Ecological effects of underwater destruction of detonators in Lake Ormtjärn, Sweden: the impact from lead

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Abstract

After the Second World War, dumping in lakes was a rational way to solve the security problem with the extensive amount of unused, aging ammunition. Most commonly the ammunition was dumped in sealed boxes or as pieces. In some cases the ammunition was deliberately detonated when dumped. In Ormtjärn, a small lake in central Sweden, very high levels of lead (1900 mg/kg dry weight Pb) were detected in the sediments indicating a possible need for remediation. The lead was expected to originate from years of underwater destruction of about 1.5 million detonators containing lead azide. The lake is unique in the sense that the lead levels are among the highest in Sweden, the boundary is well defined and that no other source of pollutant is present in the lake. It is also the only known major site for underwater destruction of detonators in freshwaters in Sweden. The aim of this study was to evaluate the environmental impact from underwater destruction of detonators containing lead azide in this natural forest lake.

Samples were taken of sediment, bottom water, surface water, bottom fauna and littoral and was analysed for Pb and physical parameters in order to investigate if a possible effect on biota could be demonstrated from the heavily polluted sediment. Acute toxicity of sediment was determined with a mouse cell assay.

Results showed high to very high lead content (1500-2000 mg/kg dry weight) in sediment down to 25 cm depth evenly distributed over the whole lake. Water showed low levels (surface water) to high levels (bottom water) of Pb. Disturbance on bottom fauna was observed for BQI-index but none for O/C-index. No effect on littoral fauna was found. Acute toxicity was low for bottom

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water (*Daphnia magna*), and cytotoxicity (neutral red incorporation assay, L-929 mouse cell line) was low in the sediment.
Keyword: bottom fauna, detonators, ecological impact, lead (Pb), littoral fauna, sediment, underwater destruction.

1 Introduction

After the Second World War several amounts of ammunition were dumped in about 100 lakes in Sweden (Sjöström et al. [1]). The reason was to make a safe disposal of aging and malfunction ammunition which, if left in store, might self-explode. Dumping of ammunition was a legal disposal method until 1970s for the ammunition industry, resulting in that several lakes in Sweden today host large amount of ammunition. Some of the lakes were also used for underwater destruction of detonators. The possible needs for remediation of lakes with such ammunition deposits have been intensively discussed in Sweden i.e. as to safety issues and costs if all dumped ammunition should be removed in relation to the ecological impact if left in place. This set focus on the issue of possible long term leaching from dumped ammunition to sediment, water and biota. Lead impact on lake sediment and biota (Förstner and Kresten [2], Davis and Galloway [3], Riba et al. [4], Bäckström [5]) as well as the environmental impact from dumped ammunition (Sjöström et al. [6], Voie [7], U.S Geological Survey [8]) and underwater detonations (Karlsson et al. [9]) has been discussed in different studies. However, none of these studies could be used to predict the future effects of leaching of lead from underwater destruction of detonators. One problem is the well-known concern that an ecological impact studied in the field, often might origin from different pollutants and that it is difficult to define a strict pollutant – effect connection to the source of interest (Covello and Merkhofer [10], Tuvikene et al. [11]) in this case, the underwater destruction of detonators. Another concern is the internationally addressed need for increased ecological perspective in risk assessments (den Besten et al. [12]). In order to increase the knowledge regarding possible future ecological impact from destructed detonators, it has been of interest to find a lake with well-defined natural boundaries, where the sediments are polluted from lead azide or lead oxide, and where no other source of pollution can be expected. A study of such a well-defined lake might contribute with information on its present ecological status as well as with information on possible expected long term ecological effects from underwater detonation during which lead azide will form the product lead oxide in the explosion.

The objective of the study was to evaluate the environmental impact from underwater destruction of detonators containing lead azide, with special focus on lead and some ecological effects shown by bottom fauna in a natural forest lake. An attempt was also made to study the effects on the fish in the lake. Gillnetting resulted however only in four fishes. Analysis showed lead content in (*muscle*) up to 0,148 mg/kg for perches. Because of the limited number of fishes will the results not been included in the study but a follow-up study is however planned.

2 Experimental, material and methods

2.1 Lake Ormtjärn characterisation

Lake Ormtjärn is a small, natural forest lake located at a shooting field in the central part of Sweden. The shooting field is situated on a water dividing zone (200 m above sea level) with discharge in three directions. The lake area is 0.0085 $km^{2,}$ average depth is 4 meter and the catchment area approx. 0.5 km^2. The water retention time of the lake is estimated to be 5 months. Oxygen level decreases from 6ppm in surface water to 2 ppm in the bottom water. The pH is close to 6 (6.1in surface water and 5.9 close to the bottom), and the concentration of sulphate range from 4 ppm (surface) to 3.2 ppm (bottom). Alkalinity range from 0.7 mekv/L (surface) and to 0.3 mekvk/L (bottom) and total organic carbon (TOC) from 7ppm (surface) to 11ppm (bottom). Upper sediment (0-5 cm) has an organic content of 48% (dry weight of 70%). Underlying sediment (20-25 cm) has an organic content of 43% (dry weight 58%) (Sjöström et al. [13]).

Lake Ormtjärn has no well-defined outlet or inlet. Water arrives from a small pine vegetated hill and from a well vegetated wetland. The lake is drained by percolation through a wetland. The geological conditions represent a typical Swedish forest area.

No nearby located lake were suitable as Reference Lake i.e. with regard to geochemical and ecological status, since all surface waters in the area had been more or less affected by dumping and/or shooting activities. For this reason, natural background reference levels and conditions have been compared with studies of lakes in middle Sweden (Sjöström et al. [13]). For specific geochemical background of pollution impact from day-to day activities at the shooting fields, comparison has been made with nine nearby lakes within the shooting field (Sjöström et al. [13]).

2.2 Pollution profile

About 1.5 million detonators containing 0.5 – 1.5 g lead per detonator (lead azide ($Pb(N_3)_2$) were dumped and destroyed in the lake between 1950s and 1990s. This corresponds to approximately 1500 kg pure lead. The detonators was dumped as pieces or packed in bags, sunk in the lake and destructed by underwater detonation. No other pollution source is known for the lake. A minor background impact might be expected from the day-today shooting at the field Waleij et al. [14]. The geological geochemistry in the area does not imply naturally increased levels of lead in sediment Swedish Geological Survey [15].

2.3 Impact scheme, lead conditions and some ecological effects

There are several methods for risk assessment within the framework of remediation, where consideration is given to the balance between type of pollutant, risk of leaching, sensitivity of surrounding environment and amount of pollution Swedish Environmental Protection Agency [16] (Covello and Merkhofer [10]). To facilitate the comparison of chemical impact (lead content) and ecological impact, a simple scheme moderated from different Swedish EPA regulations has been developed within the study.

2.4 Sampling

A total of nine sediment samples were taken during three occasions in May1999 (S23; 0-5 cm and 20-25cm) Sjöström et al. [13] (O1-O7; 0-5 cm and 10-15 cm respectively) (Qvarfort et al. [17]) and May 2000 (O8; 0-5 cm). Sediment cores from the water-sediment interface down to mineralised layers were sampled. The sediment cores were split into 5 cm layers onsite, and the samples were stored in plastic boxes at +4^{o}C and dark until analysed.

Water samples were taken on three occasions; March 2000 (W1 at 0.5 m depth) (Qvarfort et al. [17]), May 2001 (W2 at 4m depth) and September 2001 (W3 at 0.5 m depth). Samples of surface and bottom water were taken by Rüthner sampler. Water samples were stored in 0.5 L acid rinsed plastic bottles (for metals) and in glass bottles (for analysis of explosives), and stored in darkness at +4^{o}C until analysed. PH was measured on site.

Bottom fauna were collected at two sites with Ekman Bottom Grab Sampler by i.e. 10 samples respectively. Samples were sieved from coarse material and placed in plastic boxes filled with 98% ethanol, and stored dark at +4^{o}C until analysed. Littoral fauna were collected along a spatial 20 m profile on the "long side" and "short end" of the Lake Ormtjärn by kick sampling according to method M42 Swedish Environmental Protection Agency [16]. Samples of emerging insects were collected on 3x5 occasions by butterfly net in surface water, air above surface water, and along the lake shore. Samples were collected in plastic boxes filled with 98% ethanol, turned over and stored dark at +4^{o}C until analysed, figure 1.

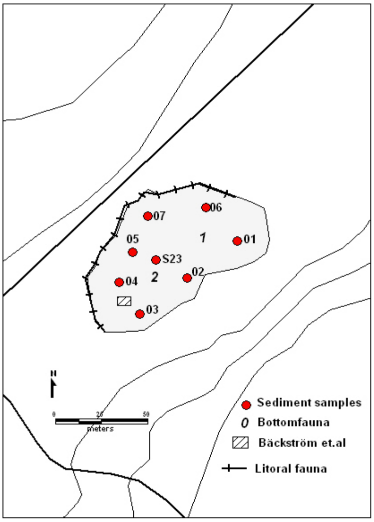

Figure 1: Sampling of Lake Ormtjärn.

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2.5 Analysis

Sediment were analysed for metals according to EPA-method 200.7 and 200.8 (modified). Metals in water were analysed by ICP-SFMS. W represent water analysis and S sediment analysis.

Table 1: Sampling and analysis.

Sample	Date	Level	Total number	Analysis
W1	00-03	0.5 m	1	pH, conductivity, alkalinity
W2	00-05	4.0 m	1	As, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb, Zn, TNT and its degradation products, RDX, HMX, picric acid. Toxicity *Daphnia magna*
W3	00-09	0.5 m	1	NO_3/NO_2, Ntot, NH4, Ptot, PO_4, pH and conductivity (mS/m), ToC, alkalinity, color
S 23	99-03	0-5/20-25 cm	1x2	As, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb and Zn, dry weight, Organic content
S1-S7	00-03	0-5/10-15 cm	7x2	
S8	00-05	0-5 cm	1	only TNT and its degradation products, RDX, HMX, picric acid. Toxicity Daphnia magna and Cytotoxicity

Water geochemistry data of Lake Ormtjärn has been provided by Bäckström [5]. Additional water analysis in this study was limited to three complementing analysis regarding explosives and water characterisation of relevance for the interpretation of fauna results. Explosives in sediment and water were analysed by HPLC and GC/MS according to Sjöström et al. [13].

Bottom fauna was analysed by abundance, and taxa. Additional analyses were made for BQI-index indicating nutrient and / or organic content in bottom water and for O/C index indicating oxygen saturation in bottom of the lake. Littoral fauna was analysed for Taxa, ASPT-index, Danish fauna index and Acidity index Swedish Environmental Protection Agency [18].

Acute water toxicity was assessed using *Daphnia magna*. The experiment was performed as a static acute toxicity test, following the procedure described in SS028180 (ISO 6341-1982: Water quality - Determination of the inhibition of the mobility of *Daphnia magna* Straus (*Cladocera, Crustacea*)). Five to ten animals, neonates < 24 h old, were added to 30 ml test solution in a 50 ml glass beaker. The exposure time was maximised to 48 h. Water temperature, pH, conductivity and dissolved oxygen were measured at the start and at the end of the test in controls and in the highest and lowest test concentrations. The number of immobilised animals was checked 24 and 48 h after test start. The water fleas were considered as immobilised when their appendages or the body failed to move upon prodding.

The water fleas were cultured in 500 ml beakers filled with 300 ml reconstituted hard water prepared in untreated tap water according to Klüttgen et al. [19]. The animals were fed daily with algae, *Selenastrum capricornutum* (approx. 10^6 cells/ ml). The water hardness was about 275 mg $CaCO_3$/l and the pH was between 7.9 and 8.2. The temperature was kept at 22±1C^o and the photoperiod was 16 h light and 8 h dark.

The test solution was prepared by diluting the water sample with the daphnia culture water. The test concentrations were prepared by serial consecutive diluting of the water sample giving a series with a diluting factor of study 1.5. Values for EC_{50} (probit analysis, SPSS soft ware) was calculated for the 24 and 48 hours of exposure.

Acute sediment toxicity, from sediment water extracts, was assessed by a growth inhibition assay using L-929 cells (mouse fibrocytes). Inhibition of cell growth were detected in a neutral red incorporation assay (NRI), initially described by Borenfreund and Puerner [20] and adapted to L-929 fibroblasts by Sauvant et al. [21]. Cells were grown in a cultivation medium containing EMEM (Eagles Minimum Essential Medium, Gibco), complemented with 10% FCS (Fetal Calf Serum, Gibco), 1% L-Glutamine (Gibco), 1% NEAA (Non Essential Amino Acids, Gibco) and 50 mg/ml Gentamycine (antibiotics, MERCK), and incubated in humidified atmosphere at 37°C and 5% carbon dioxide thus adjusting pH to 7.2. Toxicity measurements were performed as cell culture growth inhibition tests in 96 well microtiter plates (Becton Dickinson Labware, NJ, and USA). Cells were exposed for 72 h to a mixture of growth media and sediment extracts, produced by the extraction procedure (L/S ratio 2,5:1, shaking in 50°C for 14h), proposed by Wahle and Kördel [22] in proportions of 50, 25, 10 and 1 vol% respectively. Prior to exposure all extracts were filtered through 0, 22µm Millipor© as sterility is required.

2.6 Impact scheme, geochemical conditions and ecological effects

A coarse scheme has been developed summarizing the impact from underwater destruction of detonators. The impact level has been moderated from and related to Swedish regulations and recommendations approved by Swedish environmental protection agency [23], sediment, bottom fauna and littoral fauna Swedish Environmental Protection Agency [24], and toxicity (Daphnids and L-929, see 2.4) also linking to normally occurring follow up activity ("trigger for remediation / monitoring or other"). Five levels of impact were chosen for summarizing the observed effects;

1. Very low level	little or none impact or background level – *no action*
2. Low level	slight impact or near background level – *no action*
3. Medium level	significant impact - *normally not causing action*
4. High level	large impact - *might cause action if supported by other risk factors*
5. Very High level	very large impact - *normally causing action*

3 Results

3.1 Sediment and water

Sediment samples showed high content of lead in all parts of Lake Ormtjärn. Lead content were highest at level 0-5 cm (2090-1570 mg/kg dry weight) with a slight decrease at level 10-15 cm (1970-1290 mg/kg dry weight). The sample at 25 cm depth had a lead content of 1940 mg/kg dry weight. Bottom water samples contained up to 3.4 µg/L for Pb. Other analysed metals showed low to moderate levels. No explosives or degradation products were detected in sediment or bottom water. Physical and nutrient conditions of the lake were good with pH at 6.1 and alkalinity of 17.8 mg/L $CaCO_3$, representing the natural conditions of one common type of Swedish soft water forest lakes. Results of geochemical analysis of water and sediment are shown in, tables 2a-c.

Table 2a: Geochemistry sediment Lake Ormtjärn. The metal contents in µg/L.

Sample	Level cm	Dry weight %	Organic content %	As	Cd	Cu	Hg	Pb	Zn
S23 0-5	0-5	70,1	48,7	0,588	0,349	14,9	0,263	2090	235
S24 20-25	20-25	57,9	43,3	0,812	0,281	13	0,252	1940	204
O1 0-5	0-5	4.6	48.3	1.05	0.366	13.4	0.49	1570	196
O1 10-15	10-15	10.5	33.1	0.611	0.232	9.55	0.212	1290	164
O2 0-5	0-5	7.8	39	0.458	0.168	9.82	0.109	1780	182
O2 10-15	10-15	10.9	35.3	0.412	0.178	10.4	0.0805	1500	185
O3 0-5	0-5	4.1	50.9	0.959	0.37	15.3	0.431	1910	238
O3 10-15	10-15	7.7	44.4	0.682	0.266	13.8	0.324	1890	201
O4 0-5	0-5	4	49.9	0.81	0.395	14	0.162	1820	246
O4 10-15	10-15	7.8	40.4	0.52	0.183	10.5	0.0963	1760	182
O5 0-5	0-5	5.5	48.9	0.753	0.332	15.7	0.162	1950	270
O5 10-15	10-15	7.2	46.8	0.447	0.245	12.2	0.114	1970	225
O6 10-15	10-15	10.5	34.4	0.333	0.186	9.14	0.0942	1310	157
O7 0-5	0-5	27.2	50.3	0.828	0.365	16	0.164	1750	239
O7 10-15	10-15	38.7	44.3	0.565	0.248	13.2	0.299	1670	190
O8 0-5	0-5	6		0.74	0.28	14.7	0.28	1810	213

Table 2b: Water chemistry Lake Ormtjärn.

Sample	Depth (m)	As	Cd	Cu	Hg	Pb	Zn
W2 bottom water	4	0.174	0.082	3.49	0.0026	3.43	22.9

Table 2c: Physical conditions Lake Ormtjärn.

Sample	Depth (m)	Temp	pH	Conductivity /mS/m)	CaCO3	Alkalinity	N total	Nitrite-nitrate	P total	Phosphate
		T°C			mg/L	mg/L	mg/L		ug/L	
W1 bottom water	4	6	6.1	42.0		17.8				
W3 surface water	0.5	10	6.19	3.3	53.4		0.4	<0.02	10	2

Analysed concentrations of the explosives (TNT) were all below the detection limit < 1ng/L.

3.2 Bottom fauna and littoral fauna

Bottom fauna showed a significant higher abundance and number of taxa along the shore of the lake (B1) compared to the centre of the lake (B2). Abundance/m^2 was average 1700 for (B1) and 200 for (B2). Total number of taxa at (B1) was 8 (*Potamothrix/Tubifex sp., Chaoborus flavicans, Arctopelopia, Procladius sp., Tanypus sp., Chironomus sp., Chironomus sp plumosus, Chironomus sp thummi, Polypedilum sp.*) compared to 2 taxa for (B2) (*Leuctra sp. and Chaoborus flavicans*). BQI –index and O/C index was low for both sites (0-1) respectively (0-0.3) indicating high content of nutrients and/or organic content and good oxygen saturation in bottom water and sediment. Both numbers of taxa as well as abundance was to be considered low for station (B2) and slightly less effected for (B1) Swedish Environmental Protection Agency [23] indicating a disturbed ecological status in the midst of the lake but less disturbed conditions along the shore, table 3.

Lithoral fauna showed a total of 33 taxa from 9 families (*Bivalvia, Oligochaeta, Crustacea, Ephemeroptera, Odonata, Heteroptera, Coleoptera, Trichoptera* and *Diptera*). Number of taxa as well as abundance was indicating undisturbed ecological conditions at the shore of the lake. ASPT-index was 5.9; Danish fauna index 5 and Acidity index 4, table 4.

3.3 Toxicity

The bottom water of Lake Ormtjärn was not toxic to newborn *Daphnia magna.* The number of immobilised or mortal / total animals was zero after both 24 h and 48 h in undiluted samples of bottom water.

The toxicity of the sediment from Lake Ormtjärn was compared to toxicity of sediment taken from the nearby lake Svarta Sjön, which is of approximately the same size as Lake Ormtjärn. Results showed no significant toxic effect of extracts from Lake Svarta Sjön or Lake Ormtjärn in the cytotoxicity test, figure 2.

Table 3: Bottom Fauna Lake Ormtjärn (depth of sampling 4 meters).

Lake Ormtjärn	Sample no. B1										Statistics - Sample no. B1		
Local 1	1	2	3	4	5	6	7	8	9	10	Mean value	%	S.D.
Taxa													
Oligochaeta													
Potamothrix/Tubifex sp.	0	0	0	0	1	0	1	0	1	0	0,3	0,8	0,5
Chaoboridae													
Chaoborus flavicans	13	8	5	3	1	14	4	11	13	24	9,6	25,0	6,9
Chironomidae													
Arctopelopia-typ	0	1	0	0	0	0	0	0	0	0	0,1	0,3	0,3
Procladius sp.	0	0	1	0	1	1	3	2	0	1	0,9	2,3	1,0
Tanypus sp.	0	0	0	0	0	0	1	0	0	0	0,1	0,3	0,3
Chironomus sp.	1	5	1	0	5	4	3	2	9	3	3,3	8,6	2,6
Chironomus sp. plumosus-ytp	10	6	35	0	7	37	43	23	33	41	23,5	61,2	16,3
Chironomus sp. thummi-typ	0	0	0	0	0	0	0	0	4	1	0,5	1,3	1,3
Polypedilum sp.	0	1	0	0	0	0	0	0	0	0	0,1	0,3	0,3
Organisms/sample	24	21	42	3	15	56	55	38	60	70	38,4		22,0
Organisms/m^2	1066,6	933	1866,5	133	667	2488,64	2444,2	1688,72	2666,4	3110,8	1706,5		979,7
Taxa/sample	3	5	4	1	5	4	6	4	4	4	4,0		1,3
Taxa total	8												
BQI-index	1												
O/C-index													

Table 3: Continued.

Ormtjärn	Sample no. B2										Statistics - Sample no. B2		
Local 2	1	2	3	4	5	6	7	8	9	10	Mean value	%	Stdav
Taxa													
Plecoptera													
Leuctra sp.	0	0	0	0	0	0	1	0	0	0	0,1	2,2	0,3
Chaoboridae													
Chaoborus flavicans	1	0	1	0	27	7	2	4	1	1	4,4	97,8	8,2
Individuals/ sample	1	0	1	0	27	7	3	4	1	1	4,5		8,2
Individuals/m^2	44,44	0	44,44	0	1199,9	311,08	133,32	177,76	44,44	44,44	200,0		364,2
Taxa/sample	1	0	1	0	1	1	2	1	1	1	0,9		0,6
Taxa/ total	2												
BQI-index	0												
O/C-index													

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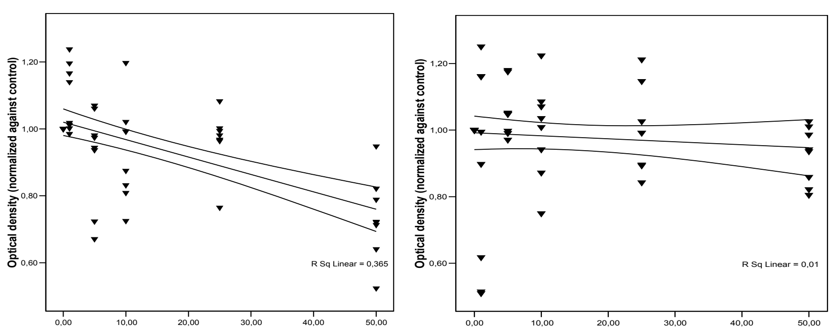
Table 4: Littoral fauna; identified taxa, ASPT-index, Danish fauna index and Acidity index.

Litoral fauna Lake Ormtjärn				
Bivalvia	Odonata	Heteroptera	Trichoptera	Diptera/tvåvingar
Sphaeridae	Coenagrionidae sp.	Notonecta glauca	Holocentropus dubius	Dixidae
Oligochaeta	Coenagrion hastulatum	Hesperocorixa linnaei	Oxyethira sp.	Ceratopogonidae
Tubifex/ Potamothrix sp.	Aeshna juncea	Sigara sp.	Limnephilidae sp.	Chironomidae
Crustacea	Aeshna grandis	Coleoptera	Limnephilus sp. (L. rhombicus?)	
Asellus aquaticus	Corduliidae sp.	Gyrinus minutes	Limnephilus sp. (L. griseus?)	
Ephemeroptera	Leucorrhinia dubia	Haliplidae sp. (larv)	Nemotaulius punctatolineatus	
Cloeon inscriptum	Leucorrhinia rubicunda	Haliplus fulvus	Agrypnia sp.	
Leptophlebia vespertina	Libellula quadrimaculata	Porhydrus lineatus	Oligotricha striata	
		Ilybius sp. (larv)	Molannodes tinctus	

ASPT-index	5,9
Danish faunaindex	5
Acidity index	4



(a) Lake Svarta Sjön (b) Lake Ormtjärn

Figure 2: (a) Lake Svarta Sjön – dose-response for L-929 cell culture exposed to sediment water extract and (b) Lake Ormtjärn – dose-response for L-929 cell culture exposed to sediment water extracts. Data are presented with linear regression and 95% confidence interval.

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4 Discussion

Very high levels of lead (2090-1240 mg/kg dry weight) were found in the sediment of the Lake Ormtjärn caused by underwater destruction of detonators. No other source of concern for heavy metal contamination was present. The background value for lead as well as possible impact from shooting field were within local background levels (30-197 mg/kg dry weight) and it could be concluded that the underwater destruction of detonators was the source of the high lead levels. The impact from the underwater destruction of detonations was summarized in a coarse impact scheme to facilitate the discussion of the lead conditions and ecological status in the environmental risk assessment of Lake Ormtjärn, table 5.

Table 5: Chemical impact of lead and ecological status.

Lake Ormtjärn level of impact	Very low level	Low level	Medium level	High level	Very High level
Chemical impact of lead					
Sediment Lead (Pb) content (0-25 cm)				X (all levels)	X (surface)
Water Lead (Pb) content			X (surface water)	X* (bottom water)	
Ecological status					
Water acute toxicity (*Daphnia magna*)	X				
Sediment acute toxicity (*Cytotoxicity*)	X				
Bottom fauna				X (detonators found in sediment core)	
Littoral fauna		X			

1. Very low level — Background level – very low risk for biological effect
2. Low level — Small impact or near background level – low risk for biological effect – no action
3. Medium level — Noticeable impact – biological effect might occur – normally not causing action
4. High level — High impact – increasing risk for biological effect - might cause action if supported by other risk factors
5. Very High level — Very high impact – increased risk for biological effect even for short time exposure – normally causing action

The concentration of lead in sediment was high in all parts of the lake down to 25 cm level depth. The even distribution was explained by the effects of numerous detonations during the underwater destruction. The total content of lead in the upper 25 cm of the sediment was calculated to be approximately 2000 kg. This is more than the expected 1500 kg from detonators known to be destructed in the lake. The difference may be caused by the fact that in practice more than 1.5 million detonators were destructed. The concentration of heavy metals including lead in the surface water samples was low. However but in the bottom water high lead concentration were found (3,4 µg/L). No explosives or other chemical anomalies were detected in water or sediment.

The results are consistent with an earlier investigation by Bäckström [5], who studied the chemical status as well as the mobility of lead and other trace elements in Lake Ormtjärn through analysis of surface water, pore water and the solid phases of the sediment (the later by use of sequential extraction). The sequential extraction by Bäckström [5] showed that that 2% (30 ppm) of total lead was ion exchangeable, between 43% and 32% of the total lead was extracted in the acid soluble and reducible fraction, respectively, 23% was ox disable and 1% residual. By using the PHEREQC-2 model it was also shown that the limiting phase for lead in the pore water was expected to be cerussite ($PbCO_3$). The calculated mobility of lead from the sediment was partly confirmed by pore water analysis and the content in the bottom water, (8µg/L) compared to lead in surface water (2µg/L). In surficial water, the concentration of lead was supposed to be mainly controlled by an internal iron-lead cycle.

The concentration of lead in the water (< 8µg/l) was not high enough to induce acute effects in *Daphnia magna*. The lead concentration was about 7500 times below measured 48 h acute EC_{50} for lead in *D. magna* (Milan et al. [24]). However, the total concentration of lead in the water was at the level which would have induced toxic effects as inhibition of growth or reproduction in the water flea (Berglind [26]).

No acute toxicity (L-929 cytotoxicity) was found in the upper part of the polluted sediment of Lake Ormtjärn despite high levels of lead. It is suggested that only a small fraction bio available lead exists in the top sediment phase due to strong interaction with the matrix. High organic carbon content (48%) leads to the conclusion that lead is strongly bound to functional groups within the organic material. Cat-ion exchange between protons and divalent lead is also expected to be low at neutral pH. Furthermore, soluble lead in the water phase may have reduced bioavailability due to interaction with dissolved organic matter (Kördel [27]), but also with inorganic ligands e.g. carbonate, phosphate and mineral particles. According to Sauvant et al. [21], IC50 for lead (Lead nitrate) in L-929 cells (24 h of exposure) is 580 mg/L. Hence, the extraction yield from 14 h shaking in 50°C did not exceed those levels of lead required for an acute response in L-929, even though the test is expected to be more sensitive with an exposure time of 72 h used in the present study.

The study showed that the *bottom fauna* in the centre of Lake Ormtjärn were disturbed with low abundance and number of taxa. In the centre of the lake, the most disturbed area, several detonators were found in the sediment samples. Closer to shore, bottom fauna showed a more normal abundance and taxa. The concentration of lead in the sediment was very high at both sites, so no obvious explanation for the significant difference in bottom fauna related to lead (Pb) levels could be made. Oxygen saturation as well as nutrient conditions and depth (4 m) were normal and comparable at both sites. The littoral *fauna* in the lake was rich in abundance and taxa showing no obvious sign of impact. The fauna conditions were expected to be worse if not improved by the relatively high pH and high nutrient status of the Lake Ormtjärn.

It is concluded that underwater destruction of detonators containing lead azide can cause very high levels of lead at more than 25 cm depth in the sediment of a lake. Leaching of lead to the water phase and further exposure for e.g. bottom fauna can be expected over long time. If pH is high and if oxygen saturation and nutrient conditions are favourable the expected ecological effect by the lead contamination may be high in near vicinity of the sediment (bottom fauna, bottom water) but low in the remaining part of the lake. This is in accordance with international studies where lead has been identified to bio diminish through the food chain (Southward et al. [28]).

5 Recommendations and outlook

No remediation of Lake Ormtjärn is recommended at present. For the long-term assessment of impact in Lake Ormtjärn and from underwater destruction of detonators containing lead azide in similar typical Swedish forest lakes; pH, nutrient conditions and oxygen saturation has been identified as possible key “triggers” in an ecological chain of impact. Considering the high potential of pollution from the sediment and the regional natural acid conditions, monitoring of the conditions and pH, will be of key importance for a regularly update regarding any future need for remediation of the lake. Also, if remediation is considered, the hazard of unexploded ordnance and possible effect on human health and safety as well lake ecology must be addressed.

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