Regolith in wetlands with high nature values

Physical and chemical properties

Gustav Sohlenius

Marina Becher

Anton Boman

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Gustav Sohlenius, Marina Becher
Geological Survey of Sweden

Anton Boman, Geological Survey of Finland

Abstract

Since most of the Forsmark area has been uplifted above sea level during the last 1 000 years, there are several shallow ponds that still have not been filled with regolith, e. g., gyttja, and peat. A large part of the regolith in the area is lime rich. These two factors explain the high nature values of several of the wetlands in the area.

The groundwater table in some wetlands may potentially be lowered during construction and operation of the repository for spent nuclear fuel. Groundwater-table drawdown may in turn cause oxidation of sulphide minerals and compaction of the uppermost organic rich regolith. The latter may cause low pH and high metal concentrations in the water. However, periods with low groundwater levels also occur during dry periods and the processes mentioned above may consequently also take place naturally.

In this study, regolith from six wetlands with high nature values were studied in the field and samples were taken for further analyses. The uppermost deposits are characterised by thin layers of gyttja, peat, and gyttja rich sand and clay deposits. The peat and gyttja layers have high water content and could be compacted if the wetlands are dry for a longer period. The layers of organic deposits are generally thin (a few decimetres) and the potential compaction during a period with low groundwater table is therefore small. It has not been possible to determine if the sand in the studied wetlands is underlain by glacial clay or not.

The potential for acidification has been studied and the results show that deposits from at least three of the studied wetlands (7, 14 and 16) may become acid if exposed to air. The potentially acid deposits in two of these wetlands are, however, overlain by peat that may protect from oxidation during periods of low groundwater table.

Sammanfattning

Till största delen har Forsmarksområdet genom landhöjningen stigit ur havet under de senaste tusen åren och därför finns här flera våtmarker med grunda gölar vilka ännu inte fyllts med t ex gyttja och torv. Jordarna i området innehåller dessutom i stor utsträckning kalk. Dessa förhållanden gör sammantaget att flera av våtmarkerna i området har höga naturvärden.

Vid byggnationen av förvaret för använt kärnbränsle finns det en risk att grundvattennivån i vissa av dessa våtmarker sänks. Detta kan leda till kompaktion av de ytliga jordarterna samt att sulfidmineral oxiderar. Det sista kan förorsaka lågt pH och höga metallkoncentrationer i våtmarkernas vatten. Perioder med lågt grundvatten förekommer även under torra perioder och processerna som beskrivs ovan kan därför även uppkomma naturligt.

Jordarter från sammanlagt sex våtmarker med höga naturvärden har undersökts i fält och provtagits för vidare analys. De ytliga jordarterna i de undersökta våtmarkerna kännetecknas av tunna lager av gyttja, torv och gyttjiga sand- och lerjordar. Torvlagren har en hög vattenhalt och skulle kunna kompakteras om våtmarkerna torrläggs under en längre period. Eftersom dessa torvlager är tunna (ett par decimeter) kommer effekten av kompaktion bli begränsad om grundvattenytan sjunker. Det har inte varit möjligt att, med de metoder som använts här, fastställa om det sandlager som förekommer i våtmarkerna underlagras av glaciallera.

Den försurande potentialen har undersökts och resultaten visar att det finns potentiellt sura jordar i åtminstone tre av de undersökta våtmarkerna (7, 14 and 16). I två av dessa överlagras dock den potentiellt sura jorden av torv vilken skulle kunna skydda underliggande jordlager från oxidation.

Contents

1   Introduction

The present study includes stratigraphical data of regolith from six wetlands with high nature values. The deposits have been analyzed for selected chemical and physical properties. Regolith, also called Quaternary deposits (in the following abbreviated QD), refers to all unconsolidated deposits overlying the bedrock. The study was performed according to the activity plan AP SFK-19-023 "Jordartsgeologiska undersökningar i gölar och våtmarker", Version 1.0. The methods used are described in SKB MD 131.001, Version 1.0 (see Table 1-1). Some of the methods used in this study are, not described in that MD but there are descriptions and references to these methods in the text below. The Activity Plan and method description are SKB internal controlling documents. The six studied wetlands are shown in Figure 1-1.

The Geological Survey of Sweden (SGU) is responsible for field work and reporting. A large part of the laboratory work was carried out at the Geological Survey of Finland (GTK). Certain laboratory work was conducted at the Swedish University of Agricultural Sciences (SLU) and at SGU.

Table 1-1. Controlling documents for the performance of the activity.

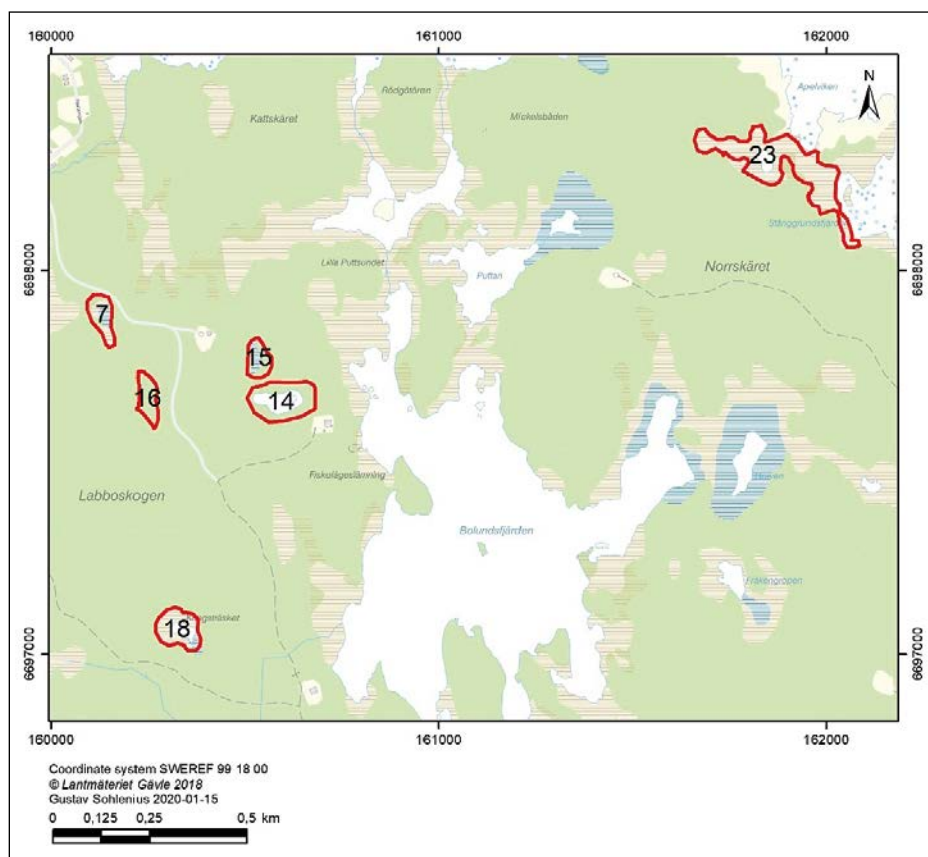| Activity plan		
Jordartsgeologiska undersökningar i gölar och våtmarker	AP SFK-19-023	1.0
Method description		
Metodbeskrivning för jordartskartering	SKB MD 131.001	1.0

Figure 1-1. The six studied wetlands.

2 Objective and scope

Six wetlands with high nature values were studied. The groundwater table in these wetlands may potentially be lowered during the planned building of the repository for spent nuclear fuel (Hamrén et al. 2010). All the studied wetlands consist of ponds surrounded by fen areas. The ponds are shallow and may consequently be drained if the groundwater table drops. The high nature values might then be negatively affected due to changed physical and chemical properties of the uppermost QD. Dry conditions can cause oxidation of the reduced QD in the wetlands and thereby lead to acidic conditions mainly due to oxidation of sulphidic minerals. Acid soils formed due to sulphide oxidation are called acid sulphate soils, whereas the reduced sulphidic sediment are called potentially acid sulphate soils. There are numerous studies describing how acid sulphate soils formed due to sulfide oxidation (e.g. Sohlenius and Öborn 2004, Åström 1997), and these soils are known to affect surface waters by low pH and high metal concentrations. A lowering of the groundwater table may also cause irreversible compaction of the uppermost unconsolidated regolith. However, it is possible that the processes mentioned above also occur naturally during dry periods with a low groundwater table.

This study aims at determining the acid potential and risk of compaction of the uppermost regolith in the six wetlands. It is possible that compaction may affect the vegetation in the wetlands and thereby nature values. The study also aims at determining the stratigraphy of the QD in the wetlands. The physical and geochemical properties of the QD are important since it may be necessary to regulate the groundwater table artificially by infiltration of water.

3 Execution

The methods used for sampling and classification of QD are described in detail in SKB MD 131.001 (see Table 1-1). Almost the same classification of QD was used in this study as in SGU's earlier investigations in the area (Persson 1985, 1986). For an up to date nomenclature the reader is referred to SKB MD 131.001 and to the report describing the map of QD that was produced during SKB´s site investigation (Sohlenius et al. 2004). The method for determination of pH is described in Becher et al. (2019), methods for acidity, metals and sulphur in Mattbäck et al. (2017) and finally the method for determining sulfides is described in Dalhem (2016).
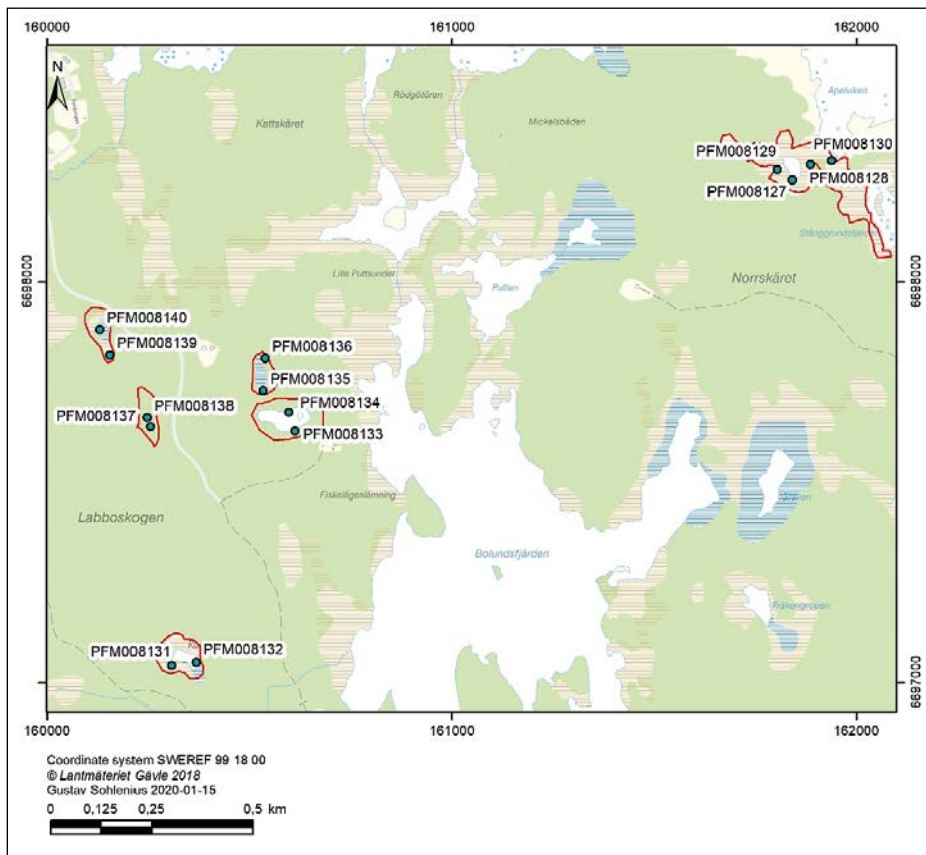
Figure 3-1. *Location of the investigated sites in the six wetlands.*

3.1 Field work

The studied sites are shown in Figure 3-1. A hand driven probe and a Russian peat corer (Figure 3-2) were used for sampling and determination of the stratigraphy of QD.

In the field pH was measured directly on the sampled deposits (altogether 30 measurements) according to a method described in Becher et al. (2019). Samples were taken for further analyses to determine the risk of acid conditions due to oxidation of sulfidic minerals.

Altogether 27 samples were taken to the laboratory were pH was measured after oxidizing the samples (see below). 17 samples were taken for determination of carbon and water contents. Twelve samples were frozen shortly after sampled and later analysed for sulphides at GTK.

All field data have been digitally stored in the SICADA database.

Figure 3-2. The hand driven probe (upper picture) and the Russian peat corer (lower) used for sampling.

3.2   Analytical methods

The sampled sites are shown in Figure 3-1. At SGU altogether 27 samples were analysed for incubation pH and 17 samples were analysed for water content. The same 17 samples were analysed for organic and total carbon content at SLU. At GTK 14 of the incubated 27 samples were analysed for acidity. Twelve samples were analysed for sulphides at GTK. These samples were taken at the same levels as the samples analysed for acidity However, samples from two additional levels were analysed for acidity (from wetlands 7 and 23). Metals and total sulphur were analysed on 13 samples (the same samples as analysed for acidity but not the one from wetland 7). The exact sampling depth for each analysed sample is shown in the result section.

The contents of water and organic carbon was analysed to determine if the deposits are sensitive to compaction. To avoid evaporation samples were kept in plastic bags before analysing the water content. Water content is defined as the percentage of water in the fresh samples and was determined at SGU by first weighing the wet samples and thereafter weighing the samples after oven drying at 105 °C. Organic carbon and total carbon were determined at SLU. For organic carbon CO_2 was measured after burning a sample at 550 °C. Total carbon was determined by measuring the amount of CO_2 produced when heating the samples to 1 350 °C. Total carbon constitutes organic carbon and inorganic carbon. The latter is mainly bound in carbonate minerals (mainly calcite $CaCO_3$). It is therefore possible to use the difference between total carbon and organic carbon as an estimate of the amount of carbonates. Carbonates have a high potential to buffer acidity that may be created due to oxidation of sulphides.

To determine if pH drops due to sulphide oxidation samples were oxidised (incubated) in the laboratory at SGU. The samples were thereafter sent to GTK for determination of acidity (H^+/kg). Acidity depends on many factors, such as occurrence of organic matter, content of calcium and sodium compounds (especially carbonates), clay minerals, aluminum and iron oxides, and occurrence of sulfidic material, which is usually the main contributor to elevated acidity levels. During incubation, the samples were kept wet by regular addition of deionized water. The exposure of oxygen in combination with wet conditions make the sulphide minerals to oxidise. The pH was measured in the samples after an incubation period (9 weeks) and if the pH during this period had dropped below 4 (minerogenic samples) or below 3 (peat samples), and if the pH drop was larger than 0.5 pH units compared to field-pH (i.e. measured during field sampling) the pH drop was considered to be due to sulphide mineral oxidation (also peat contain minerals such as sulphides).

Samples for sulphide analysis (n = 12) were frozen directly after sampling and thawed before analysed. The total sulphide content in these 12 samples was determined with the CRS-method (chromium reducible sulphur). In short, the method implies that each sample is reacted with an acidic (HCl) chromium(II) solution in an oxygen-free environment (by nitrogen purging) followed by heating of the sample slurry. Hydrogen sulfide gas is evolved and the sulphide concentration is determined by trapping H_2S (i.e. the sulfide) in a Zn-acetate solution followed by titration with iodine (Dalhem 2016).

Altogether 13 samples were sent to another laboratory (Labtium Oy in Kuopio) for analysis of total sulphur as well as other elements. Aqua regia (hydrochloric acid and nitric acid) was used to dissolve these 13 samples. That reagent dissolves all material except the most resistant minerals. The solutions were thereafter analysed using ICP-OES for mineral soil materials (n = 10) The analytical package for minerogenic samples also include analysis of Ag, Al, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, La, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Sb, Sc, Sr, Th, Ti, V, Y, and Zn (Mattbäck et al. 2017). Sulphur in three peat samples were analysed with a "sulphur analyser" measuring the amount of sulphur emitted when heated the samples to 1 400 °C (Mattbäck et al. 2017).

Titratable incubation acidity (13 samples) gives an indication of the amount of acidity (H^+/kg) that can be formed in the deposits due to oxidised conditions. After the incubation period, the titratable incubation acidity was determined by mixing a known amount of sample (c 1.5 g dry weight) in a beaker with 1 M (M = mole/L) KCl (60 mL) and letting the mixture shake for 4 hours and stand for about 12–16 hours. Thereafter, the mixture was titrated up to pH 5.5 and 6.5 using 0.015 M NaOH (Mattbäck et al. 2017). The analyses were performed at GTK´s laboratory in Kokkola, Finland.

3.2.1 Classification of acid sulphate soils

Acid sulphate soils are classified based on their field pH and pH following oxidation of sulphidic minerals. Sulphidic materials are defined as any soil containing ≥ 0.01 % sulphidic-S (by dry weight). If sulphide analyses cannot be performed, it is also possible to use total sulphur together with expert knowledge in order to indicate presence of sulphidic materials. In short, if the material displays pH < 4 for mineral soils and pH < 3 for organic soils, in an oxidized material (either field conditions or after oxidation) the material is classified as an acid sulphate soil. Samples that are reduced (unoxidized) are let to oxidize in the laboratory for at least 9 weeks where after pH is measured.

3.2.2 Classification of acidification potential

In order to further estimate the possible acidification of the environment it is important to also measure how much acidity, expressed as mmole H^+/kg, which is formed during oxidation. This is performed after the sample has been incubated (9 weeks) and is done by titrating a soil:KCl slurry (1:40) with NaOH to a pH of 5.5 and 6.5 (used e.g. in Australia, Dear et al. 2014). Based on the current knowledge on soil acidification processes and possible environmental consequences, the acidifying potential is classified into three categories based on the produced acidity measured at pH 5.5:

1) High acidification potential, > 100 mmole H^+/kg

2) Moderate acidification potential, 10–100 mmole H^+/kg)

3) Low acidification potential, < 10 mmole H^+/kg)

4 Results

4.1 Stratigraphical field studies

The stratigraphy of QD was determined in the field and the results are shown in Table 4-2 to Table 4-7, including results from previous studies. The sampled sites are shown on maps of QD (Figure 4-3 to Figure 4-7). Figure 4-2 presents a legend explaining the QD types shown on the maps (Sohlenius et al. 2004). The general stratigraphy in the six studied wetlands, as shown in Table 4-1, is in accordance with previous stratigraphical studies (Sohlenius and Hedenström 2009, Hedenström and Sohlenius 2008). All the QD layers in Table 4-1 are, however, not present in all the studied wetlands. The glacial clay is often overlain by a layer of sand and gravel that is often difficult or impossible to penetrate with the field equipment used in the present study. In the present study glacial clay was only observed in wetland 23. In wetlands 16, 18 and 23 there are, however, results from previous studies showing that parts of these wetlands are underlain by glacial clay (see Table 4-2 to 4-7).

In wetland 7 and 16 there are results from geophysical investigations that indicate that the postglacial sand is underlain by glacial clay (Mattsson 2013, 2020). There are, however, no stratigraphical studies showing the occurrence of glacial clay in wetland 7. Geophysical investigations in wetland 14 do not indicate the presence of clay but these measurements were conducted in the vicinity of, and not within, the wetland. Coring in wetland 14 did not show if the postglacial sand and gravel is underlain by glacial clay. However, the floor of the pond of wetland 14 almost lacks boulders and stones that are characteristic for till. It is therefore possible that the till beneath the wetland is partly covered by a layer of glacial clay (Figure 4-1). The pond of wetland 7 partly lacks stones and boulders and may, as suggested by geophysical investigations, be underlain by glacial clay. Glacial clay may also occur beneath wetland 15. That wetland is rich in stones and boulders and it is therefore not likely that there is a continuous clay layer beneath that wetland. In summary, to verify the occurrence of glacial clay beneath wetlands 7 and 14 additional studies are needed. There are several methods to do such invsestigations but a cobra drill could probably be used without disturbing the nature values.

Figure 4-1. *The floor of the pond of wetland 14 lacks boulders and stones, indicating that the till is overlain by layers of sand and clay. It has, however, not been possible to verify the occurrence of clay by the methods used hitherto.*

Table 4-1. The general stratigraphical distribution of QD in the studied wetlands. This stratigraphy is in accordance with the one described during the site investigation (e.g. Hedenström and Sohlenius 2008).

Type of deposit	Depositional environment	
Peat	Wetland	Youngest
Gyttja (partly calcareous)	Lake	
Clay gyttja	Sheltered marine environments such as bays	
Sand/gravel	By streams and by waves at the sea floor	
Glacial clay	Deposited at the sea floor by meltwater from the inland ice	
Till	Deposited by the inland ice	Oldest

Bog peat
Fen peat
Gyttja
Clay gyttja
Clay gyttja with a thin surface layer of peat
Clay gyttja with a thin surface layer of postglacial silt
Clay gyttja with a thin surface layer of postglacial fine sand
Clay gyttja with a thin surface layer of postglacial sand--gravel
Clay (not specified)
Postglacial fine sand
Postglacial sand
Postglacial sand with a thin surface layer of peat
Postglacial sand with a thin surface layer of gyttja clay
Postglacial sand--gravel
Postglacial gravel
Postglacial gravel with a thin surface layer of peat
Postglacial shingle
Glacial silt
Glacial clay
Glacial clay with a thin surface layer of peat

Glacial clay with a thin surface layer of postglacial gyttja clay
Glacial clay with a thin surface layer of postglacial sand
Glacial clay with a thin surface layer of postglacial gravel
Recent fluvial sediment
Glaciofluvial sediment
Glaciofluvial sediment covered with till
Till
Clayey till or boulder clay
Clayey till with a thin surface layer of peat
Clayey till with a thin surface layer of postglacial sand
Till with a thin surface layer of peat
Till with a thin surface layer of gyttja clay
Till with a thin surface layer of postglacial sand
Till with a thin surface layer of sand--clay
Till with a thin surface layer of glacial clay
Boulder deposit
Precambrian bedrock
Precambrian bedrock with a thin surface layer of peat
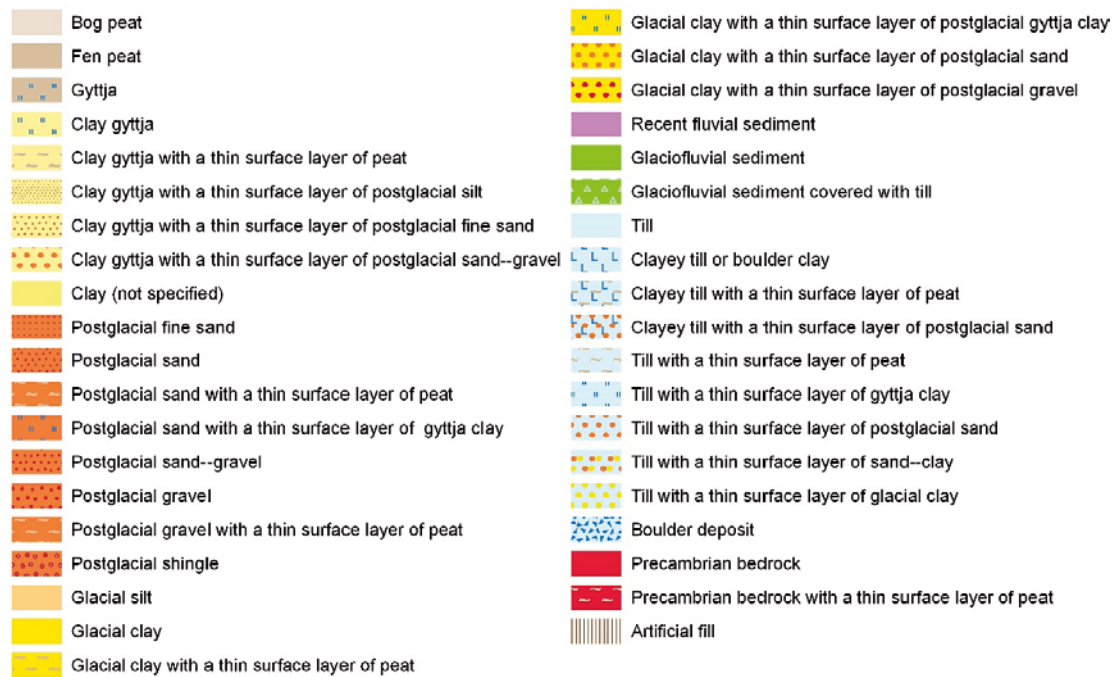Artificial fill

Figure 4-2. *Legend explaining the QD types shown on the maps of Figure 4-3 to Figure 4-7.*

Figure 4-3. *The investigated sites in wetland 7. Green circles represent sites investigated in previous studies and black triangles sites investigated within the present study.*

Table 4-2. Stratigraphical distribution of QD of wetland 7.

Id	Depth below ground/water surface	Termination	Quaternary deposit
PFM008139 (1)	0.00–0.30		Peat
	0.30–0.50	Boulder/stone	Clay gyttja
PFM008140 (1)	0.00–0.35		Water
	0.35–1.00		Gyttja
	1.00–1.10	In the same layer	Postglacial sand
PFM006283 (3)	0.00–0.30		Peat
	0.30–0.60		Clay gyttja
	0.60	Boulder/stone	Till
PFM007548 (2)	0.00	Boulder stone	Till
PFM007549 (2)	0.00–0.55		Water
	0.55–0.95		Gyttja
	0.95	Boulder/stone	Till
SFM000110 (4)	0.00–0.50	Water	
	0.50–0.60	Gyttja	
	0.60–2.30	Stone and gravel	
SFM000191 (5)	0.00–7.00	Sandy silty till	

1 Present study.
2 Sohlenius and Hedenström (2009).
3 Lokrantz and Hedenström (2006).
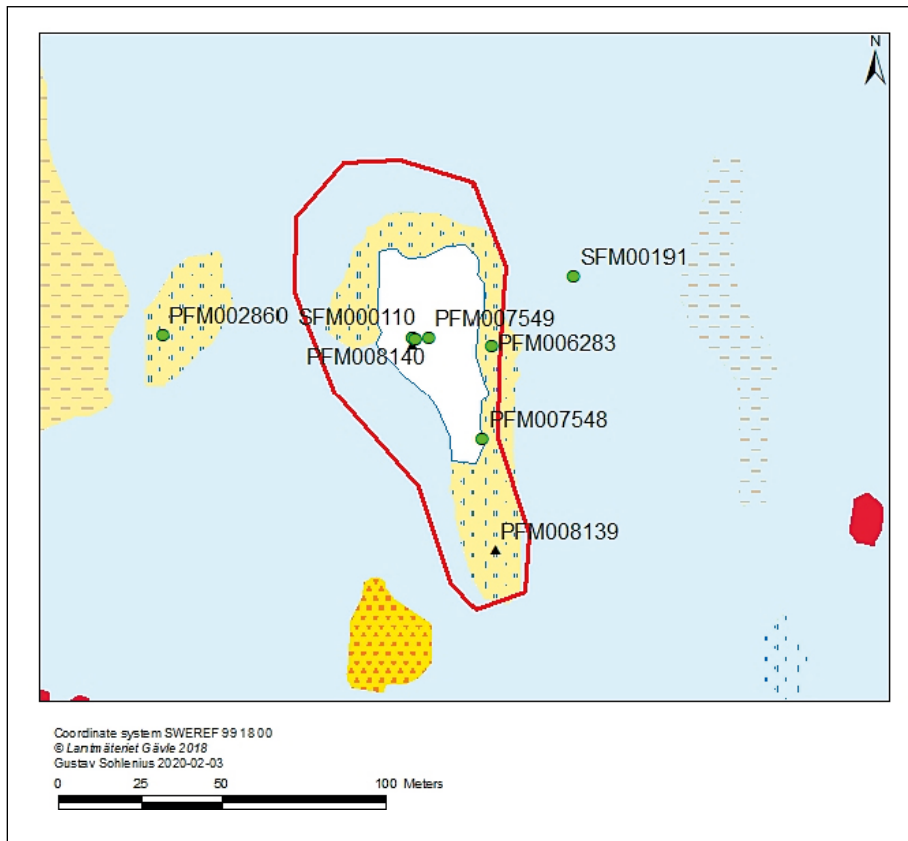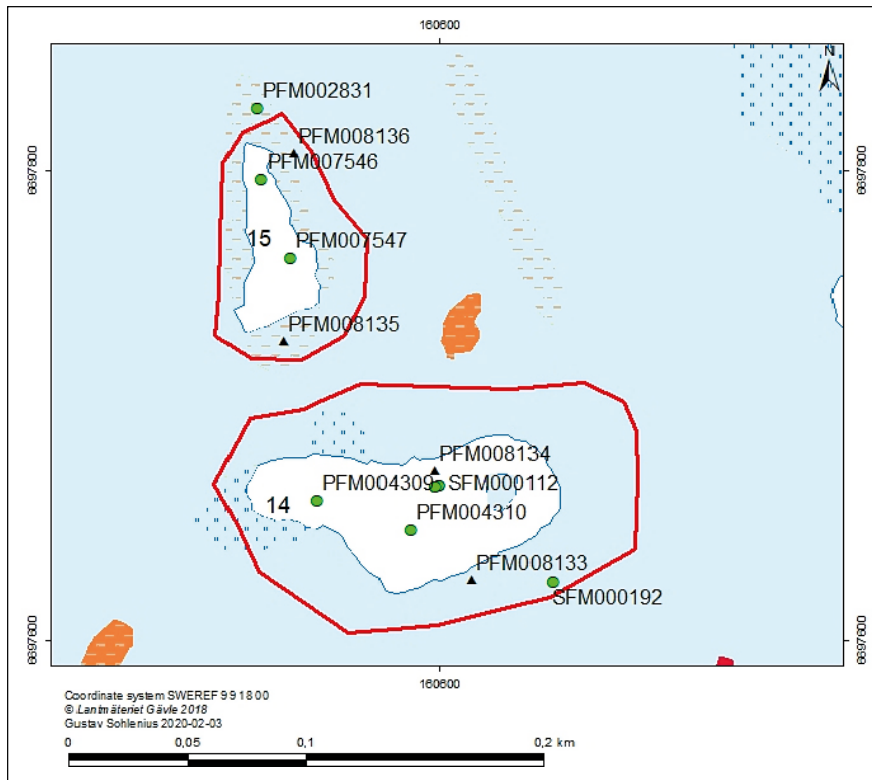4 Werner et al. (2009).
5 Sweco (2019).

Figure 4-4. *The investigated sites in wetlands 14 and 15. Green circles represent sites investigated in previous studies and black triangles sites investigated within the present study.*

Table 4-3. The stratigraphical distribution of QD of wetland 14.

Id code	Depth below ground/water surface	Termination	Quaternary deposit
PFM008133 (1)	0.00–0.20		Fen peat
	0.20–0.90	In the same layer	Postglacial sand
PFM008134 (1)	0.00–0.50		Water
	0.50–0.90		Gyttja
	0.90–1.00	In the same layer	Postglacial sand
PFM004309 (2)	0.00–0.37		Water
	0.37–0.55		Algae gyttja
	0.55–0.58		Algae gyttja
	0.58–0.65	Boulder/stone	Gravel (till?)
PFM004310 (2)	0.00–0.49		Water
	0.49–0.52		No sample obtained
	0.52–0.57		Gyttja
	0.57–0.71		Algae gyttja
	0.71–0.80		Algae gyttja
	0.80–0.83		Postglacial sand
	0.83–0.85	Boulder/stone	Stone (till?)
	0.90–1.00	In the same layer	Postglacial sand
SFM000112 (3)	0.00–0.60		Water
	0.60–1.00		Gyttja
	1.00–2.50	In the same layer	Sandy silty till
SFM00192 (4)	0.00–7.00	Bedrock	Silty sandy till

1 This study.
2 Hedenström (2003, 2004).
3 Werner et al. (2009).
4 Sweco (2019).

Table 4-4. The stratigraphical distribution of QD in wetland 15.

Id code	Depth below ground/water surface	Termination	Quaternary deposit
PFM008135 (1)	0.00–0.30		Fen peat
	0.30–0.40		Gyttja rich sand
	0.40–0.50	Boulder/stone	Postglacial sand
PFM008136 (1)	0.00–0.20	Boulder/stone	Fen peat
PFM002831 (2)	0.00–0.25		Fen peat
	0.25	Boulder/stone	Till
PFM007546 (3)	0.00–0.60		Water
	0.60	Boulder/stone	Till
PFM007547 (3)	0.00	Boulder/stone	

1 This study.
2 Sohlenius et al. (2004).
3 Sohlenius and Hedenström (2009).

Figure 4-5. *The investigated sites in wetland 16. Green circles represent sites investigated in previous studies and black triangles sites investigated within the present study.*

Table 4-5. The stratigraphical distribution of QD of wetland 16.

Id code	Depth below ground/water surface	Termination	Quaternary deposit
PFM008137 (1)	0.00–0.60		Peat
	0.60–0.70		Clay gyttja
	0.70–0.60	In the same layer	Postglacial sand
PFM008138 (1)	0.00–0.40		Water
	0.40–0.60		Gyttja rich sand
	0.60–0.80	In the same layer	Postglacial sand
SFM00114 (4)	0.00–0.30		Gyttja
	0.30–1.85	Same layer	Sandy silt
SFM00115 (4)	0.00–0.30		Gyttja
	0.30–1.05	Same layer	Sandy silt
SFM00132 (5)	0.00–0.50		Artificial fill
	0.50–2.80	Same layer	Till
SFM00133 (5)	0.00–0.30		Artificial fill
	0.30–0.90		Glacial clay
	0.90–2.00	Same layer	Till
SFM00134 (5)	0.30–0.70		Glacial clay
	0.70–1.10	Same layer	Till
SFM00135 (5)	0.40–1.00		Glacial clay
	1.00–1.30	Same layer	Till
PFM006284 (3)	0.00–0.70		Water
	0.70–0.80		Gyttja
	0.80–1.20		Clay
	1.20	Boulder/stone	Till
PFM007501 (2)	0.00–0.30		Clay gyttja
	0.30	Boulder/stone	Till
PFM007502 (2)	0.00–0.65		Clay gyttja
	0.65–0.75		Postglacial sand
	0.75	Boulder/stone	Till?
PFM007503 (2)	0.00–0.30		Clay gyttja
	0.30	Boulder/stone	Till
PFM007504 (2)	0.00–0.10		Water
	0.10–0.45		Clay gyttja
	0.45–0.50		Gravel
	0.50–0.95		Glacial clay
	0.95	Boulder/stone	Till
PFM007552 (2)	0.00–0.80		Water
	0.80	Boulder/stone	Till

1 This study.
2 Sohlenius and Hedenström (2009).
3 Lokrantz and Hedenström (2006).
4 Werner et al. (2009).
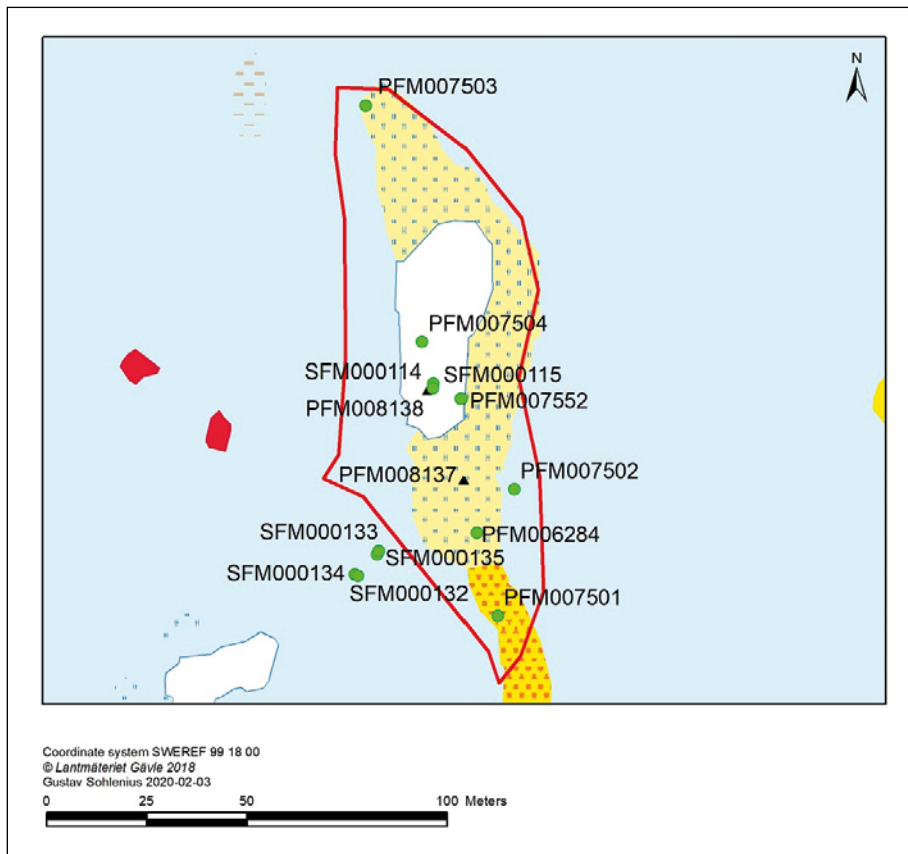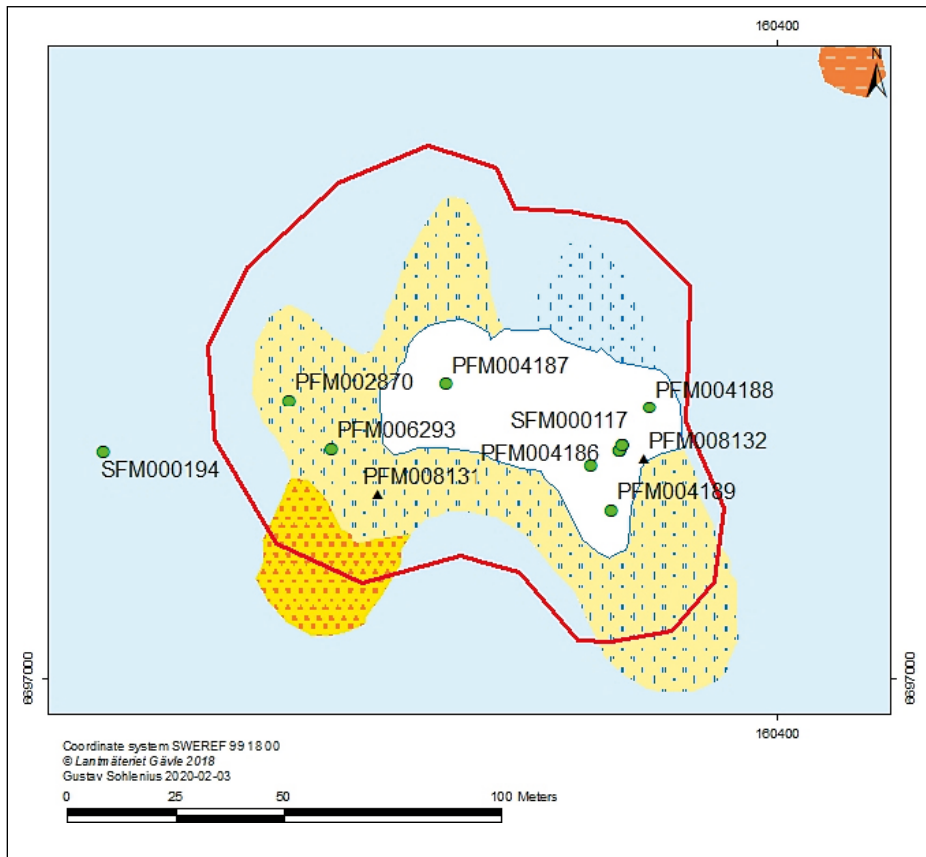5 Werner et al. (2014).

Figure 4-6. *The investigated sites in wetland 18. Green circles represent sites investigated in previous studies and black triangles sites investigated within the present study.*

Table 4-6. The stratigraphical distribution of QD in wetland 18.

Id code	Depth below ground/water surface	Termination	Quaternary deposit
PFM008131 (1)	0.00–0.40		Fen peat
	0.40–0.70		Clay gyttja
	0.70–0.80	In the same layer	Postglacial sand
PFM008132 (1)	0.00–0.50		Water
	0.50–0.80		Gyttja rich sand
	0.80–1.10	In the same layer	Postglacial sand
PFM004186 (4)	0.00–0.38		Water
	0.38–0.57		Fine detritus gyttja
	0.57–0.86		Calcareous gyttja
	0.86–0.92		Clay gyttja
	0.92–1.40		Postglacial gravelly sand
	1.40–2.05		Glacial clay
	2.05–2.27		Sand
	2.27	Boulder/stone	Till
PFM004187 (4)	0.00–0.39		Water
	0.39–0.44		No sample obtained
	0.44–0.68		Calcareous gyttja
	0.68–0.86		Algae gyttja
	0.86–0.91		Calcareous gyttja
	0.91–0.94		Postglacial silty sand
	0.94–1.10		Postglacial gravelly sand
	1.10–1.32		Glacial clay
	1.32–1.50		Glacial clay
	1.50	Boulder/stone	Till
PFM004188 (4)	0.00–0.41		Water
	0.41–0.53		No sample obtained
	0.53–0.80		Calcareous gyttja
	0.80–0.90		Algae gyttja
	0.90–0.93		Postglacial sand
	0.93–1.53		Postglacial sandy gravel
	1.53	Boulder/stone	Till?
PFM004189 (4)	0.00–0.40		Water
	0.40–0.50		Gyttja
	0.50–0.60		Calcareous gyttja
	0.60–0.67	Boulder/stone	Till
PFM006293 (3)	0.00–0.40		Gyttja
	0.40	Boulder/stone	Till
PFM002870 (2)	0.00–0.50	Other QD	Clay gyttja
SFM000117 (5)	0.00–0.60		Water
	0.60–1.00		Gyttja
	1.00–1.50		Sand
	1.50–2.10		Silty clay
	2.10–2.60		Silty sand
	2.60–3.20	In the same layer	Till
SFM000194	0.00–1.00		Clay
	1.00–1.80	Bedrock	Friction soil (probably till)

1 This study.
2 Sohlenius et al. (2004).
3 Lokrantz and Hedenström (2006).
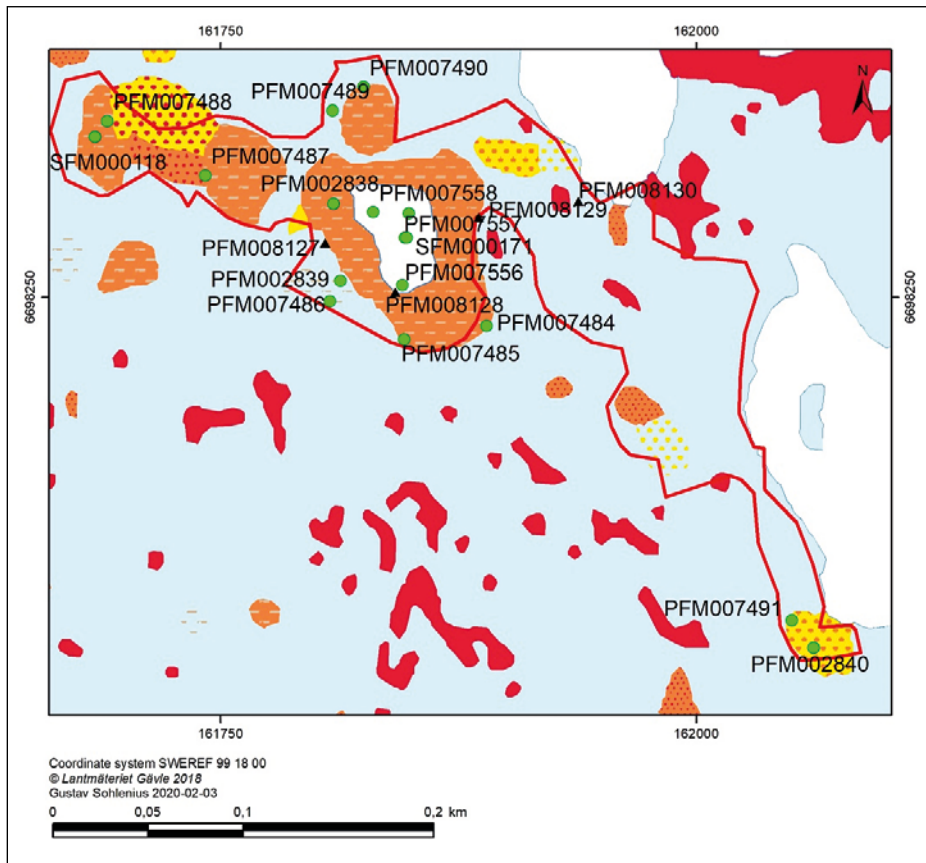4 Hedenström (2003, 2004).
5 Werner et al. (2009).
6 Sweco (2019).

Figure 4-7. *The investigated sites in wetland 23. Green circles represent sites investigated in previous studies and black triangles sites investigated within the present study.*

Table 4-7. The stratigraphical distribution of QD in wetland 23.

Id code	Depth below ground/water surface	Termination	Quaternary deposit
PFM008127 (1)	0.00–0.20		Fen peat
	0.20–0.30	In the same layer	Postglacial sand
PFM008128 (1)	0.00–0.10		Fen peat
	0.10–0.20	In the same layer	Postglacial sand
PFM008129 (1)	0.00–0.20		Fen peat
	0.20–0.30	In the same layer	Postglacial sand
PFM008130 (1)	0.00–0.10		Fen peat
	0.10–0.30	In the same layer	Glacial clay
PFM002838 (3)	0.00–35		Fen peat
	0.35–100	Other QD	Sand
PFM002839 (3)	0.00–25		Fen peat
	0.25	Boulder/stone	Till
PFM002840 (3)	0.00–0.10		Sand
	0.10–1.00	Clay	Clay
PFM007484 (2)	0.00	Boulder/stone	Till?
PFM007485 (2)	0.00	Boulder/stone	Till?
PFM007486 (2)	0.00–0.35		Clay gyttja
	0.35–0.40		Postglacial sand
	0.40–1.25		Glacial clay
	1.25	Boulder/stone	Till
PFM007487 (2)	0.00	Boulder/stone	Till
PFM007488 (2)	0.00	Boulder/stone	Till?
PFM007489 (2)	0.00–0.10		Postglacial sand
	0.10–1.00		Glacial clay
	1.00	Boulder/stone	Till
PFM007490 (2)	0.00–0.20		Clay gyttja
	0.20	Boulder/stone	Till
PFM007491 (2)	0.00–0.50		Sand
	0.50–1.20		Glacial clay
	1.20	Boulder/stone	Till
SFM00118 (4)	0.0–0.30		Water
	0.30–0.60		Gyttja
	0.60–1.60	In the same layer	Sandy silty till
SFM000171 (5)	0.00–0.90		Water
	0.90–2.00	Bedrock	Silty till

1 This study.
2 Sohlenius and Hedenström (2009).
3 Sohlenius et al. (2004).
4 Werner et al. (2009).
5 Sweco (2019).

4.2 Results of geochemical analyses

Results from analyses of total and organic carbon and water content are shown in Table 4-8, which also shows pH before and after 4 and 9-weeks incubation. Acidity and incubation pH determined at GTK are shown in Table 4-9. Results from analyses of sulphur, sulphides and calcium are shown in Table 4-10.

The peat samples contain close to 50 % organic carbon, showing that these deposits almost entirely constitute organic material (Table 4-9). Analyses of the uppermost sediment below the ponds of wetlands 15, 16 and 18 were first characterised as gyttja (organic content > 20 % of dry weight). The results show unexpectedly low contents of water and organic material and are therefore characterised as gyttja rich sand/gravel. The low water content in these deposits is caused by the lower porosity in coarse grained deposits compared to fine-grained. The difference between total and organic carbon is generally low (Table 4-8), indicating that the calcium carbonate is low (a few per mille) or absent in the analysed samples. However, the gyttja rich sand in wetland 18 contain 0.5 % inorganic carbon indicating the presence of calcium carbonate. Furthermore, the calcium content in some of the gyttja samples are high (Table 4-10), which indicate presence of calcium carbonate in these samples. Furthermore, during the sampling shells were observed in some of the gyttja samples. Hence, the calcium carbonate may have been oxidized already during the determination of organic carbon, causing an underestimation of carbonates.

The water content of the peat layers was around 90 % and the gyttja from the bottom of the ponds of wetlands 7 and 14 had a water content just below 90 %. All these organic layers may be compacted if the groundwater table drops in these wetlands. The layers with high water contents are, however, thin (max c 0.6 m) and the effect of compaction should therefore be limited to a few decimetres in terms of ground subsidence. That might occur due to a low groundwater table caused by the repository, but also due to naturally occurring dry conditions.

At GTK incubation-pH (n = 14) was measured on every sample prior to the first acidity titration (Table 4-9). Based on the pH, six samples (PFM008134_1, PFM008137_3, PFM008137_4, PFM008139_2, PFM8140_1 PFM008140_2) had pH values below the diagnostic levels (pH 3 or 4) and were therefore classified as hypersulphidic material (i.e. acid sulphate soils). Incubation pH from the same layers determined by SGU (Table 4-8) shows that these deposits can be characterised as acid sulphate soils. However, pH in one of the samples (PFM8140_1) was above 4 when determined at SGU. That sample was probably not completely oxidised when analysed by SGU.

Table 4-8. Results from measurements of pH, water content and carbon content.

Sample id	Wetland id	Depth below ground surface (m)	QD type	pH field	pH (4w)	pH (9w)	Water content (%)	total-C (%)	org-C (%)
PFM008128_1	23	0.05	Peat	6.45	6.22	6.1	89.26	35.6	35.3
PFM008128_2	23	0.15	Sand	6.88	7.36	7.02	29.04	0.69	0.69
PFM008130_1	23	0.05	Peat	7.07	7.61	7.52			
PFM008130_2	23	0.15	Glacial clay	7.74					
PFM008130_3	23	0.25	Glacial clay	7.64	8.17	7.89			
PFM008131_1	18	0.15	Peat	6.82	7.4	6.6	92.21	48.7	48.5
PFM008131_2	18	0.45	Clay gyttja	7.08					
PFM008131_3	18	0.55	Clay gyttja	7.41	7.64	7.61	83.02	15.7	15.2
PFM008131_4	18	0.65	Clay gyttja	6.98					
PFM008131_5	18	0.75	Sand	7.33	7.56	7.58			
PFM008132_1	18	0.75	Gyttja rich sand	7.18	7.6	7.49	56.36	2.94	2.38
PFM008132_2	18	1	Sand	6.77	7.79	7.65			
PFM008133_1	14	0.1	Peat	6.39	6.3	5.67	91.56	37.8	37.6
PFM008133_2	14	0.25	Sand	6.49	6.71	6.1			
PFM008134_1	14	0.85	Gyttja	6.88	5.3	2.87	85.90	9.08	9.07
PFM008134_2	14	0.95	Sand	7.54	7.6	7.57			
PFM008135_1	15	0.2	Peat	6.47	5.81	5.53	88.33	45.2	45.1
PFM008135_2	15	0.35	Gyttja rich sand	6.42	5.67	5.46	49.20	4.30	4.28
PFM008135_3	15	0.5	Sand	7.4	5.47	5.24			
PFM008136_1	15	0.1	Peat				93.68	43.4	43.2
PFM008137_1	16	0.35	Peat	6.8					
PFM008137_2	16	0.45	Peat	6.73	6.18	6.14	91.92	47.7	47.5
PFM008137_3	16	0.65	Clay gyttja	6.88	4.44	3.12	64.05	5.66	5.65
PFM008137_4	16	0.75	Sand	6.63	4.76	3.23			
PFM008138_1	16	0.5	Gyttja rich sand	6.81	7.59	7.51	42.36	3.65	2.72
PFM008138_2	16	0.7	Sand	7.23	7.69	7.67			
PFM008139_1	7	0.2	Peat	7.1	7.4	7.58	90.00	43.5	43.0
PFM008139_2	7	0.4	Clay gyttja	6.7	4.55	3.46	71.86	6.33	6.32
PFM008140_1	7	0.7	Gyttja	7.65	7.32	5.5	88.59	12.5	12.2
PFM008140_2	7	0.9	Gyttja	7.68	7.07	3.93	83.75	9.33	9.30
PFM008140_3	7	1.05	Sand	7.62	8.53	7.77			

Acidity analyses (Table 4-9) were performed on duplicates for all samples (n = 14). In general, the results for acidity were consistent between the duplicates, but for three samples (PFM008134, PFM008139 and PFM008140) there was quite a large difference between the duplicates. The reason for this is most likely that the samples had been oxidizing and producing more acidity between the analytical runs. Samples having zero acidity is due to the samples having pH values above 5.5 (or 6.5) after incubation and these samples are therefore classified as having no acidity and thereby no acidifying potential. Three samples had acidities exceeding 100 mmole H^+/kg and are classified as having a high acidifying potential. Two samples had acidities slightly above 70 mmole H^+/kg and are classified as having a moderate acidifying potential. One sandy sample had an acidity of 7.5 mmole H^+/kg and is classified as having a low acidifying potential.

For sulphide analysis (Table 4-10), a few samples were run on duplicates (n = 3) and quadruplicates (n = 1). Also, total sulphur from Labtium Oy is presented in Table 4-10. When comparing total sulphide with total sulphur, it seems that the majority of sulphur is either present as sulphate or present in its organic form. Three samples showed concentrations below the detection limit (100 ppm S (0.01 %)). This also means that these three samples are not classified as sulphidic, whereas all other samples contained sulphidic material (i.e. ≥ 0.01 % sulfidic-S). In general, the precision for the sulphide analyses are regarded as good. The main contributor to the discrepancy between the results from the re-runs seems to be difficulties to obtain a homogenous sample for each run as some of the samples were very organic rich and watery, making it difficult to weigh in the same proportions of water and soil/organic material for every separate analytical run. This could perhaps have been avoided if the organic rich materials had been cut into smaller pieces already during sampling.

Multi-element analysis of Ag, Al, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, La, Li, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sb, Sc, Sr, Th, Ti, V, Y, and Zn are not commented on in this report. These data are not presented in this report (except S and Ca, Table 4-10) but have been delivered to SKB's Sicada database.

Table 4-9. Results from analyses of pH and acidity preformed at GTK. Acidity was determined twice for each sample.

SKB id	Wetland id	Sample_depth	QD type	Incubation pH	Acidity pH 5.5 mmol H^+/kg	Acidity pH 6.5 mmol H^+/kg
PFM008128_1	23	0–0.1	Peat	6.3	0	14.3
PFM008128_1	23	0–0.1	Peat		0	15.7
PFM008128_2	23	0.1–0.2	Sand	6.3	0	0.5
PFM008128_2	23	0.1–0.2	Sand		0	0.4
PFM008131_3	18	0.5–0.6	Clay gyttja	7.5	0	0
PFM008131_3	18	0.5–0.6	Clay gyttja		0	0
PFM008132_1	18	0.7–0.8	Gyttja rich sand	7.2	0	0
PFM008132_1	18	0.7–0.8	Gyttja rich sand		0	0
PFM008134_1	14	0.9	Gyttja	2.8	262	323
PFM008134_1	14	0.9	Gyttja		344	427
PFM008135_2	15	0.4	Gyttja rich sand	5.4	0	14.5
PFM008135_2	15	0.4	Gyttja rich sand		2.0	14.7
PFM008137_2	16	0.4–0.5	Peat	5.9	0	39
PFM008137_2	16	0.4–0.5	Peat		0	35
PFM008137_3	16	0.6–0.7	Clay gyttja	2.9	77	103
PFM008137_3	16	0.6–0.7	Clay gyttja		77	104
PFM008137_4	16	0.7–0.8	Sand	3.3	7.5	10.0
PFM008137_4	16	0.7–0.8	Sand		7.6	9.6
PFM008138_1	16	0.4–0.6	Gyttja rich sand	7.2	0	0
PFM008138_1	16	0.4–0.6	Gyttja rich sand		0	0
PFM008139_1	7	0.0–0.3	Peat	6.9	0	0
PFM008139_1	7	0.0–0.3	Peat		0	0
PFM008139_2	7	0.3–0.5	Clay gyttja	3.3	175	241
PFM008139_2	7	0.3–0.5	Clay gyttja		188	255
PFM008140_1	7	0.6–0.8	Gyttja	3.8	71	119
PFM008140_1	7	0.6–0.8	Gyttja		74	122
PFM008140_2	7	0.8–1.0	Gyttja	3.4	136	192
PFM008140_2	7	0.8–1.0	Gyttja		294	385

Table 4-10. Sulphides and sulphur. Note that some of the samples have been analysed several times.

SKB id	Wetland id	Sample depth (below ground surface)	QD type	Total sulfide	Total sulphur, mineral	Total sulphur, organic	Ca ppm
				ppm *	ppm **	ppm **	
PFM008128_1	23	0–0.1	Peat	980		5 900	
PFM008131_3	18	0.5–0.6	Clay gyttja	< 100	11 300		37 300
PFM008132_1	18	0.7–0.8	Gyttja rich sand	325	8 800		28 100
PFM008132_1	18	0.7–0.8	Gyttja rich sand	262	8 800		28 100
PFM008134_1	14	0.9	Gyttja	182	11 600		7 550
PFM008135_2	15	0.4	Gyttja rich sand	< 100	1 380		6 230
PFM008137_2	16	0.4–0.5	Peat	781		8 600	
PFM008137_2	16	0.4–0.5	Peat	545		8 600	
PFM008137_3	16	0.6–0.7	Clay gyttja	214	4 030		4 350
PFM008137_4	16	0.7–0.8	Sand	260	1 100		2 190
PFM008138_1	16	0.4–0.6	Gyttja rich sand	< 100	1 960		23 000
PFM008138_1	16	0.4–0.6	Gyttja rich sand	< 100	1 960		23 000
PFM008139_1	7	0.0–0.3	Peat	375		5 400	
PFM008139_2	7	0.3–0.5	Clay gyttja	418	9 380		9 120
PFM008140_1	7	0.6–0.8	Gyttja	636	11 400		16 700
PFM008140_1	7	0.6–0.8	Gyttja	549	11 400		16 700
PFM008140_1	7	0.6–0.8	Gyttja	607	11 400		16 700
PFM008140_1	7	0.6–0.8	Gyttja	469	11 400		16 700

* Detection limit < 100 ppm.
** From Labtium Oy.

5   Discussion

The results from this study are in line with the general stratigraphy presented in (Sohlenius and Hedenström 2009) and shown in Table 4-1. However, the uppermost sediments in wetlands 16 and 18 have earlier been characterised as gyttja (Lokrantz and Hedenström 2006, Hedenström 2004), but was in this study characterised as gyttja rich sand. In this study the characterisation was based on results from analyses in the laboratory and should therefore be more reliable than earlier determinations which were based on field observations. The postglacial sand in the studied wetlands is at least partly underlain by glacial clay. The stratigraphy has been investigated using hand driven equipment, and it was therefore not always been possible to determine if the sand is underlain by glacial clay. The clay has a low hydraulic conductivity which might have future implications since there are plans to improve the groundwater levels in the wetlands by artificial infiltration.

The results show that some of the gyttja sediments in wetlands 7, 14 and 16 will become acid if oxidized. Results from analyses of the sulphide contents suggest, however, that the sulphide content in these deposits is too low for explaining the acidity produced during the oxidation process. It is therefore possible that the acid conditions, at least partly, are due to processes other than sulphide oxidation. Alternatively, oxidation of Fe^{2+} or organic material may cause acid condition. Alternatively, some of the sulphides were not dissolved during sulphide content determination. The high sulphur content in the deposits suggests that the sulphide contents are or have been higher than shown by the results. Regardless of chemical processes, it is obvious that some of the deposits will become acid if exposed to oxygen. The potentially acid fine-grained gyttja sediments produced more acidity compared to the sand sample that also became acid after oxidation. The gyttja deposits have consequently a larger potential to affect surrounding waters compared to the sand. Furthermore, all potentially acid deposits except the gyttja from wetland 14, were found beneath peat that might prevent oxygen from reaching underlying deposits during periods with a low groundwater table. Gyttja deposits from wetlands 16 and 18 contain sulphides and have a high total sulphur content. The high calcium content and low acidity in these deposits suggest that acid formed during oxidation is buffered by carbonate dissolution.

In summary, there are several factors that will decrease the risk for development of acidic conditions during periods of low groundwater levels. However, the surficial occurrence of potentially acid deposits in wetland 14 shows that there are deposits that might affect the water quality during dry conditions. Even though not detected, surficial potentially acid deposits may also occur in the other studied wetlands. It is therefore recommended that pH in the water is monitored if the wetlands in the future are temporarily affected by groundwater-table drawdown.

The uppermost organic rich deposits may be affected by compaction during periods of low groundwater table. However, these layers are thin, and the effect of compaction should therefore be small in terms of ground subsidence. The compaction of peat is probably at least partly a reversible process, even though long periods with a low groundwater levels may cause irreversible oxidation of peat. Short periods with dry conditions and compaction can be assumed to occur naturally.

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