2\,SO_4^{2-} + 4\,H^+ \quad (1)$$

$$FeS + 2\frac{1}{4}\,O_2 + 2\frac{1}{2}\,H_2O \text{ -> } Fe(OH)_3 + SO_4^{2-} + 2\,H^+ \quad (2)$$

The formation of sulfuric acid causes acidification of soils and consequently dissolution of toxic metals and their leaching to watercourses results in deterioration of the ecological status of aquatic ecosystems. The reclamation of AS soils for cultivation by field drainage, dredging of main drains and poldering expose subsoils for oxidation and once initiated the negative impacts may last a longtime (Österholm & Åström, 2004). Furthermore, in exceptionally dry summers, evapotranspiration lowers the groundwater table deeper than drainage alone which enhances the oxidation of sulfidic materials in subsoils and results in increased acid loads (Dent D. L., 1986; Österholm, et al., 2015).

In Europe, the largest cultivated AS soil areas are located on the coasts of Baltic Sea in Finland (Figure 1). Since more than a century ago, land has been reclaimed for cultivation without properly knowing the negative consequences to the environment. Liming has converted AS soils fertile and now they are highly valued for their excellent crop yields. Unfortunately, the liming for agricultural purposes does not mitigate acid loadings (Palko & Weppling, 1994). The aim of the EU Water Frame Directive was to reach good quality for surface waters, including AS soil areas, until 2015 (EU, 2015), but the target was not reached. The new time frame was set to 2027 and now more efficient practical water protection measures are urgently needed.

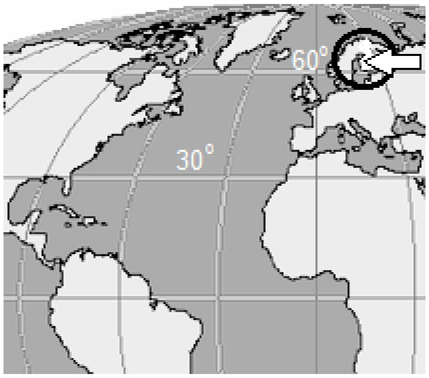

Figure 1. The location of the acid sulfate (AS) soil area on the coast of the Baltic Sea in Finland.

Material and methods

An 18.4-ha experimental field was established to study controlled drainage and sub-irrigation as a mitigation method for acid loadings from cultivated AS areas in 2010. The field was located in western Finland in Söderfjärden (63◦02’N, 21◦53’E). The area on the coast of Bothnia Gulf was partly reclaimed for cultivation already in the 18th century (Edén, 2012). The lowest part of the area has been drained by pumping since 1926, but because the post-glacial land-uplift at the rate of 8 mm per year (Johansson et al. 2004) other parts can currently be drained by gravity. The soils of the experimental field are *Sulphic Cryaquepts* according to Soil Taxonomy (Österholm, et al., 2015). At the beginning of the experiment in 2010, the oxidized horizons reached down to 1.5 m, and below that depth the soil contained sulfidic materials (S_{tot} 0.8%) (Yli-Halla, 2012). The average annual air temperature in the region was 4.2 °C and the annual long term precipitation was 552 mm (1981-2010) (Finnish Meteorological Institute 2016).

The experiment consists of three privately owned cultivated fields where each was subjected to a different water management practice: 1) normal subsurface drainage (ND), 2) controlled drainage (CD) and 3) sub-irrigation (CDI) (Fig. 2). In all fields, subsurface pipes were at a depth of 1.1 m with spacing from 20 to 40 m, although they were originally drained separately during 1948-2010. Lateral flow of groundwater between fields and seepage to the main drain was prevented by vertical plastic sheet installed in 2010 to reach the depth of 1.8 m, i.e. the structureless subsoil (Österholm and Rosendahl, 2012). The main drain was dredged by farmers in autumn 2014. Spring barley and spring wheat were grown in the fields using similar cultivation practices.

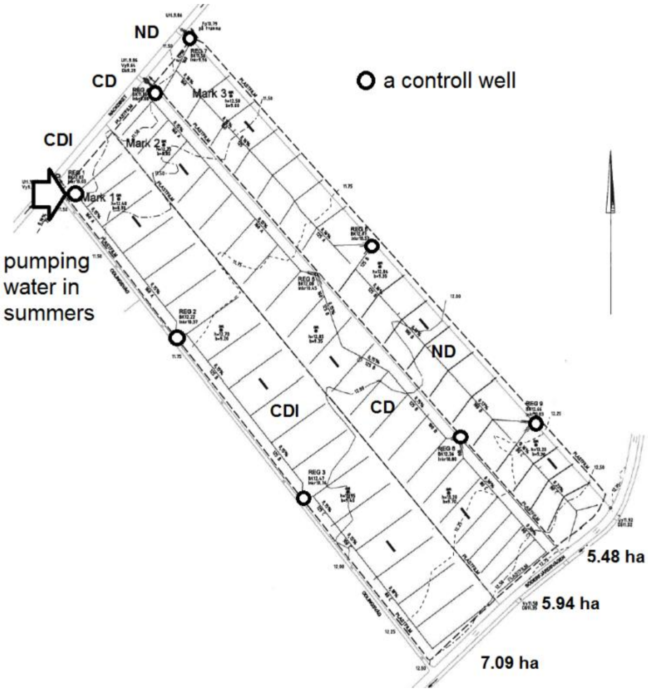

Figure 2. The map of experiment field with three drainage methods: normal subsurface drainage (ND), controlled drainage (CD) and sub-irrigation (CDI). The surface area of the fields separated by the plastic sheet is smaller than the field area; ND = 5.663 ha, CD = 5.969 ha and CDI = 6.753 ha.

Each field was divided into three sections owing to a control well for the regulation of groundwater for the whole field. In ND, no regulation was applied. After cultivation practices, the water regulation depth of CD and CDI was set at 0.7 m below the soil surface in winters. The regulation was set off in spring during snow melting and set on at 0.6 m after spring cultivation practices. In CDI, water was pumped from main drain into the lowest control well when the groundwater table dropped below 0.6 m from the soil surface in summers. The amount of water pumped in CDI and water balance of the fields are presented in Table 1. In summer 2015 no water was pumped because the main drain ran out of water.

Table 1. The water balance of the fields having normal subsurface drainage (ND), controlled drainage (CD) and sub-irrigation (CDI) in 2011-2015. The surface runoff is neglected.

	CDI				CD		ND	
	Precipitation	Subirrigation	Drainage	Evapotranspiration	Drainage	Evapotranspiration	Drainage	Evapotranspiration
	mm a^{-1}	mm	mm	mm	mm	mm	mm	mm
2011[a]	658	31	249	439	292	366	244	414
2012[a]	748	50	311	487	336	412	278	470
2013[a]	562	12	235	339	280	282	259	303
2014	552	28	255	325	333	219	278	274
2015	682	-	299	383	345	337	322	360

[a] From (Österholm, et al., 2015).

Monitoring of groundwater level as well as the quantity and quality of discharge water were started in spring 2010 while the different water management practices began after the calibration period in summer 2011. Groundwater level in each section of the fields was measured manually on a monthly basis from perforated groundwater pipes installed to the depth of 2.5 m. In the lowest section of fields, groundwater was logged continuously (EHP-QMS, Finland). The water flow was monitored in drainage outlets (EHP-Ultrasonic Flow monitoring system) (Österholm, et al., 2015) and electrical conductivity (EC) of discharge water by probes (WTW, Trescon). Samples for acidity, concentrations of SO_4^{2-} and EC were taken from discharge water fortnightly during the runoff periods. The acidity of discharge water (mmol L^{-1}) was determined according to the standard SFS 3005 by titrating with NaOH to the end point of pH 8.3. In the laboratory, water samples were analysed for SO_4^{2-} and EC. For the quality control, the continuously logged groundwater and EC were systematically compared with the manual measurement and laboratory determination, respectively.

The correlation between EC and SO_4^{2-} is generally found to be high in waters draining from AS soil areas (Toivonen & Österholm, 2011) and SO_4^{2-} concentrations of discharge waters are assumed to reflect well the oxidation of sulfidic material in AS soils because no other important sources for SO_4^{2-} exits in the area (Åström & Åström, 1997). According to equations 1 and 2, one mole SO_4^{2-} indicates that two moles of acidity is formed. The total losses of SO_4^{2-} from the fields were estimated using mean daily discharge (L s^{-1} ha^{-1}) and SO_4^{2-} concentration. Daily SO_4^{2-} concentrations were estimated using two different methods: 1) linear interpolating of SO_4^{2-} concentration between sampling, and 2) calculation based the on relationship between SO_4^{2-} and daily logged EC (Fig. 3).

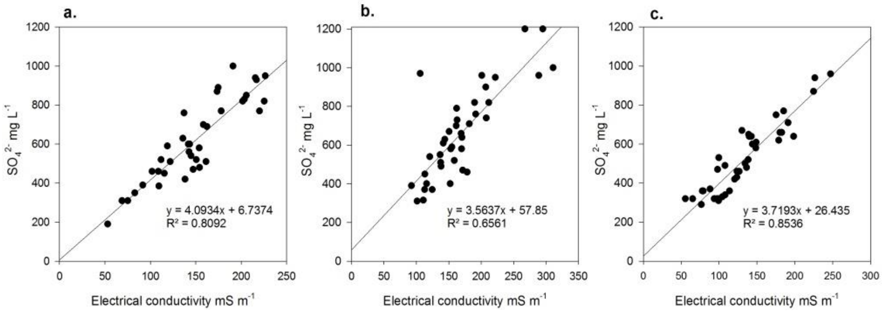

Figure 3. Relation between laboratory measured SO_4^{2-} (mg L^{-1}) and logged EC (mS m^{-1}) of discharge water in a) normal subsurface drained field (ND), b) controlled drained field (CD) and c) sub-irrigated field (CDI).

Results

In ND, groundwater dropped into the sulfidic horizon in every winter and summer. The groundwater regulation in CD shortened the time the groundwater dropped, but could not prevent it entirely. In CDI, the groundwater could be kept above the sulfidic horizon nearly throughout the summers in 2011-2014. However, without sub-irrigation in 2015, groundwater dropped down into the sulfidic horizon for three months similar to that of CD, while in ND it was at this depth for five months (Fig. 4).

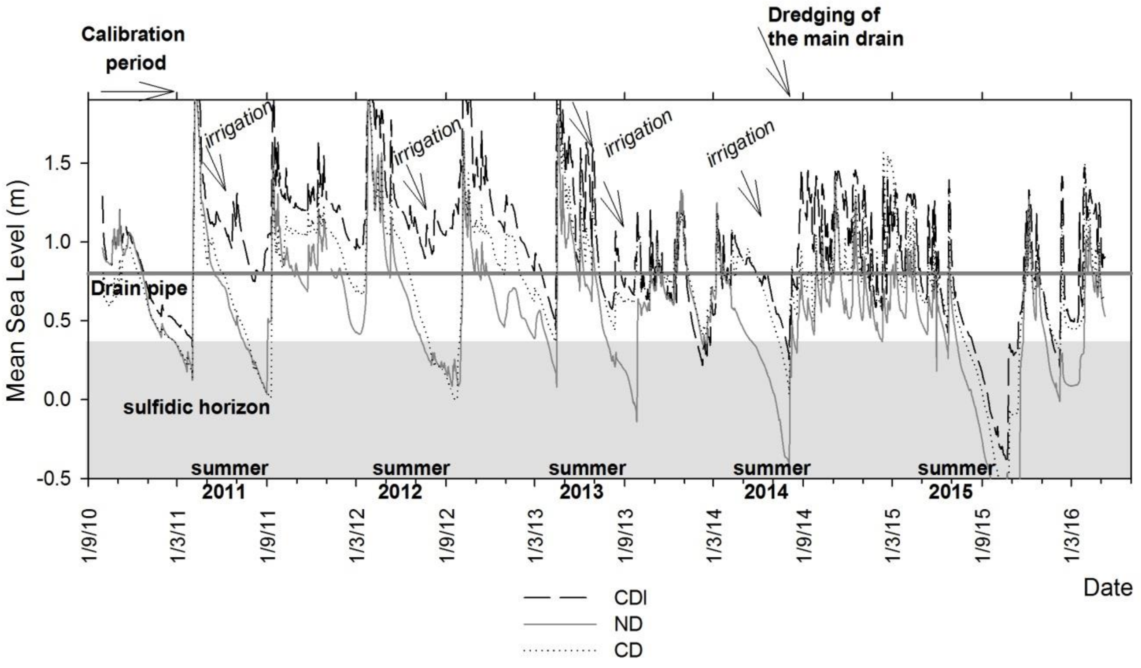

Figure 4. The depth of groundwater in the lowest section in the normal subsurface drained (ND), controlled drained (CD) and sub-irrigated (CDI) field. Sulfidic horizon is in grey while the average depth of lateral subsurface drain is indicated with a horizontal line. Sub-irrigation events in CDI, the end of the calibration period, and the date of dredging of main drain are indicated with arrows.

In 2011—2014, the acidity and SO_4^{2-} of drain water in CD and CDI was mainly lower than in ND (Fig. 5 a,b). However, in late 2015 the acidity was more than 1 mmol L^{-1} higher in CD and CDI than in ND corresponding with higher concentrations of SO_4^{2-} (Fig. 5 b). As compared to ND, concentrations of SO_4^{2-} were 200-700 mg L^{-1} higher in CD and 400 mg L^{-1} higher in CDI at the end of year 2015.

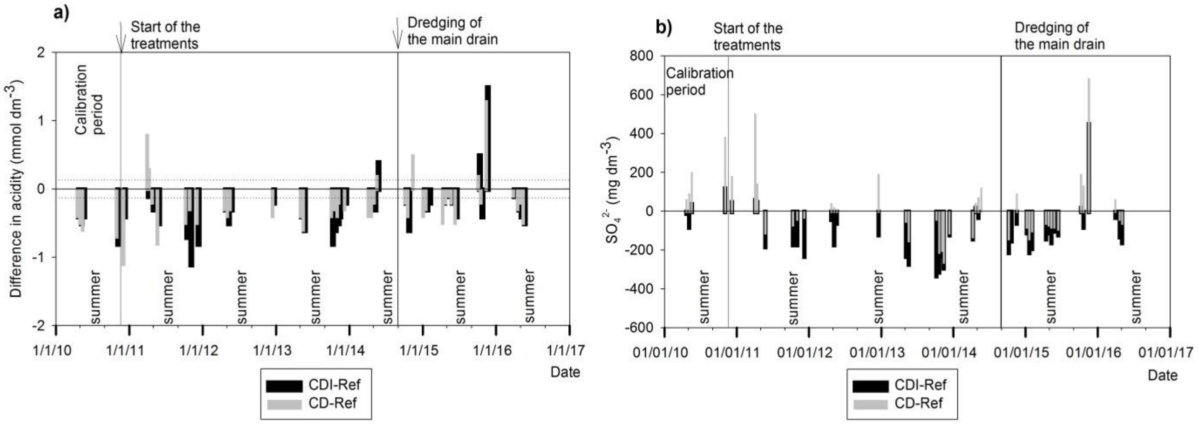

Figure 5. a) Differences in acidity of discharge water between normal subsurface drained (ND) and controlled drained (CD) fields, ND and in sub-irrigated (CDI) fields, and b) difference in SO_4^{2-} of discharge water between ND and CD, ND and CDI.

Although the cultivation practices and crops were the same in all fields, the discharge per hectare was considerably higher in CD than in ND and CDI which had nearly equal discharges. The difference between CD and the two other fields is clearly seen in the five years cumulative discharge curves of the fields (Fig. 6a). The annual difference in the discharge between CD and CDI or ND ranged from 20 mm up to 78 mm (Table 1).

The yearly SO_4^{2-} losses from fields ranged in ND from 15 to 16 kmol ha^{-1} a^{-1}, in CD from 15 to 20 kmol ha^{-1} a^{-1} and in CDI from 10 to 14 kmol ha^{-1} a^{-1}. The interpolation method gave on average 10% higher estimation for the total SO_4^{2-} losses than the estimation based on logged EC values. However, both methods gave similar ranking with the lowest SO_4^{2-} losses for CDI (Fig. 6 b. and c.) In CDI, the yearly SO_4^{2-} losses were on average 22% lower than in ND.

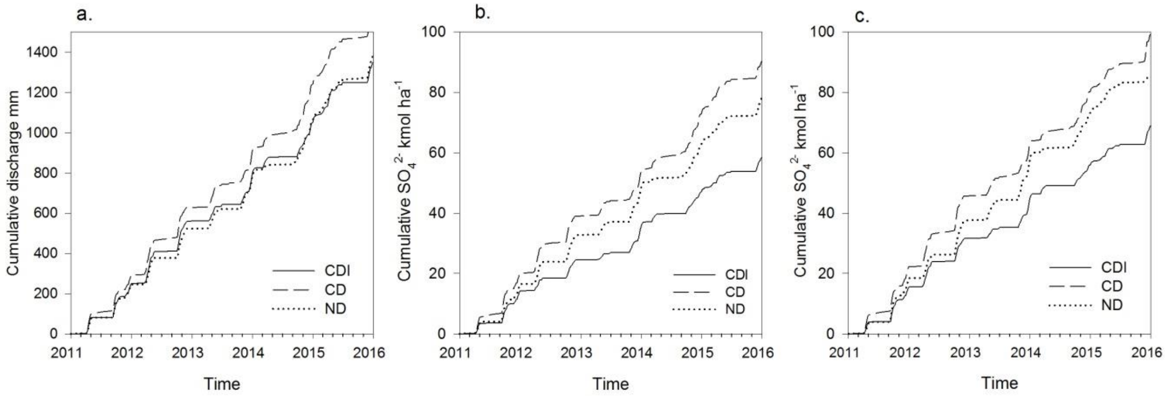

Figure 6. a) Cumulative discharge (mm) of normal subsurface drained subfield (ND), controlled drained field (CD) and sub-irrigated field (CDI) in 2011-2015, and b) cumulative SO_4^{2-} losses (kmol ha^{-1}) estimated by logged EC values and c) cumulative SO_4^{2-} losses (kmol ha^{-1}) estimated by interpolation for ND, CD and CDI in 2011-2015.

Discussion

In the experimental field, groundwater was the deepest in summers after dry periods and generally in late winter before snow melting, resembling the common seasonal trend of groundwater in that region of Finland (Soveri, 1985). An exception was during the winter of 2014-2015 which was unusually mild and limited precipitation as snow occurred (Finnish Meteorological Institute 2016). Therefore, precipitation was able to replenish groundwater during winter resulting in the high variation of groundwater (Fig. 4). In the summer of 2015, groundwater levels dropped deeper than ever in the course of the experiment in all the fields although the precipitation was about the same as the long term average precipitation (Finnish Meteorological Institute 2016). Therefore, the dredging of the main drain in autumn 2014 probably affected the drop of groundwater levels in summer 2015. Moreover, groundwater of CDI dropped similarly to CD because irrigation could not be supplied.

Before dredging in summers 2011 - 2014, groundwater could be kept higher in CD and CDI than the ND. Consequently, the acidity of drain water as well as SO_4^{2-} concentration were generally lower in CD and CDI than ND and still in summer 2015 (Fig. 5a. and b). However, the acidity and SO_4^{2-} concentrations of drain water being higher in CD and CDI than ND in autumn 2015 which is in agreement with theory that acid pulses occur when groundwater drops deep during exceptionally dry summers. In the spring of 2016, the acidity of drain water as well as SO_4^{2-} concentration was again slightly lower in CD and CDI than in ND. That might be due to higher groundwater in CD and CDI than in ND in the winter of 2015.

Even if the SO_4^{2-} concentrations were lower in CD than in ND the higher discharge resulted in higher total SO_4^{2-} losses from CD than from ND. It is peculiar that in CD the discharge per hectare was higher than in CDI and in ND because the precipitation in these closely located fields could be assumed to be the same. The surface runoff was not taken into account in the calculation because the fields are very flat. Therefore, during the springtime flooding water might run from the other fields to CD and percolate into its drainage system and caused higher drainage water discharge. Regardless of sub-irrigation, CDI and ND were almost equal in discharge. The reason for that was supposedly higher transpiration in CDI than in ND which attributed to higher groundwater levels similarly reported by Virtanen et al. (2013) and Epie et al. (2014). The average annual leaching of SO_4^{2-} from the fields is in the same order of magnitude as calculated for an AS soil area previously (Österholm & Åström, 2004). However, in CDI the annual SO_4^{2-} leaching was up to 37% (6 kmol ha^{-1} a^{-1}) lower than in ND. That means 12 kmol less acidity formed per hectare per year in CDI than in ND which is equivalent 0.6 tons lime ($CaCO_3$) per hectare per year assuming complete dissolution of limestone. The advantage of groundwater regulation is the influence on deep soil layers whereas liming affects mainly top soils.

Conclusion

The drop of groundwater into the critical sulfidic horizon could be slowed down or prevented using controlled drainage and particularly by sub-irrigation in cultivated AS soil fields. However, due to dredging of main drain, the regulation of groundwater failed and sub-irrigation could not be arranged due to shortage of water. Therefore, when the dredging of main drains is planned in AS soil areas the water management of fields, the need of water for irrigation has to be taken into consideration. Higher groundwater in CD and in CDI slightly decreased the acidity of discharge water. However, the volume of discharge waters was high. Therefore, a 22% decrease in acidity losses with CDI is reasonable in the long run. Nevertheless, still more reduction in acid losses is needed to reach the target of good quality of surface waters in AS soil areas by 2027. A combination of sub-irrigation with other mitigation methods, such as liming, might be fruitful for further studies.

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