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Assessment of aquatic pollution, remedial measures and juridical obligations of an acid sulphate soil area in western Finland

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Reclaiming of Holocene sulphide-bearing sediments, widespread in the coastal areas of Finland, has enabled oxidation of sulphides to a depth of 1–3 m and the subsequent development of acid sulphate soils (pH < 4). This work is concerned with spatial hydrogeochemical patterns, remediation measures and the juridical obligation to improve water quality in one such area, i.e. the Rintala plain (23 km^2) in mid-western Finland. Streams draining acid sulphate soils in Rintala are more acid (pH ~ 4 and acidity ~ 4 mmol l^{-1}) and carry significantly higher concentrations of SO_4^{2-}, Al, Ca, Cd, Co, Cu, F, Mn, Ni, Pb, Se, Sr and Zn than those draining forest and rural areas in the vicinity of the Rintala plain and organic-rich soils located on the plain. The juridical obligation to improve the water quality is inappropriate as it does not consider the main reason for the poor water quality, i.e. drainage by subsurface drainage pipes, and because of the equality principle (other acid sulphate soil areas have just as poor water quality but do not have such an obligation). Groundwater management, i.e. keeping the groundwater level as high as possible, is recommended as the best management practice.

Key words: acid sulphate soils, sulphur, metals, acidity, pH, hydrogeochemistry, drainage, groundwater management

Introduction

Holocene sulphide-bearing marine sediments are common on the coastal plains of Finland. Drainage of these by open ditches started in the 18th century and was strongly intensified after 1950 when agricultural machines and the use of subsurface drainage became more common. As a consequence, the groundwater level has dropped considerably, ena-

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bling oxygen to penetrate and oxidise metal sulphides. This oxidation process, which produces large amounts of acidity (e.g. van Breemen 1973), has resulted in the development of more than 1 m deep acid soils (pH 2.5–4), referred to as active acid sulphate (AS) soil, in an area covering up to 3000 km^2 of the coastal plains of Finland (Palko 1994). In these acidic soils, a number of chemical elements are mobilised and ultimately washed away with runoff, resulting in low pH (< 5) and strongly elevated concentrations of major and trace elements in adjacent streams (Weppling 1993, Lahermo et al. 1996, Åström and Åström 1997, Eden et al. 1999, Åström and Spiro 2000, Åström 2001, Sundström et al. 2002). This causes severe hydrobiological harm, including occasional fish death and disturbance in fish reproduction (e.g. Hildén et al. 1984, Urho et al. 1990, Kjellman et al. 1994).

The Rintala plain, that is in the focus of this study, is 23 km^2 of which about 70% (17 km^2) consists of AS soil (pH < 4; Fig. 1) that has developed on parent sediments with S concentrations between 0.2% and 1.1%. Almost all of the AS soil in Rintala are Sulfic Cryaquepts in Soil Taxonomy (Soil Survey Staff 2003) and, as elsewhere in Finland, only a small minority (~5%) of the AS soil are Typic Sulfaquepts. The clay content is between 25–35% below the plough layer (hydrometer analysis; data from Österholm and Åström 2002). The remaining area consists of moderately acidic soils (pH 5–6.5) with either low S-concentrations (< 0.1%) or very high concentrations of organic matter (C > 4%; Fig. 1). The development of active AS soil and the subsequent discharge of acid- and metal rich waters from Rintala did not start until the early 19th century (and even then only on a rela-

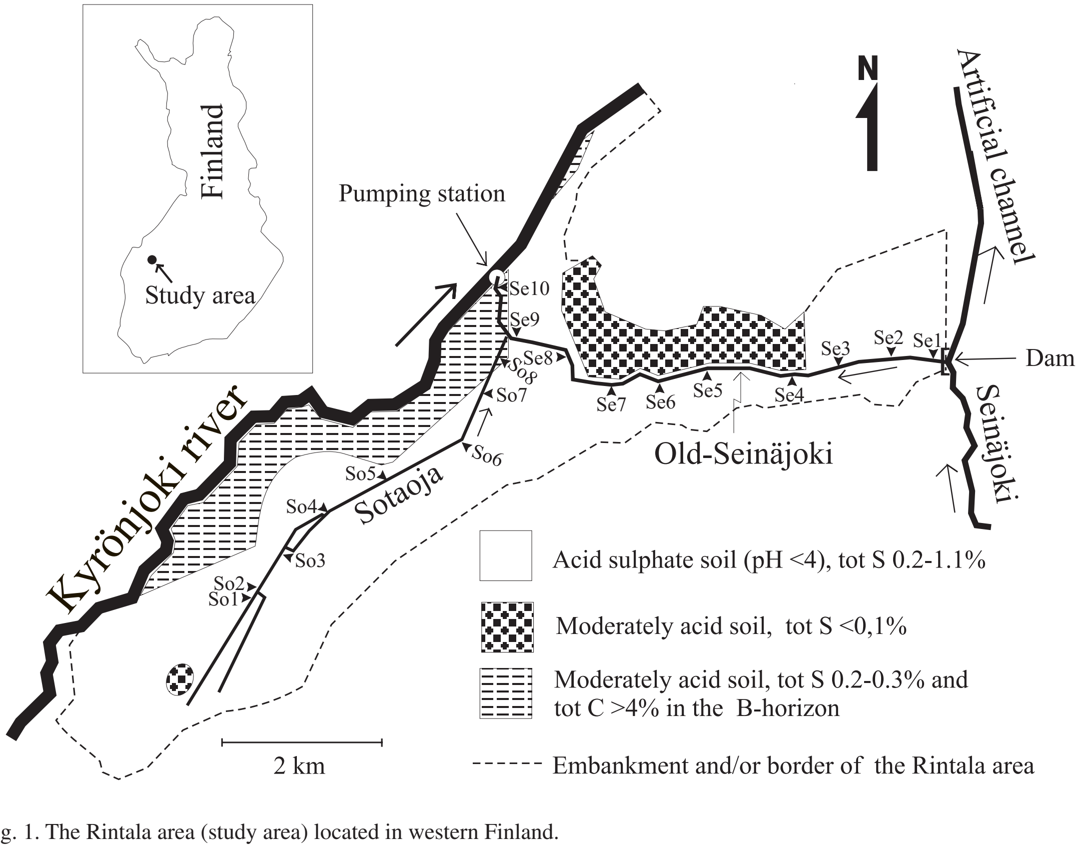

Fig. 1. The Rintala area (study area) located in western Finland.

tively small scale) when Sotaoja stream was dug through the central and southern parts of the area (Fig. 1) and the peat cover was burned (Österholm and Åström 2004). Thereafter a network of surface ditches have successively been dug denser and deeper throughout the area. To make the drainage efficient enough for modern agricultural activities, subsurface drainage was introduced in the1950s and became the main drainage type in the 1970s. Since 1982, most of the water in Seinäjoki stream has been redirected into an artificial channel, allowing only ca. 120 l s^{-1} (Aarno Halttu, personal communication) into old-Seinäjoki stream through the dam. This water consists of natural water from the Seinäjoki stream (ca. 80%; Fig. 1) and artificial water from a purifying plant (not indicated on the map). In order to even more efficiently control the hydrology of the Rintala plain, in the early 1980s embankments were raised along the Kyrönjoki river to prevent flooding and a pumping station was built at the old-Seinäjoki outlet (Fig. 1) to maintain stable water levels. Another pumping station was built in the northernmost part of the area but its capacity is only a few percents of the former. Hence, it has a small impact for the area as a whole, and because it is operated in a similar manner as the other pumping station, no further attention has been paid to it in this study. The Finnish Environment Institute (Finnish state) applied for the environmental permit for building of the embankments and pumping stations and the water-rights court granted it in 1984. The water-rights court, however, considered that these procedures could increase the metal- and acid load on Kyrönjoki river. In connection with the renewal of the environmental permit in 1992, the Finnish Environment Institute was obliged to improve the quality of the drainage water either by preventing the oxidation of the soils or by treating the water before letting it into Kyrönjoki river. The Finnish Environment Institute which regarded this obligation (among others) as unreasonable, appealed against the decision to the water-rights court of appeal in 1994. The appeal did not result in any changes regarding the obligation to improve the water quality. The environmental permit needs to be renewed by the end of year 2005 and in connection with this, the fulfillment of the above mentioned obligation will be examined. Rintala is the only AS soil area in Finland which is under such an obligation.

In this paper, we characterise the surface-water quality of the Rintala plain, and based on that characterisation and other available information and field experiences, we discuss how the water quality of the area should be improved and how the juridical obligation of the area should be answered.

Methods

Stream-water samples were collected in October 1997 (autumn) and May 1998 (spring) at eight sites along Sotaoja stream, ten sites along old-Seinäjoki stream and 15 sites (in spring only) in low-order streams (small ditches), which includes 6, 4 and 5 streams draining AS soils, organic rich soils and forest & rural areas (in the vicinity of Rintala) respectively. At ten sites in autumn and at seven sites in spring samples were taken in duplicate. The samples were filtered (0.45 µm) and acidified with ultrapure HNO_3 and then analysed for Al (6.9%), As (2.7%), Ba (6.0%), Ca (5.8%), Cd (2.0%), Co (2.0%), Cr (5.1%), Cu (4.1%), Fe (4.1%), K (7.8%), Mg (5.8%), Mn (13.1%), Ni (7.3%), Pb (24.7%), Se (6.7%), Sr (4.0%), V (4.0%) and Zn (3.8%) concentrations with the inductively-coupled-plasma mass-spectrometry (ICP-MS) and inductively-coupled-plasma atomic-emission-spectrometry (ICP-AES). The relative standard deviation (analytical precision), calculated from the duplicates, is indicated in brackets above. The electric conductivity, pH, acidity (SFS 3005) and concentrations of $(NO_2^- + NO_3^-)$-N (concentrations as nitrite-nitrogen + nitrate-nitrogen and indicated below as NO_{2_3}-N; SFS 3030), NH_4^+-N (concentrations as ammonium-nitrogen; SFS 3032), P (SFS 3026), Cl (SFS 3006), SO_4^{2-} (concentrations as sulphate; SFS 5738), F (SFS-EN ISO 10304-1) and total organic carbon (TOC; SFS-EN 1484) were determined in the laboratories of the West Finland Regional Environment Centre. Runoff data was obtained from the measuring weir, monitored and maintained by the Finnish Environment Institute, at the nearby Kainastonluoma reclaim area.

Results and discussion

Hydrochemistry of low order streams

In spring 1998, the low-order streams draining AS soils were more acid (median pH 4.0), had significantly higher electric conductivity (median 136 mS m^{-1}) and carried significantly higher concentrations of SO_4^{2-}, Al, Ca, Cd, Co, Cu, F, Mn, Ni, Pb, Se, Sr and Zn than those draining forest and rural areas in the vicinity of the Rintala plain and organic-rich soils located on the plain (Table 1). With the exception of Pb, this suite of elements is also clearly elevated in other similar streams draining Boreal AS soils (Åström and Björklund 1995, Åström and Åström 1997) and, with the exception of Al, depleted in the B-horizon in AS soil in Rintala (Cd, Se and F not determined; Österholm and Åström 2002). On the contrary, elements that

Table 1. Hydrochemistry of low-order streams draining acid sulphate soils, organic-rich soils and forest & rural areas in Rintala in May 1998, and of headwater streams in Finland (Lahermo et al. 1996).

	Acid sulphate soil			Organic-rich soils			Forest and rural			Headwater streams
	n = 6			n = 4			n = 5			n = ca. 1150
	min	med	max	min	med	max	min	med	max	med
Temperature (°C)	2.8	7.5	7.7	3.5	6.4	9.4	3.2	4.6	9.1	–
pH	3.7	4.0	4.2	5.5	5.7^{A}	6.0	5.1	5.5^{A}	6.6	5.9
EC (mS m^{-1})	108	136^{TF}	194	51	60^{F}	63	6	10	27	4
Acidity (mmol l^{-1})	2.0	4.0^{TF}	8.0	1.0	1.4^{F}	2.2	0.2	0.2	0.3	–
SO_4^{2-} (mg l^{-1})	510	700^{TF}	1200	76	97^{F}	130	13	15	63	3
NO_{2_3}-N (mg l^{-1})	2.7	6.7^{F}	8.3	11.2	15.3^{AF}	19.0	0.1	0.2	0.8	0.5
NH_4^+-N (mg l^{-1})	0.1	1.0^{F}	2.6	0.4	0.4	0.5	0.0	0.2	0.8	–
P (µg l^{-1})	18	31	72	58	79^{A}	98	30	81^{A}	181	–
Cl (mg l^{-1})	23	39^{F}	53	42	56^{F}	65	3	10	27	1
F (mg l^{-1})	0.6	1.5^{TF}	3.5	0.2	0.3^{F}	1.2	0.1	0.1	0.1	0.1
TOC (mg l^{-1})	6	10	25	25	31^{AF}	45	16	24^{A}	26	–
Al (mg l^{-1})	3.3	11.8^{TF}	59.5	0.0	0.1	0.1	0.1	0.5	0.6	0.1
As (µg l^{-1})	0.4	0.7	2.0	0.3	0.7	1.1	1.2	1.7^{AT}	2.9	0.4
Ba (µg l^{-1})	12	23	28	55	85^{AF}	98	16	24	27	10
Ca (mg l^{-1})	22	50^{TF}	139	10	25^{F}	28	5	5	22	4
Cd (µg l^{-1})	0.6	1.0^{TF}	3.5	0.1	0.2	0.3	0.1	0.1	0.1	< 0.02
Co (µg l^{-1})	58	110^{TF}	363	2	4	5	2	4	10	0.2
Cr (µg l^{-1})	1.1	2.2	5.9	1.6	2.3	2.8	1.2	1.6	2.4	0.5
Cu (µg l^{-1})	7.7	17.0^{TF}	150.6	2.4	4.8	5.5	5.5	7.5^{T}	8.6	0.6
Fe (mg l^{-1})	0.37	0.90	3.54	0.12	0.36	0.56	0.39	0.59	0.92	0.68
K (mg l^{-1})	5.0	7.8^{F}	21.0	2.6	5.3	6.6	1.7	3.2	6.8	0.7
Mg (mg l^{-1})	16	25^{F}	106	8	22^{F}	26	2	2	6	1
Mn (mg l^{-1})	3.1	5.7^{TF}	17.2	0.2	0.8^{F}	0.9	0.1	0.1	0.2	0.03
Ni (µg l^{-1})	87	156^{TF}	554	5	8	9	5	11	44	0.5
Pb (µg l^{-1})	0.4	0.8^{TF}	10.3	b.d.	0.2	0.3	0.1	0.3	0.4	0.2
Se (µg l^{-1})	0.7	2.2^{TF}	6.5	b.d.	0.3	0.4	b.d.	0.2	0.3	0.1
Sr (µg l^{-1})	185	361^{TF}	807	71	192^{F}	217	27	28	82	22
V (µg l^{-1})	0.1	0.3	0.5	0.4	1.2^{A}	1.7	1.7	1.8^{AT}	2.3	0.5
Zn (µg l^{-1})	170	329^{TF}	1103	10	18	36	12	26	71	4

^{A} Significantly ($\alpha = 0.1$) higher than for streams draining acid sulphate soil (Mann Whitney)

^{T} Significantly ($\alpha = 0.1$) higher than for streams draining organic-rich soils (Mann Whitney)

^{F} Significantly ($\alpha = 0.1$) higher than for streams draining forest & rural areas (Mann Whitney)

EC = electric conductivity

TOC = total organic carbon

are not enriched in the AS soil-waters (Ba, Cr, V) are not depleted in the soils (Österholm and Åström 2002). There is, thus, no question that the acidity and high metal concentrations of the Rintala surface waters originate in the zone of active oxidation and weathering in the AS soil.

A characteristic feature of streams draining organic-rich soils is high TOC, NO_{2_3}-N and Ba concentrations, and of those draining forest and rural areas weakly but significantly elevated As and V concentrations (Table 1). Both stream types also have significantly higher P concentrations than those draining AS soil. Because these two streams types have higher conductivity and concentrations of SO_4^{2-} and several metals than what can be considered as ”background concentrations” in the country (headwater streams; Table 1, last column), some unknown small patches of AS soil are likely to exist in the drainage areas of at least some of the streams of these groups.

Hydrochemistry of the Sotaoja stream

In the upper Sotaoja stream (So1-So3; Fig. 1) in autumn 1997, the concentrations of the AS soil related determinants occur in high concentrations: those of SO_4^{2-}, Al, Ca, Cd, Co, Mn, Ni, Se and Zn were similar to the maximum concentrations and those of Cu, Pb, F and H_3O^+ similar to the median concentrations in the low-order streams (Table 1 and 2). In the lower Sotaoja stream (So4-So8, Fig. 1), the concentrations of these determinants were approximately half as high as those in upper Sotaoja (Table 2). A similar downstream pattern exists for NH_4^+-N, Fe, K and Mg (Table 2). There are three reasons for this pattern: (1) in the area that drains to upper Sotaoja, widespread fresh AS soil deliver large quantities of elements into drainage, (2) downstream of So3, Sotaoja merges with a relatively big stream (twice as large as upper Sotaoja; not indicated in the map) which rises in the forest and rural areas east of the Rintala plain (Fig. 1) and contains relatively low element concentrations, resulting in dilution of the Sotaoja stream water (Table 2), and (3) the lower reaches of Sotaoja stream (So4-So8) receives discharge both from AS soils and organic-rich soils (Fig. 1).

In spring 1998, there was a similar spatial pattern, i.e. the concentrations of the AS soil related determinants including K and Mg (Table 2) were approximately twice as high in the upper (So1-So3) as in the lower Sotaoja (So4-So8), indicating similar sources, hydrological pathways and controls in the two seasons. However, in spring the overall concentration level was only approximately half as high as that in autumn, and in upper Sotaoja, as expected, the concentration level was overall similar to the median of the water samples collected on the same occasion from low-order streams draining AS soil (Table 1 and 2). Two possible explanations for the lower element concentrations in spring are: (1) different hydrological conditions indicated by the higher runoff (16 l s^{-1} km^{-2}) than in autumn (6 l $s^{-1}km^{-2}$) resulting in dilution, and/or (2) the acidity and elements released by oxidation and weathering in the AS soil in the summer were primarily leached in autumn (Palko and Yli-Halla 1993), leaving behind a minor pool of mobile compounds which were leached the following spring.

Hydrochemistry of the old-Seinäjoki stream

In autumn 1997, pH was circumneutral and the concentrations of elements were overall low at Se 1 (Table 3; Fig. 1). This is due to discharge of larger quantities of circumneutral dilute water from the dam (probably up to 250 l s^{-1}). From Se1 to Se10 (Fig. 1) there was an overall increase in the concentrations of many variables (Table 3), explained by the downstream increase in the proportion of AS soil.

In spring 1998, the downstream variations in the concentrations of V, As, P and TOC were small and unsystematic (Table 3). In contrast, the concentrations of all other variables increased through the upper reaches (from Se1 to Se3), decreased through the middle reaches (from Se4 to Se7) and increased again through the lower reaches (from

Table 2. Analytical results for samples collected in Sotaoja stream and the main inflow ditch.

OCTOBER 1997									
Sample	So1	So2	So3	Inflow ditch	So4	So5	So6	So7	So8
Temperature (°C)	1.2	1.5	2.1	0.9	1.3	1.6	1.5	1.4	1.4
pH	3.9	3.9	3.9	4.3	4.1	4.1	4.2	4.2	4.2
EC (mS m^{-1})	206	205	176	64	100	126	118	117	114
Acidity (mmol l^{-1})	5.9	5.5	6.4	1.1	2.4	3.2	2.8	2.8	2.7
SO_4^{2-} (mg l^{-1})	1170	1300	1240	223	600	685	650	600	600
NO_{2_3}-N (mg l^{-1})	6.6	7.3	8.0	2.8	4.1	6.6	5.7	5.7	5.8
NH_4^+-N (mg l^{-1})	0.33	1.53	1.65	0.16	0.54	0.86	0.69	0.68	0.65
P (mg l^{-1})	0.02	0.03	0.05	0.02	0.03	0.02	0.02	0.03	0.03
Cl (mg l^{-1})	41	43	41	28	32	35	35	33	35
F (mg l^{-1})	2.20	2.15	2.30	0.55	1.05	1.27	1.19	1.12	1.14
TOC (mg l^{-1})	13	12	12	22	23	19	18	20	19
Al (mg l^{-1})	20	39	46	6	14	25	16	17	17
As (µg l^{-1})	1.08	1.67	1.73	1.53	1.55	1.49	1.33	1.29	1.49
Ba (µg l^{-1})	24	30	27		34	41	35	35	39
Ca (mg l^{-1})	94	146	159	41	60	92	72	71	70
Cd (µg l^{-1})	2.81	4.44	4.98	1.07	2.13	2.35	1.82	1.72	2.08
Co (µg l^{-1})	257	416	477	89	172	215	175	163	171
Cr (µg l^{-1})	1.5	2.4	3.1	1.7	2.0	2.6	1.9	1.9	2.4
Cu (µg l^{-1})	22	36	42	19	24	29	22	21	23
Fe (mg l^{-1})	1.41	1.78	1.48	0.81	0.97	1.00	0.81	0.77	0.81
K (mg l^{-1})	18	32	34	10	14	18	14	15	15
Mg (mg l^{-1})	83	142	167	31	58	88	64	66	68
Mn (mg l^{-1})	20	21	20	4.6	12	17	13	13	13
Ni (µg l^{-1})	335	560	645	176	274	334	250	257	258
Pb (µg l^{-1})	1.1	2.0	2.4	0.6	1.0	1.5	0.8	0.8	0.8
Se (µg l^{-1})	4.5	7.0	7.5	1.7	3.3	4.6	3.9	3.6	3.8
Sr (µg l^{-1})	781	1205	1244		522	685	585	557	602
V (µg l^{-1})	0.22	0.34	0.35	1.06	0.79	0.76	0.60	0.61	0.70
Zn (µg l^{-1})	842	1241	1349	334	598	729	601	557	631

Se8 to Se10; Table 3). The strong increase in the upper reaches is due to the moderate contribution of circumneutral dilute water from the dam (approximately 120 l s^{-1}), and the impact of high runoff (16 l s^{-1} km^{-2}) from the agricultural fields underlain mainly with AS soil (Fig. 1). The decrease in concentrations in the middle reaches is explained by the contribution of dilute water mainly from forest and rural areas and to some extent from S-poor agricultural soils (non AS soils) to the north (Fig. 1). In the lower reaches, below the low-S area (Se8-Se10), the increase in concentrations was due to high inputs from agricultural fields underlain mainly with AS soil (catchment of Sotaoja stream in particular). At the outlet (Se10), the water was more acidic and had higher concentrations of elements than in autumn, despite the fact that the Sotaoja stream, which drains extensive areas of AS soils, was more acidic and had higher element concentrations in the latter season (Table 2). This reverse trend is explained mainly by two factors: (1) overall lower pH and higher element concentrations in the water exiting the AS soil in autumn, resulting in deterioration of the water quality in Sotaoja stream in that season, and (2) the proportion of water exiting AS soil relative to that discharged from the dam was considerably higher in spring, resulting in deterioration of the water quality in old-Seinäjoki stream in that season. Hence, the temporal and spatial variations in water quality

Table 2. (Continued)

MAY 1998									
Sample	So1	So2	So3	Inflow ditch	So4	So5	So6	So7	So8
Temperature (°C)	7.4	7.1	6.7	6.5	6.6	7.1	6.0	6.0	6.1
pH	3.9	4.0	4.0	4.5	4.3	4.4	4.4	4.4	4.4
EC (mS m^{-1})	146	142	137	47	82	88	91	88	86
Acidity (mmol l^{-1})	5.1	4.8	4.4	0.8	2.0	1.5	2.5	2.2	2.0
SO_4^{2-} (mg l^{-1})	710	670	690	170	360	360	420	410	410
NO_{2_3}-N (mg l^{-1})	10.0	10.6	11.4	4.2	3.1	9.3	9.3	9.5	9.7
NH_4^+-N (mg l^{-1})	1.31	1.32	1.30	0.18	0.63	0.74	0.65	0.64	0.65
P (mg l^{-1})	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05
Cl (mg l^{-1})	29	31	30	28	25	33	30	30	29
F (mg l^{-1})	1.70	1.70	1.50	0.39	0.81	0.88	0.87	0.86	0.84
TOC (mg l^{-1})	14	14	15	20	19	20	19	19	20
Al (mg l^{-1})	25	17	16	1	5	7	4	6	7
As (µg l^{-1})	0.92	0.70	0.68	0.59	0.56	0.74	0.48	0.60	0.74
Ba (µg l^{-1})	27	17	21		26	41	35	28	43
Ca (mg l^{-1})	92	65	58	13	27	41	24	33	32
Cd (µg l^{-1})	2.13	1.57	1.76	0.33	0.74	1.04	0.60	0.81	1.04
Co (µg l^{-1})	233	165	173	29	69	94	55	76	96
Cr (µg l^{-1})	3.3	2.0	2.5	1.0	1.4	1.9	1.4	1.3	2.0
Cu (µg l^{-1})	29	21	21	7	10	13	8	10	13
Fe (mg l^{-1})	1.51	1.10	0.97	0.25	0.49	0.58	0.32	0.41	0.44
K (mg l^{-1})	13	10	12	4	6	9	4	7	7
Mg (mg l^{-1})	53	39	42	8	19	29	16	23	25
Mn (mg l^{-1})	13	9	10	1.4	4	5	3	4	5
Ni (µg l^{-1})	329	226	241	49	98	129	77	108	134
Pb (µg l^{-1})	1.0	0.9	0.8	0.2	0.4	0.6	0.4	0.5	0.5
Se (µg l^{-1})	2.7	1.8	2.0	0.3	0.7	0.9	0.7	0.8	1.2
Sr (µg l^{-1})	609	437	433		200	303	185	254	335
V (µg l^{-1})	0.33	0.26	0.25	0.50	0.40	0.51	0.34	0.40	0.56
Zn (µg l^{-1})	623	467	488	94	209	281	167	230	280

EC = electric conductivity
TOC = total organic carbon

in the area are complex, but overall the water quality is very poor and typical for AS soil affected waters.

Appropriate methods for improvement of water quality

In stream liming, i.e. applying lime in the streams in Rintala, is not motivated because of the great amounts of lime needed (> 100 t CaO per year) to reduce the acidity and the huge amounts of metals leached (e.g. 50 kg Al ha^{-1} a^{-2} in upper Sotaoja; Österholm and Åström 2004) which, if neutralisation would be successful, would create a big problem with metal precipitates in the drains. If, despite its limitations, in-stream liming would be used in Rintala, a choice of conventional limestone ($CaCO_3$) powder might be appropriate in the old-Seinäjoki stream while the high acidity in the Sotaoja stream (> 2 mM L^{-1}; Table 2), in accordance with recommendations by Weppling (1997), would require the use of easily-dissolved hydrated lime or quick lime (CaO) in order to optimize the neutralisation effect and costs.

Table 3. Analytical results for samples collected in Seinäjoki stream.

OCTOBER 1997 Sample	Se1	Se2	Se3	Se4	Se5	Se6	Se7	Se8	Se9	Se10
Temperature (°C)	4.3	3.4	3.2	2.9	3.2	3.2	3.5	3.4	3.4	3.2
pH	6.6	5.6	5.5	5.7	5.6	5.3	5.5	5.3	5.3	4.6
EC (mS m^{-1})	11	15	14	17	25	25	23	21	21	31
Acidity (mmol l^{-1})	0.1	0.2	0.2	0.2	0.3	0.4	0.3	0.4	0.4	0.6
SO_4^{2-} (mg l^{-1})	14	30	34	41	62	67	64	51	63	106
NO_{2_3}-N (mg l^{-1})	2.2	1.2	1.2	1.8	3.6	3.2	3.1	1.9	2.1	2.0
NH_4^+-N (mg l^{-1})	0.06	0.11	0.08	0.08	0.11	0.11	0.10	0.06	0.08	0.13
P (mg l^{-1})	0.12	0.07	0.06	0.08	0.08	0.06	0.05	0.05	0.05	0.06
Cl (mg l^{-1})	8	10	10	12	16	14	14	11	11	13
F (mg l^{-1})	0.11	0.16	0.17	0.18	0.23	0.24	0.23	0.18	0.22	0.30
TOC (mg l^{-1})	20	19	20	22	18	18	17	22	25	22
Al (mg l^{-1})	0.03	0.30	0.44	0.37	0.29	0.63	0.53	0.82	0.93	2.56
As (µg l^{-1})	1.14	0.72	1.05	1.24	0.80	1.12	0.99	1.48	1.18	1.03
Ba (µg l^{-1})	11	11	13	15	13	16	14	16	17	20
Ca (mg l^{-1})	7	7	10	10	13	16	17	14	16	18
Cd (µg l^{-1})	0.03	0.07	0.11	0.10	0.15	0.23	0.20	0.22	0.21	0.66
Co (µg l^{-1})	0.3	5	7	7	9	14	13	13	16	32
Cr (µg l^{-1})	0.7	0.5	0.8	0.9	0.7	1.0	0.9	1.2	1.0	1.3
Cu (µg l^{-1})	10.0	6.7	8.5	6.9	5.5	8.7	7.8	8.3	8.4	9.5
Fe (mg l^{-1})	0.23	0.14	0.26	0.30	0.16	0.28	0.29	0.62	0.50	0.51
K (mg l^{-1})	3.1	2.5	3.4	3.6	4.9	5.3	5.4	4.6	4.8	5.0
Mg (mg l^{-1})	2.2	3.3	4.7	4.8	5.8	7.2	7.2	6.7	8.1	12.9
Mn (mg l^{-1})	0.02	0.27	0.42	0.39	0.54	0.76	0.78	0.71	0.97	1.97
Ni (µg l^{-1})	4	10	16	15	20	30	29	28	33	53
Pb (µg l^{-1})	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.2
Se (µg l^{-1})	0.2	0.4	0.5	0.3	0.4	0.6	0.7	0.6	0.6	0.8
Sr (µg l^{-1})	34	41	59	65	69	90	83	78	86	126
V (µg l^{-1})	0.25	0.15	0.28	0.33	0.25	0.44	0.46	0.84	0.65	0.57
Zn (µg l^{-1})	19	38	47	47	58	79	88	70	80	158

Passive treatment methods which utilize biological and chemical processes that traditionally have been used for treatment of mine drainage, are tested on AS soil drainage in Rintala (Successive Alkaline Passive Treatment) and in McLeods creek, Australia (Closed Tank Reactor; Desmier et al. 2002). In the method used in Rintala, water is infiltrated through a 0.5 m thick layer of organic material on top (removing O_2 and Fe^{3+}, and retaining metals through sulphate reduction and adsorption) and a 0.5 m thick layer of limestone below (reducing acidity). Thereafter, metals not yet retained are precipitated as hydroxides in a settling pond by aeration. While these methods can significantly increase the pH and remove metals from the treated water, the volume of water which can be treated will be too low to have a significant impact on the overall water quality in an area like Rintala with 17 km^2 of AS soil and an average runoff of about 7 l s^{-1}km^{-2}. Furthermore, as this study shows, the Rintala streams are in most parts diluted by non-AS soil drain waters which further increases the amounts of waters that would have to be handled. If these passive treatments were to be used on a large scale in the area, although not recommended by the authors, the hydrochemical data of this study shows that upper Sotaoja, where the AS soil waters are undiluted and of very poor quality, is the best choice of location (Table 2).

Soil surface liming (about 10–30 t ha^{-1} 5 years) on AS soil keeps the pH above 5 in the plough layer and turns these otherwise rather unfertile

Table 3. Continued

MAY 1998 Sample	Se1	Se2	Se3	Se4	Se5	Se6	Se7	Se8	Se9	Se10
Temperature (°C)	9.7	8.8	9.0	9.1	8.7	7.7	7.7	7.3	6.9	7.2
pH	5.7	4.2	4.2	4.3	4.3	4.4	4.4	4.3	4.3	4.4
EC (mS m^{-1})	10	82	90	76	68	56	54	59	61	70
Acidity (mmol l^{-1})	0.2	2.4	2.6	2.0	1.7	1.3	1.2	1.2	1.4	1.5
SO_4^{2-} (mg l^{-1})	25	380	410	350	250	220	230	220	250	260
NO_{2_3}-N (mg l^{-1})	0.8	3.6	4.1	3.5	3.6	3.2	3.2	3.5	3.9	6.6
NH_4^+-N (mg l^{-1})	0.23	1.17	0.98	0.74	0.51	0.42	0.32	0.26	0.26	0.46
P (mg l^{-1})	0.07	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04
Cl (mg l^{-1})	7	27	32	28	27	23	21	22	22	25
F (mg l^{-1})	0.13	1.10	1.20	0.93	0.79	0.68	0.56	0.57	0.66	0.77
TOC (mg l^{-1})	20	12	11	12	13	16	15	16	16	18
Al (mg l^{-1})	0.32	10.4	12.2	10.6	8.21	3.3	2.9	3.12	4.43	5.86
As (µg l^{-1})	0.74	0.72	0.74	1.04	0.90	0.66	0.63	0.61	0.80	1.02
Ba (µg l^{-1})	24	22	29	31	25	22	16	17	19	33
Ca (mg l^{-1})	6	36	46	46	39	20	16	18	26	38
Cd (µg l^{-1})	0.08	0.70	0.95	0.89	0.79	0.38	0.35	0.40	0.60	1.01
Co (µg l^{-1})	5	70	93	86	73	35	30	36	55	87
Cr (µg l^{-1})	1.1	2.1	2.1	2.1	1.8	1.4	1.1	1.0	1.4	1.7
Cu (µg l^{-1})	4.0	17.7	21.1	19.7	15.1	8.4	8.0	8.1	11.1	14.3
Fe (mg L^{-1})	0.31	0.86	1.05	1.01	0.83	0.44	0.39	0.39	0.57	0.60
K (mg l^{-1})	2.2	7.0	9.5	9.8	8.7	4.8	3.4	4.4	5.9	8.5
Mg (mg l^{-1})	2.6	20.6	25.9	25.4	22.3	10.9	9.4	10.9	16.0	24.9
Mn (mg l^{-1})	0.24	3.39	4.56	4.35	3.77	1.74	1.54	1.95	2.93	4.65
Ni (µg l^{-1})	10	127	165	152	127	62	53	59	90	135
Pb (µg l^{-1})	0.2	0.5	0.6	0.6	0.4	0.4	0.3	0.4	0.4	0.6
Se (µg l^{-1})	-	2.1	2.8	2.5	1.9	0.9	0.7	0.7	1.1	1.3
Sr (µg l^{-1})	38	256	339	328	282	137	113	127	186	296
V (µg l^{-1})	0.47	0.35	0.33	0.50	0.64	0.52	0.50	0.51	0.66	0.81
Zn (µg l^{-1})	22	257	331	309	258	123	106	125	173	266

EC = electric conductivity
TOC = total organic carbon

lands into some of the most productive farm lands in Finland. However, the lime (in at least short term) does not penetrate below the plough layer where most of the acidity is stored (Weppling 1997, Österholm and Åström 2002) and does therefore not have a notable impact on drainage waters (Palko 1994, Puustinen 2001). Even if the lime would penetrate into deeper soil layers, the amounts needed to neutralise the soil acidity are unrealistically high in an area like Rintala where the chemical drainage depth is about 1.8 m (Österholm and Åström 2002). *Lime filter drainage* is a relatively new technique in Finland where lime is applied around the subsurface pipes (Weppling 1997). This method seems to significantly reduce the drain water acidity and precipitates metals into the soils around the drain pipes. However, since the method is basically based on neutralisation of acidity by lime, the lime reservoir is depleted in a few years in AS soil areas like Rintala (Triipponen 1997, Puustinen 2001) and there is an obvious risk that remobilisation of metal precipitates around the drain pipes will then occur. Nonetheless, at one test site in W. Finland (Ilmajoki), it seems that by combining lime filter drainage and controlled drainage (method described below) the neutralisation capacity is both prolonged and increased (Bärlund et al. 2004). Hence, it would be worthwhile to monitor that test site for some more years in order to make a better judgement on the functionality of the combination of the two techniques.

Groundwater management, i.e. keeping the groundwater table as high and as stable as possible, hampers soil oxidation, and thus, acidity production and metal mobilisation is reduced. It might also reduce the upward movement of acid waters, by retarding capillary forces, during dry periods (Pelanteri 1998). Furthermore, maybe the most important factor with groundwater management, which has received little or no attention when evaluating environmental measures on ASS, is that it seems to reduce the amount of drain outflow very effectively. On (non AS soil) farmlands in Sweden (Wesström et al. 2001, 2003) and North Carolina (Gilliam et al. 1997) it has been observed that controlled pipe drainage (CPD) can reduce the drain outflow by 30% or more due to increased evapotranspiration and crop growth. The reduction in runoff is highest in dry years, while in rainy years it may have little or no effect on runoff (Gilliam et al. 1997). Consequently, even if groundwater management would not affect the water quality from AS soil to a large extent, it is likely to have a great impact on the total amount of metals and acidity being leached from these soils per unit of time. Controlled pipe-drainage is suitable for agricultural lands with a low relief (< 2%) and a high hydraulic conductivity (> 0.5 m d^{-1}, Evans and Skagg 1989), and is becoming increasingly popular in western Finland (Rainer Rosendahl, personal communication). Technically, the subsurface drainage pipes are lead into a well where the height of the groundwater can be controlled by adjusting the height of the output valve (riser). The idea with CPD is to enable trafficability by keeping drainage intensity high (low riser and/or bottom valve open) during cropping and harvesting and to minimise drainage at other times in order to prevent overdrainage. Besides from its potential ability to reduce S oxidation and metal release, it is claimed to increase the crop yield. Promising results (regarding water-quality) have been obtained with CPD at an AS soil site in Ilmajoki, western Finland (Joukainen and Yli-Halla 2003, Bärlund et al. 2004), which is an area close to Rintala and with rather similar soil properties. However, at another test site in western Finland (Korsholm) where the groundwater is naturally high, the groundwater could not be further raised by CPD, and consequently the water quality was not improved (Bärlund et al. 2004). There are also maintenance problems at several other CPD sites (i.e. very low groundwater level), possibly due to (1) evapotranspiration, (2) bypass seepage to the main ditch and (3) the bottom valve is kept open (enabling maximum drainage) for too long in connection with field work, resulting in overdrainage. It has been suggested (e.g. Joukainen and Yli-Halla 2003) that it may be necessary to pump water into the control wells in order to maintain the high groundwater level. But, if the groundwater is artificially raised (not just maintained on a fixed level), it can not be excluded that this would increase rinsing of acidity and metals from the soils. For the Rintala area we thus recommend, without having considered the economical aspects, groundwater management with CPD preferably combined with construction of one or several dams in Sotaoja and stricter regulation of the water level at the pumping stations.

Raised bed drainage, a method used on AS soils in Australia and Vietnam, could be a potential method on Finnish AS soils in combination with conventional groundwater management (Ian White and Mike Melville, personal communication). The advantage is that the field is trafficable even at high groundwater levels and that crop yields are good, while one of the disadvantages is that all farming machines need to have the same wheel shaft width. Furthermore, as the soil structure is permanently destroyed below the wheel lanes, the width between the lanes can not be changed later. This technique has not yet been trialed on Finnish AS soils.

The use of the traditional *open ditches* instead of subsurface drainage on AS soil areas would have a significant positive effect on the water quality (Palko and Yli-Halla 1993), but due to several agricultural drawbacks and the fact that most of the Rintala area is already drained by subsurface pipes, it can not be considered as a potential method for Rintala.

The juridical obligation to improve water quality

The juridical obligation to improve the water quality in the Rintala area is based on the assumption that the embankment of Kyrönjoki river and the construction of the pumping stations might have a negative effect on the water quality in Kyrönjoki river. Above it is clearly demonstrated, that the acids and metals are derived from the acidic subsoil horizons, which have developed because of water table drawdown caused by extensive ditching operations over the last two hundred years (the last few decades in particular). Hence, the control of the water quality of the area is the groundwater level of the area and therefore we argue above that better ground water management (rise in groundwater table) is the key to a better water quality in the future.

As a result of the embankment of Kyrönjoki river and the construction of the pumping stations, it has been possible to release excess water (and lower the groundwater table) earlier in the spring. On the other hand, prior to these engineering manipulations, the water level in the Old-Seinäjoki stream was occasionally much lower than at present (Vesihydro 1992) as there was no pumping station and associated dam to prevent outflow during dry periods. Because of these contrasting effects and the fact that long-term data on water quality and ground water levels does not exist for the area, it is not possible to determine whether the highlighted works have forced the ground water to drop and concomitantly the water quality to deteriorate. The opinion of the authors is therefore, in line with the Finnish Environment Institute appeal in 1994, that the juridical obligation of the Rintala area is unreasonable.

Considering the present-day expectations of surface water quality highlighted e.g. in the EU Water Framework Directive (CEC 2000), the surface water originating from the Rintala AS soil have unacceptable loads of acidity and potentially toxic metals. In this sense, a juridical obligation would be justified, but it should, unlike the present one, focus on the source of the problems (water table drawdown caused by ditching). Also, due to the equality principle, any water-quality related juridical obligation should not focus specifically on Rintala, because the AS soil of this area do not supply more acids and metals than other typical AS soils of the region (Åström 1996) and they comprise only 1–2% and 5–10% of all cultivated AS soil in Finland (Yli-Halla et al. 1999) and the Kyrönjoki catchment (Erviö 1975) respectively.

Conclusions

The concentrations of AS soil related determinants in the runoff from the Rintala AS soil are similar to that of other AS soil areas in western Finland. The chemistry of the water emptying from the Rintala pumping station into Kyrönjoki river is controlled by the extent of release of acids, metals and other compounds from the AS soils, and by the extent to which the AS soil runoff is diluted (and neutralised) by water from the dam, the forest & rural areas and the organic-rich soils. At a runoff similar or lower than that in October 1997 ($\leq 8\ \mathrm{l\ s^{-1}km^{-2}}$), the water from the dam is the most important dilutant. In order to improve water quality in Rintala, groundwater management by controlled pipe drainage, preferably combined with a dam in Sotaoja and possibly stricter regulation at the pumping station, is recommended because: (1) the relief and soil type are suitable for controlled pipe drainage, (2) it would reduce temporal overdrainage common in the area, (3) the amounts of metals and acidity released with current drainage practices is too high to be cleaned ex situ, (4) it has the potential to improve the water quality and reduce amount of runoff and (5) it has the potential to be accepted by farmers. The current juridical obligation for Rintala is not justified, because it fails to address the reason for the poor water quality, i.e. previous and current drainage works.

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SELOSTUS

Vesistön saastumisen arviointi, parannustoimenpiteet ja juridiset velvoitteet happamalle sulfaattimaa-alueelle Länsi-Suomessa

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Rikkipitoiset maat ovat yleisiä Suomen länsirannikolla. Näiden maiden kuivatus on johtanut rikin hapettumiseen ja ns. happamien sulfaattimaiden (pH < 4) muodostumiseen. Mailta huuhtoutuu runsaasti happamuutta, rikkiä ja metalleja, mikä aiheuttaa merkittävää ekologista haittaa monissa Länsi-Suomen vesistöissä. Tässä työssä käsitellään alueellista vesigeokemiaa, keinoja vähentää ympäristökuormitusta ja juridisia velvoitteita Rintalan pengerrysalueella.

Rintalan pengerrysalue (23 km^2) sijaitsee Kyrönjoen varrella Seinäjoen lounaispuolella. Happamia sulfaattimaita kuivattavat ojat ovat huomattavasti happamampia (pH = 4 ja happamuus = 4 mmol l^{-1}) ja niissä on paljon suuremmat SO_4^{2-}-, Al-, Ca-, Cd-, Co-, Cu-, F-, Mn-, Ni-, Pb-, Se-, Sr- ja Zn-pitoisuudet kuin ei-happaman (korkea humuspitoisuus) alueen ojissa sekä pengerrysalueen ulkopuolelta tulevien metsä- ja asutusalueiden ojissa. Nämä ei-happamat ojat ja Seinäjoen vanhaan uomaan päästetty vesi voivat laimentaa Rintalasta Kyrönjokeen johdettavan veden happamuutta ja metallipitoisuuksia jopa yli 90 %, mutta veden laatu on silti huono.

Alueen pengerryksen ja rakennettujen pumppausasemien vuoksi Rintalan alueelle on asetettu velvoite parantaa ulosjohdetun veden laatua. Velvoitetta on perusteltu sillä, että mainitut rakennelmat voivat huonontaa veden laatua. Kun otetaan huomioon nykypäivänä pintaveden laadulle asetettuja odotuksia (mm. EU:n vesipuitedirektiivi), sulfaattimaiden aiheuttamaa ympäristökuormitusta olisi aiheellista käsitellä oikeudessa. Velvoitetta ei kuitenkaan voida pitää tarkoituksenmukaisena, koska salaojitusta, joka on pääsyy veden huonoon laatuun Rintalan ja muun Suomen sulfaattimaa-alueilla, ei oteta lainkaan huomioon. Tämän lisäksi Rintala on ainoa pengerrysalue, jolle tällainen velvoite on asetettu, vaikka alueen veden laatu laimentamattomissa ojissa ei ole huonompi kuin muiden vastaavien alueiden veden laatu. Pohjaveden tarkempi kontrolli, ensisijaisesti säätösalaojituksella, olisi todennäköisesti paras keino happamuuden ja metallipäästöjen pienentämiseksi.