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Monitoring, sizing and removal efficiency in stormwater ponds

ABSTRACT

Retention ponds and wetlands are frequently used in stormwater management to remove pollutants, reduce flow peaks and improve scenic views in parks and along roads. This study analyzes the correlation between long-term removal efficiency of pollutants (total suspended solids and heavy metals) and specific pond area (ratio between effective drainage area and surface area). For this purpose, all data on ponds in Sweden that have been monitored were collected and evaluated. The results show that of 27 measured ponds only nine had monitoring programs that were correctly designed to reveal anything about pollutant removal; this is because grab samples had been used to a large extent. There was no possibility to establish a correlation between specific pond area and long-term removal efficiency, even when the pond area was adjusted with regard to the amount of dead zones. This constitutes a "negative" research finding, but an important one since it indicates that other factors ought to be included when retention ponds are to be sized and designed, such as concentration of pollutants and vegetation.

Keyword: urban drainage, pond, wetland, specific pond area, efficiency, Sweden, heavy metals.

ABSTRACT (in Swedish)

Idag används allt oftare dammar för att ta hand om dagvatten. Dessa typer av dammar, eller våtmarker, renar vatten genom att suspenderat material och tungmetaller sedimenterar, men kan också utjämna flöde, se vackra ut och förbättra den biologiska mångfalden. I den här studien analyseras kopplingen mellan reningsgrad och specifik dammyta, dvs kvoten mellan avrinningsområdets hårdgjorda yta och dammyta. I studien samlades all tillgänglig provtagningsdata in som gjorts i Sverige. Inventeringen visade att bara nio av 27 provtagningar var korrekt utförda för att säga något om dammens reningsgrad. Detta berodde på att stickprovsmetodik ofta använts. Resultatet visar förvånade nog att det inte går att hitta ett samband mellan reningsgrad och specifik dammyta, detta även om den specifika ytan korrigerats genom att dammens dödzoner tagits bort. Trots att ett samband saknas är resultatet betydelsefullt då det pekar på att andra faktorer spelar en betydande roll för reningen, såsom vegetation eller föroreningsbelastning. Slutsatsen är därför att provtagningar behöver göras mer noggrant och att dagvattendammar inte bör utformas enbart utifrån specifik dammyta.

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1. INTRODUCTION

During the last decades there has been an increasing interest in using retention ponds (wet ponds) and wetlands in stormwater management. In Sweden, among other countries, ponds were originally used to reduce flow peaks but are nowadays also used as a measure to improve water quality and to add ecological value, as well as improving the scenic views in parks and along roads and highways. From an engineering perspective, however, detention and water quality are in focus. With these objectives, there are three aspects to consider when sizing and/or designing a stormwater pond. The first is to decide whether there should be a bypass, regulating how much water is to enter the pond. The second is to decide how much water is to be detained from a storm event in order to reduce flooding downstream. This can be regulated through detention volume, outlet configuration and emptying rate. The third aspect is to decide how much of the pollutants is to be removed [1, 2]. It is interesting to note that there is a contradiction between the last two aspects. Maximum performance of pollutant removal is obtained by maximizing the amount of permanent pool, to minimize the detention capacity. To obtain a maximum effect regarding detention is to do the opposite, i.e. to minimize the amount of permanent pool.

Many models that describe removal efficiency are presently based on Hazen's surface load theory. This theory states that the amount of particles which settle is a function of settling velocity, surface area, inflow and amount of turbulence. It is therefore not surprising that some guidelines for how to size retention ponds are based on the ratio between effective drainage area and surface area, i.e. the specific pond area, e.g. [3, 4]. Other approaches to size stormwater ponds are to use the ratio between mean runoff volume and pond volume [5, 6] or a mean residence time approach [7, 8]. However, these different approaches also relate to factors such as drainage area and pond size. In the first case, runoff volume is related to effective drainage area, and pond volume is related to surface area. In the second case, residence time is determined by inflow (precipitation and effective drainage area) and pond volume (or pond area, since most ponds have water depths between 0.5 and 2 m). Hence, the conclusion is that effective drainage area and surface area ought to be factors that determine pollutant removal ratios. But there is no unified opinion on how to size or design these ponds in order to efficiently remove TSS and heavy metals. As an example, some authors emphasize factors such as concentration of pollutants, vegetation, climate, hydraulics, and biological processes [9, 10].

The aim of this article is to evaluate how important the specific pond area is for long-term removal efficiency. In order to cast light on this research area, a limited study was initiated to collect and analyze all monitoring programs that have been carried out in Sweden on retention ponds [11]. The idea was to obtain a comprehensive picture by collecting results from conducted surveillances. In this work, of course, there was no possibility to influence which parameters had been measured, or to carry out new measurements.

2. METHODOLOGY

2.1. Collecting results from conducted surveillances

In the procedure of collecting results from conducted surveillances on pollution removal efficiency of retention ponds in Sweden, two previously executed pond inventories were used, one published [12] and one unpublished. Moreover, six regional road administrations and 14 municipalities were interviewed for further monitoring data, in addition to a scanning of Swedish national libraries for reports and theses with monitoring data of retention ponds.

The studied systems may be categorized as wetlands or ponds depending on which definition one chooses. But all ponds/wetlands included are constructed to detain and improve stormwater quality, have a mean depth between 1 and 2 m, with a surface area of 100–20,000 m^2, and have fringing vegetation. A restriction in this study was that the ponds investigated should have only gravitationally driven inflows and outflows, and therefore ponds with pumping systems were excluded. Stormwater treatment constructions like ditches were excluded as well. It was quickly discovered that the amount of data found in the majority of the surveillance reports was principally insufficient to allow meaningful comparison between sites. There were often no data on precipitation, description of catchment areas or water quality etc. Also data on the pond characteristics such as water depth, vegetation density and hydraulic efficiency (effective volume ratio, residence time distributions etc.) were seldom mentioned in the reports. Consequently, sufficient pond performance parameters were not available without starting new field measurements on the investigated ponds. The result was therefore that the only reasonable relationship left to analyze was that between the pollutant removal of TSS and heavy metals and the specific pond area.

2.2 To measure pollutant removal efficiency

The pond surveillance reports included descriptions of stormwater pollutant removal efficiency, but since many of the surveillances were based only on grab sample procedures, i.e. comparing single instantaneous pollutant concentration samples from the inlet and outlet (equation 1), the quality of these results were too low to be used in this study. Grab sampling methods may be sufficient for investigating pollutant removal efficiencies in systems with more stable flow conditions and smaller variations in pollutant concentrations, e.g. the situation in a wastewater treatment plant, but not for retention ponds due to the intermittent flow and pollutant concentration fluctuations during storm events. Pollutant removal efficiency has to be determined through mass balance methods comparing pollutant masses between in- and outflow (equation 2).

$$R = 100 \ (C_{in} - C_{out}) \ / \ C_{in} \quad (\%) \tag{1}$$

$$R = 100 \ (M_{in} - M_{out}) \ / \ M_{in} \quad (\%) \tag{2}$$

R = Removal efficiency
C = Concentration (in and out)
M = Mass (in and out)

If the pond volume is large in relation to the average inflow stormwater volumes (during rain events), much of the latter will remain in the pond during dry weather periods until a subsequent rain event displaces this water from the pond. Studies have

shown that 90 % of the removal takes place during dry weather periods, and very little is removed during the actual storm events [4]. The complex and fluctuating nature of rain depths and intensities and the lengths of dry weather periods result in a large variation of pollutant removal efficiencies when different storm events are studied. The removal efficiency also varies with the time of year, mainly due to variations in biological activities and rain frequencies. Therefore, long-term pollutant removal efficiency has to be determined through mass balance calculations for a series of consecutive storm events rather than from a single storm event [3, 4], since the removal efficiency varies significantly between different events; see Figure (1**)**. The longer the measurements, the more accurate is the estimation of removal efficiency.
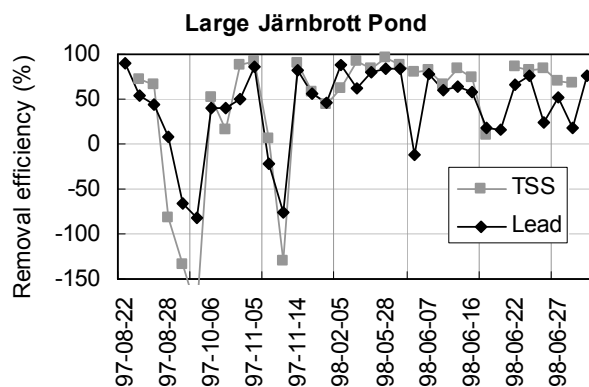

Figure **1** Variations of removal efficiency for the stormwater pond Järnbrott, Göteborg, based on the mass balance approach for single storm events [4]

2.3 Adjusted specific pond area

In order to investigate whether poor pond hydraulics had any effect on the correlation between pollutant removal and specific pond area, each pond area was adjusted according to the amount of dead zones within the pond. It is well known that pond design affects hydraulic conditions, e.g. that ponds with high length-to-width ratios receive higher residence time [13-15], but also that hydraulics affects the pollutant removal efficiency [16-18], since turbulence and low effective volume (i.e. amount of dead zones) reduce the removal capacity. This has also put forward by Hazen [19] in his surface load theory (equation 3). Here, the turbulence parameter, n, represents a number of hypothetical basins in series, so that a high value of n represents a low turbulence condition and a low n-value the opposite. It should be noted that this value of turbulence is equivalent to the N-parameter in the tank-in series model that is used to calculate removal of BOD or nitrogen [20]. In both models the n or N parameter represents turbulent conditions, where a value of 1 is given for very poor conditions, 3 for good conditions, and 8 for very good conditions – i.e. turbulence has a negative effect on the removal efficiency. Thomas and Archibald [21] suggested that n can be calculated by $t_{mean}/(t_{mean} - t_p)$, where t_{mean} is the mean residence time and t_p is the peak time in an RTD function described in Figure (2). It can also be added that Fair and Geyer [19:596] wrote that turbulence may contribute to short-circuiting of flow, and since this is often the case, some researchers understand the n-parameter as a representation of short-circuiting [22].

$$R = 1 - \left(1 + \frac{1}{n}\frac{v_0}{Q/A}\right)^{-n} \tag{3}$$

where

R = proportion of particles removed having this settling velocity
v_0 = settling velocity
Q = wet pond discharge
A = wet pond surface area
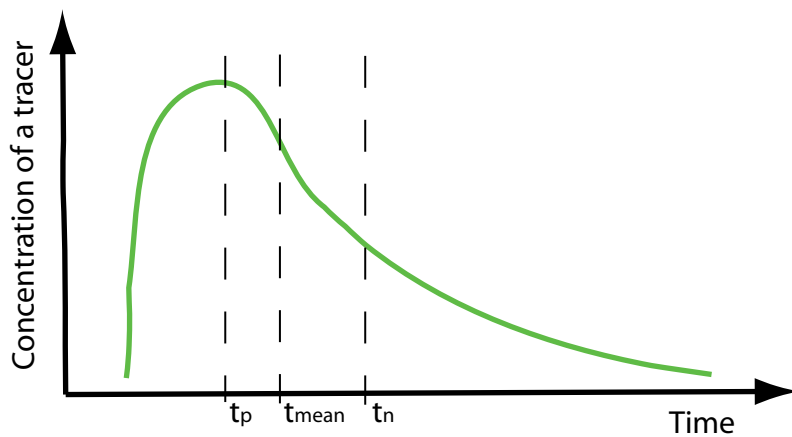n = number of hypothetical basins in series

Figure **2**. A residence time distribution (RTD) from a typical tracer experiment. Common parameters are mean residence time t_{mean}, peak time t_p, and nominal residence time t_n.

In order to take poor hydraulic performance into consideration, each pond area included in the investigation was adjusted so that the resulting pond area better matched the effective area. This was made through Thackston's [13] equation, which defines effective volume ratio (ratio between mean residence time and nominal residence time) as equal to the ratio between effective pond volume and total pond volume (equation 4). Similarly, the effective area can be calculated by assuming the same relationship and an approximately constant depth [23]. Each specific pond area was then reduced according to its effective volume ratio; i.e. a pond with a specific pond area of 100 m^2 ha^{-1}, and with 70 % effective volume ratio, implies an effective specific pond area of 70 m^2 ha^{-1}.

$$e = \frac{t_{mean}}{t_n} = \frac{V_{effective}}{V_{total}} \tag{4}$$

e = effective volume ratio
V = pond volume
t_{mean} = mean residence time
t_n = nominal residence time (i.e. pond volume/mean flow)

However, the monitoring programs did not provide much information on pond hydraulics or characteristics such as data on effective volume ratio, flow pattern, pond topography, residence times and pond volume. The exceptions were Stora

Järnbrottsdammen, where a tracer study had been carried out; and in *Krubban* and *Bäckaslöv* where Computational Fluid Dynamics modelling was undertaken to determine the residence time distributions. For the remaining ponds, the effective volume ratio had to be calculated according to equation (5) [13]. This equation relates the effective volume ratio to pond length (L) and width (W), which must be regarded as a rather rough calculation, since it does not consider factors such as water velocity, vegetation or layout that otherwise are considered to have an effect on the hydraulics. In one case *(Eriksmåla)* the effective volume ratio was roughly estimated since it consisted not of one pond, but of one pond followed by two parallel ponds. The resulting effective volume ratios are seen in Table (3).

$$e = 0.84\left[1 - e^{(-0.59L/W)}\right] \tag{5}$$

3. MONITORING PROGRAMS AND LONG-TERM REMOVAL EFFICIENCY

The literature and interview inventory that were carried out resulted in 51 monitored ponds. Of these reports, 24 included only sediment field measurements whereas 27 included water quality field measurements. Of the latter ponds, sixteen were measured through grab sampling procedures with no automatic sampling or measuring equipment, and in two the removal efficiency was measured during a single rain event only (although with mass balance approach). A more correct measurement strategy – mass balance approach including automatic samplers and flow meters – to determine the pollutant removal efficiency was thus used in only nine ponds. This means that defective or inaccurate monitoring programs were used in 18 of the 27 cases. Among the remaining 9 ponds one was excluded due to long series of missing data.

Interestingly, of the 27 ponds, 13 did not include any flow measurements at all, or had the flow estimated 'by eye'. This makes it impossible to calculate any pollutant masses entering or leaving the pond, and thus also impossible to estimate any pollutant removal efficiency of these ponds. It may be added that grab samples sometimes are an appropriate method in an urban drainage context, e.g. to investigate water toxicity. However, that was not the case among the ponds included in this study, since they all had monitoring programs that were designed to estimate prevailing removal efficiencies. For the remaining eight ponds with accurate flow measurement, the flow was measured either by velocity-height (v-h) probes, V-notch weirs or Parshall flumes (water level), by helix current meter or by hydrological or hydraulic computer simulations.

The eight ponds that were selected for further analysis are listed in Table (1). The pond *Krubban* consists of three ponds in series and, with three samplers and flow meters installed, it then provides two different pond setups: one small pond (pond 1) and one large pond (pond 1+2+3) [4]. The monitoring period and number of monitored rain events are shown in Table (2). In Table (3) the long-term removal efficiency for total suspended solids (TSS), zinc (Zn), lead (Pb), cadmium (Cd) and copper (Cu) is presented for the eight ponds. In Figure (3) the long-term removal efficiency has been plotted as a function of specific pond area (m^2/ha).

Table **1**. Size and number of ponds, impervious catchment area, and the specific pond area

Pond	Number of ponds in series	Pond area A_d [m^2]	Impervious catchment area φA [ha]	Specific pond area A_d/φA [m^2 ha^{-1}]
Kolardammen	2	15 000[1)]	208[1)]	72
Large Järnbrott pond	1	6 200	123[2)]	40[2)]
Small Järnbrott pond	1	530	2.6	204
Krubban (1)	1	4 100	17	241
Krubban (1+2+3)	3	11 800	17	694
Bäckaslöv	1	18 000	140	120
Välenviken	1	2 000	60	33
Eriksmåla	3	160	1.0	160
Vallby	1	200	4.3	46

[1)] According to personal communication with Thomas Lagerwall, 11 November 2005.
[2) [4]].

Table **2** eriod of monitoring, number of rain events measured, and data sources

Pond	Number of rain events	Period of monitoring	Reference
Kolardammen	-	April – October 2002	[24]
Large Järnbrott Pond	65	July 1997 – June 1998	[25]
Small Järnbrott Pond	20[3)]	July 1995 – June 1996	[26]
Krubban (1)	13	May 1998 – July 1998	[25]
Krubban (1+2+3)	6	May 1998 – July 1998	[25]
Bäckaslöv	-	June – November 1997	[27]
Välenviken	6	11 June – 23 June 2004	[28]
Eriksmåla	15 [4)]	June 2000 – September 2001	[29]
Vallby	15	1999 – 2000	[30]

[3)] Metals were measured in ten rain events.
[4)] Number of events when the sampler was emptied.

Table **3**. Pollutant removal efficiency for the eight ponds and effective volume ratio, e (%)

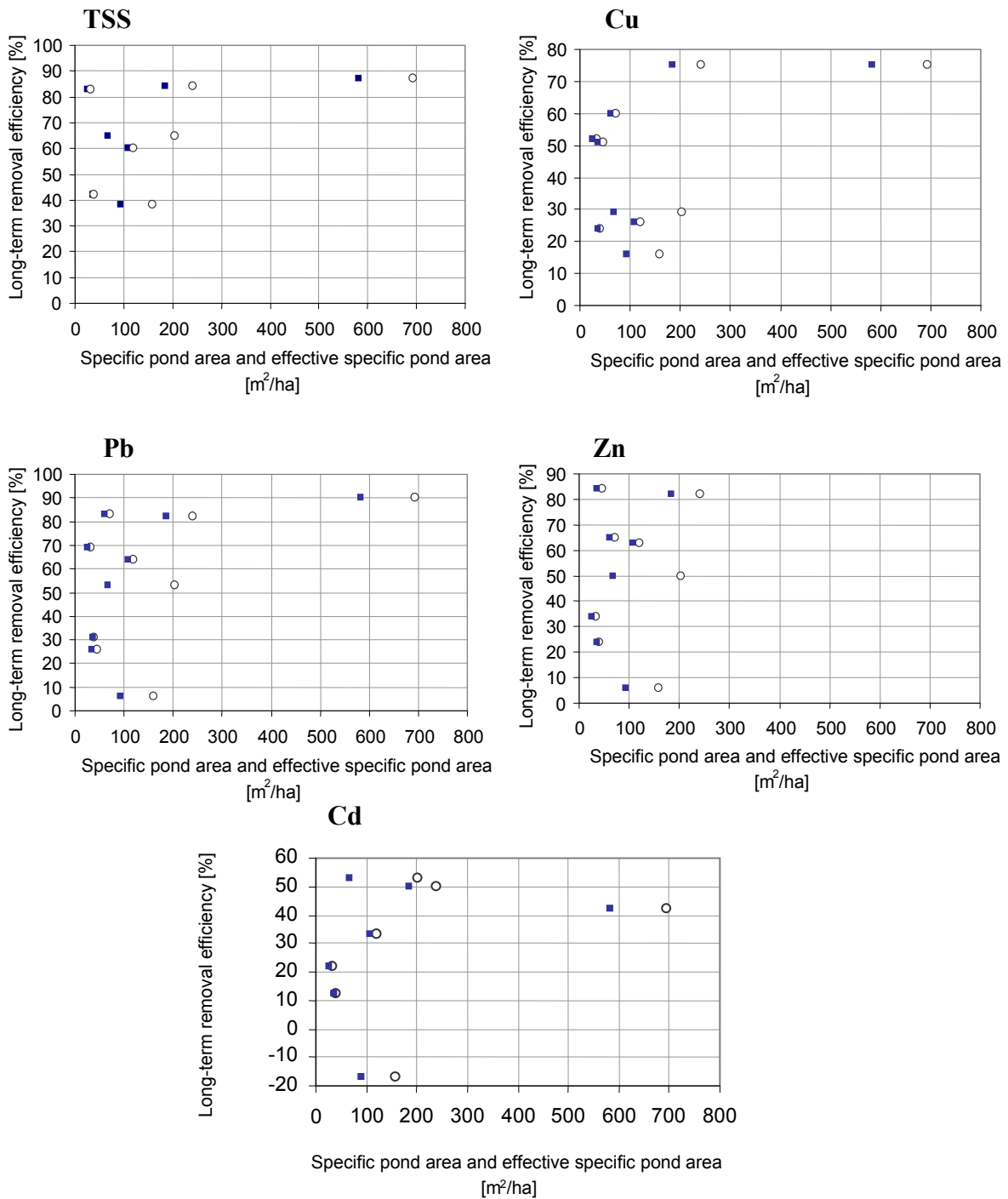| Pond	TSS	Zn	Cu	Pb	Cd	e
Kolardammen	nd	65	60	83	nd	84
Large Järnbrott Pond	42	24	24	31	12	90
Small Järnbrott Pond	65	50	29	53	53	33
Krubban (1)	84	82	75	82	50	77
Krubban (1+2+3)	87	nd	75	90	42	84
Bäckaslöv	60	63	26	64	33	91
Välenviken	83	34	52	69	22	80
Eriksmåla	38	6	16	6	-17	60
Vallby	nd	84	51	26	nd	77

Figure **3.** Long-term removal efficiencies of TSS, Pb, Cd, Zn och Cu. The circles mark the removal efficiencies as a function of specific pond area, while the squares mark the effective specific pond area, i.e. with the areas revised according to effective volume. This shifts each mark horizontally to the left.

The results show that there is no connection between pollutant removal efficiencies and specific pond area. There are "large" as well as "small" ponds that exhibit poor as well as good removal efficiency. Consequently, the values are so scattered that no statistical analysis is meaningful. Further, the result did not display any clear relationship between the long-term removal efficiency and the adjusted specific pond area (i.e. *effective* specific pond area); see Figure (3). This means, quite surprisingly, that the present study could not show that hydraulics has any major effect on pollutant removal.

4. DISCUSSION

It is shown in Figure (3) that ponds with a specific pond area above 200 m^2 ha^{-1} generally demonstrate good removal capacity. However, in this study there were only three ponds representing specific areas above 200 m^2 ha^{-1}. Moreover, there were ponds with considerably less specific area that exhibited removal efficiencies with the same order of magnitude. To develop a better relationship, other parameters than specific pond area might be used, e.g. the relation between pond volume and average runoff volume during storm events. But more important is to include other factors such as effects of vegetation or pollutant load. Vegetation does have both the effects through processes such as filtration, adsorption, biological assimilation or chemical transformation [10, 31] and effects on flow pattern [32, 33]. Specific pond area is a very convenient factor for retention ponds' designers to apply, since it only demands data on pond area and catchment area – although unfortunately less precise, at least according to this study.

It seems that research on pond and wetland design and sizing has to develop further and to result in guidelines directed towards ecological engineers working with sustainable drainage (which includes stormwater ponds and wetlands). Even if sedimentation processes are regarded by many as dominant, as in Hazen's settle model, the role of vegetation and other factors may be important. This is also put forward by Lung and Light [34] who believe that vegetation can play a major role.

It may be added that it is difficult to conduct field measurements aimed at monitoring ponds. Pollutant removal efficiency is technically cumbersome, time-consuming and expensive [35]. But to us it seems better to measure a few ponds more accurately, with regard to flow measurement, frequency and length of sampling period, than many ponds with e.g. grab samples. It can also be assumed that there are uncertainties in the collected data used in this study. Even if a correctly designed monitoring program was used in the eight cases, there still remain uncertainties connected with data quality due to inaccuracies caused by winter conditions, poor storage of water samples, mechanical problems with a sampler, or flow measurements.

5. CONCLUSION

This study demonstrates that almost 70 % of all Swedish monitoring programs for pond removal efficiency surveillance, identified in this study, were incorrectly designed. The most common problem was that the measurements consisted of grab samples, which are not suitable when flow fluctuates. Further, it was found that the amount of data in the majority of the surveillance reports was insufficient to allow meaningful comparison between sites, with the exception of specific pond area. This was because the reports often lacked data on many parameters such as water quality, vegetation, hydraulics and

pond characteristics. Among the remaining ponds (with well-designed monitoring programs), there was no possibility to establish a correlation between specific pond area and long-term removal efficiency. This was also the case when the specific pond area was adjusted according to the amount of dead zones, i.e. ineffective pond area. This indicates that there are additional factors than specific pond area that ought to be considered when stormwater ponds are sized and designed, such as concentration of pollutants and vegetation.

ACKNOWLEDGEMENT

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