Performance of the flooded TMF at Stekenjokk:

25 years of follow-up

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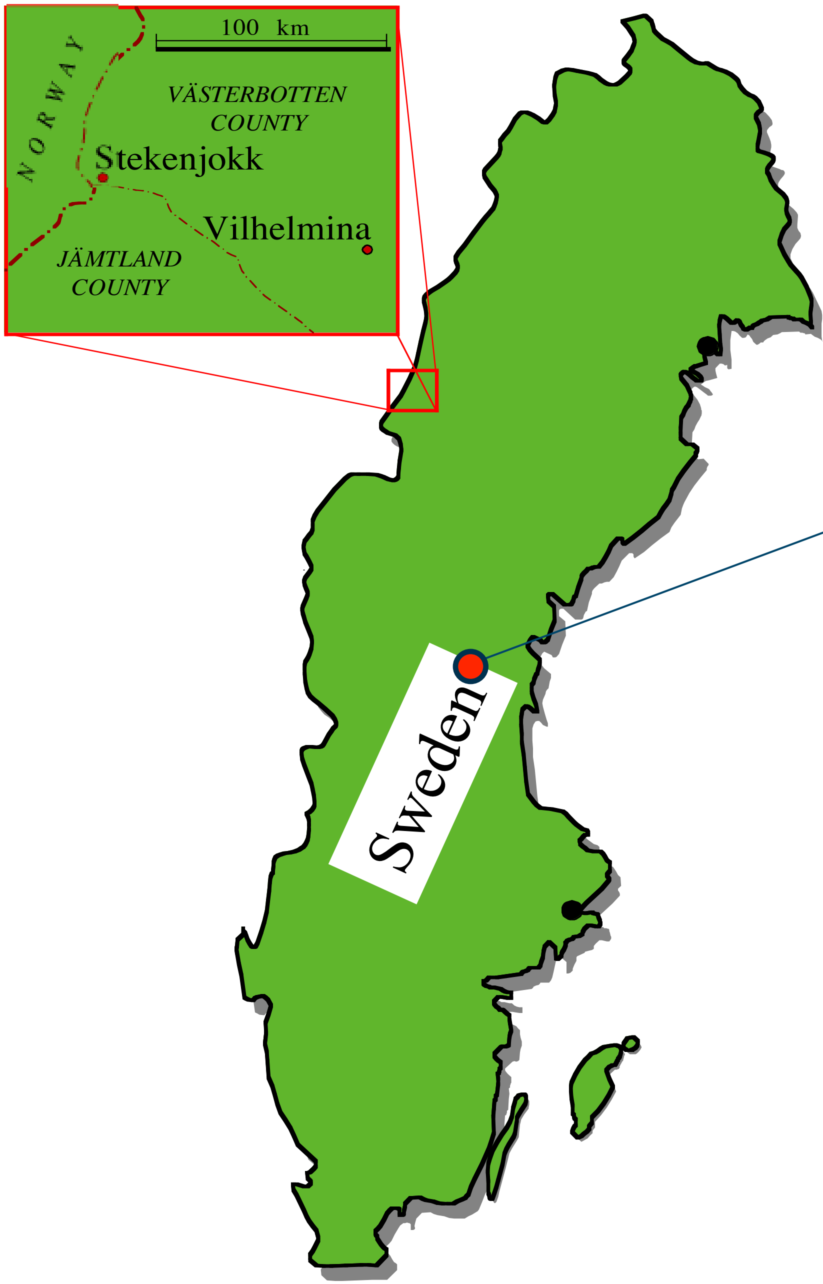
NEW BOLIDEN


100 km
NORWAY
VÄSTERBOTTEN COUNTY
Stekenjokk
Vilhelmina
JÄMTLAND COUNTY
Sweden


Europe
ICELAND
NORWAY
SWEDEN
FINLAND
RUSSIA
ESTONIA
LATVIA
LITHUANIA
DENMARK
IRELAND
UNITED KINGDOM
THE NETHERLANDS
BELGIUM
GERMANY
POLAND
BELORUSSIA
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MOLDAVIA
ROMANIA
FRANCE
SWITZERLAND
SLOVENIA
CROATIA
BOSNIA & HER.
SERBIA
BULGARIA
ITALY
KOSOVO
MACE-DONIA
ALBANIA
GREECE
TURKEY
CYPRUS
PORTUGAL
SPAIN
MOROCCO
ALGERIA
TUNESIA

Stekenjokk

- The Cu and Zn mineralisation discovered in year 1918
- Sensitive environment +800 m.a.sl. in the Lapland mountains
- 8 Mton of ore mined mainly underground 1976 – 1988
- 2,1 Mton tailings used in back-fill
- 110 ha tailings pond containing 4.4 Mton tailings

S	20 %
Zn	0.65 %
Cu	0.2 %
$CaCO_3$	7 %

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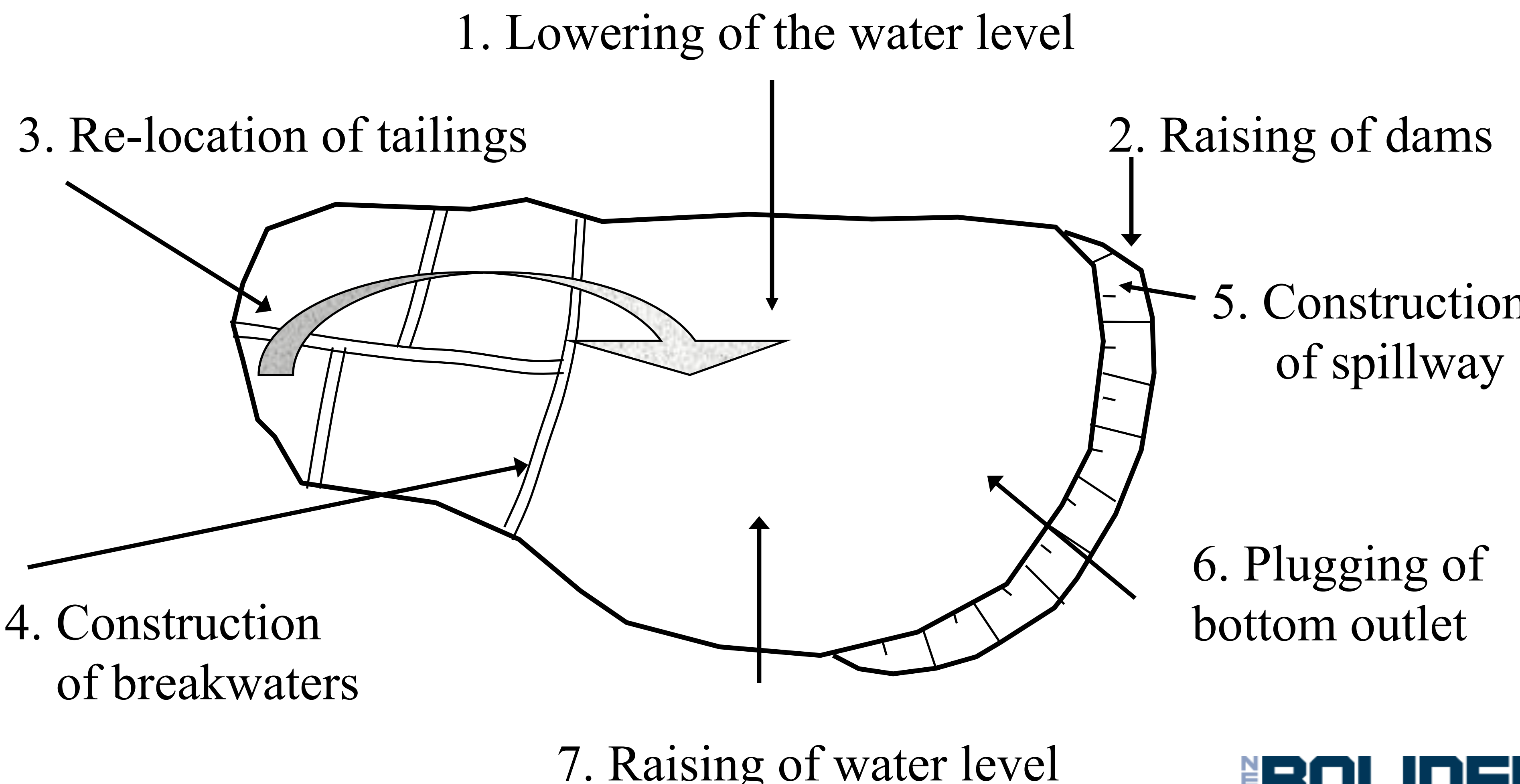
Evaluated closure options

Initial closure objectives were:

- Safe environment
- Prevent TMF from becoming a major source of ML/ARD
- Landscape integration

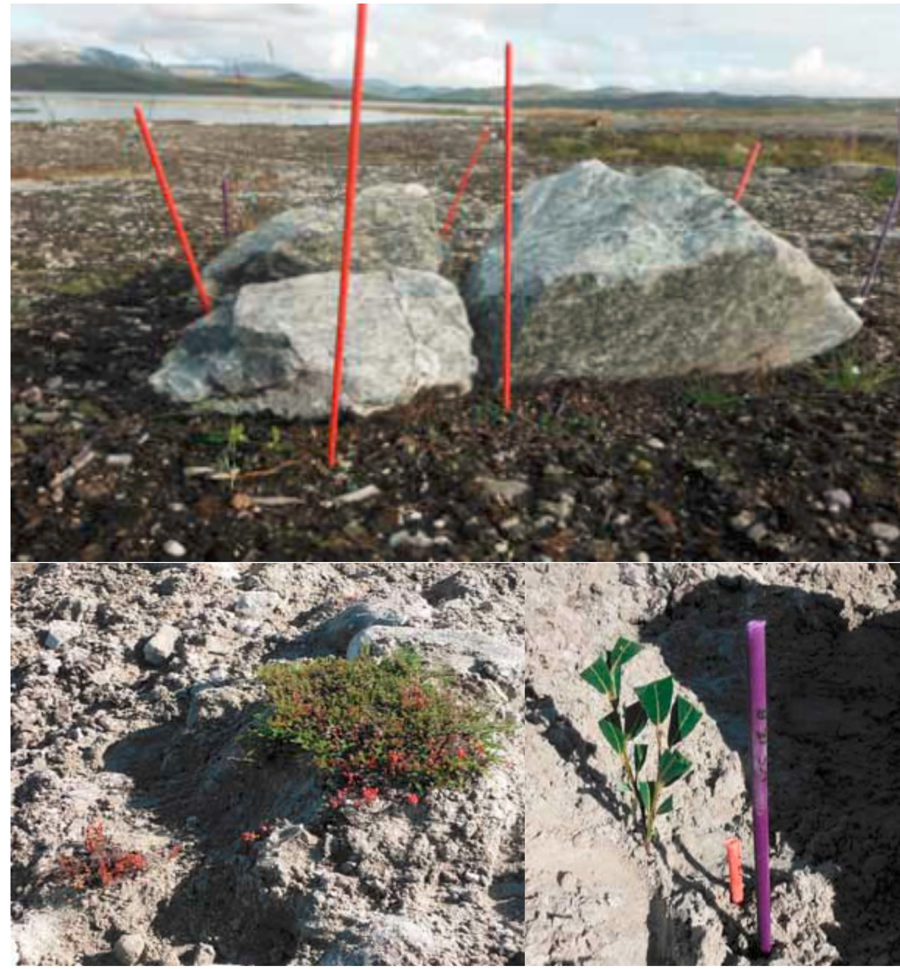
Method	Rating	Cost (MSEK)
Flooding	1	15
Dry cover	2	120
Depyritization	-	45
Buffering	-	30

Stekenjokk TMF - applied measures 1990-1991



Closure follow-up program

- **Discharge water flow and quality**
- Water level variations in the pond
- Stability of the breakwaters
- Re-suspension of tailings
- Dam leakage flow and quality
- Re-vegetation
- Fish inventory and metal uptake
- Incoming surface water streams
- Follow-up on the water balance
- **Scientific geochemical investigations (Techn. Univ. Luleå)**
- **Dams safety**



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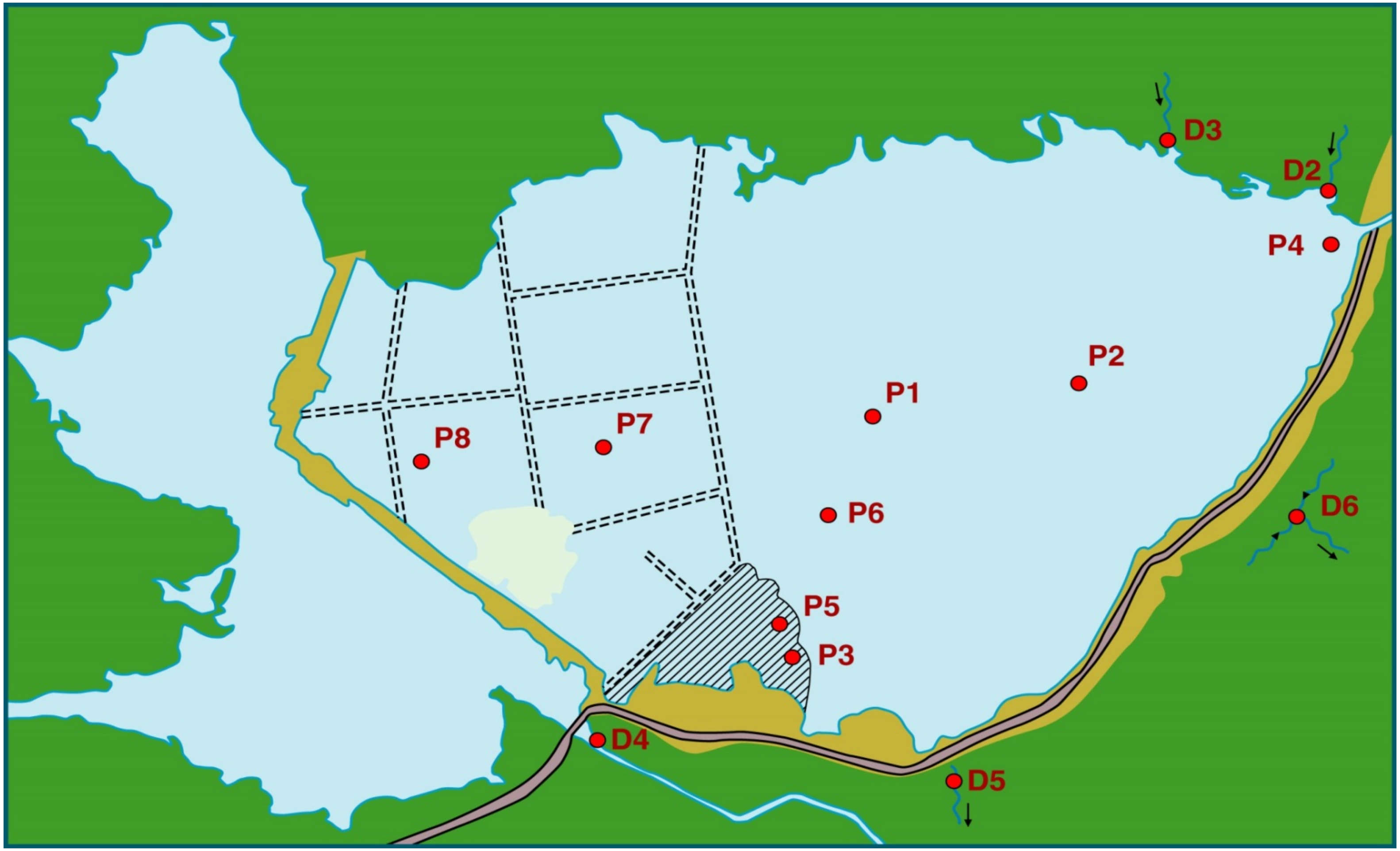
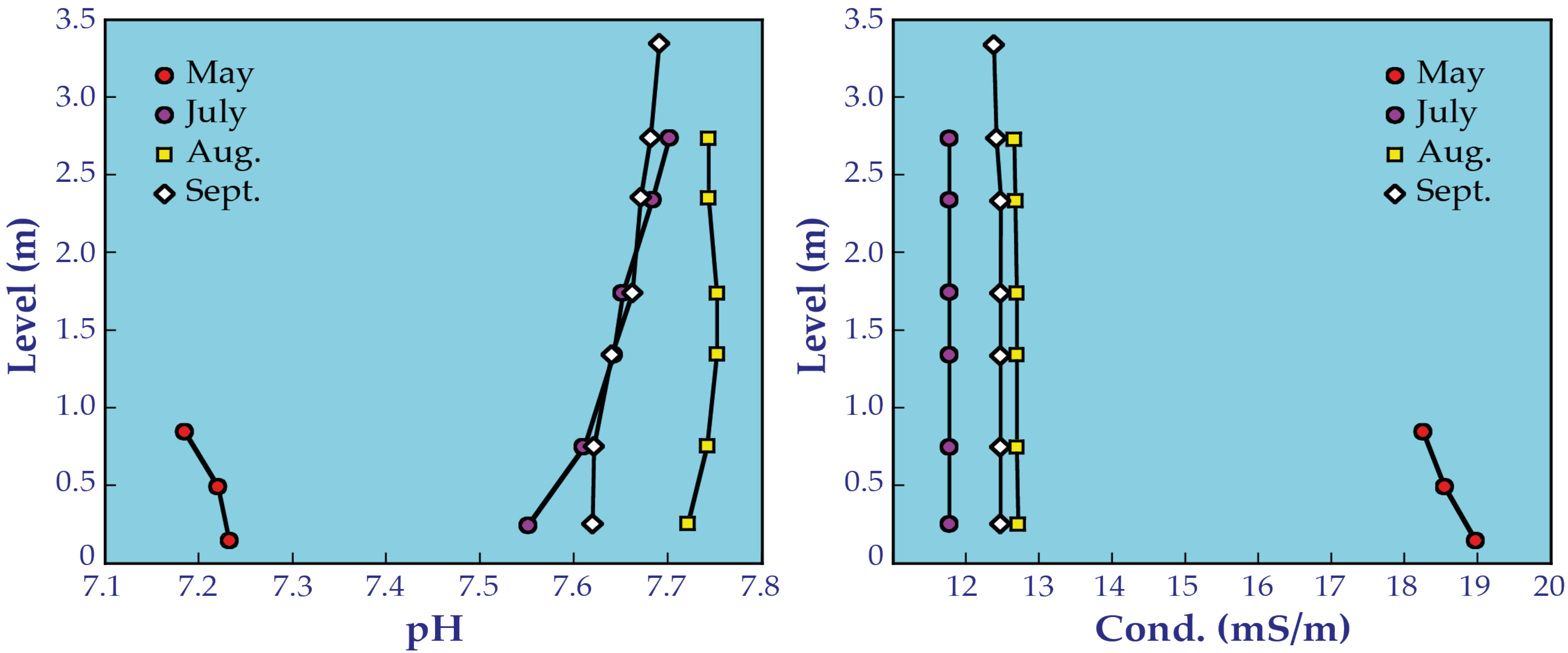
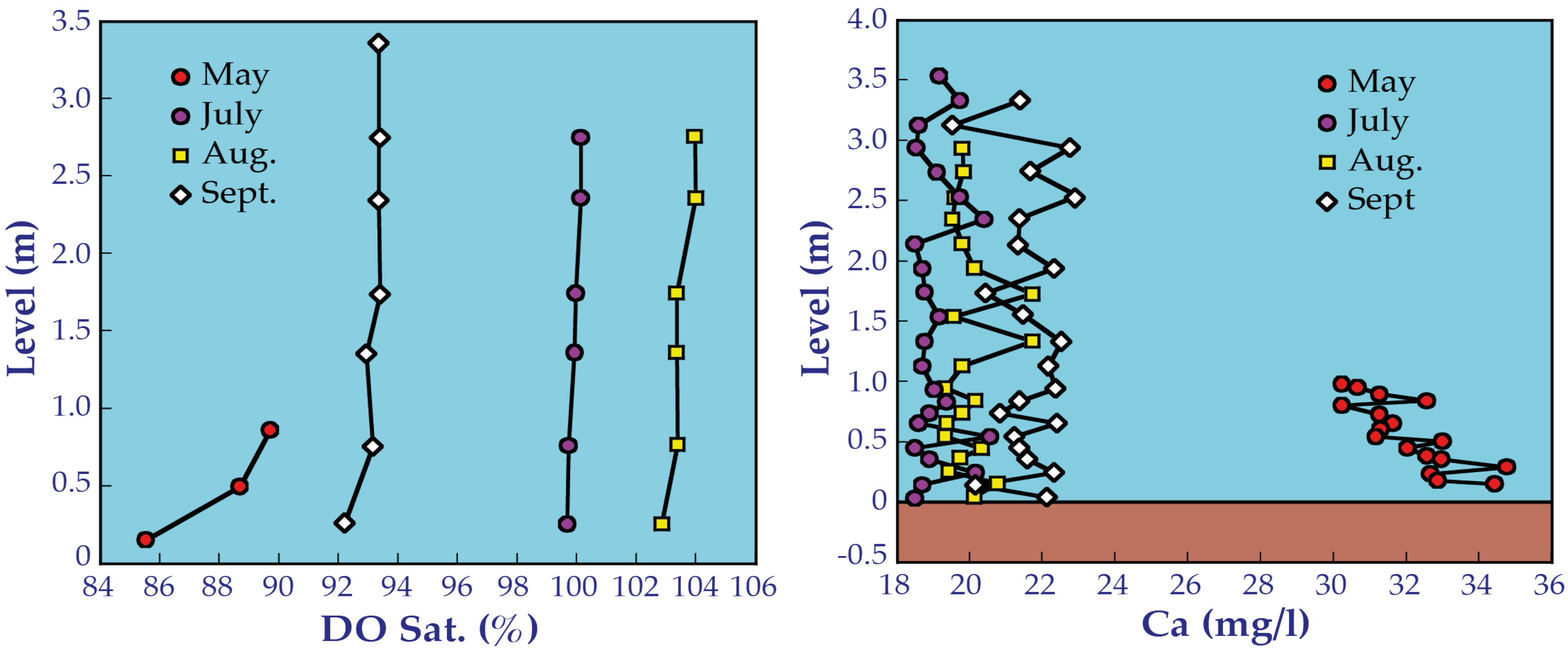
Geochemical studies



From Ljungberg et al, 1997



Results from Station P1 (from Ljungberg et al, 1997).



Results from Station P1 (from Ljungberg et al, 1997).

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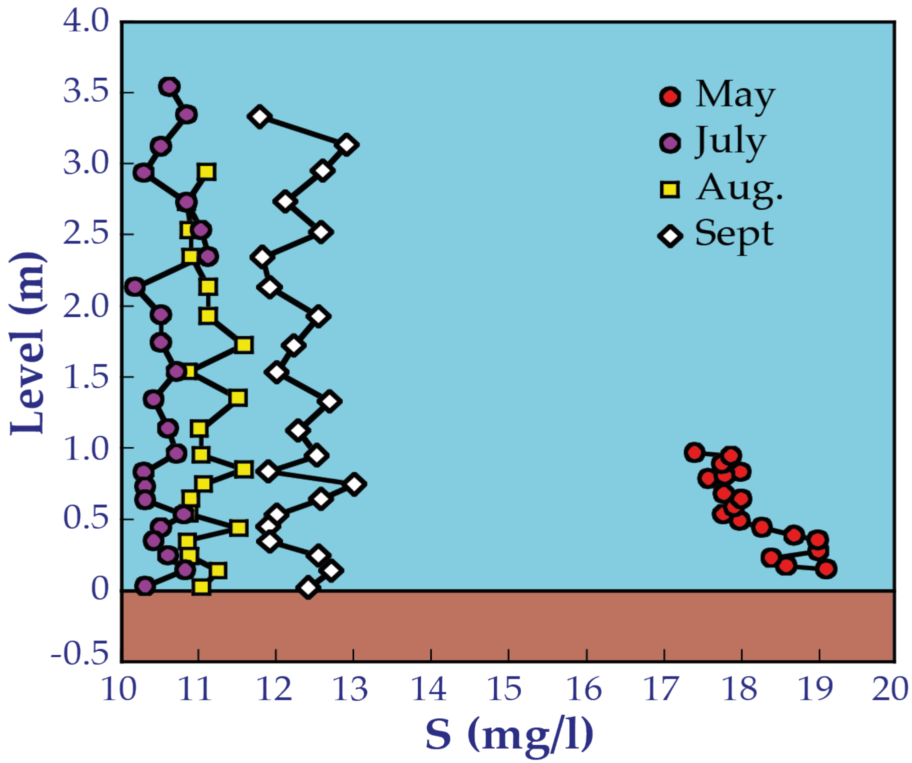

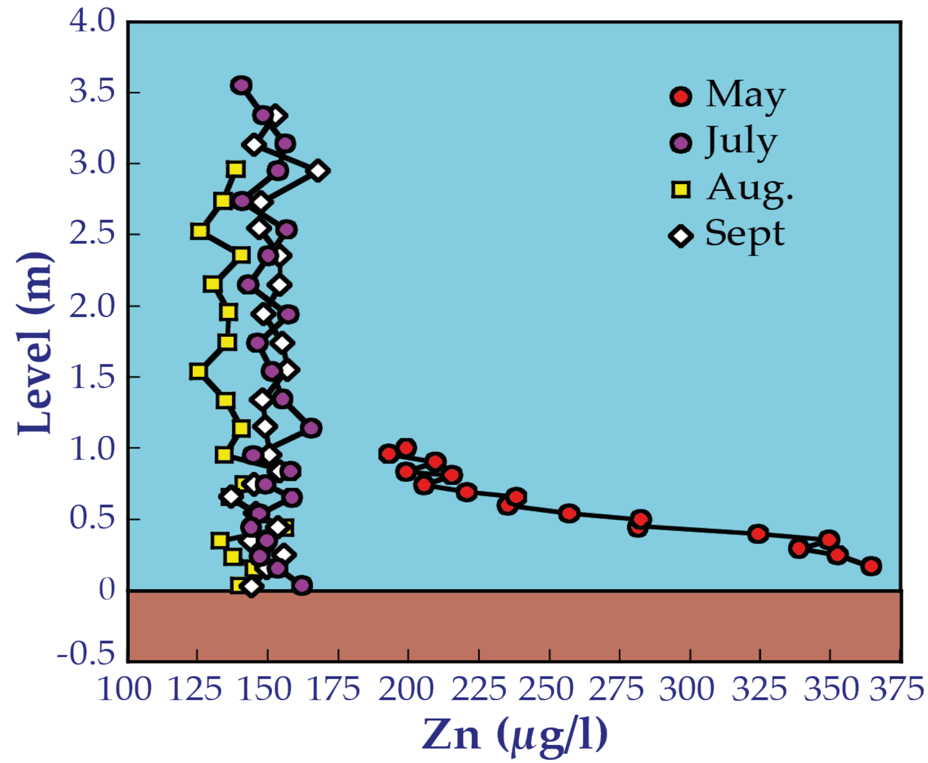

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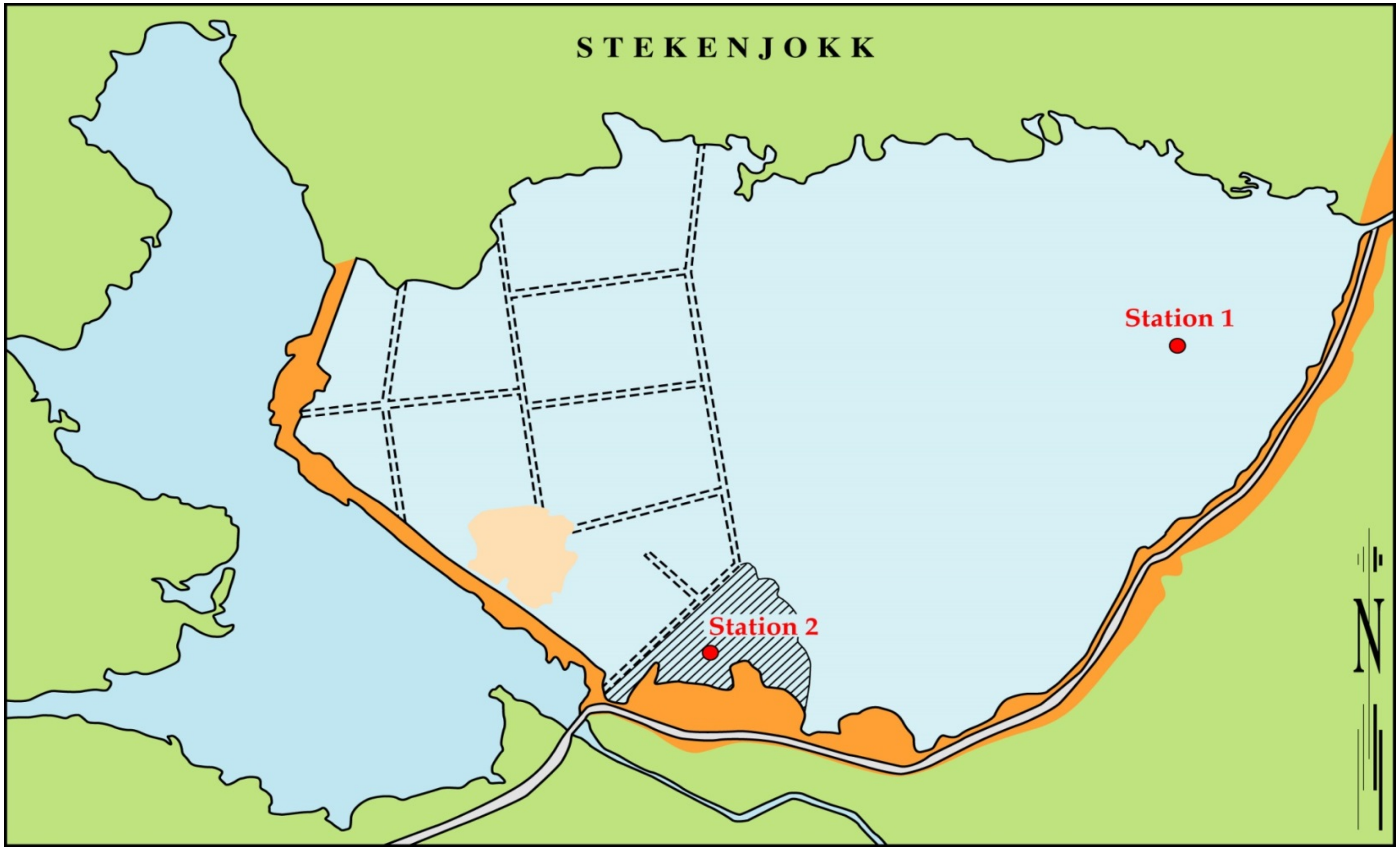
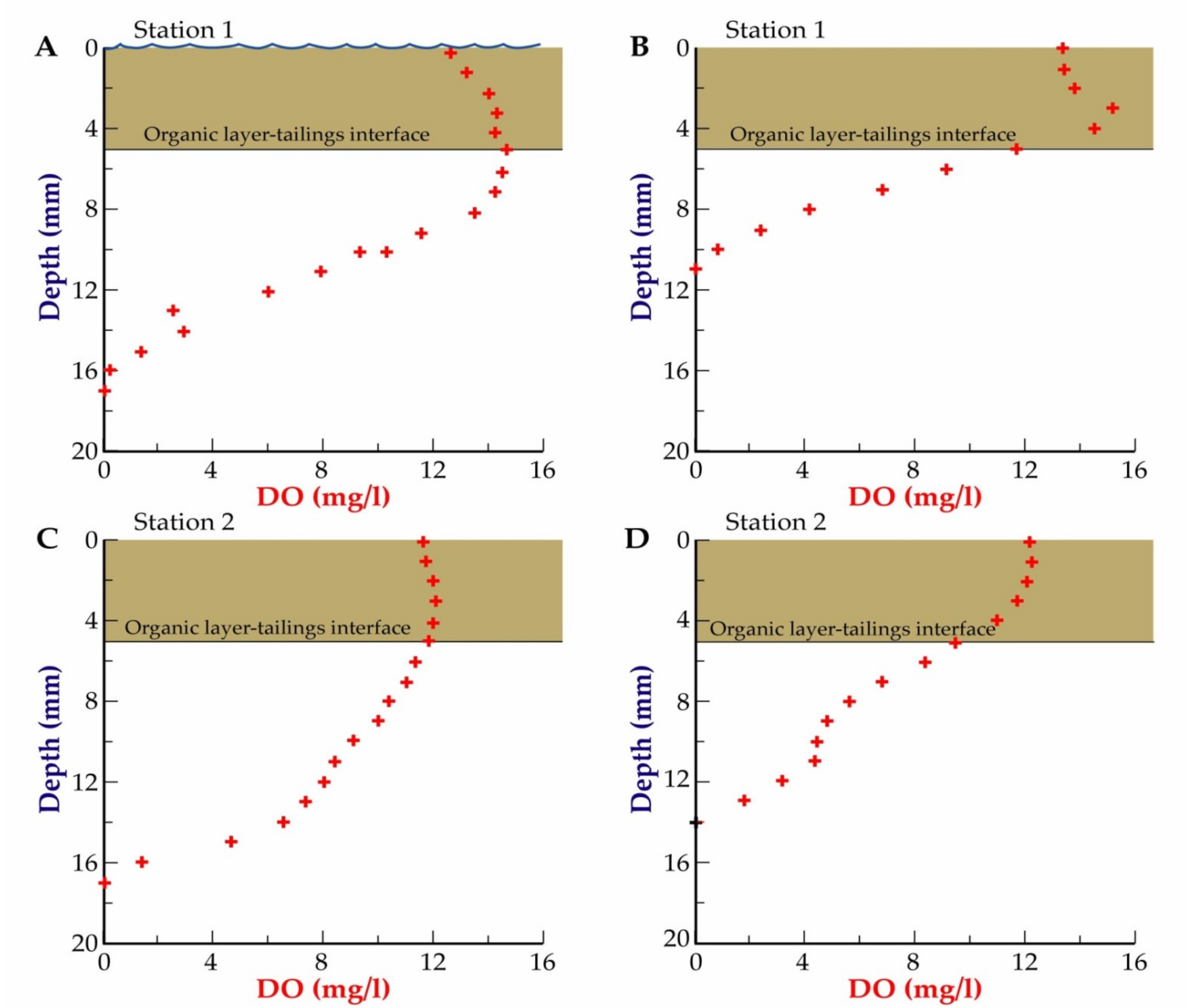
Geochemical studies



From Holmström and Öhlander, 1999.

BOLIDEN



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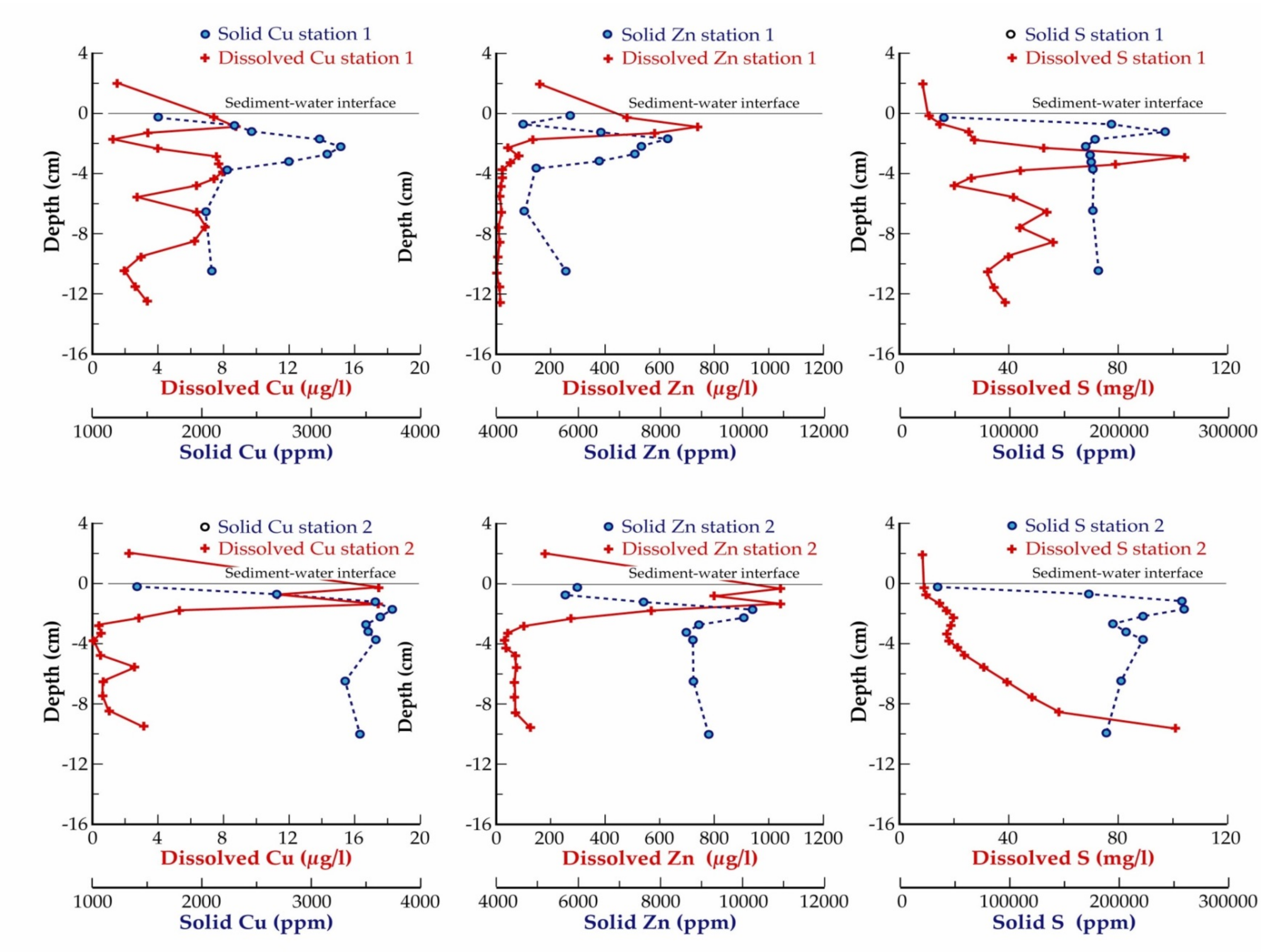

Results from Holmström and Öhlander, 1999.

Geochemical studies: Conclusions

- The pond water is well mixed in summer and oxic throughout the year.
- Oxygen is available to approx.10 mm depth in the tailings.
- Higher concentrations occur in the water below the ice during the winter.
- Diffusion from pore water is the major source of elements in the pond water.
- Re-suspension is minor, and oxidation of re-suspended sulphides is not an important metal source to the pond water.
- Thin layers rich in Fe- and Mn-oxyhydroxides have formed in the uppermost part of the tailings, and a thin sediment layer rich in organic matter has developed on top of the tailings.

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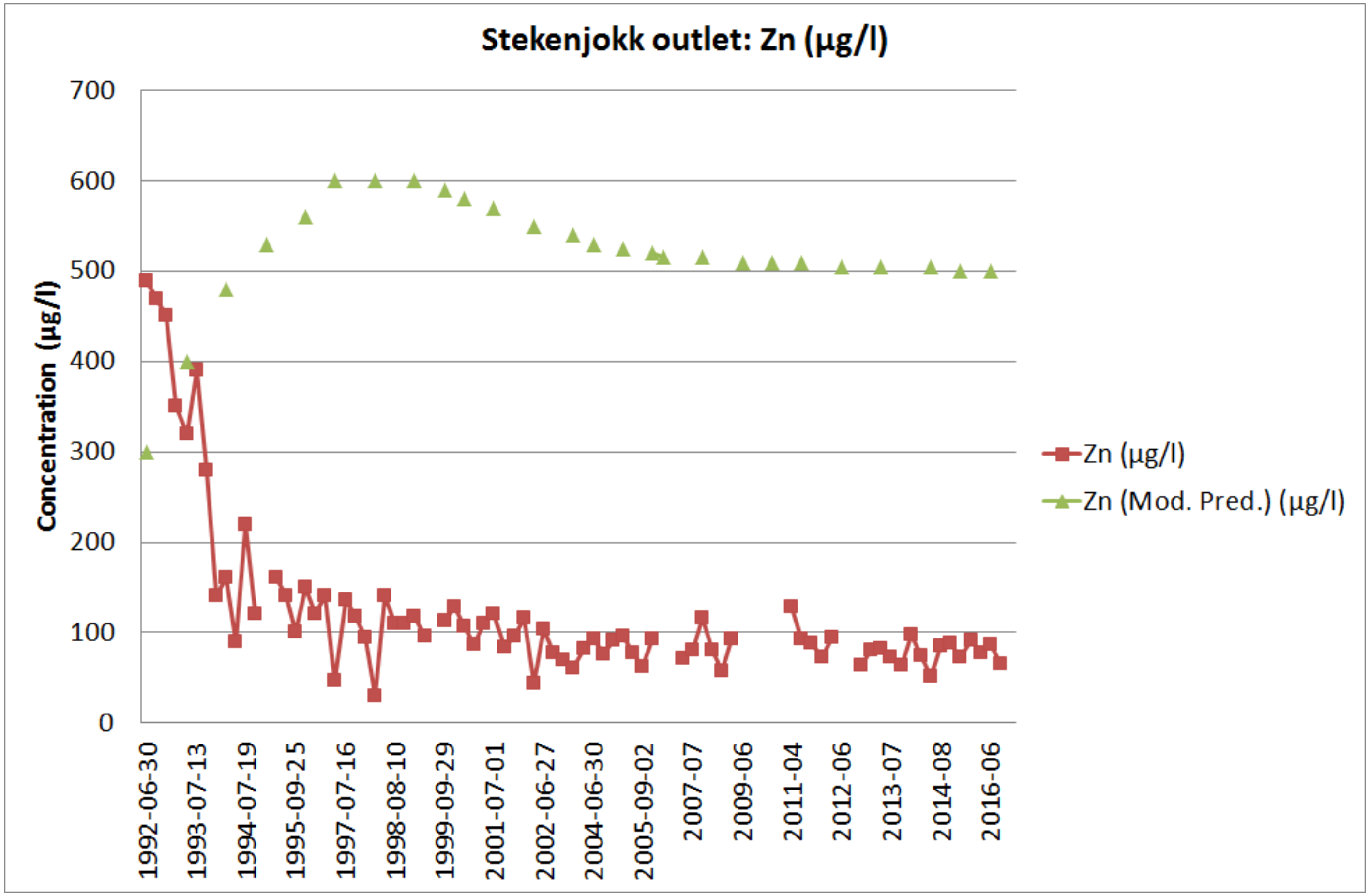
Stekenjokk: Overall performance
Evolution of zinc concentration in discharge 1992-2016



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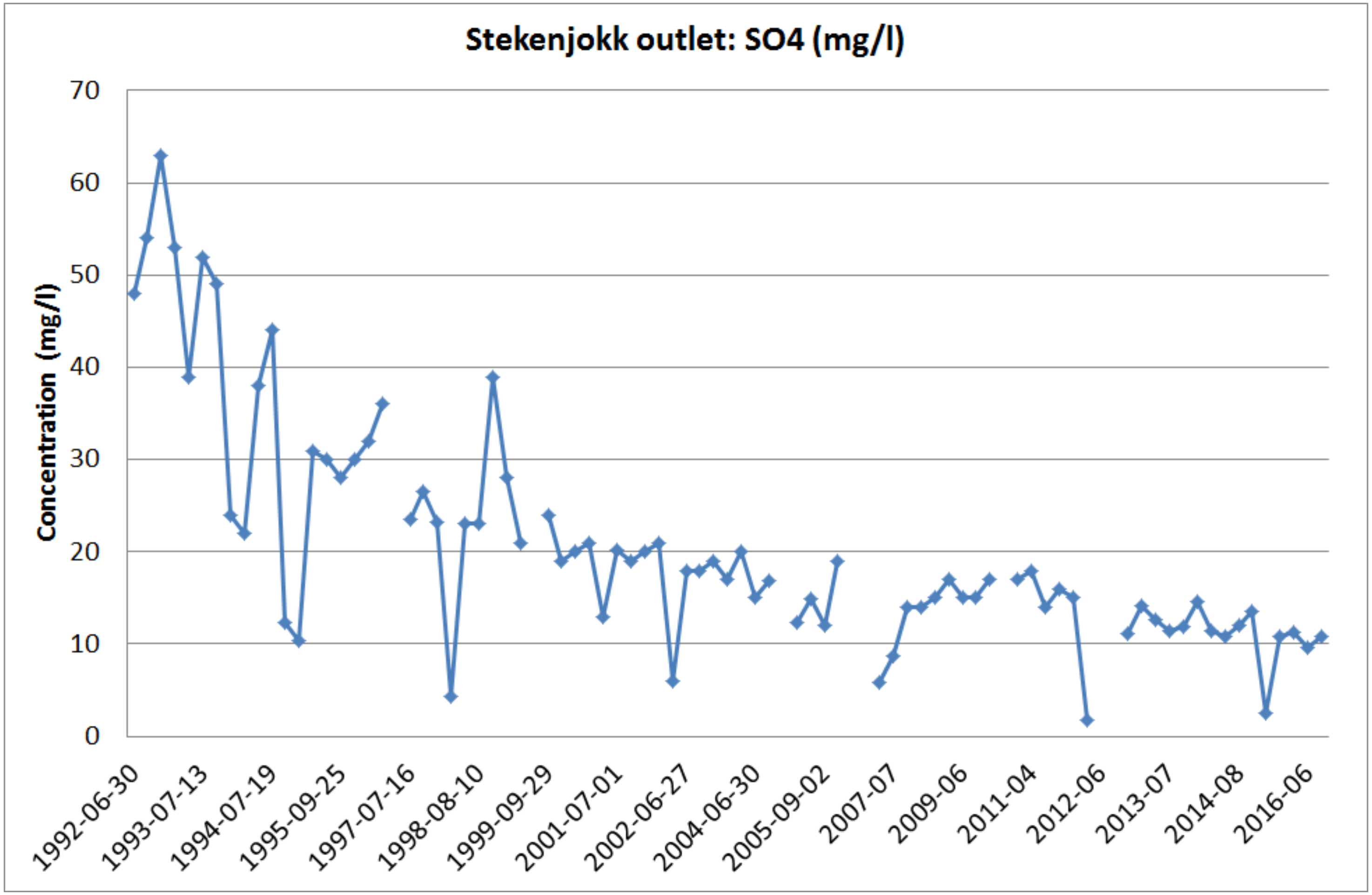
Stekenjokk: Overall performance
Evolution of sulphate concentration in discharge 1992-2016



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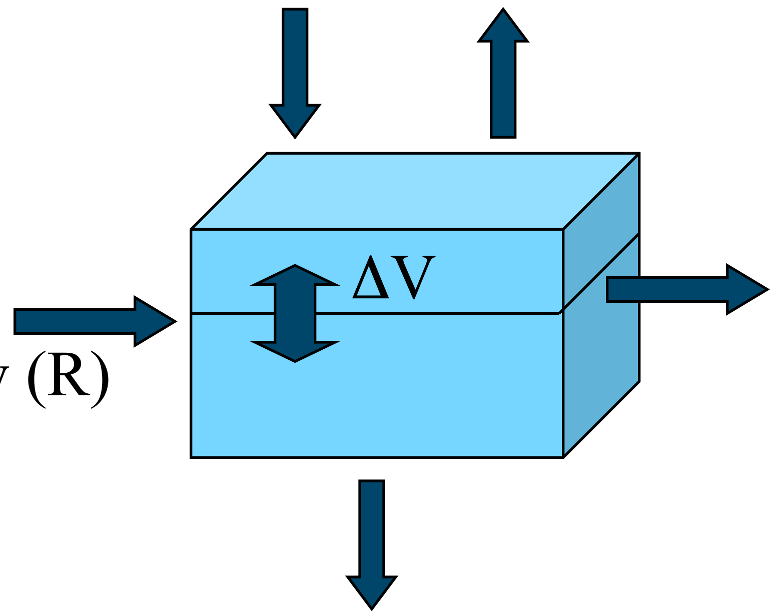
Water balance



Assumption: $V_{In} + V_{Out} = \Delta V = 0$

Overall performance: Quantitative evaluation

Mass balance (free water volume)

$$m_{In} + m_{Out} = \Delta m$$

$$m_{In} = Pc_P + Rc_R + m_s$$

$$m_{Out} = Oc_O + Lc_a$$

$$\Delta m = V\Delta c_a$$

Assumption:

- Sulphate is conservative in the system and can be used as an indicator of sulphide oxidation

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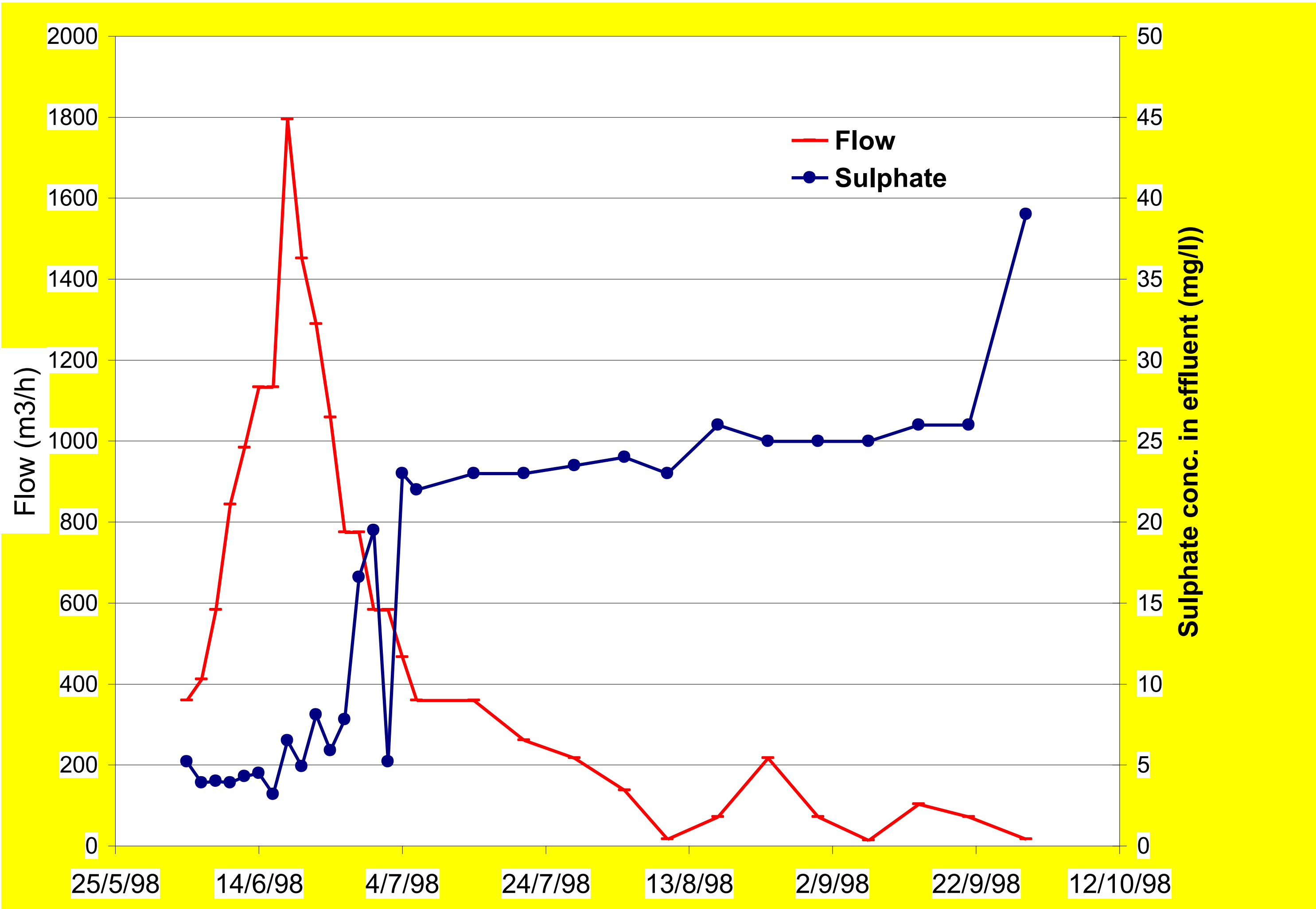
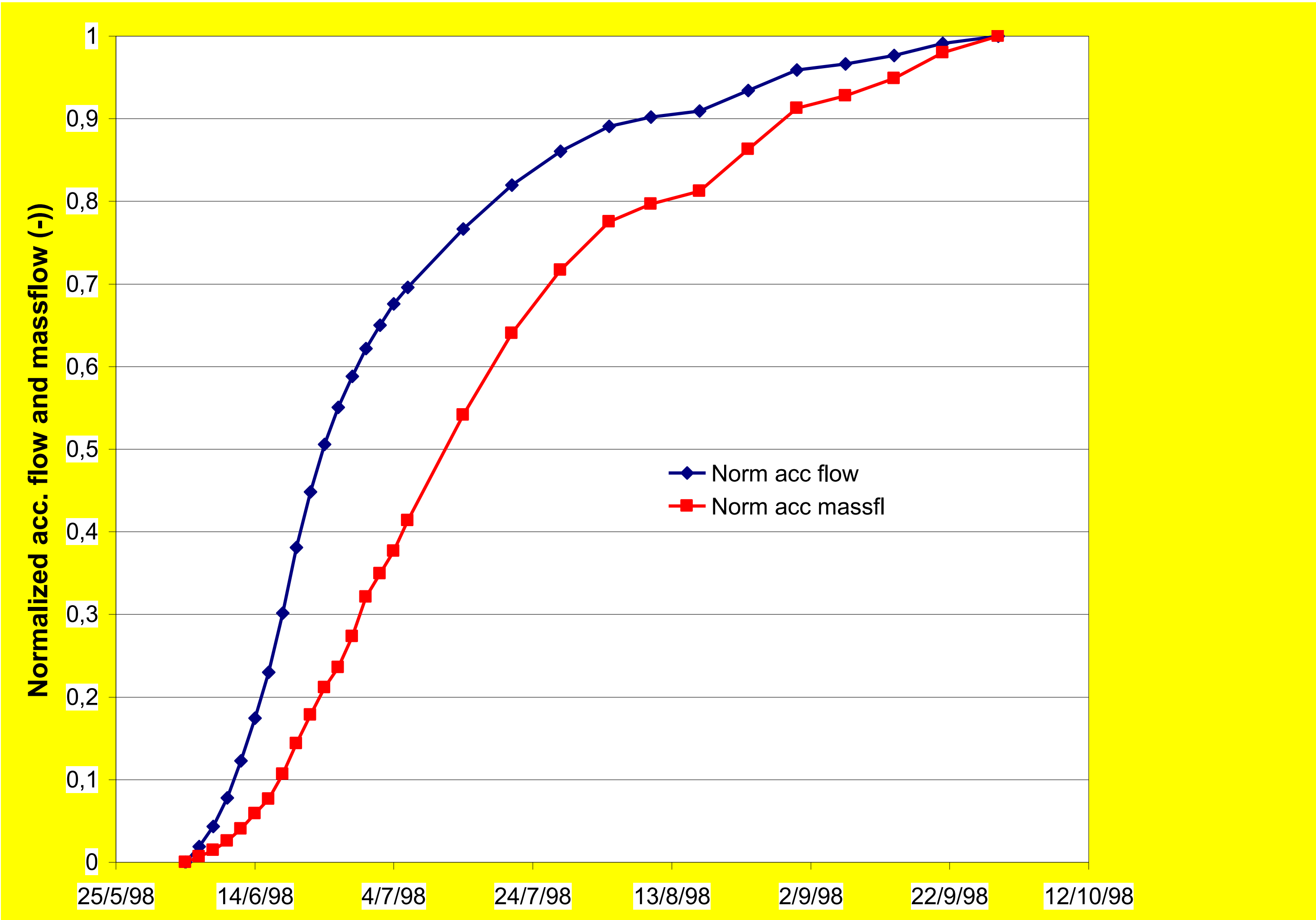
Effluent flow and sulphate concentration 97/98



Normalised effluent flow and mass flow 97/98



Initial mass balance for sulphate

	Year (ton)										
	92/93	93/94	94/95	95/96	96/97	97/98	98/99	99/00		2014/2015	2015/2016
In											
Precipitation	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6		1,8	1,8
Run	3,6	3,6	3,6	3,6	3,6	3,6	3,6	3,6		3,0	3,0
Out											
Drainage	-60	-30	-28	-10	-18	-12	-10	-11		-8	-8
Leakage	-18	-12	-11	-11	-9	-8	-8	-7		-4	-4
ΔStorage											
Δm	-44	-22	-14	-2	-11	-6	-5	-6		-2,5	-2,5
Source term											
m_s	28	14	19	13	10	8	7	6		4	4

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End of presentation?

Assuming all the sulphate in the source term comes from sulphide oxidation:

- In 97/98 8 ton SO_4 corresponds to an O_2 flux of approx. 0,15 mol O_2/m^2 y.
- In 2015/2016 4 ton SO_4 corresponds to an O_2 flux of <0,1 mol O_2/m^2 y.

Good overall performance that compares to the best that can be achieved with composite dry covers.

However, it is interesting to look at the source term, m_s.

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Source term - m_s

It is necessary to add a source term, m_s, to balance the calculations. There are several potential sources of sulphate:

- oxidation of sulphides in tailings within the pond
- oxidation of sulphides in waste-rock use in closure
- **diffusion of sulphate from the tailings pore water**
- dissolution of secondary minerals (e.g. gypsum)
- etc...

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Sulphate diffusion rate from pore water

Estimation of sulphate diffusion rate from the pore water in the tailings to the free water column:

$c(z, 0) = c_i$ for $z > 0$

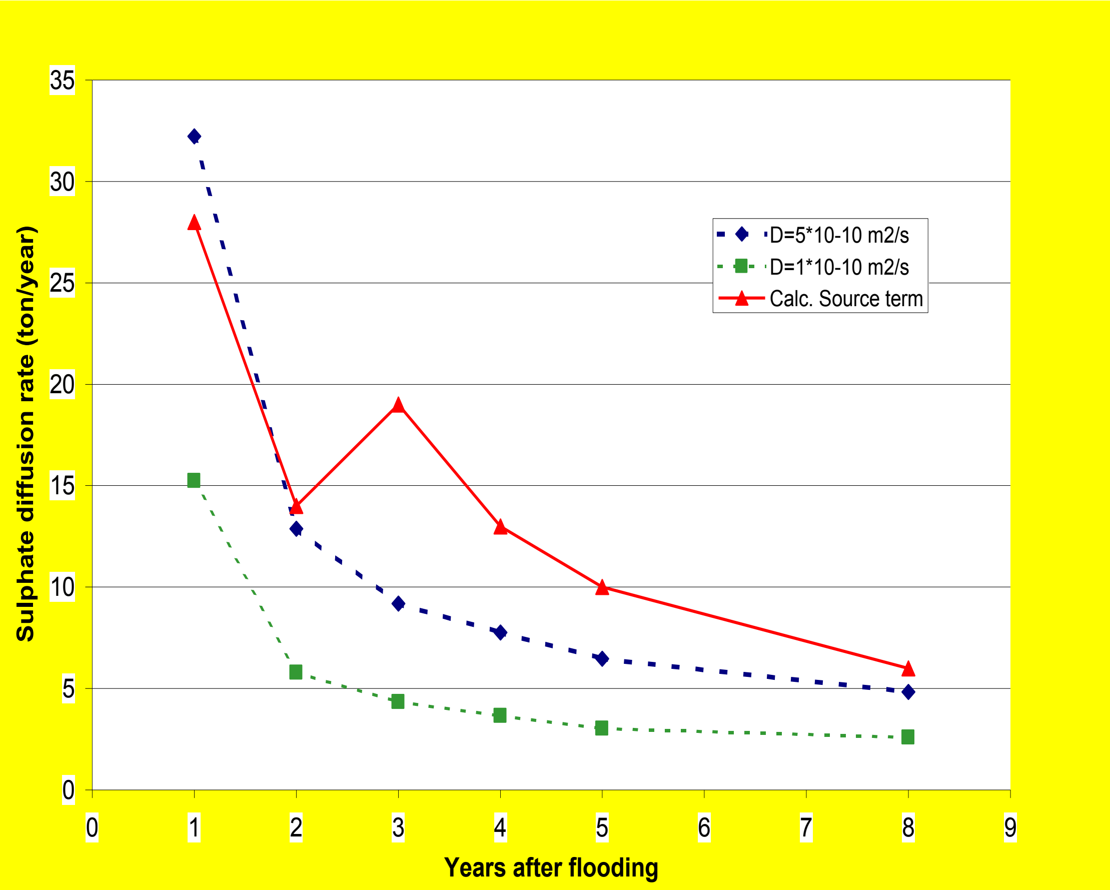
$c(0, t) = 0$ for $t \geq 0$

$c_i = 500$ mg/l

$D = 1.1 \cdot 10^{-9}$ m^2/s at 5°C

$D_{eff} = 20\text{-}50$ % of D

$$c(z,t) = c_i \, erf\left(z \sqrt{\frac{1}{4 D_{eff} t}} \right)$$



Refined mass balance

	Year (ton)								
	92/93	93/94	94/95	95/96	96/97	97/98	98/99	99/00	Total
Source term									**104**
m_s	28	14	19	13	10	8	7	6	
Diffusion									
m_{Diff} "High"	33	13	9	8	7	6	6	5	**87**
m_{Diff} "Low"	15	6	5	4	3	3	3	3	**42**
$ms-m_{Diff}$	-5 to 13	1 to 8	10 to 14	5 to 9	3 to 7	2 to 5	1 to 4	1 to 3	**17 to 62**

5 ton SO_4 corresponds to an O_2 flux of < 0,1 mol O_2/m^2 y assuming all of it originates from pyrite oxidation

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Conclusions: Overall performance

- The measured water quality in the pond has out-performed design predictions after flooding.

A mass balance for sulphate indicates:

- The flooding solution reduces oxygen flux to the sulphide tailings effectively .
- The sulphate release to the pond water corresponds to a resulting oxygen flux of <0,1 mol O_2/m^2 y.

But…….

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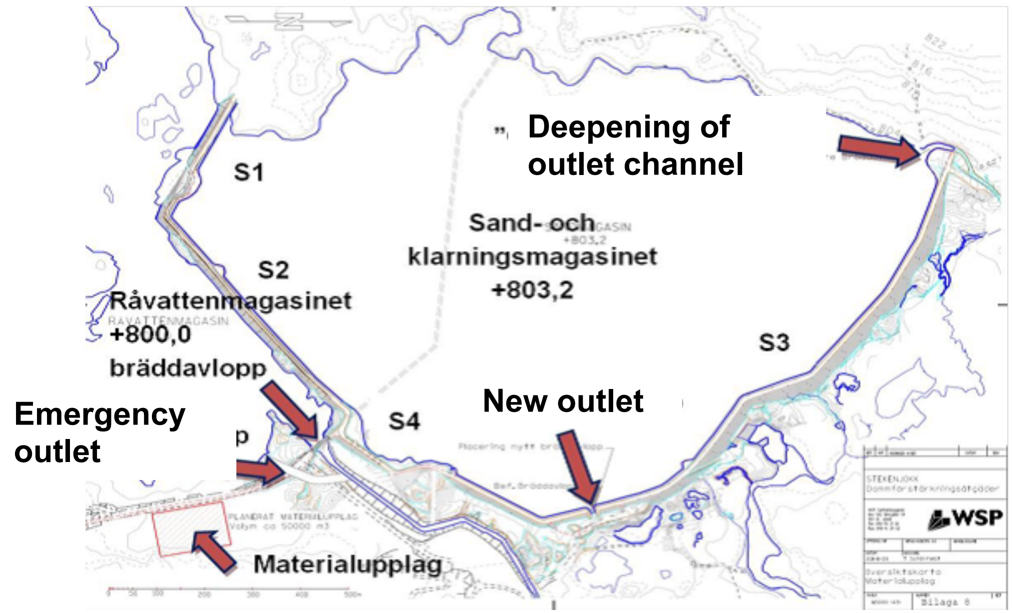
Dam safety measures after closure

- Deepening of outlet channel 1995
- New outlet and safety berm 1999
- New emergency outlet at the raw-water reservoir 2010
- Increase in discharge capacity of outlet 2012 (MPF).



……and…….

Dam safety measures 2014-2017

New erosions protection

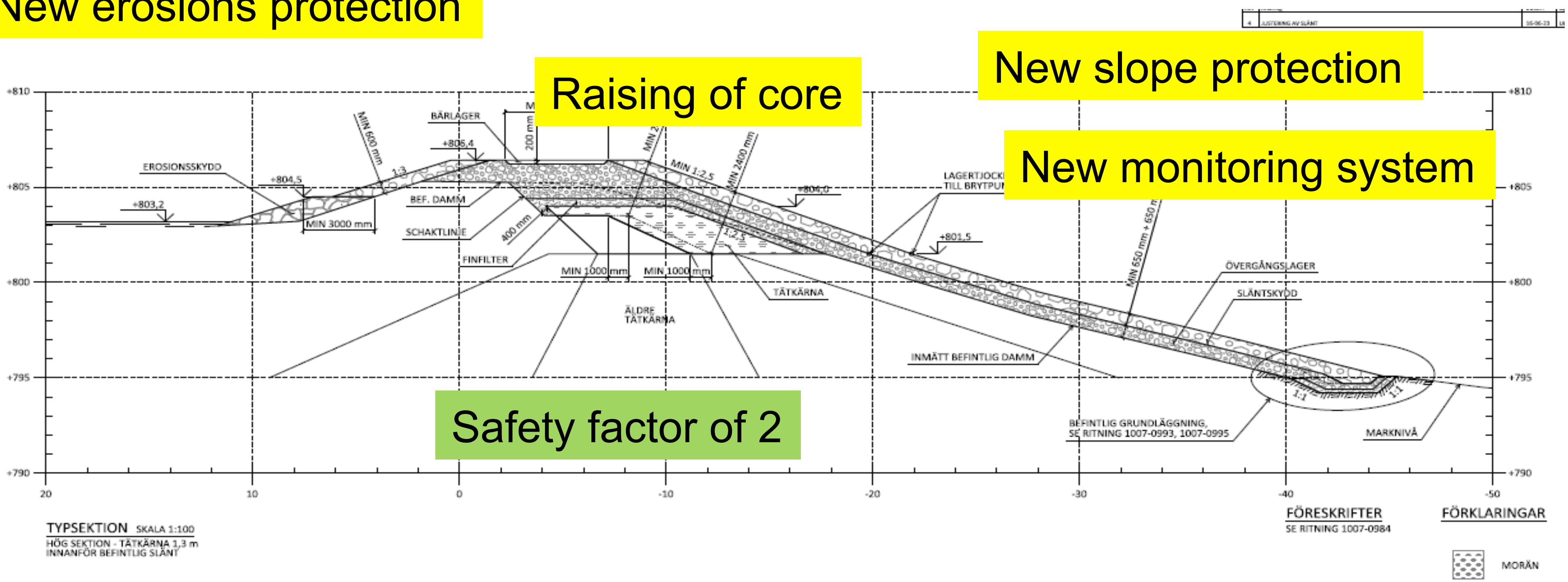
Raising of crest

Raising of core

New slope protection

New monitoring system

Safety factor of 2



Improvement of dam construction @ 120 MSEK

Surveillance and control

Currently the surveillance and control includes:

- Monitoring of water level
- Monitoring of dam leakage in 3 points
- Monitoring of water levels in 14 points
- Inspections according to Mining-RIDAS
- Environmental follow-up

Overall conclusions

- The implemented closure was a ”retrofit” aimed to be acceptable to the environment and stakeholders
- The flooded TMF outperform design expectations with regard to oxygen transport.
- Dam safety has been a challenge

If designed today, improvements could be made:

- Designing and building long-term stable dams according to ICOLD recommendations
- Avoiding PAF material in dams, breakwaters and in erosion protection
- Adding a diffusion barrier at closure on top of tailings
- Leading the creek through the pond

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Thank you!

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Extra slides

MINERALOGICAL COMPOSITION OF TAILINGS

Gangue minerals	***Sulphide minerals***
Quartz	Pyrite
Muscovite	Pyrrhotite
Chlorite	Sphalerite
Calcite	Chalcopyrite
	Galena
	Arsenopyrite

Average chemical composition of tailings

	%		ppm
SiO_2	34.8	As	1280
Al_2O_3	5.8	Ba	300
CaO	6.5	Cd	30
Fe_2O_3	27.6	Co	60
K_2O	0.8	Cr	26
MgO	4.8	Cu	1900
MnO	0.09	Mo	48
Na_2O	0.04	Ni	22
P_2O_5	0.2	Pb	1600
TiO_2	0.15	Sr	92
S	17.5	V	160
LOI	17.7	W	10
		Zn	6600

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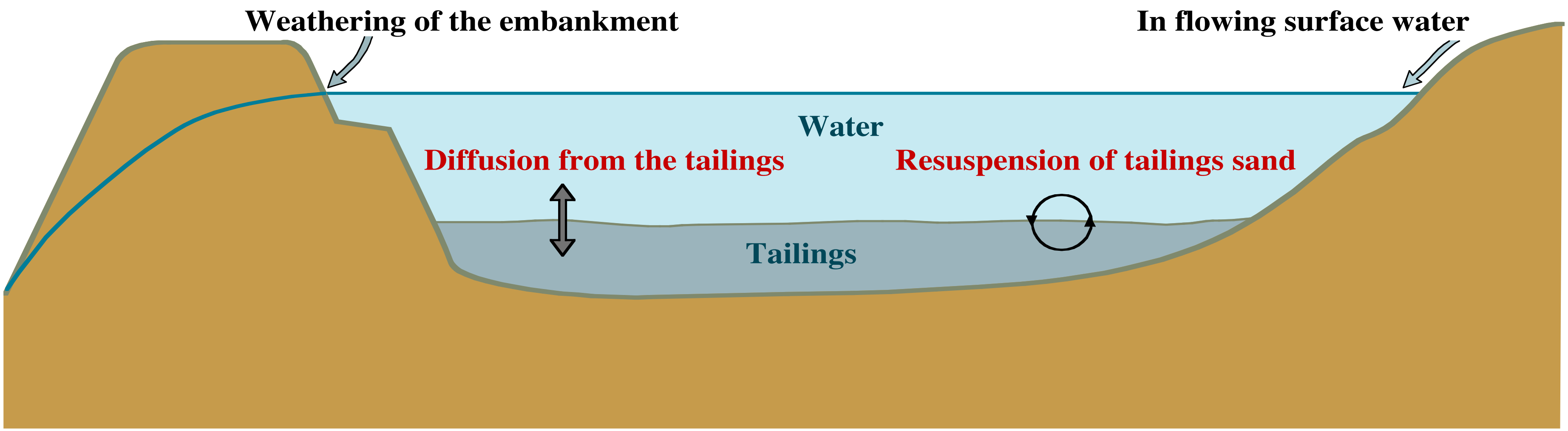
Distribution range of analysed elements between the dissolved and suspended phase. A high value indicates that the major part of the element is dissolved and vice versa.

Element	*Winter/Spring (May)* *5 samples* *[Diss./(Diss.+Susp.)%]*	*Summer (August)* *7 samples* *[Diss./(Diss.+Susp.)%]*	*Autumn (September)* *3 samples* *[Diss./(Diss.+Susp.)%]*
[% ± s.d[2]]			
Si	92.9±0.0	87.1±0.1	88.1±0.0
Al	24.7±0.1	21.1±0.1	12.2±0.0
Ca	~100	~100	~100
Fe	b.d	40.4±0.1	16.8±0.1
K	99.8±0.0	99.1±0.0	99±0.0
Mg	99.9±0.0	99.5±0.0	99.5±0.0
Mn	26.8±0.1	92.7±0.0	79.4±0.0
Na	99.9±0.0	99.6±0.0	99.8±0.0
As	78.5±0.0	70.4±0.1	79.6[1]
Ba	95.5±0.1	92.4±0.0	95.4±0.0
Cd	92.4±0.0	95.7±0.0	95.7±0.0
Co	64.1±0.1	93.5±0.0	90.1±0.0
Cu	72.7±0.1	69.9±0.0	57.5±0.2
Hg	99.7±0.0	b.d	b.d
Ni	97.3±0.0	96.7±0.0	97.8±0.0
Pb	b.d	35.8±0.04	b.d
Sr	~100	99.9±0.0	99.9±0.0
Zn	97.7±0.0	95.1±0.0	96.5±0.0
S	~100	~100	~100

b.d = The analysis of the dissolved phase was below the detection limit.
[1] = Only one value.
[2] = The standard deviation is very small for most elements and has been rounded off.


Weathering of the embankment
In flowing surface water
Water
Diffusion from the tailings
Resuspension of tailings sand
Tailings

Average composition of the water column (dissolved phase) during a year (1995). The background has been sampled in the stream Stekenjokken upstream from the pond.

Element	*Winter/Spring (May) 38 samples*	*Summer (July/August) 107 samples*	*Autumn (September) 50 samples*	*Background (September) 1 sample*
[mg/l±s.d]				
Ca	32.0±1.2	19.7±1.0	21.8±0.8	6.9
Fe	0.009±0.005	0.042±0.013	0.011±0.004	0.028
K	0.51±0.13	0.58±0.34	0.35±0.09	b.d
Mg	1.12±0.04	0.68±0.06	0.78±0.03	0.46
Na	1.30±0.18	1.00±0.24	0.85±0.10	0.75
S	18.±0.5	10.9±0.5	12.2±0.4	1.7
Si	0.33±0.14	0.96±3.40	0.26±0.19	0.61
[µg/l±s.d]				
Al	1.04±0.73	3.97±0.68	2.01±0.71	10.30
As	0.44±0.11	0.34±0.09	0.34±0.11	b.d
Ba	2.85±0.13	1.89±0.27	1.99±0.16	1.34
Cd	1.07±0.20	0.69±0.06	0.65±0.06	0.06
Co	0.07±0.03	0.16±0.05	0.13±0.02	0.17
Cu	2.03±0.44	1.71±0.18	1.57±0.20	1.18
Hg	0.25±0.03	b.d	b.d	b.d
Mn	7.9±7.8	24.5±8.9	8.0±1.2	30.4
Ni	2.21±0.24	1.38±0.35	2.17±0.22	0.37
Pb	0.23±0.16	0.18±0.06	0.16±0.06	0.11
Sr	66.6±2.8	43.7±2.3	47.7±1.4	22.0
Zn	268±53	142±15	150±8	13

b.d = below the detection limit.

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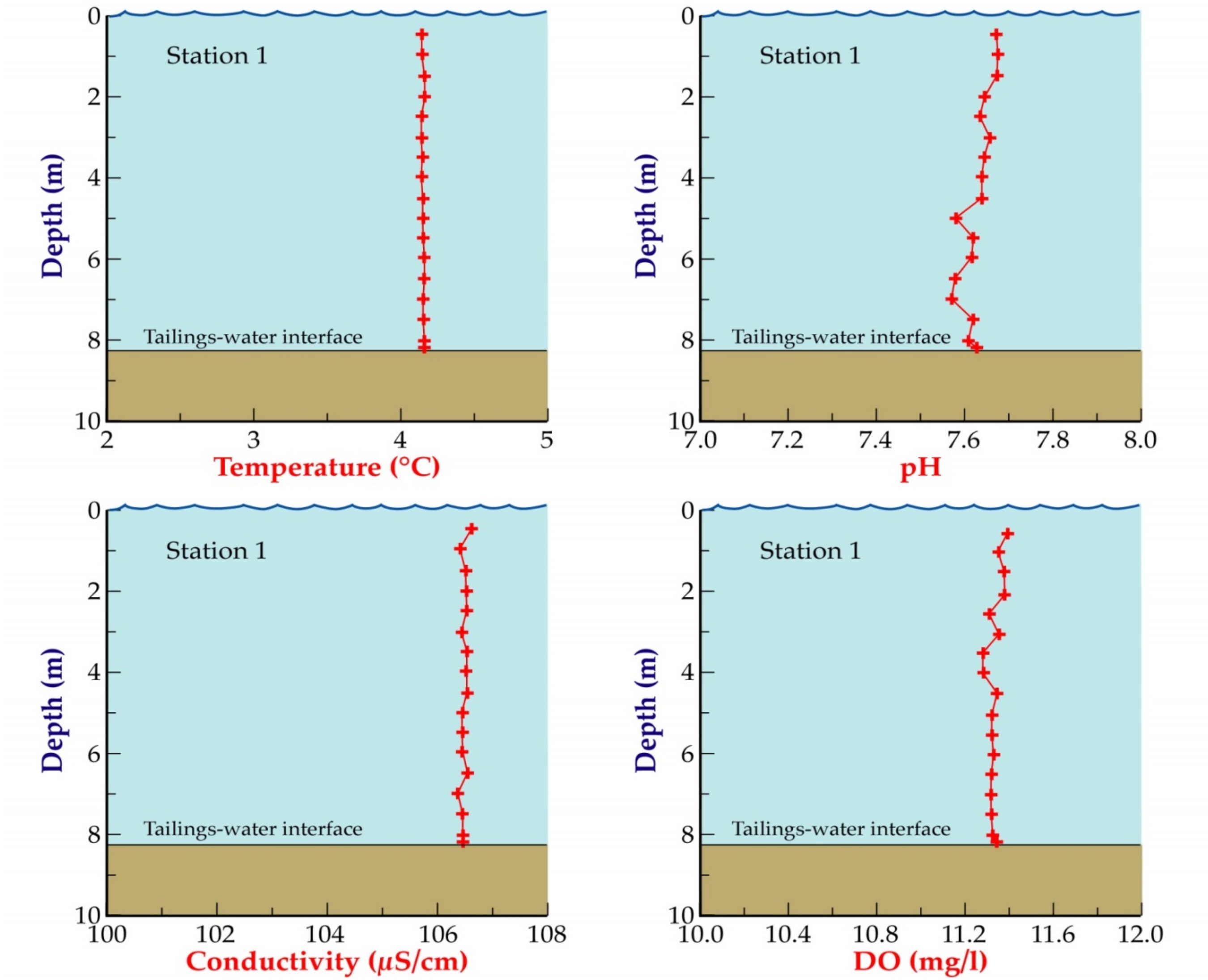
Average composition of the suspended phase in the pond during a year (1995).

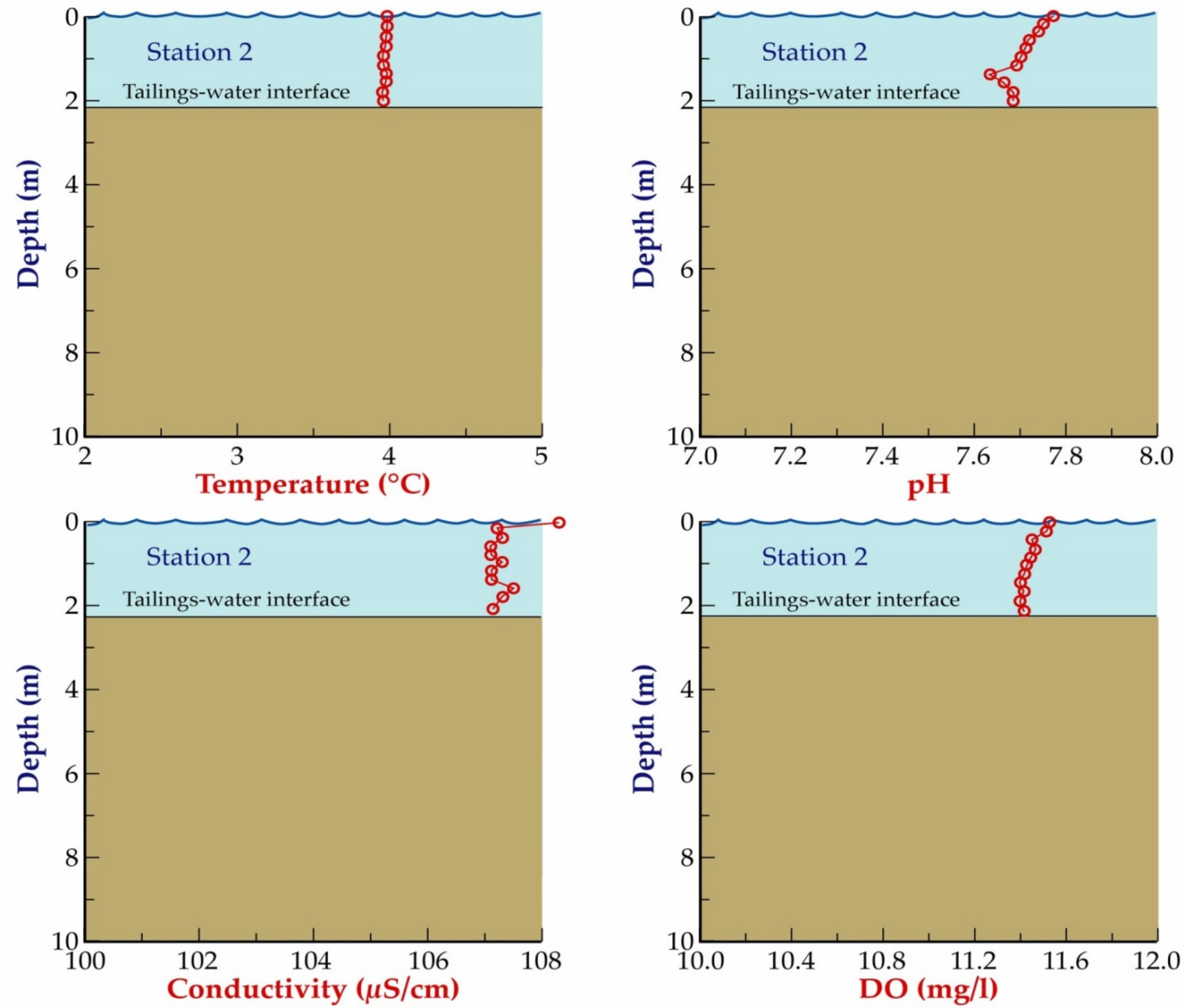
Parameter	*Winter/Spring (May) 5 samples*	*Summer (August) 7 samples*	*Autumn (September) 3 samples*	*Average composition 15 samples*
[mg/l±s.d]				
Suspended load[1]	0.17±0.08	0.28±0.11	0.27±0.10	0.23±0.50
[weight%±s.d]				
Si	9.9±1.6	18.4±2.6	19.1±3.1	15.0±6.1
Al	2.01±0.34	5.06±0.66	6.96±3.04	4.27±2.48
Ca	5.68±0.50	4.51±0.69	4.14±0.97	4.52±1.43
Fe	21.0±3.8	20.5±4.5	17.8±5.1	19.3±6.3
K	0.55±0.47	1.26±0.33	1.35±0.25	1.05±0.50
Mg	0.84±0.15	1.28±0.14	1.59±0.28	1.13±0.43
Mn	8.91±1.63	0.51±0.14	0.80±0.24	2.92±4.04
Na	0.64±0.63	1.34±0.35	0.82±0.25	0.90±0.53
P	0.89±0.14	0.59±0.13	0.63±0.18	0.63±0.21
Ti	0.09±0.03	0.33±0.07	0.40±0.11	0.26±0.16
[ppm±s.d]				
As	724±157	485±120	380±133	545±186
Cd	534±127	122±30	121±40	261±215
Co	173±35	36±10	61±29	87±68
Cu	4682±1014	2895±696	6179±5730	4157±2635
Hg	4.28±1.27	3.46±1.18	3.06±1.30	3.66±1.23
Ni	395±82	170±43	211±110	254±124
Pb	1940±432	1215±338	1330±607	1483±518
Sr	153±28	220±22	170±20	181±57
V	91±39	125±51	120±26	108±51
Y	36±9	52±6	56±14	46±15
Zn	39627±8256	27032±6775	23185±8293	30551±9804
S	39938±7086	37061±8970	34618±11534	37616±8377

[1] The amount of non-organic material (calculated with the ashweight), i.e the actual load including organic material may be several times higher.

NEW BOLIDEN



H. Holmström, B. Öhlander / Applied Geochemistry 14 (1999) 747–759



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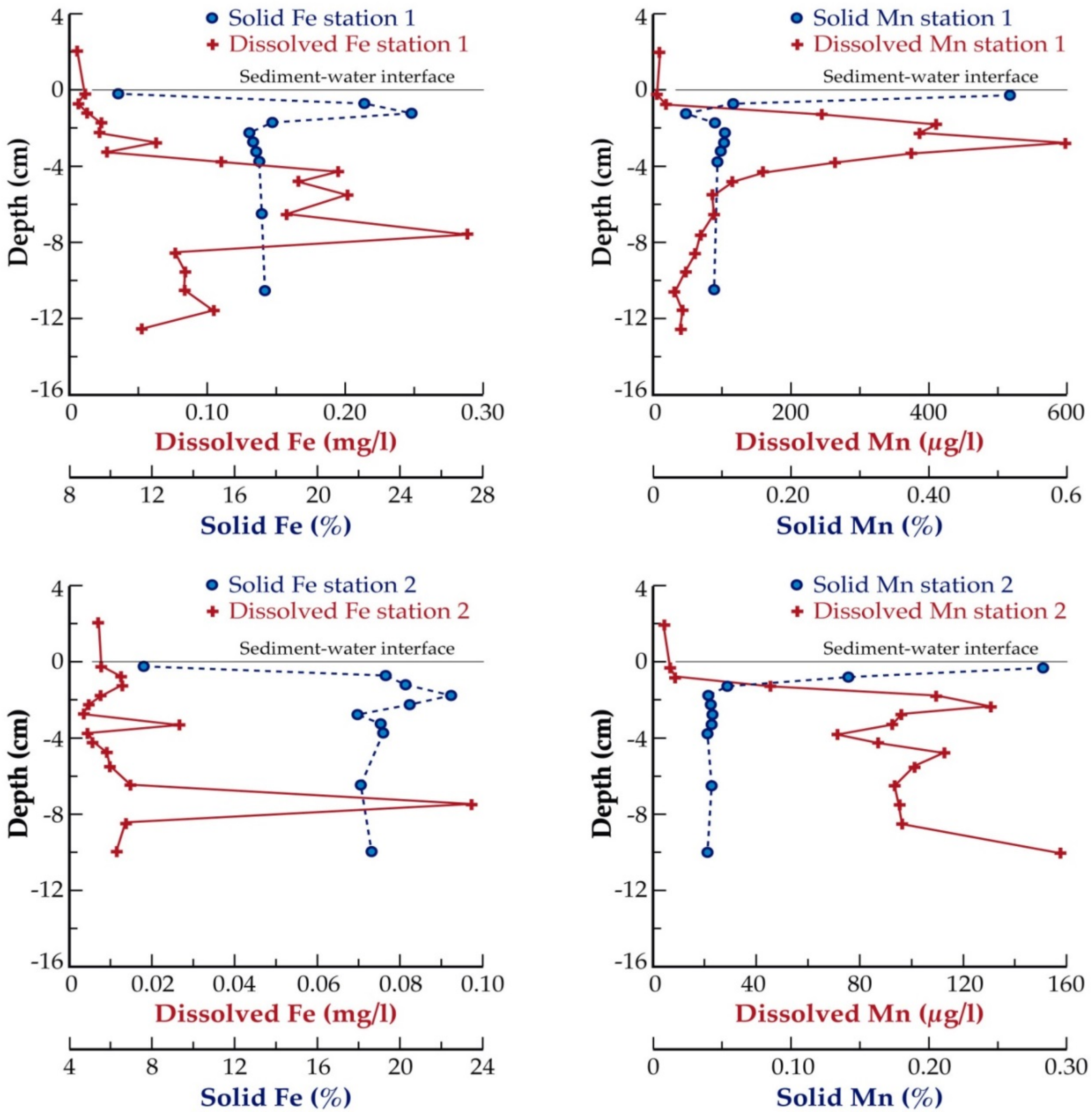

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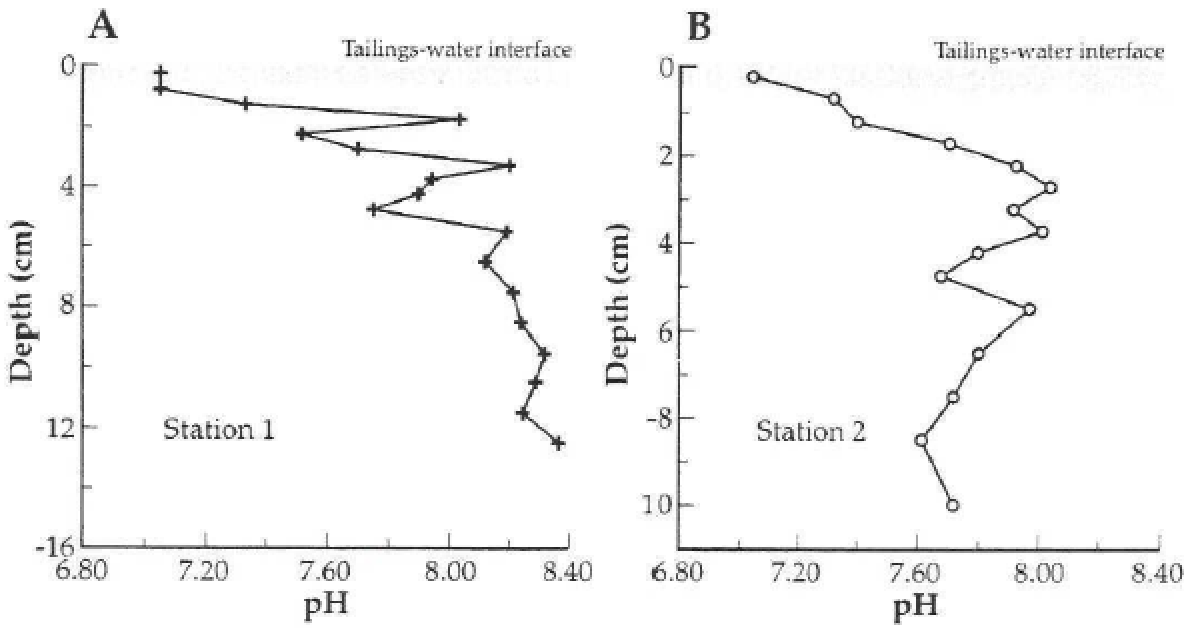

Fig. 7. pH of pore water at Station 1 (a) and Station 2 (b). Depth scale in centimetres. Organic layer is shaded.

H. Holmström, B. Öhlander / Applied Geochemistry 14 (1999) 747–759