Ecological Risk Assessment of Trace Elements Accumulated in Stormwater Ponds within Industrial Areas

Sylvia Waara (sylvia.waara@hh.se)
Halmstad University: Hogskolan i Halmstad https://orcid.org/0000-0003-0553-7918
Frida Johansson
Halmstad University: Hogskolan i Halmstad

Research Article

Keywords: metals, metalloids, detention ponds, sediment quality, geoaccumulation index, risk quotients

Posted Date: May 20th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-468037/v1

Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on December 21st, 2021. See the published version at https://doi.org/10.1007/s11356-021-18102-0.

Ecological risk assessment of trace elements accumulated in stormwater ponds within industrial areas

Sylvia Waara[1*], Frida Johansson[1,2]

[1*] Department of Environmental and Biosciences, Rydberg Laboratory of Applied Sciences, Halmstad University, Box 823, 301 18 Halmstad, Sweden, Email: sylvia.waara@hh.se

[2] Present address: SWECO AB, Halmstad, 302 20 Halmstad, Sweden, Email: frida.johansson@sweco.se

[*]Corresponding author: Sylvia Waara, sylvia.waara@hh.se, phone +46729773608

Key words: metals, metalloids, detention ponds, sediment quality, geoaccumulation index, risk quotients

Acknowledgements

This study was financially supported by the Municipality of Ängelholm. We thank Nikolina Ström and Docent Karl-Otto Waara for their assistance with sampling. Dr David Green, University of Halmstad is gratefully acknowledged for carefully reviewing the manuscript and for the assistance with the figures.

Abstract

Stormwater ponds can provide flood protection and efficiently treat stormwater using sedimentation. As the ponds also host aquatic biota and attract wildlife there is a growing concern that the sediment bound pollutants negatively affect aquatic organisms and the surrounding ecosystem. In this study we used three methods to assess the accumulation and the potential ecological risk of 13 different heavy metals and metalloids (e.g. trace elements) including both elements that are frequently monitored and some which are rarely monitored in sediment from 5 stormwater ponds located within catchments with predominately industrial activities. Ecological risk for organisms in the older ponds was observed for both commonly- (e.g. Cd, Cu, Zn) and seldom- (e.g. Ag, Sb) monitored trace elements. The 3 methods ranked the degree of contamination similarly. We show that methods usually used for sediment quality assessment in aquatic ecosystems can also be used for screening the potential risk of other trace elements in stormwater ponds and may consequently be useful in stormwater monitoring and management. Our study also highlights the importance of establishing background conditions when conducting ecological risk assessment of sediment in stormwater ponds.

Introduction

Urban stormwater runoff may cause flooding and pollution in downstream watercourses if neither the flow is reduced nor the pollutants are removed (Baekken 1994, Maltby et al 1995; Blecken et al. 2012, Sharley et al. 2016). Today, stormwater is often retained and treated in wetlands or stormwater ponds (also called stormwater detention ponds or urban ponds), either alone or in combination with other techniques (Marsalek et al. 2005; Blecken et al. 2017; Jefferson et al. 2017; Sharley et al. 2017; Crane 2019). The type and quantity of pollutants in stormwater runoff which accumulates in a specific wetland or stormwater pond depends on the catchment area, climatic factors, land use and percentage impervious surfaces (Färm and Waara 2005; Casey et al. 2006; Frost et al. 2015; Søberg et al. 2016; Blecken et al. 2017; Sharley et al. 2017; Crane 2019).

Recently, concern has been raised over the ecological risks to aquatic life in wetlands and stormwater ponds and for the surrounding wildlife caused by the accumulated sediment. For example, Sharley et al. (2017) sampled 98 wetlands in the Melbourne region and found that catchments with >10 % industrial land use were at a greater risk of containing contaminants at values which exceeded ecological guideline values and waste disposal guidelines. Additionally, a study in Minnesota by Crane (2019) found that industrial areas in Minnesota were more contaminating than residential and commercial areas, leading to statistically significant increases in zinc and some organic micropollutant

content in the studied stormwater ponds. This suggests that stormwater ponds in catchments with industrial activity may accumulate high levels of trace elements which could pose a significant risk to the ecosystem.

In studies of trace element accumulation in stormwater ponds, only a few selected heavy metals (e.g. Cd, Cu, Ni, Pb, Zn) are typically monitored (Färm and Waara 2005; Casey et al. 2007; Egemose et al. 2015; Blecken et al. 2017; Sun et al. 2019). However, there are many other potentially ecologically harmful trace element contaminants. Herein, 13 different trace elements representing both commonly- and seldom- monitored trace elements were selected, and their accumulation in five ponds in catchments with industrial activity were studied. In addition, P and S were analysed to determine whether their concentrations correlated with those of the trace elements, and therefore if they could provide overall contamination values. The patterns and relationships between trace elements with P, S and sediment characteristics were analysed using Principal Component Analysis and Classification. Furthermore, three methods which are commonly used for assessing sediment quality in lakes and watercourses but rarely used for stormwater ponds and wetlands were used to assess the degree of contamination and ecological risk. The accumulation of elements in the ponds compared to background levels was assessed using Müller's geoaccumulation index, I_{geo}, (Müller 1969), while ecological risk was assessed using Håkanson's Potential Ecological Risk Index (RI) (Håkanson 1980) and by the Risk Quotient Methodology (RQ-method) (European Chemicals Bureau 2003) which nowadays, under REACH, is called Risk Characterisation Ratios (RCRs) (ECHA 2016) and therefore hereafter referred to as the RCR-method. To our knowledge, I_{geo} and RI have not been used to assess risk in stormwater pond sediment. The RCR-method is partly used as sediment guidelines, which in this study serve as PNEC values for calculating RCRs, are frequently compared to measured values when assessing the quality of stormwater sediment (Färm et al. 2003; Andersson et al. 2004; Färm and Waara 2005; Jang et al. 2010; Blecken et al. 2012; Allen et al. 2017; Sharley et al. 2017; Crane 2019). However, RCRs have not been calculated nor evaluated in previous studies. By combining the results from each method, the ponds at the highest risk and the trace elements of highest concern were identified and provided essential guidance for our continued contaminant monitoring.

Materials and Methods

Study site

The sampled stormwater ponds are in the municipality of Ängelholm in southern Sweden. The characteristics of the ponds and their catchment is presented in Table 1; and their design and sediment thicknesses are presented in Fig. 1. The ponds were designated Pond A and B (DUM 20 and DUM3,

Åkerslund 26:3), pond C (DUM 23, Rebbelberga 14:6), pond D (DUM 8, Rebbelberga 19:2) and pond E (DUM 19, Munka-Ljungby 52:20) and they are located with catchments with mainly industrial activity. The industrial areas have been developed at different paces from when the respective ponds were built and consequently the percentage impervious area has been changing over time. The industrial activity is diverse, and it consists of workshops, shops and storage of building materials including metals, storage of vehicles for building and construction work, haulage companies, a bus company, car testing facilities, the major recycling plant in Ängelholm and the power plants of Ängelholm and Munka Ljungby. Pond A-D are located less than 1 km apart and pond E is located about 5 km east of the other ponds in the village of Munka Ljungby. The stormwater ponds were designed to prevent flooding in downstream areas.

Table 1 Characteristics of the investigated ponds. Data obtained from the Municipality of Ängelholm

Pond	Area (m^2)[1]	Catchment area (ha)[2]	% Impervious surface[1]	The ratio (in percentage) of pond area to impervious area	Age 2019 (years)
A (DUM 20)	300	6.5	50	0.9	6
B (DUM 3)	950	72.0	50	0.3	17
C (DUM 23)	2000	14.5	12[1]	1.1	2
D (DUM 8)	1300	44.3	30	1.0	18
E (DUM 19)	500	24.8	70[2]	0.3	2

[1] the impervious surface will increase when the area is fully developed

[2] the pond was constructed after the development of the industrial area

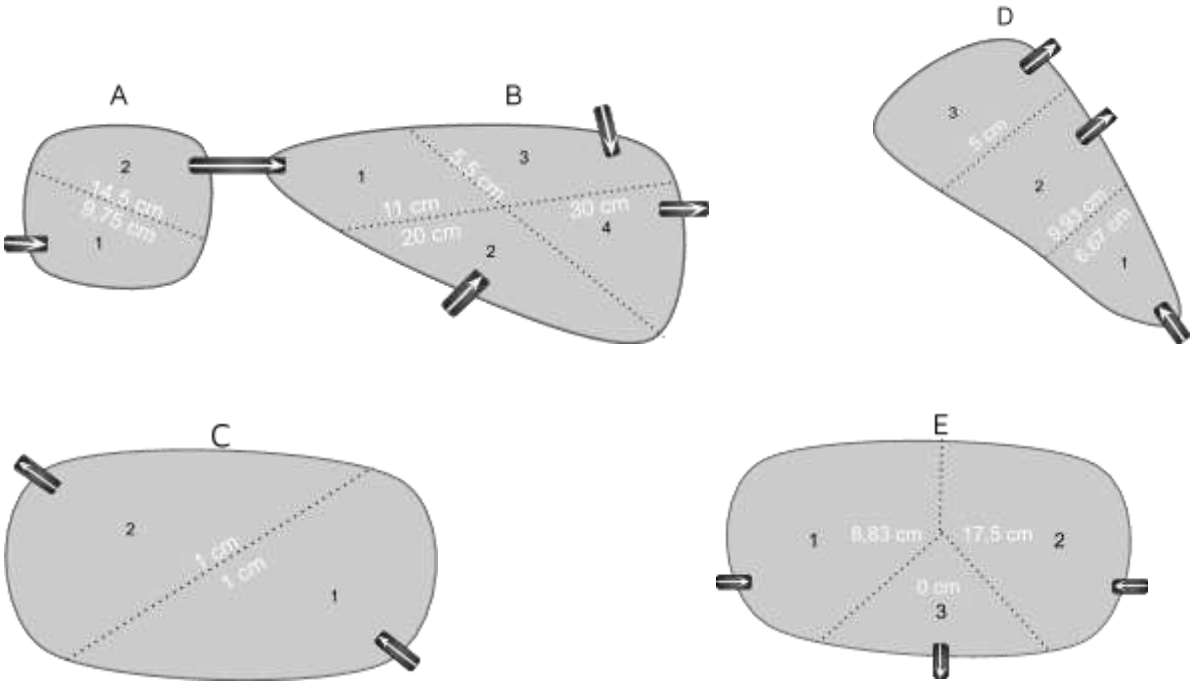


Fig 1 Design of the ponds and the measured thickness of sediment

Sediment sampling and analysis

Sediments were first sampled in April 2019. Each pond was split into as many sections as there were inlets and outlets (Fig. 1), which enabled the identification of differences in sediment characteristics and pollutant levels within a single pond. Sediment depth and sample collection was conducted using the method described by Blecken et al. (2017). Briefly, sediment samples were taken with a sediment retriever. The depth of the accumulated sediment layer (i.e. only that which was above the clay layer) was measured with a ruler while the extracted core was still in the retriever. After the sediment sample was emptied into a clean bucket, the clay layer was carefully removed, and the remaining sample was mixed thoroughly with the other 3-6 subsamples collected from the same pond section. The number of subsamples taken from each section was dependent on the section area.

In August 2019, surface soil around the ponds A+B, C and E and well above possible waterlines was collected to determine background element concentrations in soil which in this area is dominated by kaolinite clay mineral. Subsurface soil was collected randomly using a small clean spoon and then mixed thoroughly before analysis. At this time, a sample from E3 was also taken as it was not possible to retrieve a sample with the core sampler during the first sampling because this part of the pond is covered with macadam. Additionally, although no accumulation of sediment was evident above the macadam, it was possible to collect the material deposited around and under the macadam layer and around the macrophyte roots using a gloved hand in order to avoid sampling the underlying clay layer.

The particle size distribution of the samples was determined according to ISO 11277:2009 ”Soil quality — Determination of particle size distribution in mineral soil material — Method by sieving and sedimentation”. The determination of dry matter was conducted according to Swedish Standard (SS) 28113 ”Determination of dry matter and ignition residue in water, sludge and sediment”. The elemental composition of the samples was analysed with inductively coupled plasma sector field mass spectroscopy (ICP-SFMS). In all cases, samples were digested in concentrated acid. For the elements As, Ba, Cd, Co, Cr, Cu, Hg, Ni, P, Pb, S, V and Zn, samples were heated and mixed in concentrated HNO_3; whereas for Ag and Sb, samples were treated with *aqua regia* (3:1 HCl:HNO_3). General guidelines of the method are found in SS EN ISO 17294-1 ”Water quality — Application of inductively coupled plasma mass spectrometry (ICP-MS) — Part 1: General guidelines.” Analysis was conducted according to ISO 17294-2:2016 ”Water quality — Application of inductively coupled plasma mass spectrometry (ICP-MS) — Part 2: Determination of selected elements including uranium isotopes (modified)” and USA EPA 200.8 ”Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma-Mass Spectrometry”. All analyses were carried out by a certified laboratory.

127 The division of trace elements into commonly-monitored (i.e. Cd, Cr, Cu, Hg, Ni, Pb, Zn) and seldom-
128 monitored (Ag, As, Ba, Co, Sb, V) was related to the frequency the elements were quantified in
129 literature studies such as those presented in Table 5.

130 *Data analysis*

131 Calculations and statistical analyses were conducted using Statistica 13.5.0.17, TIBCO Software Inc.
132 Multivariate analysis was conducted using the module Principal Component Analysis and Classification.
133 Computational details are described in the software in the document ¨Principal Components &
134 Classification Analysis – Computational Details¨.

135 *Determination of the contamination degree using the geoaccumulation index (I_{geo})*

136 The single element geoaccumulation index, I_{geo}, developed by Müller (1969) is generally used for
137 comparing current metal levels in sediment to pre-industrial levels (Zhu et al. 2013; Manoy and Padhy
138 2014; Duodo et al. 2016; Wang et al. 2016; Wang et al. 2018; Li et al. 2020). It is calculated using
139 Equation 1:

140 $$I_{geo} = log_2\left(\frac{C_i}{1.5\ x\ B_i}\right) \qquad \text{(Equation 1)}$$

141 where c_i is the measured concentration of the examined metal in the sediment, and B_i is the
142 geochemical background concentration. Here B_i was calculated as the average value obtained from
143 three soil samples taken around ponds A+B, C and E. An adjustment factor of 1.5 was used to account
144 for possible variations in background values as well as minor anthropogenic influences. Müller (1969)
145 used a graded scale of classification (Table 2):

146 **Table 2** Classification of I_{geo} (Müller 1969)

Class	Description	I_{geo} value
0	Unpolluted	$I_{geo} \leq 0$
1	Slightly polluted	$0 < I_{geo} \leq 1$
2	Moderately polluted	$1 < I_{geo} \leq 2$
3	Moderately/severely polluted	$2 < I_{geo} \leq 3$
4	Severely polluted	$3 < I_{geo} \leq 4$
5	Severely/Extremely polluted	$4 < I_{geo} \leq 5$
6	Extremely polluted	$I_{geo} > 5$

147 The sum of the average I_{geo} values for all trace elements determined in each pond were calculated and
148 used to generate a risk ranking for each respective pond. These values were then compared to values
149 obtained from two other risk ranking methods described below. Negative values (i.e. unpolluted; class
150 0) were set to zero.

Ecological risk assessment using the potential ecological risk index (RI)

The RI method was developed by Håkanson (1980) for assessing the potential ecological risks in sediment in freshwater ecosystems in Sweden. This was determined from the quantity of 7 elements (As, Cd, Cr, Cu, Hg, Pb and Zn) and one persistent organic pollutant (PCB); and continues to be used for ecological risk assessments of heavy metals in sediments (Manoj and Padhy 2014; Duodu et al. 2016; Jiao et al. 2017; Wang et al. 2018; Zhuang et al. 2018; Wei et al. 2019; Li et al. 2020). The RI method considers the hazard of metals to humans and ecosystems from two aspects - the abundance principle and the release effect - where the potential toxicity of a metal is inversely proportional to its abundance. The index includes the risk factor, Er^i, for a given substance (Equation 2), the sum of which being the Potential Ecological Risk Index (RI) (Equation 4; Håkanson 1980):

$$Er^i = Tr^i x\, C_f^i \quad \text{(Equation 2)}$$

$$C_f^i = \frac{C_o^i}{C_n^i} \quad \text{(Equation 3)}$$

$$RI = \sum_i^n E_r^i = \sum_i^n T_r^i \; x\, C_f^i \quad \text{(Equation 4)}$$

where Tr^i is the toxic response factor of substance *i*, C_f^i =is the contamination factor of substance *i*, C_o^i is the concentration of substance *i* in the sediment, and C_n^i = concentration of substance *i* in the background.

Here, C_f^i was calculated as the average value obtained from 3 soil samples taken around ponds A+B, C and E. The toxic response factors (*Tr*) for each element were obtained from previously published studies (Table 3). For a single substance, the risk factor value (*Er*) and the sum of risk factors (RI) were classified according to (Håkanson 1980, Table 4).

172 **Table 3** Toxic response factors used for calculating the Potential Risk Index (Håkanson 1980)

Element	*Tr*	Source
Ag	17.5	Aksu et al. 1998
As	10	Håkanson 1980
Ba	2	Yang et al. 2015
Cd	30	Håkanson 1980
Co	5	Zhang et al. 2017
Cr	2	Håkanson 1980
Cu	5	Håkanson 1980
Ni	5	Zhang et al. 2017
Pb	5	Håkanson 1980
Sb	7	Wang et al. 2018
V	2	Zhu et al. 2013
Zn	1	Håkanson 1980

173

174 **Table 4** Classification of Potential Ecological Risk Index (Håkanson 1980)

Level of potential ecological risk	Er^i value	Level of ecological risk	RI value
Low	$Er^i < 40$	Low	RI < 150
Moderate	$40 \leq Er^i < 80$	Moderate	150 ≤ RI < 300
Considerable	$80 \leq Er^i < 160$	Considerable	300 ≤ RI < 600
High	$160 \leq Er^i < 320$		
Very high	$Er^i \geq 320$	Very high	RI ≥ 600

175

176 *Ecological risk assessment using the risk characterisation ratio method (RCR-method)*

177 The derivation of RCRs (the term Risk Quotients is also commonly used) for assessing ecological risk is
178 used in many fields, such as for evaluating the risk of chemicals within the EU (ECHA 2016), the risk of
179 emerging pollutants in landfill leachate (Nika et al. 2020), or the potential risk of pharmaceuticals in
180 surface waters (Zhou et al. 2019). The RCR is derived by dividing the Predicted or Measured
181 Environmental Concentration (PEC or MEC, respectively) by the Predicted No Effect Concentration
182 (PNEC), where a RCR ≥ 1 indicates a risk of deleterious effects to the ecosystem by the pollutant in
183 question. The PNEC is usually derived using toxicity data for sediment dwelling organisms, but where
184 this data is lacking other methods such as the Equilibrium Partitioning Model which use toxicity data
185 for pelagic species can be used (CIS 2011). PNEC values are often generated when Environmental
186 Quality Standards are set, such as those under the Environmental Quality Standard Directive of the EU
187 (Directive 2013/39/EU). In this study, we use data from when EQS were set for metals and metalloids
188 in water, soil and sediment in the Netherlands (Crommentuijn et al. 2000); as equivalent data are still
189 lacking for most sediment contaminants in Swedish and European legislation. Models and data from

the Netherlands have also been used for developing guideline values for contaminated soil in Sweden (Swedish Environmental Protection Agency 2009). An RCR was consequently calculated using Equation 5:

$$RCR_i = \frac{MEC_i}{NC_i} \quad \text{(Equation 5)}$$

Where RCR_i is the risk characterisation ratio for element *i,* MEC_i is the measured concentration of element *i* in the sample, and NC_i is the negligible concentration of element *i.* Values for NC_i were calculated using the modified Eq-P method; and take into account mixture effects. Elements at concentrations lower than or equal to their *NC* is not expected to cause negative long-term effects in the ecosystem (Crommentuijn et al. 2000). NCs were available for all trace elements except Ag, for which the Danish Default Guideline Value (DGV) of 1.5 mg per kg of dry weight (mg/kg DW) for sediments was used as PNEC value (Ministry of Environment and Food of Denmark. 2017).

The sum of average RCR values for all trace elements in each pond were calculated to enable risk ranking with I_{geo} and RI.

Remediation requirements

The samples were also classified using the generic guideline values for contaminated soil developed by the Swedish Environmental Protection Agency (2009) using the guideline values in the updated list from 2016 (Swedish Environmental Protection Agency 2016). Generic guideline values were available for all trace elements except Ag (Supplementary Data Table S1). Two different generic guideline values are derived depending upon expected land use, sensitive land use (KM) and less sensitive land use (MKM). KM values are used for example if the land is going to be used for housing while MKM values are used if the land use is intended for industries.

Results and discussion

Concentrations of elements in sediment

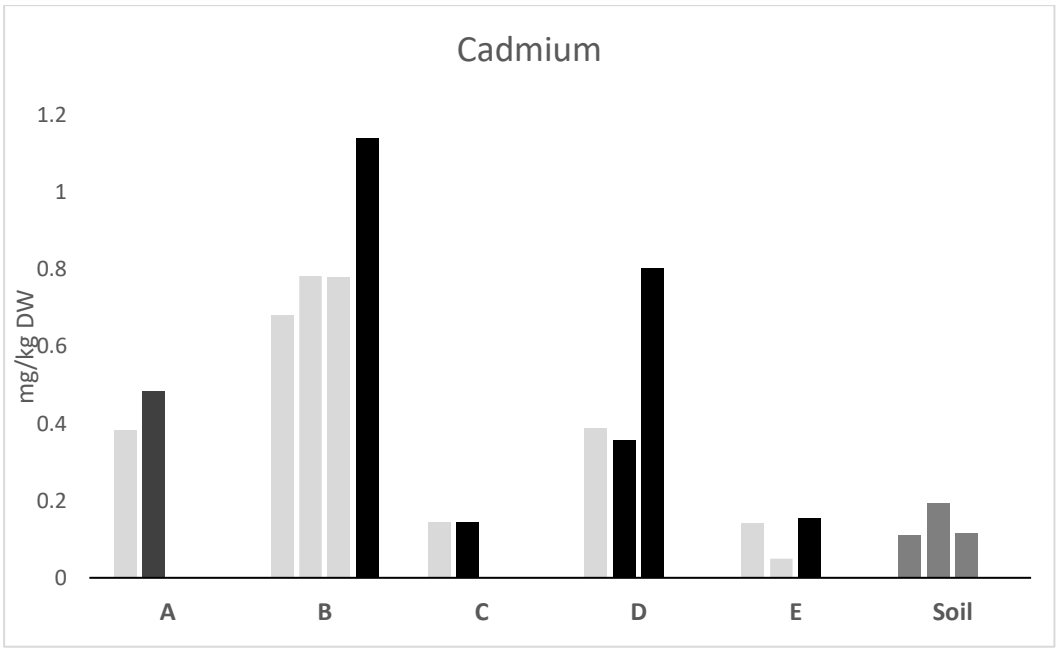
The concentrations for elements at all sampling sites and the average values for each element in each pond are presented in Supplementary Data Table S2. The measured concentrations of four commonly-monitored (Cd, Cu, Pb and Zn) and four seldom-measured (Ag, As, Ba and Sb) trace elements in stormwater ponds are presented in Fig. 2 and Fig. 3, respectively. For all elements, the highest concentrations were recorded in the older ponds (A, B and D) while the concentrations in recently constructed ponds (C and E) were generally low or close to the concentration found in the surrounding

219 soil. The mean element concentrations were ranked as follows: P > S > Zn > Ba > Cu > V > Pb > Cr > Ni
220 > Co > As > Sb > Cd > Ag. Measured concentrations for Hg never exceeded the detection limit (0.5
221 mg/kg DW), while Ag was below the detection limit (0.7 mg/kg DW) in sediments from pond C and E.

222 The element concentrations were generally similar or higher at the outlets compared to the inlets of
223 ponds. For pond A, samples from near the outlet had higher concentrations for all elements compared
224 to the inlet except for S. In pond B, all elements were found in higher concentrations near the outlet,
225 except for Co, Cr and V which were in a higher concentration around inlet B2. In pond D, all elements
226 were found in higher concentrations at outlet D3 compared to the inlet, but only Cd, Cu, Pb, S and Zn
227 were higher in concentration at outlet D2 compared to the inlet. In pond E, element concentrations,
228 except for Ag, Co, Cu, S and Sb, were generally higher at the outlet than at the inlets. Inlet E2 presented
229 the highest concentration of Co and Cu, while inlet E1 had the highest concentrations of Ag, S and Sb.
230 Finally, in pond C, a different trend was observed where Ag was below the detection limit and all other
231 element concentrations – except for those of Ba, Cr and V - were higher at the inlet than the outlet.

232 Our measured trace element concentrations were then compared with data from other studies (Table
233 5). The concentrations of commonly-monitored trace elements (i.e. Cd, Cr, Cu, Ni, Pb, Zn) were
234 detected within the same order of magnitude as those observed in several previous international and
235 national studies (Jang et al. 2010; Blecken et al. 2012; 2017; Istenič et al. 2012; Egemose et al. 2015;
236 Frost et al. 2015; Sharley et al. 2017; Crane 2019; Sun et al. 2019), but lower maximum concentration
237 values were obtained here compared to those found in ponds within industrial areas (Sharley et al.
238 2017). Blecken et al. (2012) also detected six-fold higher Cr concentrations in sediment close to
239 stormwater outlets, while Jang et al. (2010) observed four-fold higher maximum values in road
240 residues. The concentration values for seldom-monitored metals (i.e. Ag, As, Ba, Co, Sb, V) were also
241 within the same order of magnitude as previously reported values (Färm et al. 2003; Jang et al. 2010;
242 Frost et al. 2015; Sharley et al. 2017; Crane 2019). Furthermore, higher maximum concentration values
243 for these elements were found in stormwater ponds and tunnels within industrial areas (Färm et al.
244 2003; Sharley et al. 2017). Jang et al. (2010) generally observed lower maximum values in sediment
245 from stormwater ponds but the maximum concentrations of Ba was higher.

246

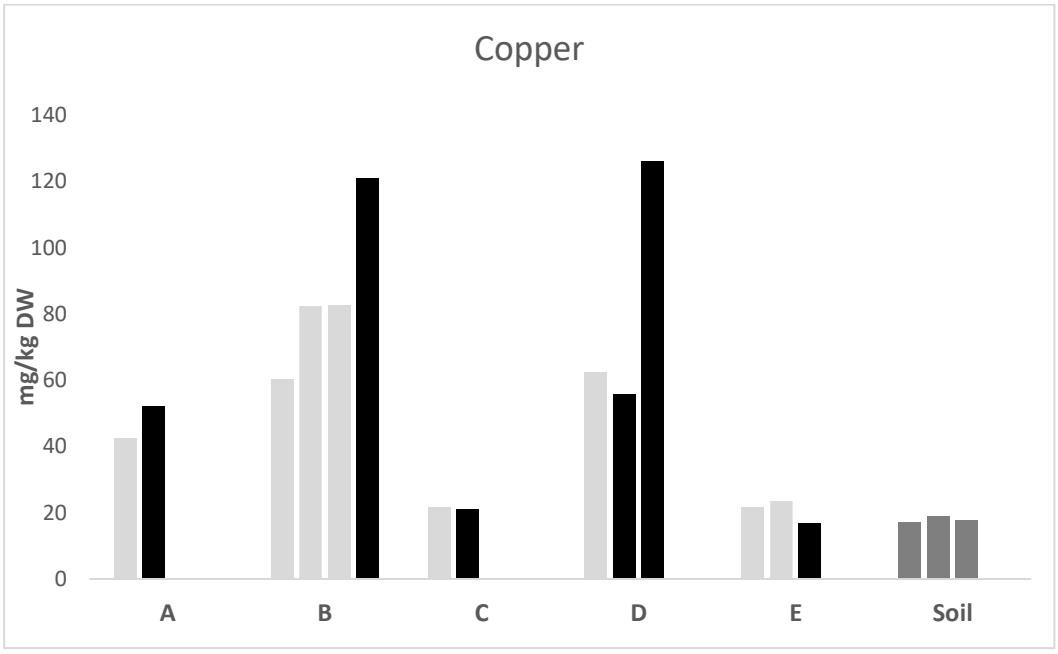


247

248

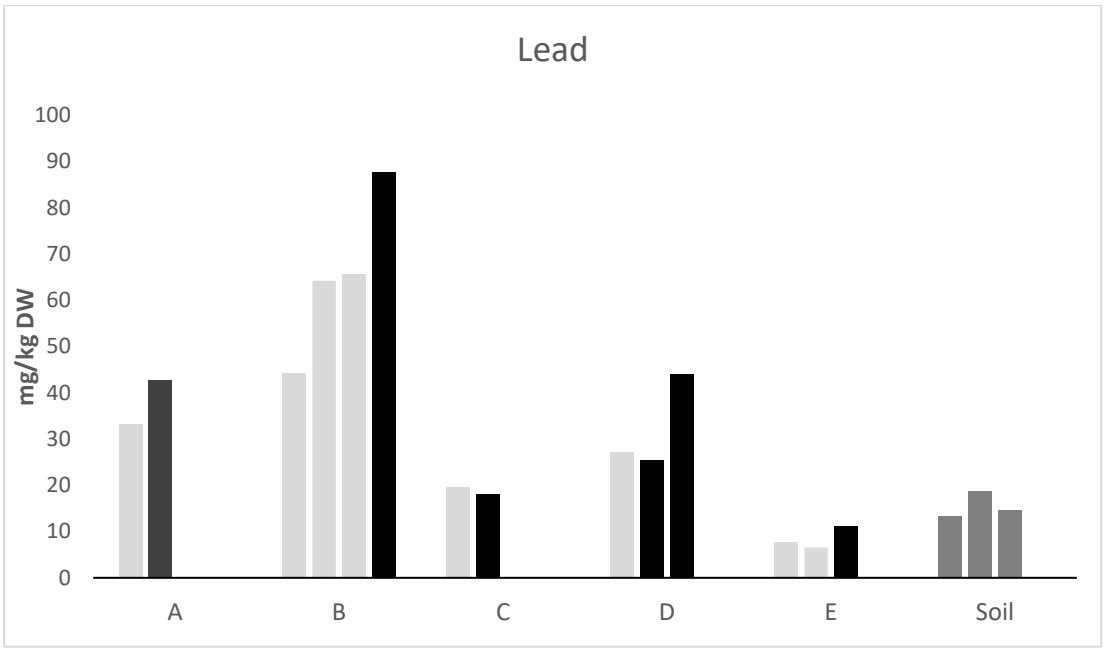
249

250



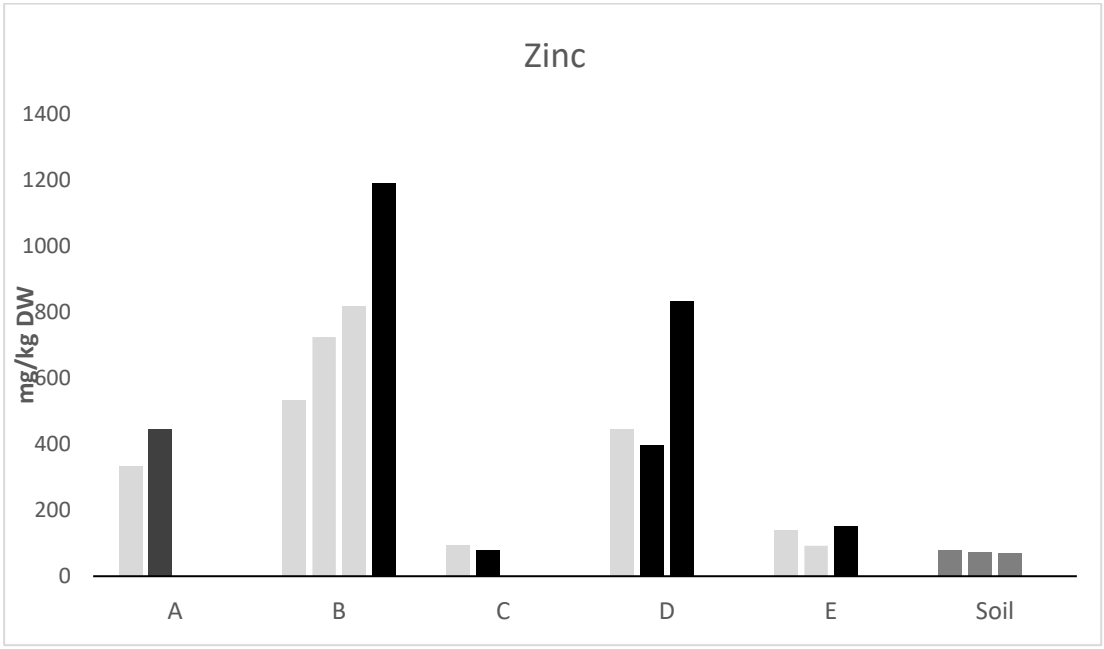
251

252



253

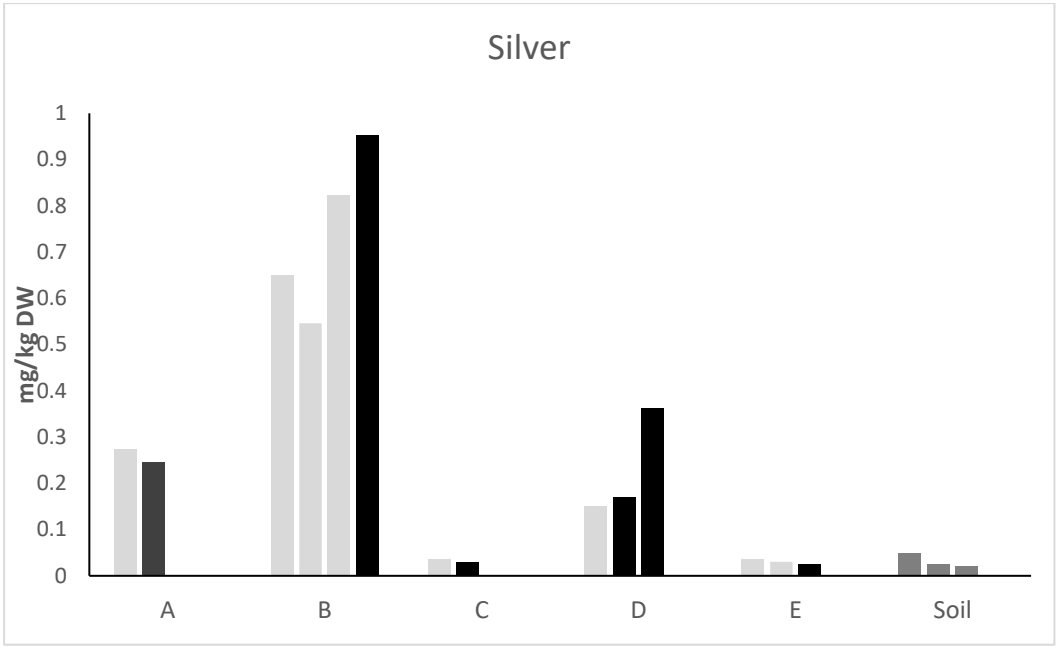
254



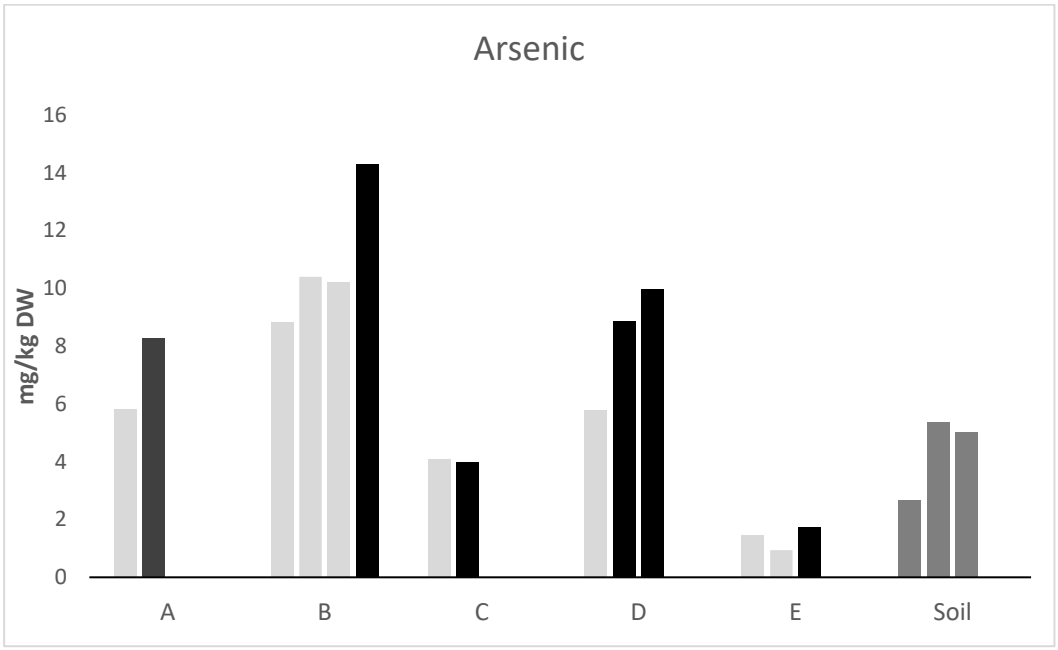
255

256 **Fig. 2** Concentrations of four commonly-monitored trace elements (Cd, Co, Pb, Zn) in sediments in
257 stormwater ponds and soil from the banks of the ponds in areas with industrial activity. Light grey
258 bars – inlets, black bars-outlets.

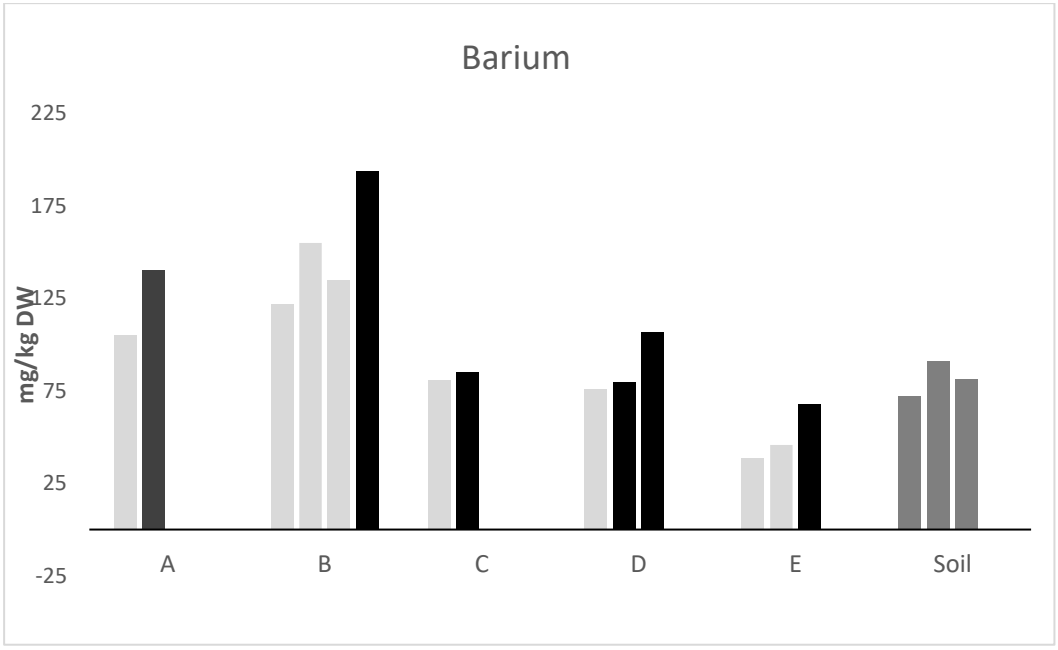
259


Silver
mg/kg DW
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
A
B
C
D
E
Soil

260


Arsenic
mg/kg DW
16
14
12
10
8
6
4
2
0
A
B
C
D
E
Soil

261



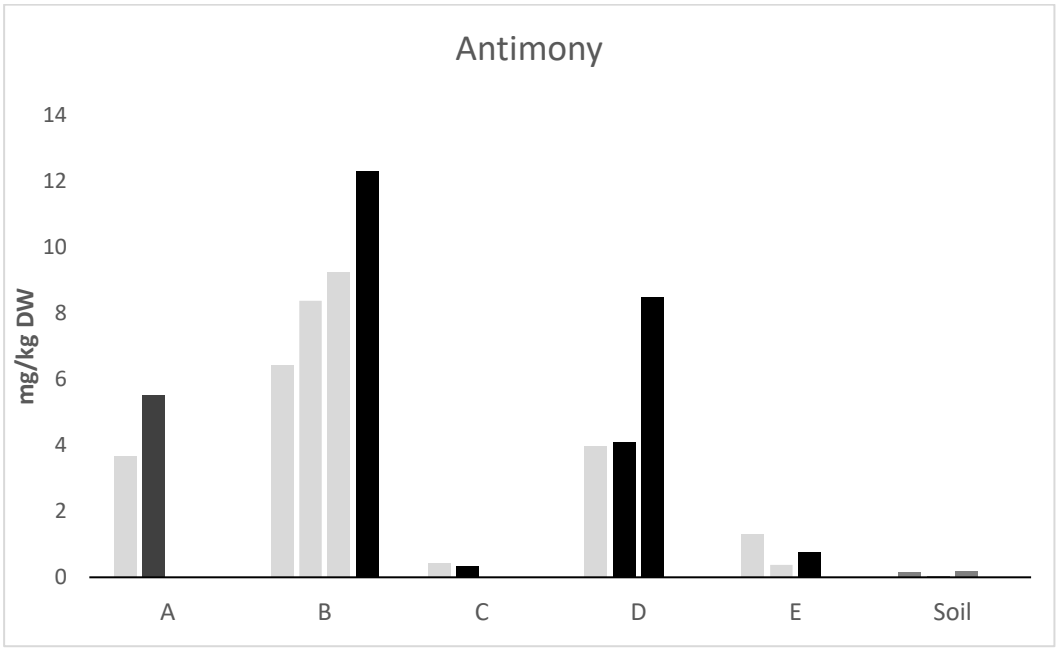


Fig. 3 Concentrations of four seldom monitored trace elements (Ag, As, Ba, Sb) in sediment in stormwater ponds and soil from the banks of the ponds in areas with industrial activity. Light grey bars – inlets, black bars-outlets

Table 5 Concentrations of trace elements in sediments from stormwater ponds, outlets and stormwater tunnels. Data is for stormwater ponds if not stated. Min-max values are presented or if not available mean ± standard deviation is used, n.a. = not analysed. N=the number of ponds studied

Referen-ce	Ag	As	Ba	Cd	Co	Cr	Cu	Hg	Ni	Pb	Sb	V	Zn
This study N=5	0.030-0.952	0.9-14.3	39-194	0.05-0.80	3.5-13.2	9.0-45.6	20.9-126.0	<0.5	6.4-34.9	6.5-87.6	0.325-12.3	15.9-75.3	78.6-1190
Crane 2019 N=15	0.99± 2.4	5.5± 2.3	147± 43	1.5±0.57	8.2± 2.8	42.0± 14.7	31.6± 10.1	0.059 ± 0.022	23.3± 7.2	39.2± 25.5	<1.2	45.3± 11.7	154.3± 79.7
Sun et al. 2019 N=12	n.a.	n.a.	n.a.	n.a.	n.a.	15-86	18-200	n.a.	17-110	9.9-76	n.a.	n.a.	57-850
Blecken et al. 2017 N=25	n.a.	n.a.	n.a.	<0.1-2.3	n.a.	2-81	3-109	n.a.	2-39	3-77	n.a.	n.a.	14-597
Sharley et al. 2017 N=98	<2-6	<5-51	40-430	<1-11	2-31	12-121	6-1090	<0.1-2.9	4-159	9-456	<5-17	14-130	12-4940
Ege-mose et al. 2015 N=37	n.a.	n.a.	n.a.	0.1-1.4	n.a.	18-62	18-62	n.a.	18-62	18-62	n.a.	n.a.	166-451
Frost et al. 2015	0.04-0.37	n.a.	64.7-507.3	0.06-0.39	3.8-20.3	9.6-60.5	9.5-42.3	n.a.	6.6-45.4	6.0-38.1	n.a.	14.3-67.5	35.5-175.4
Blecken et al. 2012 N=32	n.a.	n.a.	n.a.	0.15-1.23	3.8-25.0	64-307	17-263	n.a.	10-50	8-42	n.a.	n.a.	68-470
Istenič et al. 2012	n.a.	n.a.	n.a.	<0.5	n.a.	17-80	4-3293	n.a.	10-42	<2-220	n.a.	n.a.	26-1361

N=3													
Jang et al. 2010 N=22	<0.8	0.6-24.8	8.1-1019	<0.37 1st -5.3	n.a.	5.8-174.5	4.5-90.4	<0.02	5.4-40.4	5.6-196	n.a.	n.a.	5.4–711
Färm et al. 2003 N=3	0.314-1.70	10.2-20.7	n.a.	1.15-2.93	19.6-34.7	51.0-75.7	106-159	Kan finnas	32.0-50.5	61.4-98.2	n.a.	73.2-106	609-974

[1] wetlands
[2] stormwater outlets
[3] road residues from stormwater systems
[4] sediment from stormwater tunnels

Sediment depth and particle size distribution

The sediment depth measurements in different ponds showed that there were no significant differences in sediment depth between the areas surrounding the inlets and outlets (Fig. 1). The largest sediment depths were observed in one of the older ponds (B). Accumulation of material had already occurred at the inlets in one of the newer ponds (E), while the accumulation was still low in the other new pond (C).

The particle size distribution and the sediments varied between sampling sites across individual ponds and between ponds (Fig. 4, all data shown in Supplementary Data Table S2). Most of the sampling sites contained mainly fine material (PSsilt/clay), except for pond E. During sampling in August 2019, erosion of material from the surrounding step banks into the ponds was observed, and thus the sediment may constitute material from both the catchment and the areas directly surrounding the ponds.

A well-designed pond should accumulate coarse material at the inlets and fine material at the outlets, but we observed mixed results. Here, the stormwater ponds were constructed to prevent flooding downstream and have several inlets (e.g. B and E) or several outlets (e.g. D), therefore the hydraulic efficiency may be low. However, previous studies also reported varied results which suggested that fine sediment may also accumulate preferentially at inlets in ponds with high hydraulic efficiency (Istenič et al. 2012; Blecken et al. 2017).

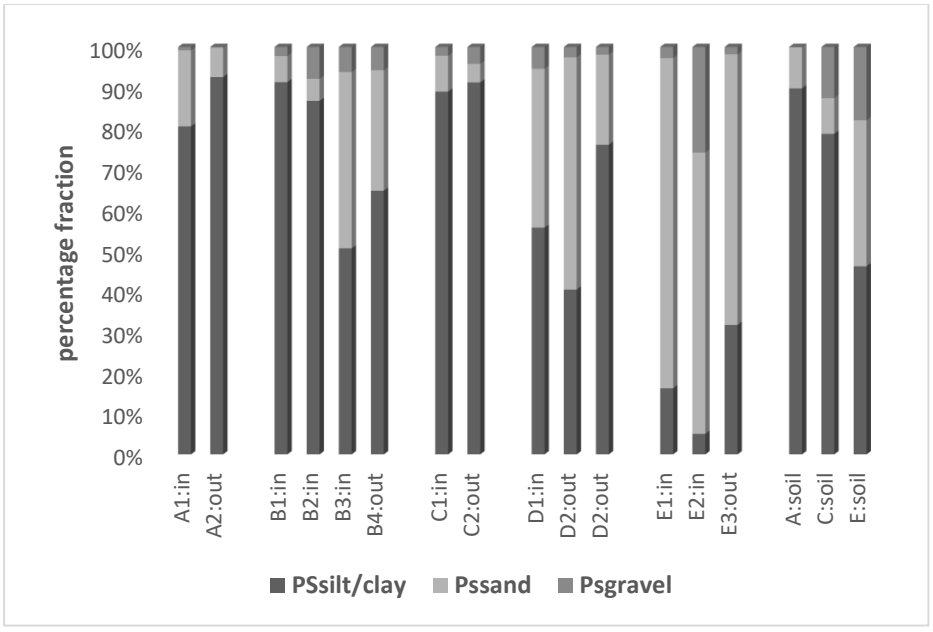


Fig. 4 Particle size distribution of the sediment in the different sampling sites in five stormwater ponds. Particle size (PS) for PSsilt/clay < 0.063 mm, PS sand 0.063- 2mm and PS gravel > 2mm

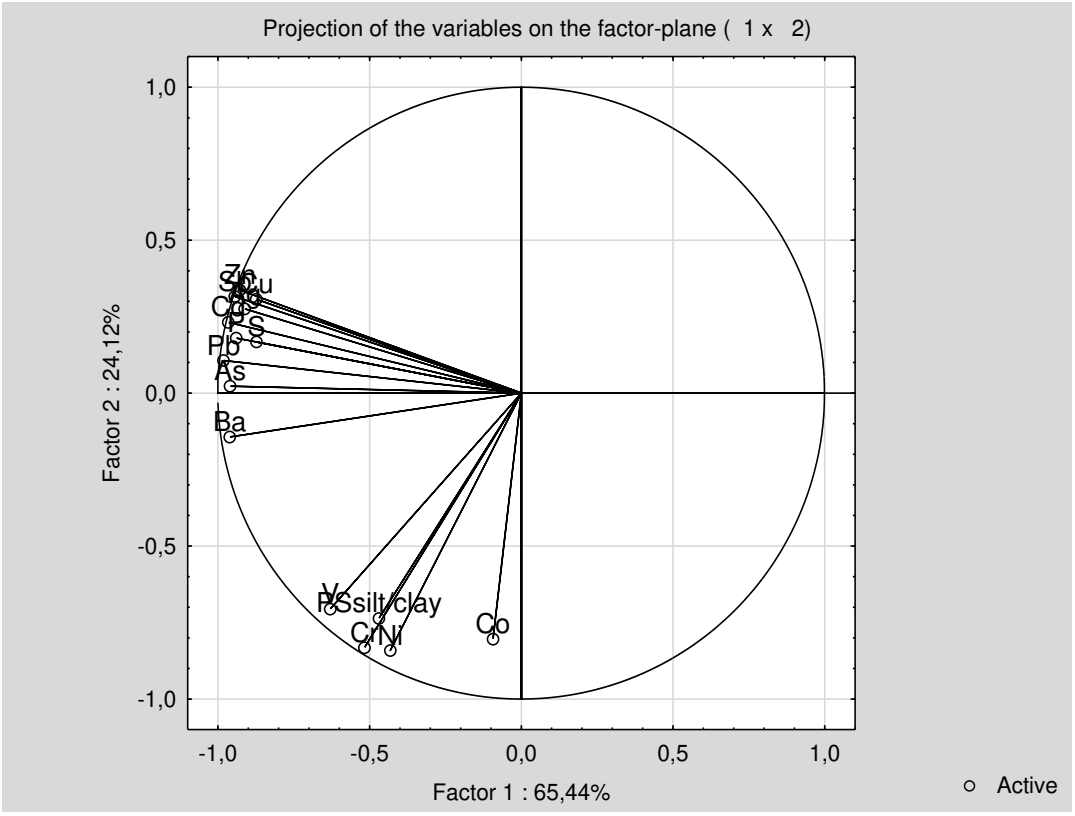
294 *Pattern and relationship between elements and sediment characteristics*

295 Trends in variation and the relationship between measured variables were further explored using PCA
296 and classification methods. PCA on all element concentration data and sediment characteristics was
297 not possible because the correlation matrix became singular indicating that the data could be
298 replicated as the linear combination of fewer variables. Therefore, PCA was conducted with the
299 element concentration and PSsilt/clay data (Fig. 5). In Fig. 5a the PCA for the 2 first Principle
300 Components is presented for the samples including the soil samples (cases n=17), the 12 trace
301 elements detected, P, S and the silt/clay fraction (variables n=15). Only 2 PCs had an eigenvalue above
302 1 and PC1 and PC2 describe 65.44% and 24.12% of the variation respectively. Two distinct groups of
303 variables were identified (Fig. 5a). The first group (Fig 5b), hereafter labelled Group A, consisted of
304 elements with a high negative loading (score) on PC1 include (in descending order) Pb, Cd, Ba, As, Sb,
305 P, Zn, Ag, Cu and S. They also all have a low positive loading on PC2 except for Ba. The second group,
306 hereafter labelled B (Fig. 5c) , consisted of elements and parameters with lower negative loadings on
307 PC1 and higher negative loadings on PC2 included (in descending order of PC 1) V, Cr, PSsilt/clay (i.e.
308 PS < 63 µm) and Ni. Co was included in the second group, but we remark that it showed a very low
309 negative loading on PC1.

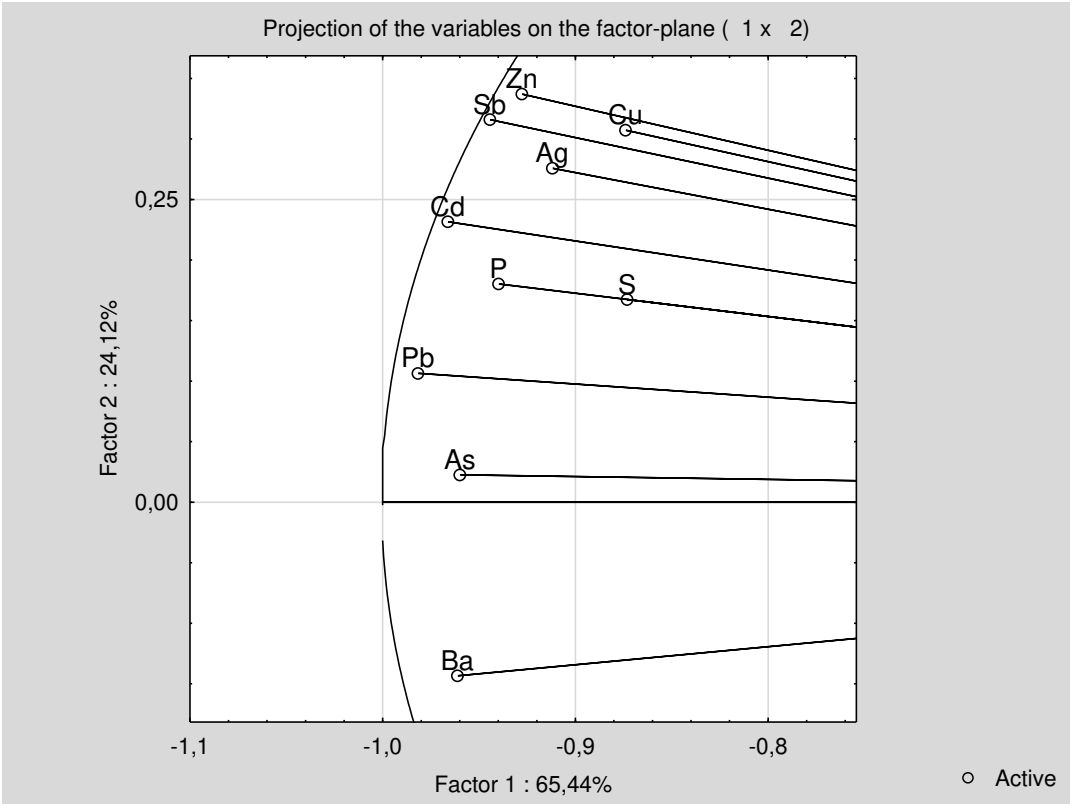
310 The projection of the cases on PC1 and PC2 showed that samples from a given pond were loosely
311 grouped (Fig. 5d). This suggested that samples taken from a single pond were more similar to each
312 other than to those from other ponds, which reflects differences in catchment characteristics. Samples
313 with the highest contamination level had the highest negative loading in PC1 (i.e. located furthest to
314 the left in Fig. 5b), which indicated that pond B was the most contaminated and pond E was the least
315 contaminated.

316 A Pearson's r correlation analysis was also conducted to identify correlations between the elements
317 and the sediment characteristics including PSclay/silt (i.e. PS < 63 µm), PSsand (i.e. PS 0.63 µm – 2 mm),
318 PSgravel (i.e. PS > 2 mm), PScoarse material (i.e. PSsand and PSgravel) and sediment depth (Table 6).
319 Statistically significant positive correlations ($p \leq 0.05$) were observed for PSclay/silt and (in order of
320 decreasing correlation) V, Cr Ni, S, Ba and Co; where the same elements also showed significant
321 negative correlation with similar amplitude with PSsand. No significant correlation between PSgravel
322 and the elements was observed. Additionally, (in order of decreasing correlation) P, Pb, Ba, Cd, Sb, Zn,
323 Ag and S were significantly correlated with sediment depth. Finally, a correlation analysis was also
324 conducted for the trace elements and the potential indicators of contamination P and S (Table 6).
325 Elements constituting Group A as identified in the PCA (see Fig. 5a,b) showed higher correlation

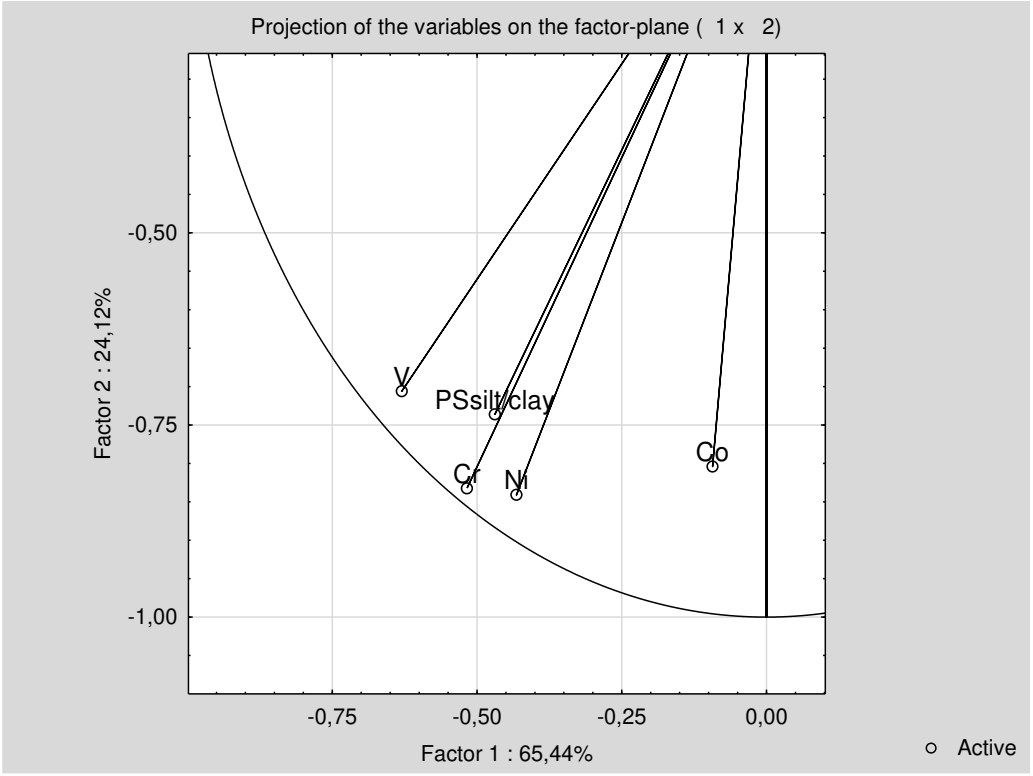
326 coefficients with P and S than those in Group B (Fig 5a,c) except for V which showed a significant
327 correlation with S. Group A elements were more strongly correlated with P than with S.



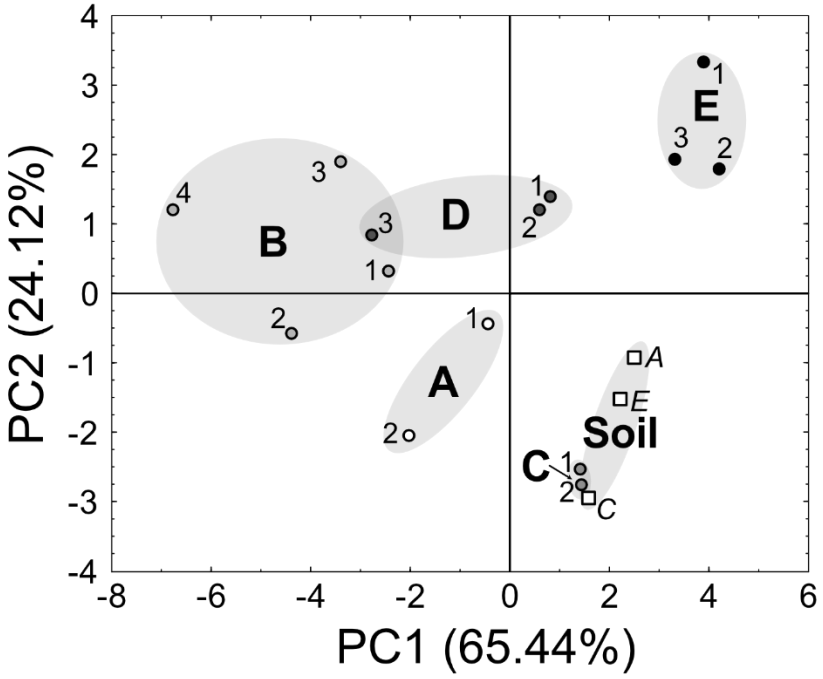
328



329



330



331

332 **Fig. 5** a) Projection of the variables on PC 1 and PC2. b) Enlarged section of PCA with Group A
333 elements c) Enlarged section of PCA with Group B elements and PSsilt/clay d) Projection of the
334 samples on PC1 and PC2

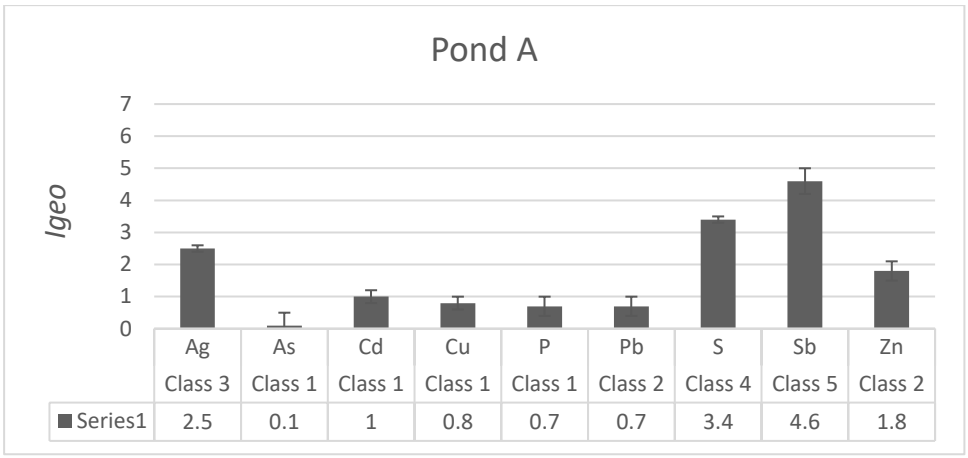
335 **Table 6** Pearson r correlations between sediment characteristics and elements. Significant correlations
336 are presented in in bold. Statistical significance was set to <0.05

Element mg/kg DW	PSsilt/clay[1] (%)	PSsand[2] (%)	Sediment depth (cm)	P mg/kg DW	S mg/kg DW
Ag	0.29	-0.31	**0.57**	**0.96**	**0.78**
As	0.48	-0.47	0.53	**0.90**	**0.82**
Ba	**0.58**	**-0.59**	**0.60**	**0.91**	**0.87**
Cd	0.38	-0.38	**0.59**	**0.93**	**0.86**
Co	**0.54**	**-0.68**	0.16	0.10	0.15
Cr	**0.91**	**-0.92**	0.16	0.46	**0.59**
Cu	0.28	-0.28	0.48	**0.76**	**0.75**
Ni	**0.85**	**-0.86**	0.14	0.42	0.47
P	0.38	-0.40	**0.62**	-------	**0.84**
Pb	0.44	-0.44	**0.61**	**0.96**	**0.86**
S	**0.59**	**-0.58**	**0.54**	**0.84**	-------
Sb	0.31	-0.31	**0.59**	**0.92**	**0.84**
V	**0.93**	**-0.92**	0.16	0.49	**0.70**
Zn	0.26	-0.26	**0.58**	**0.89**	**0.80**

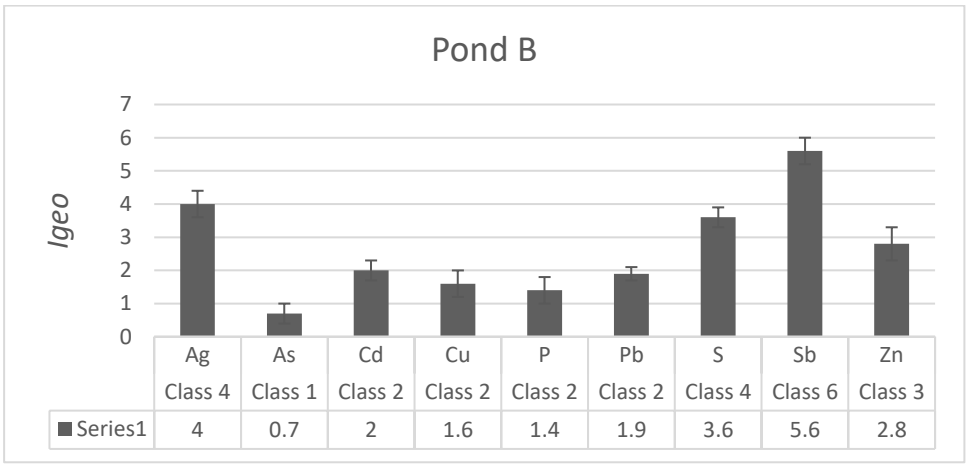
337 [1]Particle size < 0.063mm
338 [2]Particle size 0.063 mm – 2 mm
339

340 *Contamination degree using the geoaccumulation index I_{geo}*

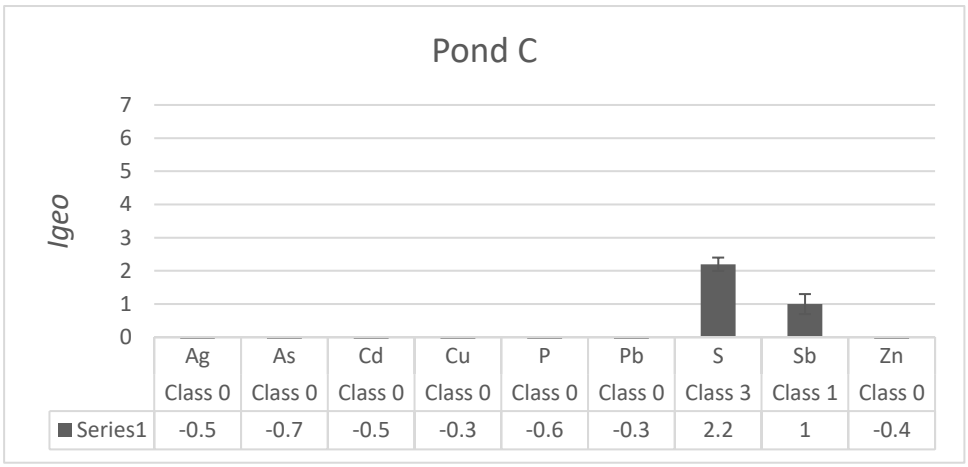
341 The single element index, I_{geo} was used to assess the degree of contamination in the sediment. The
342 mean I_{geo} values for the elements Co, Cr, Ni and V in all ponds were all negative and the sediment were
343 therefore classified as unpolluted (Class 0) with respect to these elements. The mean I_{geo} for Ba only
344 exceeded 0 in pond B (0.3±0.3). The I_{geo} for the elements Ag, As, Cd, Cu, P, Pb, S, Sb and Zn are shown
345 for each pond in Fig. 6. The complete data set for I_{geo} values is shown in Supplementary Data Table S3.
346 The highest mean I_{geo} values were obtained for Ag, S, Sb and Zn. The older ponds (A, B and D) showed
347 higher contamination degree than the newest ponds (C and E). Overall, Pond B was the most polluted,
348 showing the highest I_{geo} values for Ag (Class 4), S (Class 4) and Sb (Class 6) and Zn (Class 3). Ponds C and
349 E only showed contamination by S and Sb (both ponds) and Zn (pond E only).


Pond A
Igeo
7
6
5
4
3
2
1
0
Ag Class 3
As Class 1
Cd Class 1
Cu Class 1
P Class 1
Pb Class 2
S Class 4
Sb Class 5
Zn Class 2
Series1 2.5 0.1 1 0.8 0.7 0.7 3.4 4.6 1.8

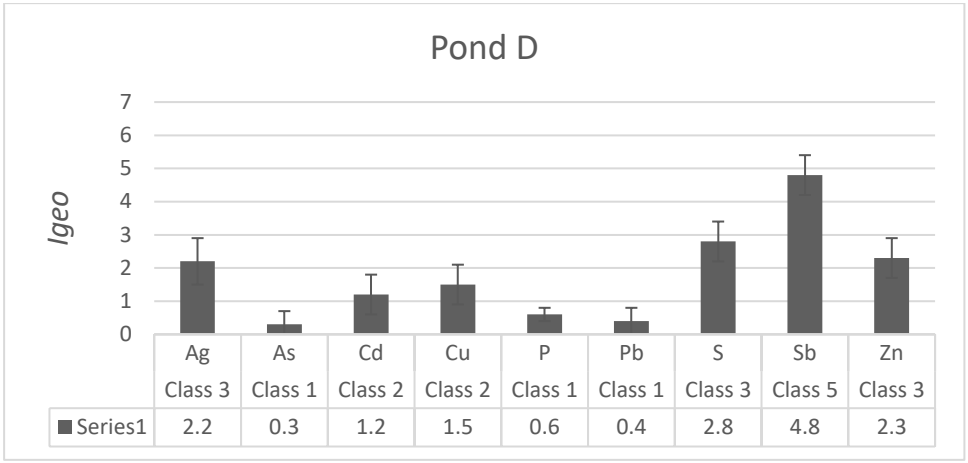
350


Pond B
Igeo
7
6
5
4
3
2
1
0
Ag Class 4
As Class 1
Cd Class 2
Cu Class 2
P Class 2
Pb Class 2
S Class 4
Sb Class 6
Zn Class 3
Series1 4 0.7 2 1.6 1.4 1.9 3.6 5.6 2.8

351


Pond C
Igeo
7
6
5
4
3
2
1
0
Ag Class 0
As Class 0
Cd Class 0
Cu Class 0
P Class 0
Pb Class 0
S Class 3
Sb Class 1
Zn Class 0
Series1 -0.5 -0.7 -0.5 -0.3 -0.6 -0.3 2.2 1 -0.4

352



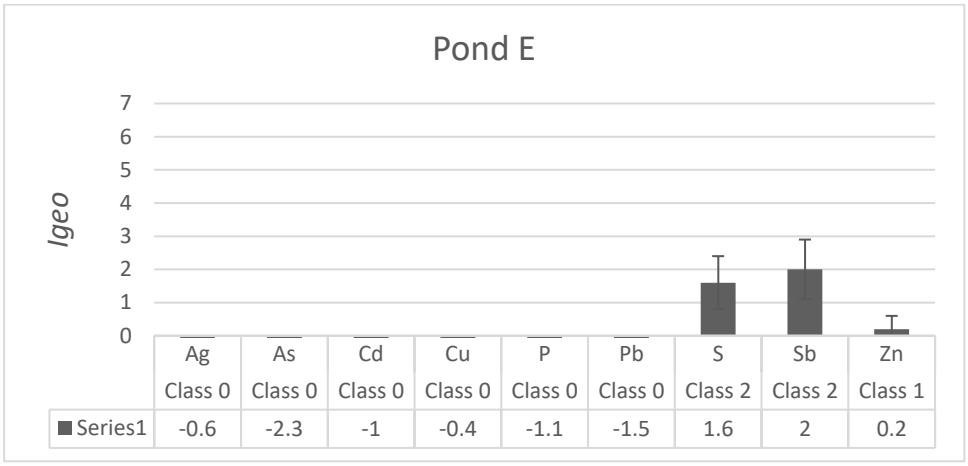


Fig. 6 Contamination degree for trace elements in the different ponds using the geoaccumulation index I_{geo}. Classification was made using mean values, and error bars present standard deviation

Ecological risk assessment using the Potential Ecological Risk Index (RI)

The mean risk factor, *Er,* for the elements As, Ba, Co, Cr, Cu, Ni, Pb, V and Zn was below 40 which suggested they provided low potential ecological risk. The *Er* values for Ag, Cd and Sb are shown in Table 7, and all data are summarised in Supplementary Data Table S4. Low risk factors (*Er* < 40) were obtained for the newer ponds C and E while the older ponds A,B and D showed very high risks (*Er* ≥ 320) for Ag and Sb.

The RI for ponds C and E were classified as low while the classifications for RI for ponds A, B and D ranged from considerable ecological risk (Class 3) to very high ecological risk (Class 4). The highest RI was obtained in pond B.

Table 7 Mean risk factor, *Er,* values for Ag, Cd and Sb with standard deviation; the RI for the sum of risk factors and the contribution, in percentage, of Ag, Cd and Sb to the RI in sediment from the five stormwater ponds

Pond	*Er*-Ag[1]	*Er*-Cd[1]	*Er*-Sb[1]	RI[2]	% Ag of RI	% Cd of RI	% Sb of RI	% Ag+Cd+Sb of RI
A	147±11 Class 3	93±16 Class 3	267±75 Class 4	593 Class 3	25	16	45	86
B	421±102 Class 5	182±44 Class 4	528±143 Class 5	1248 Class 4	34	15	42	91
C	18±2 Class 1	31±0 Class 1	22±4 Class 1	134 Class 1	14	23	16	53
D	129±66 Class 3	111±54 Class 3	321±150 Class 5	646 Class 4	20	17	50	86
E	17±3 Class 1	25±12 Class 1	48±27 Class 2	117 Class 1	16	20	39	75

[1] The risk of single element was classified as according to Håkanson (1980) and here, for convenience, it has been given a numeric classification: Class 1 Low potential ecological risk *Er* <40; Class 2 Moderate potential ecological risk 40 ≤ *Er* < 80, Class 3 Considerable ecological risk 80 ≤ *Er* < 160; Class 4 High potential ecological risk 160 ≤ *Er* < 320 and Class 5 Very high ecological risk *Er* > 320.

[2] The RI, the sum of the risk factors, was classified according to Håkanson (1980) and here, for convenience, it has been given a numeric classification: Class 1 Low ecological risk RI < 150; Class 2 Moderate ecological risk 150 ≤ RI < 300; Class 3 Considerable ecological risk 300 ≤ RI < 600; Class 4 Very high ecological risk RI ≥ 600.

Ecological risk assessment using the RCR-method

Elements with mean RCRs exceeding 1 in at least one sample are summarised in Table 8, while all data is presented in Supplementary Data Table S5. Mean RCRs in soil were < 1 for all elements except for Co and V. In pond sediment mean RCRs for Ag, As, Cd, Cr, Pb were always ≤ 1. For Ba, two samples (B2 and B4) had a RCR ≥1 (1.0 and 1.2, respectively). For Cd and Ni, only samples B4 and C1 had a RCR ≥1 (both 1.0). For Co and V all ponds except pond E had a mean RCRs of 2 > RCR ≥ 1. Finally, mean RCRs for Cu, Sb and Zn exceeded 2 in numerous samples, where the highest mean RCRs for Zn (5.6), Sb (2.8) and Cu (2.4) - and therefore the highest Sum-RCR - was obtained in pond B. The lowest sum-RCR values were obtained for the newest ponds C and E. Indeed, the sum-RCR for the surrounding soil exceeded that of pond E.

Table 8 Mean Risk Characterisation Ratio (RCR) with standard deviation for elements measured in soil and sediments in five stormwater ponds. Negligible concentrations (NC, in mg/kg DW sediment) was collected from Crommentuijn et al. (2000). Mean RCRs in bold text ≥ 1, ponds with a at least 1 sample with a RCR ≥ 1 in italics.

Pond	Ba (157)[1]	Cd (1.1)	Co (9.1)	Cu (36)	Ni (35)	Sb (3.2)	V (42)	Zn (145)	Sum-RCR[2]
A	*0.8±0.2*	0.4±0.1	**1.2±0.2**	**1.3±0.2**	0.7±0.1	**1.4±0.4**	**1.6±0.3**	**2.7±0.5**	11.1±2.1
B	1.0±0.2	*0.8±0.2*	**1.1±0.2**	**2.4±0.7**	0.7±0.2	**2.8±0.8**	**1.3±0.2**	**5.6±1.9**	17.3±4.2
C	0.5±0.0	0.1±0.0	**1.4±0.0**	0.6±0.0	**1.0±0.0**	0.1±0.0	**1.3±0.1**	0.6±0.1	6.3±0.1
D	0.6±0.1	0.5±0.2	**1.0±0.2**	**2.3±1.1**	0.5±0.1	**1.7±0.8**	**1.0±0.2**	**3.8±1.6**	12.3±4.5
E	0.3±0.1	0.1±0.1	*0.8±0.5*	0.6±0.1	0.3±0.1	0.3±0.1	0.5±0.2	*0.9±0.2*	3.9±0.4
soil	0.5±0.1	0.1±0.0	**1.4±0.3**	0.5±0.0	0.8±0.2	0.0±0.0	**1.1±0.1**	0.5±0.0	5.6±0.8

[1]NC in parenthesis

[2]sum mean RCR for all elements analysed except P and S

Remediation requirements

The complete data set is shown in Supplementary Data Table S2. The mean concentration of each element in background soil was below the respective generic guideline values for both less sensitive land use (MKM) and sensitive land use (KM). The KM value for Co was, however, exceeded in the surrounding soil from pond C. The generic guideline value for less sensitive land use (MKM) was never exceeded in pond sediments except for Zn where all samples from pond B exceeded the MKM value as did the sample D3 from pond D. Based upon means the KM value was exceeded in pond A for Zn, for pond B for As, Cd, Cu, Pb and Zn (i.e. exceeds MKM) and for pond D for Cu and Zn (i.e. Zn exceeds MKM). No sediment concentrations exceeded KM values in pond C and E. This suggest that some elements - particularly Zn - will limit the re-use of the sediments from the older ponds and they may require costly and laborious clean-up procedures (Zubala et al. 2018) when excavated in the future.

Priority ranking of ponds and elements

The ponds were then ranked according to their I_{geo}, RI and RCR values (Table 9). The rankings were similar for all methods except I_{geo} was higher in pond E than in pond C. Overall, Pond B was the most contaminated. The degree of contamination was summarised as B >>> D ≈ A > C ≈ E. The degree of contamination in ponds C and E was low such that their RCR values matched those of the surrounding soil. This confirmed that the younger ponds (C and E) were less contaminated than the older ponds. In theory, the annual accumulation of trace element should be the same if it is not influenced by other factors. In this case, it was assumed that low rainfall during 2018, 60% less than normal (Swedish Meteorological and Hydrological Institute 2021), contributed to a low accumulation. Additionally, the

418 percentage impervious surface of pond C was low (12%) as the pond was constructed before the
419 industrial area has been fully developed.

420 The 3 ranking methods used were originally developed for sediment quality assessment in lakes and
421 watercourses (Müller 1969; Håkanson 1980; Crommentuijn et al. 2000). To our knowledge, this study
422 represented the first use of I_{geo} and RI in the risk assessments of stormwater ponds sediment. The RCR-
423 method is rarely used but sediment guidelines are frequently compared to measured values when
424 assessing the quality of stormwater sediment (Färm et al. 2003; Andersson et al. 2004; Färm and Waara
425 2005; Jang et al. 2010; Blecken et al. 2012; Sharley et al. 2017; Crane 2019). It is encouraging that I_{geo},
426 for which there is no need to find neither *Tr* nor PNEC values, provided a similar ranking as the RI and
427 the RCR-method. This suggested that the I_{geo} method is suitable for evaluating the risk caused by the
428 accumulation of emerging contaminants in stormwater ponds.

429 Although the different ranking methods indicated somewhat different elements of concern (see Table
430 9), their scales for classification were different and P and S were not included in the RI and Sum-RCR
431 values. P and S are not considered toxic trace elements, but they are used in this study to investigate
432 if they are correlated with the accumulated trace elements. Both elements belong to the Group A
433 elements identified in the PCA (see Fig. 5a,b) and they were significantly correlated with the trace
434 elements with a high I_{geo} (Fig. 6). P and S are rarely analysed in sediment in stormwater ponds, but the
435 P level measured here was within the same range (358-4130 mg/kg DW) as reported by Istenič et al.
436 2012 (90-1810 mg/kg DW). The levels for S found in this study (347-3170 mg/kg DW) are within the
437 lower range of the interval found by Blecken et al. in 2012 (358-16000 mg/kg DW). Finally, while both
438 P and S showed high and significant correlation coefficients with trace elements with a high I_{geo}, P
439 showed very low accumulation compared to S. This indicated that S was generally a better indicator of
440 contamination than P, but additional studies are necessary to explore if S content can be a general
441 indicator of pollution in stormwater ponds.

442 It was assumed that the RCR values for Co, Ni and V (> 1) were questionable since I_{geo} indicated no
443 accumulation of these elements above the background reference soil (Table 9). The NC value used as
444 PNEC was derived for risk assessments made in the Netherlands, which accounted for higher local
445 background concentrations than what we observed in own reference soil (except Co and V;
446 Crommentuijn et al. 2000). There are currently no available environmental quality standard (EQS) for
447 sediment in lakes and watercourses in Sweden for most of the trace elements analysed, except for Cd
448 (EQS=2.3 mg/kg DW, NC = 1.1 mg/kg DW), Cu (EQS=36 mg/kg DW, NC = 37 mg/kg DW) and Pb
449 (EQS=130 mg/kg DW, NC = 132 m/kg DW) (HVMFS2019:25). However, replacing the NCs used in this

study with the national EQSs only marginally changed the RCRs for Cu and Pb, although the average RCR for Cd fell under 1. As both the I_{geo} and *Er* values indicated that Cd was an element of concern in pond B, Cd was kept as an element of concern overall. Denmark has set a national guideline for V to 23.6 mg/kg DW using the added risk approach (Ministry of Environment and Food of Denmark. 2017), which can be added to the background concentration. In our case, the concentration in a sample must have exceeded 71.7 mg/kg DW (i.e. 48.1+ 23.6 = 71.7) to affect the ecosystem negatively, and this level was only exceeded in sample A2 (Supplementary Data Table S2).

The NCs and the national EQSs for Cd, Cu and Pb were calculated under the assumption that the total organic carbon (TOC) was 5%, and that at a higher TOC the trace elements would bind to the organic matter and become biologically unavailable (CIS 2011). Organic C was not measured in this study, but we assume that organic C content would vary depending upon land use and amount of vegetation in the ponds.

Ag is considered an element of concern despite low RCR levels (i.e. RCR < 1) because the I_{geo} value indicated extensive accumulation and the *Er* value was high. Cu was also classified as an element of concern even though the RCR was also below 1 because the I_{geo} and Er value indicated a risk and the KM guideline was exceeded in pond B and D. As and Pb are interesting cases as the I_{geo} indicated accumulation in pond A, B and D and the RCRs were below 1, but the KM values for Pb (KM=50 mg/kg DW; NC = 132 mg/kg DW) and As (KM=10 mg/kg DW; NC =31 mg/kg DW) were exceeded in pond B. This was attributed to the setting of the generic guideline values for contaminated soil for both ecological and human risk. The RCR for Ba was above 1 only in pond B, while I_{geo} indicated only slight pollution (Class 1) and the *Er* value indicated low risk in the same pond. Consequently, Ba may not be classified as an element of concern. The high RCRs in pond A, B and D for Sb and Zn agreed directly with the I_{geo} and *Er* classification and were thereby classed as elements of high concern. Sb and Zn also show high correlation in the PCA (Fig. 5b) and may therefore have a common source of origin. In conclusion, the use and comparison of three risk assessment methods confirmed that both commonly monitored trace elements (Cd, Cu, Zn) and seldom monitored trace elements (Ag, Sb) may cause an ecological risk in the ponds.

For Ag (Färm et al. 2003; Frost et al. 2015; Sharley et al. 2017; Crane 2019) and Sb (Sharley et al. 2017; Crane 2019) we have found only a few records of measurements in stormwater ponds with catchments featuring industrial land yet the current data showed that the monitoring these elements is paramount as they showed very high accumulation compared to the background. Ag is currently used in many nanomaterials in textiles, medical products, food containers, cosmetics, paints and nano-

functionalised plastics (McGillicuddy et al. 2017). Meanwhile, Sb is used in catalysts for production of polyethylene terephthalate (PET), and in flame retardants for various materials such as paper, plastic, paints and textiles (Wang et al. 2018); and brake linings (Wang et al. 2018, Müller et al. 2020). It has recently been found in high concentration in plastic waste fractions (Viczek et al. 2020); and shown to be mobilised from microplastic in coastal estuarine sediments when extracted with fluids that simulate the digestive system of sediment dwelling invertebrates (James and Turner 2020). Significantly, Pond D is located near to a municipal recycling plant. As the industrial areas are less than 5 km apart, they may also experience similar sources of local and long-distance transport of airborne pollutants. Clearly, further studies are needed to determine whether the high accumulation of Ag and Sb in the studied stormwater ponds is a local phenomenon or not.

In this study, the total amount of certain elements was measured and risk-assessed. There are several studies that indicate that heavy metals preferentially accumulate in the roots of macrophytes and are therefore unlikely to become bioavailable via plant uptake and translocation (Istenič et al. 2012). Benthic organisms have also been shown to accumulate heavy metals in stormwater ponds such as Cd, Cr, Ni and Cu (Stephansen et al. 2014), but they might not reach toxic levels as was demonstrated by Andersson et al. (2004) and Casey et al. (2006). Recently, Sun et al. (2019) studied the biodiversity in roadside ponds and found that most of the taxa displayed in the ordination diagram were negatively correlated with the pollution levels in the water column and sediments, while a positive correlation with the pond size and the number of neighbouring ponds was observed. Whether the trace elements studied here will cause toxicity and thereby reduce the biodiversity in catchments with industrial activity remains to be explored.

Table 9 Priority ranking of contamination in the ponds and identified elements of concern based upon I_{geo}, RI and RCR

Pond	Rank Sum-I_{geo}[1]	Rank RI[2]	Rank Sum-RCR[3]	Rank[4]	I_{geo}[5]	mean-*Er*>40[6]	mean-RCR≥1[7]
	Ranking of ponds				**Elements of concern**		
A	3 (11.8)	3 (593)	3 (11.1)	3	Ag, S, Sb, Zn	Ag, Cd, Sb	Cu, Sb, V, **Zn**
B	1 (18.5)	1 (1248)	1 (17.3)	1	**Ag**, Cd, Cu, P, Pb, **S**, **Sb**, **Zn**	Ag, Cd, Sb	Ba, Cd[8], Co, Cu, Sb, V, **Zn**
C	5 (1.0)	4 (134)	4 (6.3)	4	S	None	Co, Ni, V,
D	2 (12.6)	2 (646)	2 (12.3)	2	Ag, Cd, Cu, **S**, **Sb**, **Zn**	Ag, Cd, Sb	Co, Cu, Sb, V, **Zn**
E	4 (2.1)	5 (117)	5 (3.9)	5	S, Sb	Sb	none
soil	n.a.[9]	n.a.	5.6	n.a.	n.a.	n.a.	Co, V
List elements of concern					Ag, Cd, Cu, (Pb), Sb, Zn		

[1] Sum I_{geo} in parenthesis, when calculating sum I_{geo} negative I_{geo} values have been set to 0. I_{geo} was calculated for all elements except Hg which was below detection limit in all samples. Sum I_{geo} has been calculated to enable comparison in the risk ranking of the ponds.

[2] Sum Mean Potential Ecological Risk Index in parenthesis, RI was calculate including all elements except Hg, P and S, see also Table 7.

[3] Sum Mean RCR in parenthesis, Sum RCR was calculated for all elements except Hg, P and S, see also Table 8

[4] Based upon sum of the 3 ranking methods

[5] Mean I_{geo} values classified in Class 2 or higher are included, values in Class 3 or higher in bold

[6] Mean *Er* values higher than Class 2 are included, values in bold are Class 3 or higher, see Table 7

[7] mean RCR>2 in bold

[8] for one sampling site (B4) the RCR is above 1

[9] n.a. - not applicable, soil is used in calculation of I_{geo} and RI

Conclusions

There is an urgent need to update the list of trace elements that are routinely monitored in sediment in stormwater ponds when evaluating ecological risk, especially in ponds with catchments in areas of industrial land use. The ponds in this study were mainly constructed to protect downstream areas from flooding during high flows and therefore have low hydraulic efficiency. Accordingly, some trace elements that bind to finer particles that did not sediment in the ponds might therefore flow into the river downstream. Currently, there is no information about background concentrations nor the degree of pollution of Ag and Sb in the downstream catchment nor in other catchments in the region of study. Therefore, the development of a program for monitoring numerous trace elements – significantly more than what is currently monitored - is essential. Identifying the sources of the high accumulation of Ag and Sb found in this study is another priority. Finally, we showed that the use and comparison of different assessment methods including multivariate analyses when evaluating ecological risk of

stormwater pond sediment is valuable as it highlighted different aspects of risk. For example, information from the geoaccumulation index combined with the multivariate analyses clearly demonstrated that Co, Ni and V were not accumulating and therefore their risk as identified by the RCR-method was overestimated. On the other hand, for Ag, RCRs are below 1 also in the most contaminated pond B while the geoaccumulation index and RI indicates high accumulation and high risk, triggering the need for additional studies.

Declarations

Ethics approval and consent to participate: Not applicable

Consent for publication: Not applicable

Availability of data and materials: All data generated or analysed during this study are included in this published article and its supplementary information files.

Competing interests: The authors declare that they have no competing interests.

Funding: This study was financially supported by the Municipality of Ängelholm.

Authors' contributions: Sylvia Waara: conceptualization, methodology, investigation, analysis and writing, Frida Johansson: writing, investigation and analysis. Both authors read and approved the final manuscript.

References

Aksu A, Yasar D, Uslu O (1998) Assessment of marine pollution in Izmir Bay: Heavy Metal and Organic Compound Concentrations in Surficial Sediments. Turkish Journal of Engineering and Environmental Sciences 22:387-415.

Allen D, Haynes H, Arthur S (2017) Contamination of detained sediment in sustainable urban drainage systems. Water 9:355. https://doi.org/10.3390/w9050355.

Anderson BC, Bell T, Hodson P, Marsalek J, Watt WE (2004) Accumulation of trace metals in freshwater invertebrates in stormwater management facilities. Water Qual Res Canada 39:362-373.

Baekken T (1994) Effects of highway pollutants on a small Norwegian lake. Sci Total Environ 146/147:131 – 139.

Blecken G-T, Rentz R, Malmgren C, Öhlander B, Viklander M (2012) Stormwater impact on urban waterways in cold climate: variations in sediment metal concentrations due to untreated snowmelt discharge. J Soil Sediments 12:758-773.

Blecken G, Al-Rubaei A, Viklander M, Marsalek J (2017) 25 municipal stormwater management ponds in Sweden – survey of the operational status. Bromma: Svenskt Vatten (In Swedish).

Casey RE, Simon JA, Atueyi S, Snodgrass JW, Karouna-Renier N, Sparling DW (2006) Temporal trends of trace metals in sediment and invertebrates from stormwater management ponds. Water Air Soil Pollut 178:69-77.

CIS (2011) Technical Guidance for Deriving Environmental Quality Standards, Technical report 2011-055. Common Implementation Strategy for the Water Framework Directive (2000/60/EC).

Crane JL (2019) Distribution, toxic potential, and influence of land use on conventional and emerging contaminants in urban stormwater pond sediments. Arch Environ Contam Toxicol 76:265-294.

Crommentuijn T, Sijm D, de Bruijn, J, van den Hoop M, van Leeuwen K, van de Plassche, E (2000) Maximum permissible and negligible concentrations for metals and metalloids in the Netherlands, taking into account background concentrations. J Environ Manage 60:121-143.

Duodu GO, Goonetilleke A, Ayoko GA (2016) Comparison of pollution indices for the assessment of heavy metal in Brisbane River sediment. Environ Pollut 2019:1077–1091.

577 ECHA (2016) Guidance on Information Requirements and Chemical Safety Assessment Part E: Risk
578 Characterisation. Version 3.0. May 2016, ISBN 978-92-9495-055-0.

579 Egemose S, Sønderup MJ, Grudinina A, Hansen AS, Flindt MR (2015) Heavy metal composition in
580 stormwater and retention in ponds dependent on pond age, design and catchment type. Environ
581 Technol 36:959-969.

582 European Chemicals Bureau (2003) Technical Guidance Document on Risk Assessment. Part II.
583 Environmental Risk Assessment.

584 Frost PC, Song K, Buttle JM, Marsalek J, McDonald A, Xenopoulos MA (2015) Urban biogeochemistry
585 of trace elements: What can the sediments of stormwater tell us? Urban Ecosyst 18:763-775.

586 Färm C, Johansson D, Kadic Z, Waara S (2003) Characterisation of sediment from storm water tunnels.
587 In: Tiezzi E, Brebbia CA, Usó J-L. (eds) Ecosystem and Sustainable Development, vol 2:1253-1262, WIT
588 Press, Transactions on Ecology and the Environment.

589 Färm C, Waara S (2005) Treatment of stormwater using a detention pond and constructed filters.
590 Urban Water J 2:51-58.

591 HVMFS2019:25. Classification and environmental quality standards for surface water (In Swedish).
592 Swedish Agency for Marine and Water Management.

593 Håkanson L (1980) An ecological risk index for aquatic pollution control: a sedimentological approach.
594 Water Res 14:975-1001.

595 Istenič D, Arias CA, Vollertsen J, Nielsen AH, Wium-Anderson T, Hvitved-Jacobsen T, Brix H (2012)
596 Improved urban stormwater treatment and pollution removal pathways in amended wet detention
597 ponds. J Environ Sci Health A, 47:1466-1477.

598 James E, Turner A (2020) Mobilisation of antimony from microplastics added to coastal sediment.
599 Environ Pollut 264, https://doi.org/10.1016/j.envpol.2020.114696

600 Jang Y-C, Jain P, Tolaymat T, Dubey B, Singh S, Townsend T (2010) Characterization of roadway
601 stormwater system residuals for reuse and disposal options. Sci Total Environ 408:1878-1887.

602 Jefferson AJ, Bhaskar AS, Hopkins KG, Fanelli R, Avellaneda PM, McMillan SK (2017) Stormwater
603 management network effectiveness and implications for urban watershed function: A critical review.
604 Hydrological Processes 31:4056-4080.

605 Jiao F, Ren L, Wang X, Liu W (2017) Pollution characteristics and potential ecological risk assessment
606 of metals in the sediments of Xiaoqing River, Jinan Environ Sci Pollut Res 24:15001–15011.

607 Li W, Lin S, Wang W, Huang Z, Zeng H, Chen X, Zeng, F, Fan, Z. (2020) Assessment of nutrient and heavy
608 metal contamination in surface sediments of the Xiashan stream, eastern Guangdong Province, China.
609 Environ. Sci. Pollut. Res. 27:25908–25924.

610 Maltby L, Forrow DM, Boxall ABA, Calow P, Betton C (1995) The effects of motorway runoff on
611 freshwater ecosystems: 1. Field study. Environ Toxicol Chem 14:1079 – 1092.

612 Manoj K, Padhy PK (2014) Distribution, Enrichment and Ecological Risk Assessment of Six Elements in
613 Bed Sediments of a Tropical River, Chottanagpur Plateau: A Spatial and Temporal Appraisal. J Environ
614 Prot 5:1419-1434.

615 Marsalek J, Urbonas B, Lawrence I (2005) Stormwater management ponds. In: Shilton A (Ed) Pond
616 treatment technology, IWA Publishing, London pp 433-459.

617 McGillicuddy E, Murray I, Kavanagh S, Morrison L, Fogarty A, Cormican M, Dockery P, Prendergast M,
618 Rowan N, Morris D (2017) Silver nanoparticles in the environment: Sources, detection and
619 ecotoxicology. Sci Total Environ 575:231-246.

620 Ministry of Environment and Food of Denmark. 2017. Bekendtgørelse af lov om vandplanlægning. LBK
621 nr 126 af 26/01/2017. https://www.retsinformation.dk/Forms/R0710.aspx?id=196701

622 Müller G (1969) Index of geoaccumulation in the sediments of the Rhine River. Geojournal 2:108-118.

623 Müller A, Österlund H, Marsalek J, Viklander M. (2020) The pollution conveyed by urban runoff: A
624 review of sources. Sci Total Environ 709, https://doi.org/10.1016/j.scitotenv.2019.136125.

625 Nika MC, Ntaiou K, Elytis K, Thomaidi VS, Gatidou G, Kalantzi OI, Thomaidis NS, Stasinakis AS (2020)
626 Wide-scope target analysis of emerging contaminants in landfill leachates and risk assessment using
627 Risk Quotient methodology. J of Hazard Mater 394, https://doi.org/10.1016/j.jhazmat.2020.122493.

628 Sharley DJ. Sharp MS, Bourgues S, Pettigrove VJ (2016) Detecting long-term temporal trends in
629 sediment-bound trace metals from urbanised catchments. Environ Pollut 2019:705-713.

630 Sharley JD, Sharp MS, Marshall S, Jeppe M, Pettigrove JV (2017) Linking urban land use to pollutants in
631 constructed wetlands: Implications for stormwater and urban planning. Landscape and Urban Planning
632 162:80-91.

633 Stephansen DA, Nielsen AH, Hvitved-Jacobsen T, Arias CA, Brix H, Vollertsen J (2014) Distribution of
634 metals in fauna, flora and sediments of wet detention ponds and natural shallow lakes. Ecol Eng 66:43–
635 51.

636 Sun Z, Sokolova E, Brittain JE, Saltveit SJ, Rauch S, Meland S (2019) Impact of environmental factors on
637 aquatic biodiversity on roadside ponds. Scientific Reports 9:5994.

638 Søberg LC, Vollertsen J, Blecken GT, Haaning Nielsen A, Viklander M (2016) Bioaccumulation of heavy
639 metals in two wet retention ponds. Urban Water J 13:697-709.

640 Swedish Meteorological Institute (SMHI) 2021.
641 https://www.smhi.se/data/meteorologi/kartor/karta/foregaende-ar/nederbord/

642 Swedish Environmental Protection Agency (2009) Guideline values for contaminated soil. Model
643 description and guidelines. (In Swedish) Report 5976.

644 Swedish Environmental protection Agency (2016). Updated list of guideline values. (In Swedish)
645 https://www.naturvardsverket.se/upload/stod-i-miljoarbetet/vagledning/fororenade-
646 omraden/berakning-riktvarden/generella-riktvarden-20160707.pdf

647 Viczek SA, Aldrian A, Pomberger R, Sarc R (2020) Origins and carriers of Sb, As, Cd, Cl, Cr, Co, Pb, Hg,
648 and Ni in mixed solid waste – A literature-based evaluation. Waste Manage 103:87-112.

649 Wang J-Z, Peng S-Ch, Chen T-H, Zhang L (2016) Occurrence, source identification and ecological risk
650 evaluation of metal elements in surface sediment: toward a comprehensive understanding of heavy
651 metal pollution in Chaohu Lake, Eastern China. Environ Sci Pollut Res 23:307-314.

652 Wang N, Wang A, Kong L, He M (2018) Calculation and application of Sb toxicity coefficient for potential
653 ecological risk assessment. Sci Total Environ 610-611:167-174.

654 Wei L, Cai M, Du Y, Tang J, Wu Q, Xiao T, Luo D, Huang X, Liu Y, Fei Y, Chen Y. (2019) Spatial Attenuation
655 of Mining/Smelting-Derived Metal Pollution in Sediments from Tributaries of the Upper Han River,
656 China. Mine Water Environ 38:410–420.

657 Yang J, Wang, W, Zhao M, Chen B, Dada OA, Chu Z (2015) Spatial distribution and historical trends of
658 heavy metals in the sediments of petroleum producing regions of the Beibu Gulf, China. Mar Pollut
659 Bull 91:87-95.

660 Zhang H, Jiang Y, Ding M, Xie Z (2017) Level, source identification, and risk analysis of heavy metal in
661 surface sediments from river-lake ecosystems in the Poyang Lake, China. Environ Sci Pollut Res
662 24:21902–21916.

663 Zhou S, Di Paolo C, Wu X, Shao Y, Seiler TB, Hollert H (2019) Optimization of screening-level risk
664 assessment and priority selection of emerging pollutants – The case of pharmaceuticals in European
665 surface waters. Environ Int 128:1-10.

666 Zhu X, Ji H, Chen Y, Qiao M, Tang L (2013) Assessment and sources of heavy metals in surface sediments
667 of Miyun Resorvoir, Beijing. Environ Monit Assess 185:6049-6062.

668 Zubala T, Patro M, Boguta P (2018) Variability of zinc, copper and lead contents in sludge of the
669 municipal stormwater treatment plant. Environ Sci Pollut Res 24:17145–17152.

Figures

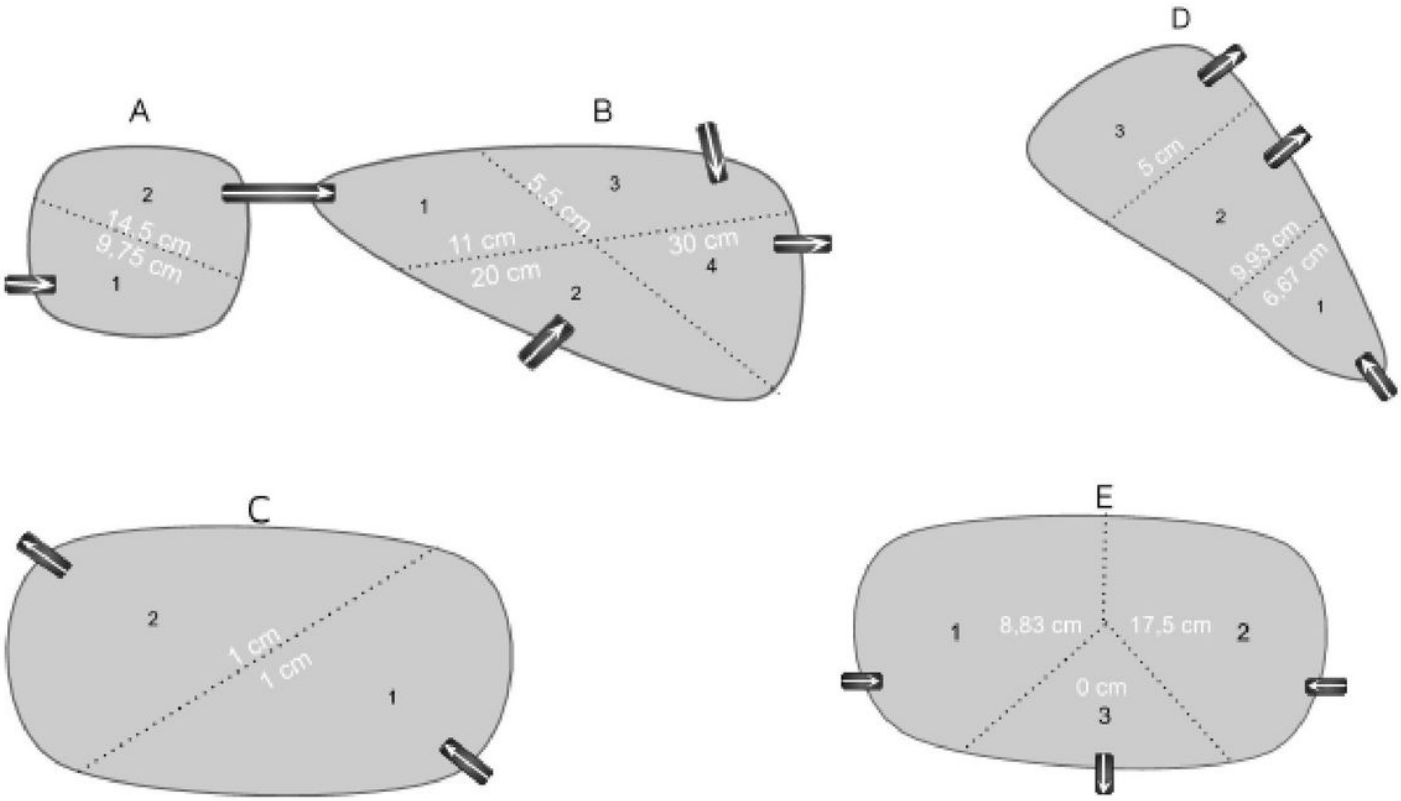


Figure 1

Design of the ponds and the measured thickness of sediment

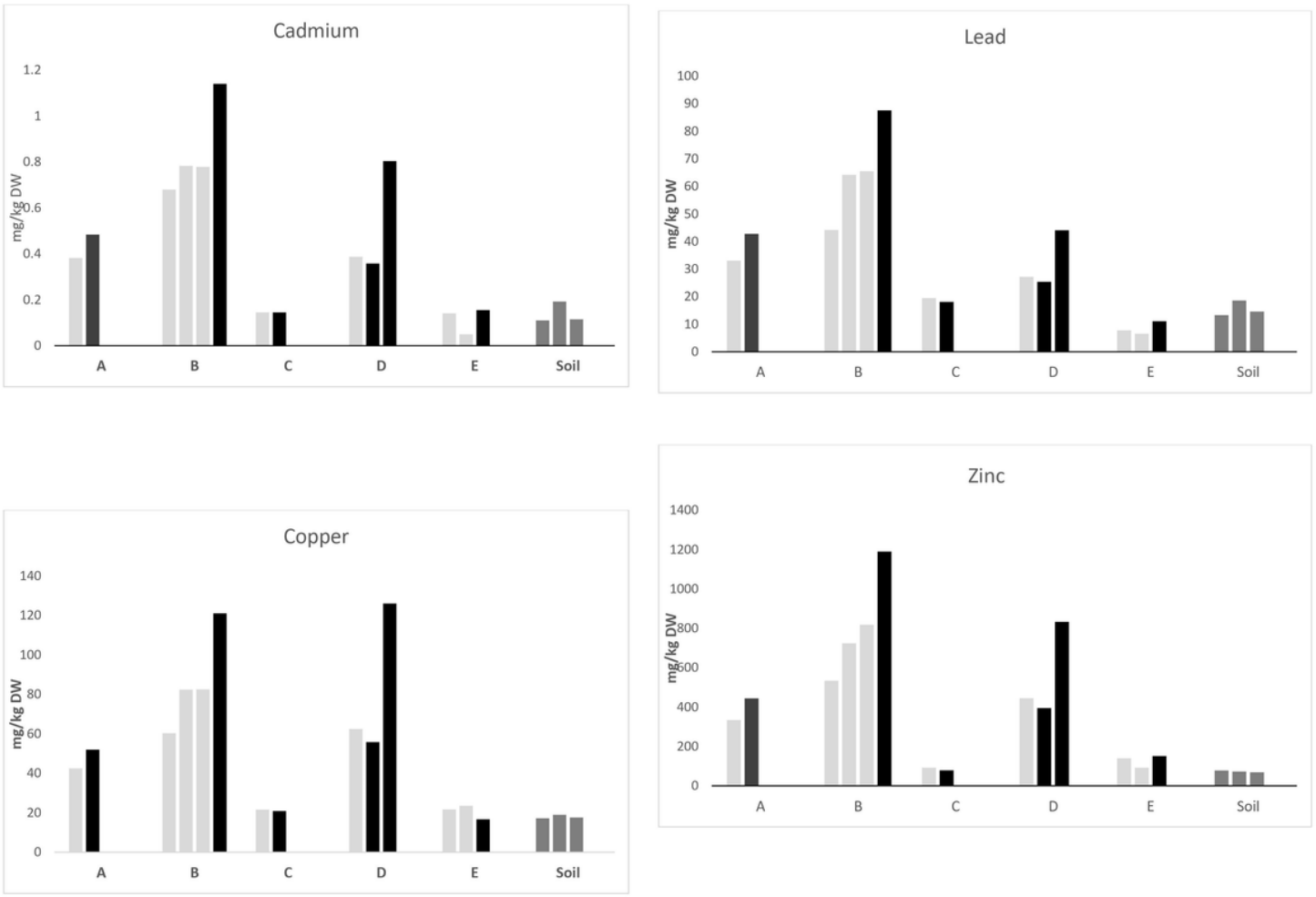


Figure 2

Concentrations of four commonly-monitored trace elements (Cd, Co, Pb, Zn) in sediments in stormwater ponds and soil from the banks of the ponds in areas with industrial activity. Light grey bars – inlets, black bars-outlets.

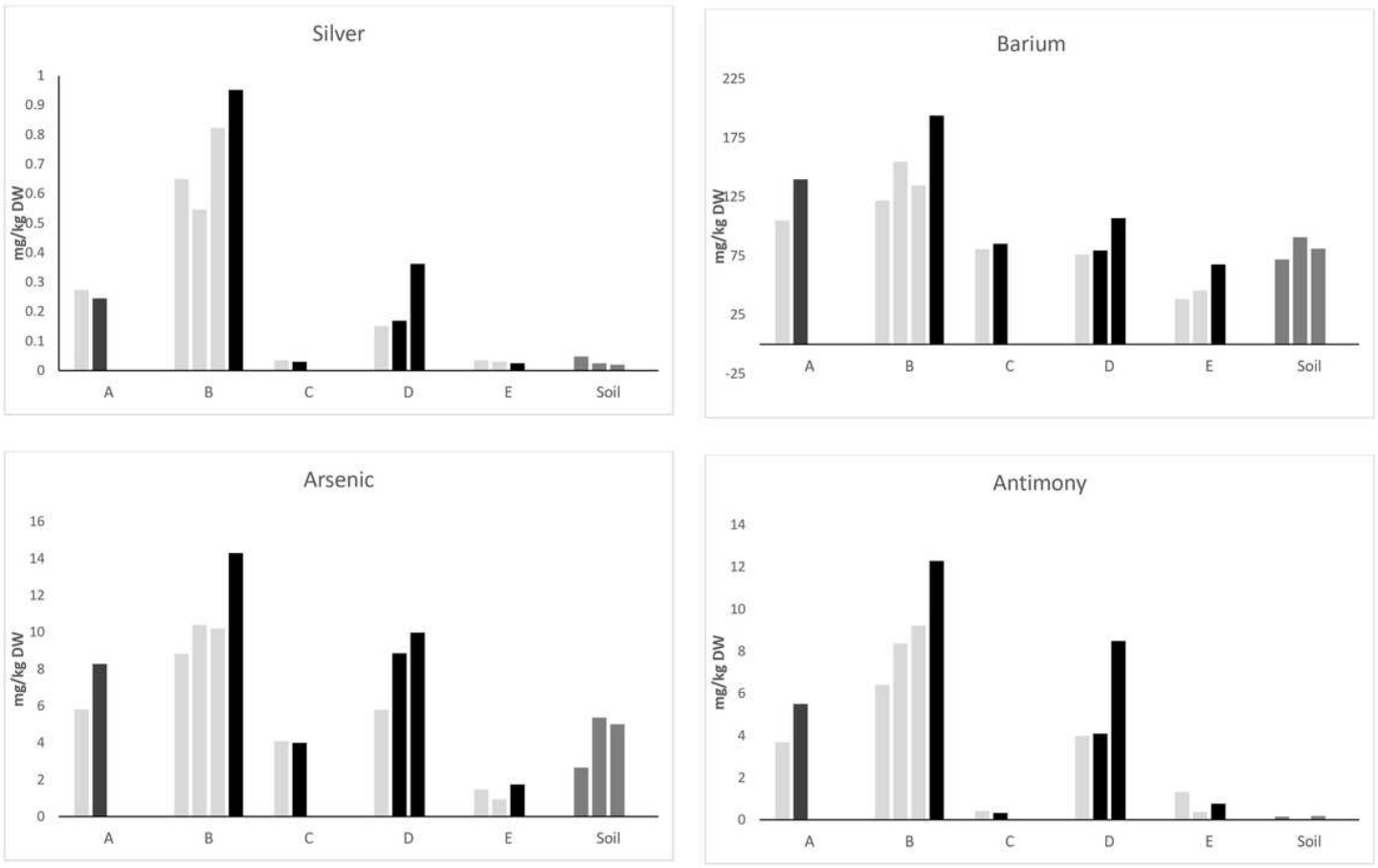


Figure 3

Concentrations of four seldom monitored trace elements (Ag, As, Ba, Sb) in sediment in stormwater ponds and soil from the banks of the ponds in areas with industrial activity. Light grey bars – inlets, black bars-outlets

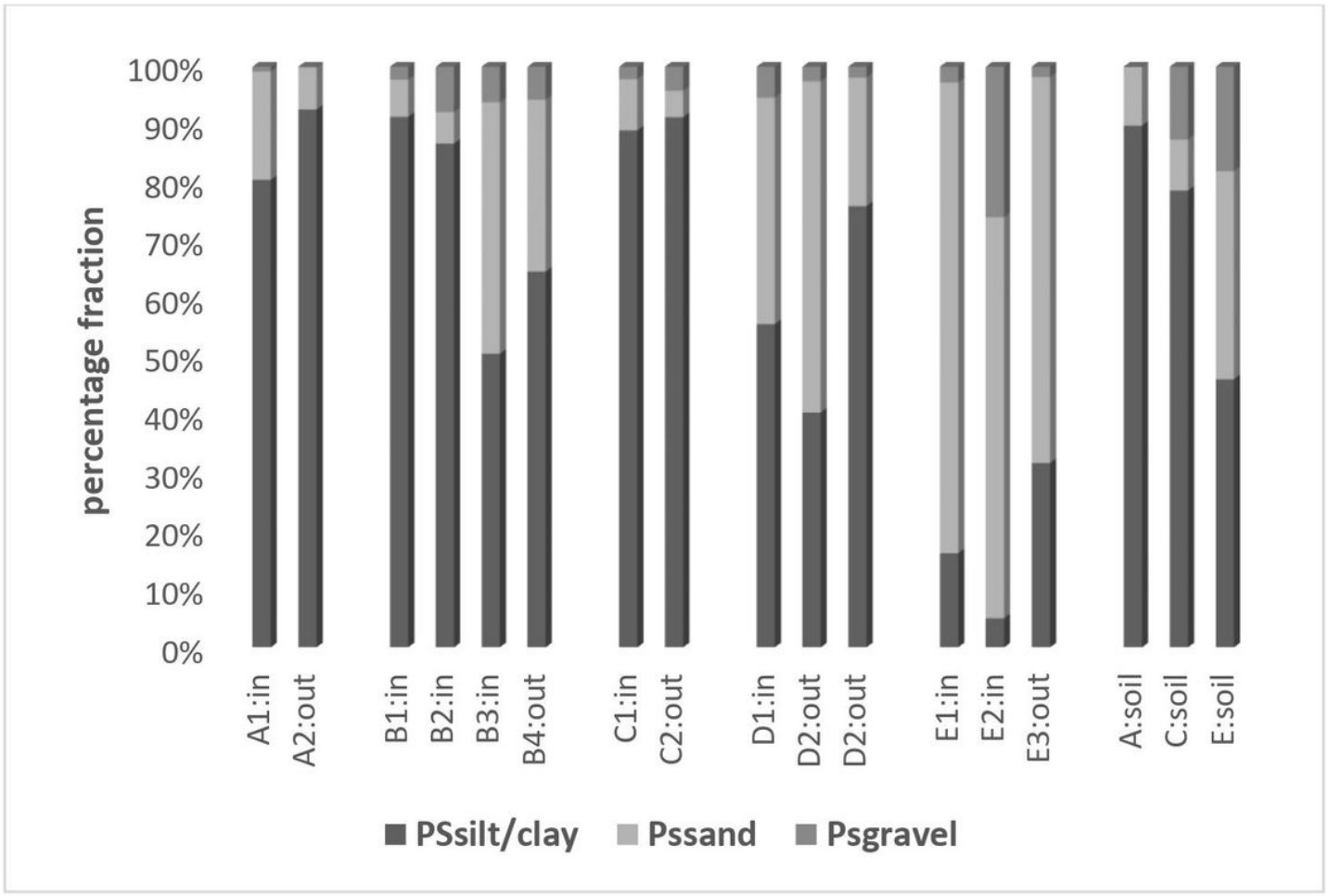


Figure 4

Particle size distribution of the sediment in the different sampling sites in five stormwater ponds. Particle size (PS) for PSsilt/clay < 0.063 mm, PS sand 0.063- 2mm and PS gravel > 2mm

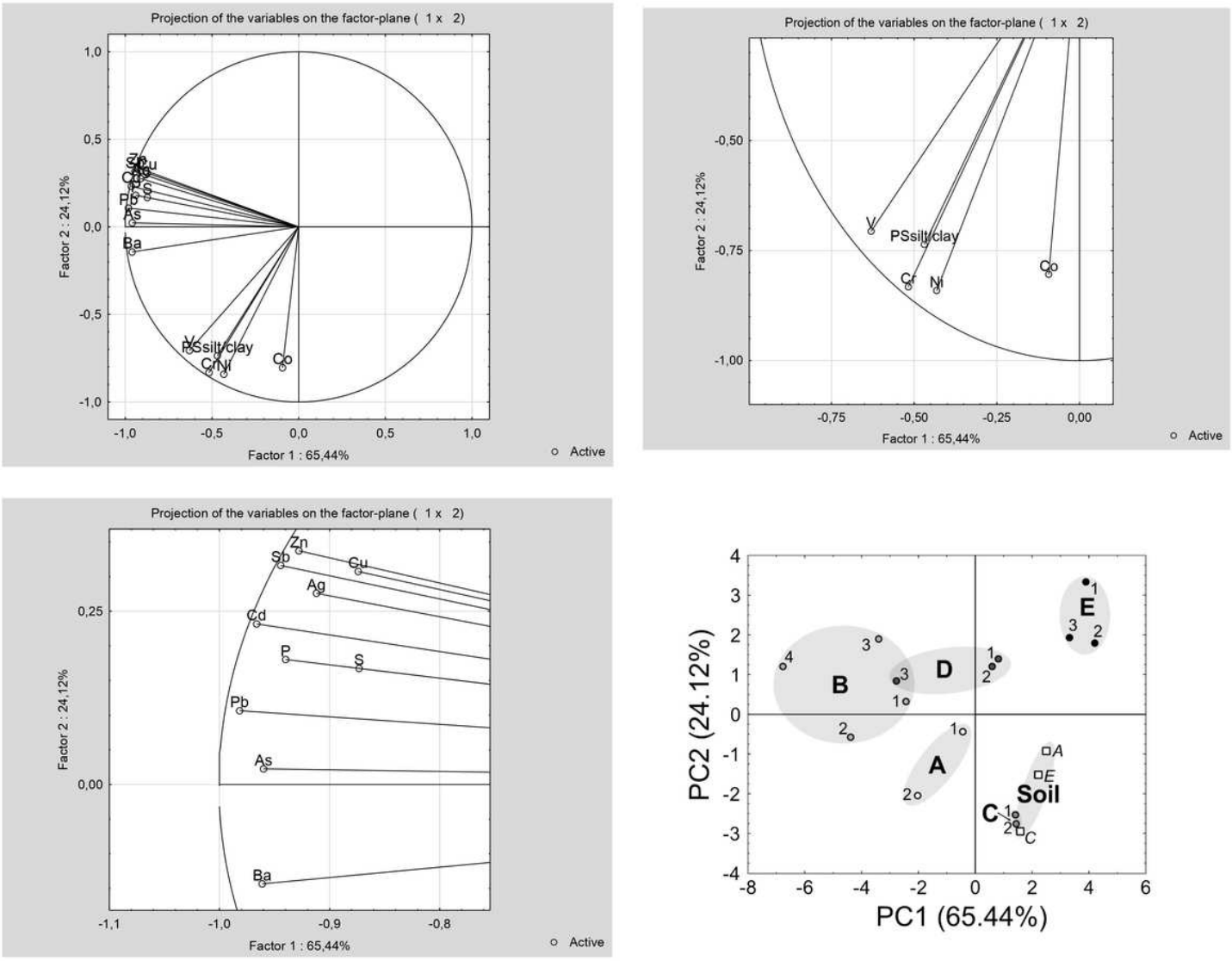


Figure 5

a) Projection of the variables on PC 1 and PC2. b) Enlarged section of PCA with Group A elements c) Enlarged section of PCA with Group B elements and PSsilt/clay d) Projection of the samples on PC1 and PC2

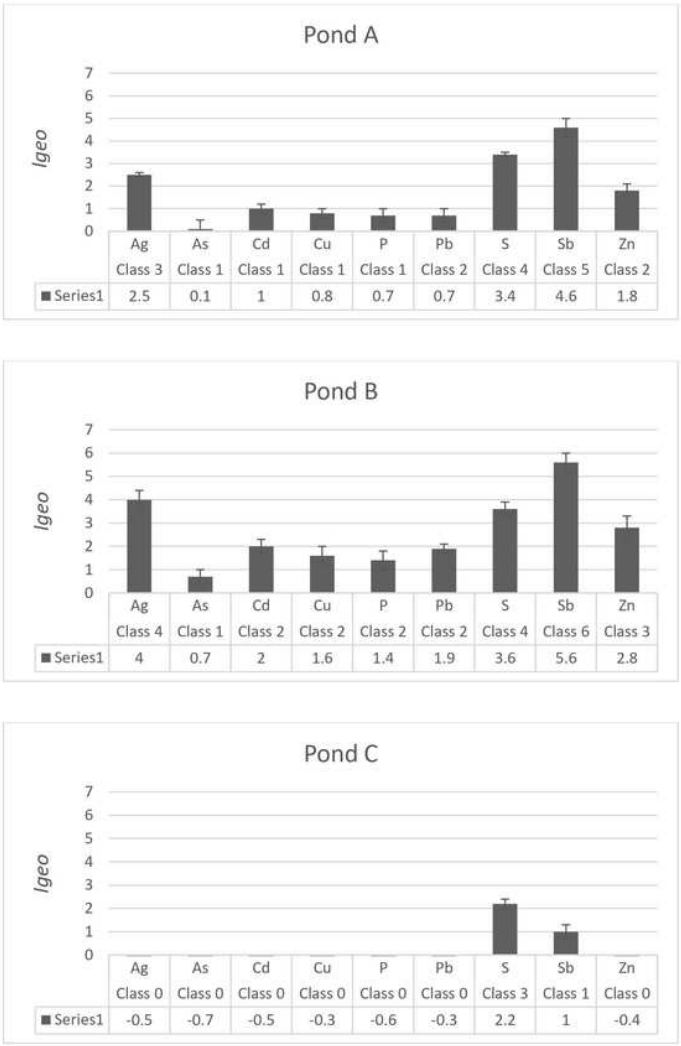


Figure 6

Contamination degree for trace elements in the different ponds using the geoaccumulation index Igeo. Classification was made using mean values, and error bars present standard deviation

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- suppltablesdagdammsubmitted.docx