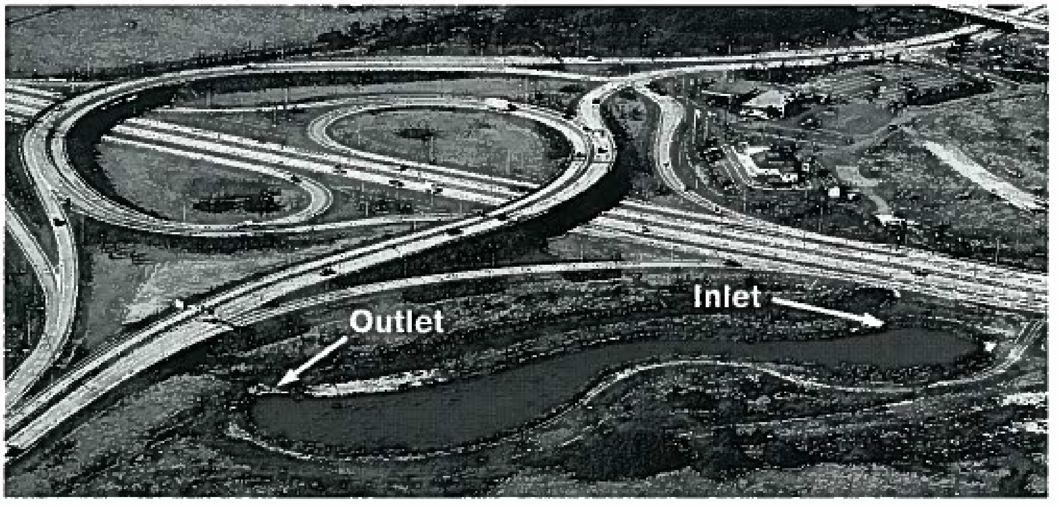
CHALMERS



Stormwater Ponds for Pollution Reduction

THOMAS J. R. PETTERSSON

Department of Sanitary Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 1999

ERRATA

The following corrections should be made in the doctoral thesis "Stormwater Ponds for Pollution Reduction".

In the thesis, *ponds* are somewhere termed ***open** ponds* in several places, which is obvious and would therefore only be termed *ponds*.

In Part 3 and Part 4, whirl should be *eddy*.

page	paragraph	to be corrected	corrected
7	1	…desired particle sizes.	…desired particle sizes **(Lloyd *et al.*, 1998)**.
10	1	An exchange of the dry….	**A theoretical** exchange of the dry….
	2	An exchange of the dry….	**A theoretical** exchange of the dry….
11	2	…of about 11 500 m^3	…of about **11 300** m^3
	2	…of about 25%. and the…	…of about 25%**,** and the…
	2	An exchange of the dry….	**A theoretical** exchange of the dry….
12	1	Automatically stormwater	**Automatic** stormwater
17	3	…and organic (VSS),	…and **volatile** (VSS),

In Paper II, Table 3, the *Removal efficiency* for Cadmium reads 88%, but should read **50%**

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Stormwater Ponds for Pollution Reduction

THOMAS J. R. PETTERSSON

Department of Sanitary Engineering
CHALMERS UNIVERSITY OF THECHNOLOGY
Göteborg, Sweden 1999

Stormwater Ponds for Pollution Reduction
THOMAS J. R. PETTERSSON
ISBN 91-7197-846-1

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 1542
ISSN 0346-718x

Dissertation no 14
Department of Sanitary Engineering
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone +46 (0)31 772 2121
Fax +46 (0)31 772 2128
E-mail: info@sani.chalmers.se
Web: www.sani.chalmers.se

Chalmers Reproservice
Göteborg, Sweden 1999

Stormwater Ponds for Pollution Reduction

THOMAS J. R. PETTERSSON
Department of Sanitary Engineering
Chalmers University of Technology

ABSTRACT

Stormwater transports particulate-bound and soluble pollution from urban areas to receiving waters during rain events. Measurements have shown that open detention ponds, originally used for flood control, effectively reduce stormwater pollutant load and have therefore been increasingly used for stormwater treatment. To fill a research gap, accurate long-term measurements have been carried out to determine the pollutant removal efficiency in existing stormwater ponds in Sweden. Physical and, to some extent, chemical processes during single storm events have been studied.

All studied stormwater ponds were equipped, at the inlet and the outlet, with continuous flow meters and automatic samplers. During storm events, suspended solids, heavy metals and nutrients were analysed. Results show that pollutant removal rates vary, during single storm events, from negative values up to almost 100%. Cumulative pollutographs, for inflow and outflow pollutants, were used for calculation of the removal efficiency. The outflow curve shows an almost straight line, where the gradient is a load coefficient useful for calculation of annual pollutant loads from the pond to the receiving waters. The pollutant removal efficiency varies for different ponds, due to different specific pond areas (pond area / impervious catchment area). For the heaviest loaded pond (40 m^2/ha) the removal efficiencies for suspended solids and heavy metals were 70% and 30-50% respectively, and for a less loaded pond (240 m^2/ha) 84% and 75-88% respectively. It could be concluded that a further increase in specific pond area above 250 m^2/ha only marginally increased the pollutant removal efficiency. Modelling and measurements of internal flow pattern in two different ponds have also been carried out. The results show that flow modelling in a stormwater pond should be performed with a three-dimensional model. In addition, the pond geometry has to be properly designed to avoid dead zones or recirculation zones that decrease the effective pond volume and consequently decrease the residence time in the pond, which is unfavourable for the pollutant removal.

Conclusions from this project are that the pollutant removal efficiency should be determined from measurements of several successive storm events and that there is an optimal size for a stormwater pond of around 250 m^2/ha.

Keywords: stormwater pond, field measurements, pollution, suspended solids, heavy metals, nutrients, reduction, flow modelling, FEM

SAMMANFATTNING

Under ett regntillfälle transporteras partikulära och lösta föroreningar från stadsområden via dagvatten till recipienten. Från mätningar har man sett att öppna ujämnings-magasin, ursprungligen avsedda för flödesutjämning, effektivt minskar förorenings-mängden i dagvatten, varför dessa numera flitigt används som en reningsmetod för dagvatten. Eftersom det finns luckor i forskningen, rörande dagvattendammars funktion, har det, inom ramen för detta projekt, genomförts noggranna mätningar i ett antal befintliga dammar i Sverige, där dammarnas förmåga att avskilja föroreningar har fastställts. Fysikaliska och i viss mån även kemiska processer har studerats.

Samtliga studerade dagvattendammar har varit utrustade med kontinuerlig flödes-mätningsutrustning och automatiska vattenprovtagare. Under regntillfällena har halterna av suspenderat material, tungmetaller och näringsämnen analyserats. Resultat från enskilda regntillfällen visar en variation i föroreningsavskiljning från negativa värden upp till nästan 100%-ig avskiljning. Ackumulerade föroreningsgrafer med inkommande och utgående föroreningsmängd har använts för att beräkna dammens långsiktiga avskiljningsförmåga. Kurvan för utgående föroreningsmängd är nästan en rak linje där lutningen på denna definieras som en belastningskoefficient till aktuell förorening. Denna belastningskoefficient kan används till att beräkna den årliga föroreningsbelastningen ut från dammen till recipienten. Förmågan att avskilja föroreningar varierar för olika dammar beroende på olika belastningar på dammarna uttryckt i specifik dammarea (dammarea/hårdgjord yta). För den hårdast belastade dammen (40 m^2/ha) är avskiljningsförmågan för suspenderat material och tungmetaller 70% respektive 30-50% och för en mindre belastad damm (240 m^2/ha) 84% respektive 75-88%. Det observerades att specifika dammstorlekar över 250 m^2/ha endast ger en marginell förbättring i förmågan att avskilja föroreningar. Modellering och mätningar av flödeshastigheter i två olika dammar har också genomförts. Resultaten visar att modellering av flöden i en dagvattendamm bör utföras med en tredimensionell modell samt att dammgeometrin bör utformas med stor noggrannhet för att undvika "döda" zoner och recirkulationszoner. Dessa inaktiva delar av dammen minskar dess effektiva volym och medför att uppehållstiden i dammen också minskar, vilket är till nackdel för förorenings-avskiljningen.

De slutsatser som kan dras från detta projekt är att bestämning av föroreningsreduktionen i en dagvattendamm skall baseras på mätningar från flera på varandra följande regntillfällen samt att det finns en optimal dammstorlek, i förhållande till den anslutna hårdgjord ytan, vilken ligger runt 250 m^2/ha.

LIST OF PUBLICATIONS

This thesis is based on the work contained in the following papers:

I Pettersson T. J. R. (1998). Water quality improvement in a small stormwater detention pond. *Water Science and Technology*, **38**(10), 115-122.
Paper presented at IAWQ 19th Biennial International Conference on Water Quality, Vancouver, Canada, 21-26 June 1998.

II Pettersson T. J. R., German J. and Svensson, G. (1999). Pollutant removal efficiency in two stormwater ponds in Sweden. In: *Proc. 8th Int. Conf. Urban Storm Drainage*, Sydney, Australia, 30 August-3 September 1999, vol 2, 866-873.

III Pettersson T. J. R. (1999). The effects of variations of water quality on the partitioning of heavy metals in a stormwater pond. In: *Proc. 8th Int. Conf. Urban Storm Drainage*, Sydney, Australia, 30 August-3 September 1999, vol 4, 1943-1946.

IV Petterson T. J. R. and Svensson, G. (1998). Particle removal in detention ponds modelled for a year of successive rain events. In: *Proc. Novatech 1998, 3rd international conference on innovative technologies in urban storm drainage*, Lyon, France, 4-6 May 1998, vol 1, 567-574.

V Pettersson T. J. R. (1997). FEM-Modelling of Open Stormwater Detention Ponds. *Nordic Hydrology*, **28**(4/5), 339-350.
Paper presented at the Nordic Hydrological Conference, Akureyri, Iceland, 13-15 August 1996.

VI Pettersson T. J. R., German J. and Svensson, G. (1998). Modelling of flow pattern and particle removal in an open stormwater detention pond. In: *Proc. HydraStorm'98*, Adelaide, Australia, 27-30 September 1998, 63-68.

ACKNOWLEDGEMENTS

Since I started my doctoral studies in 1994, there has been a lot of work carried out on the fields, in the lab and in front of the computer. There has also been a lot of travelling, participating in international conferences, and attendance in workshops and meetings in Sweden. Furthermore, the work of building up our web site has been very challenging and taking quite a time, mostly evenings and spare time. However, that work has been worthwhile since *our* web site (www.sani.chalmers.se) was selected, in 1997, as one of the best and well-structured web sites at the technical universities in Sweden. To make all these efforts possible, you need to have a number of persons around you, supporting you and sharing their ideas and knowledge with you.

First of all, I would like to thank my supervisor, associated professor Gilbert Svensson, for valuable and encouraging discussions and for always trusting in my ideas and decisions during the whole project. Thank you!

I would also like to thank the professors Greg Morrison and Torsten Hedberg for efficient and optimistic discussions and cooperation during the time at the department. I would like to thank Evy Axén at our laboratory for helping me in my work to analyse all samples that I have brought to the lab, filling up all refrigerators and freezers. Furthermore, I would like to thank the whole staff at the Department of Sanitary Engineering as well as the many colleagues at the Department of Hydraulics. I especially wish to thank all the doctoral students at the two departments, during these years, for interesting discussions during lunches and coffee breaks.

People at the Göteborg Sewage and Water Works and the municipality of Örebro, Technical Administration Board are gratefully thanked for their help and positive attitude to field measurements despite all the problems with instrument failure, of course during heavy rain events. This work never could have been accomplished without your help. Björn Brunzell at PAAB Automation in Säffle also deserves thanks for always serving us with wise answers concerning sampler maintenance.

The research has been financially supported by the Swedish Council for Building Reseach (BFR) and the Swedish Water & Wastewater Association (VA-FORSK) which are both gratefully acknowledged.

Finally, my family, the most important part of my life and I know you do not need this on paper, but anyway, thank you!

Alingsås, September 1999

Thomas

CONTENTS

Page

LIST OF TABLES Page

LIST OF FIGURES Page

PART 1 INTRODUCTION

1.1 Background

During the last 25 years (10 years in Sweden) the use of open ponds, as a method for stormwater treatment, has increased significantly in Sweden and the rest of the Western world. These ponds were originally designed to control combined sewage systems and to reduce peak flows and erosion. Since many simplified surveys of these ponds show a considerable stormwater pollution reduction at a low cost, there is an increasing interest in using open ponds.

A large proportion of the ponds, intended for stormwater treatment, are designed without any specific guidelines; instead rules of thumb and experiences from previous successful ponds are used. The lack of guidelines for pond design has given rise to demands for extensive investigations into the performance of existing stormwater ponds. There are only a few investigations where the seasonal changes and long-term pollutant removal efficiency are studied in detail. Most of them, however, are based upon grab sample surveys during single storm events where only a part of the stormwater volume has been analysed.

Pollutant removal mechanisms in these ponds refer to very complex physical, chemical and biological systems that demand extensive investigation procedures during rain events and in between successive events. This is of course a question of cost since these extensive investigations are very expensive to carry out. Nevertheless, this information is necessary since authorities put heavy demands upon stormwater treatment. Since open ponds are effective they have become a very common means of fulfilling those demands. An example illustrating this is the Swedish national road administration, which builds open ponds for treatment of highway runoff at every new highway construction. The authorities consider these ponds a sufficient measure for stormwater pollution reduction despite the fact that they are designed without a design criterion and without a follow-up programme for the performance (Lundberg *et al.*, 1998).

A more accurate method of calculating pollutant removal is to use the difference of the accumulated pollutant loads or event mean concentrations between the stormwater inflow and the pond outflow during several successive storm events. This method requires flow-weighted samples from the stormwater inflow and the pond outflow during the whole storm event. Grab samples have often been preferred due to the high investigation cost when using flow-weighted samples.

Pond geometry is of the utmost importance for the flow behaviour in the pond during a storm event. It affects the effective pond volume, excluding volumes with no water exchange in the pond, and thereby the residence time for the influent stormwater.

1.2 Objectives and scope

The aim of this study was to investigate pollutant removal in open stormwater ponds. Field measurements were planned to be carried out in a couple of existing stormwater ponds in Sweden, where the following aspects were to be studied:

- pollutant reduction mechanisms during single storm events
- long-term pollutant removal
- internal flow pattern during storm events
- particle removal through sedimentation
- chemical mechanisms during storm events and during dry periods

This thesis consists of two sections: a summary section divided into five parts and an appendix section with the produced papers. The summary consists of an introduction which reviews the background literature, an experimental part where all pond sites, field equipment and laboratory analyses are described, a paper overview where the author's papers are summarised and set in the context of the research area, a concluding part where the most important findings in this research work are stated and finally a reference section.

1.3 Literature review

In urban areas the natural water cycle is affected by an infrastructure, such as surfaces impervious to water, that concentrates flow and hinders infiltration. This causes higher stormwater velocities, thereby allowing the transport of pollutants attached to particles. Rainwater gets polluted during precipitation and during its transport over urban surfaces (*e.g.* roads and parking lots) and is named stormwater when leaving the surface (Malmqvist, 1984). Since raindrops have an erosive feature and water is a good solvent for different substances and compounds, the stormwater will carry them through the urban area until they reach the receiving water with or without a stormwater clarification. The stormwater transport capacity of particles, solids and other materials, over urban areas, depends on topology, runoff intensity and urban-surface character.

Stormwater pollutant transport models

Models for predicting pollutant transport from impervious catchment areas into the stormwater have been developed since the early 1970s, and the knowledge of this matter is rather good (Svensson, 1987; Akan, 1988; Nix *et al.*, 1988; Schroeter and Watt, 1989). Particles and sediment leave the urban surfaces, where further transport continues through the sewer system, and temporary sediment storage of graded solids can build up in the pipe bottom caused by low stormwater velocities and later on be eroded by high velocities (Perrusquia, 1991; Ota *et al.*, 1999).

To achieve accurate results from cumulative pollutant calculations, the models need to have accurate rainfall series input where also the inter-event dry periods are taken into account (Hvitved-Jacobsen and Yousef, 1988).

Stormwater quality and impacts on receiving waters

Stormwater contains a variety of pollutants originating from anthropogenic actions such as corrosion of materials from buildings, erosion of streets and roads from vehicular traffic and other activities. Stormwater originating from highways and other impervious areas has been well investigated during the last few decades and a lot of knowledge is documented (Morrison *et al.*, 1984; Ellis *et al.*, 1987).

Suspended solids, total (TSS) and organic (VSS), such as sand and clay are present in urban stormwater (Malmqvist, 1984; Maestri and Lord, 1987). Elements also significant in polluted stormwater are metals (Sansalone *et al.*, 1995), polycyclic aromatic hydrocarbons (PAH) (Sharma *et al.*, 1997), and nutrients such as nitrogen and phosphorus (Abustan and Ball, 1998). These pollutants are recognised as nonpoint-source pollution. Heavy metals (*e.g.* lead, copper, cadmium and zinc) are present in particulate and dissolved phases. PAH are mostly attached to suspended solid-associated organic matter (Schueler, 1987).

Urban runoff is caused by rainfall events and snow melt events. In a survey from 8 different investigated highway sites in the United States and Europe, it is stated that the event mean concentrations (EMC) of heavy metals are significantly higher in snow melt than in rainfall runoff (Sansalone *et al.*,1995). The magnitude of hazardous pollutants in highway runoff is to a great extent dependent on traffic intensity (Chui *et al.*, 1982).

It is known that stormwater pollution can damage the biological life in the receiving waters and the ecosystem disturbed (Wren and Bishop, 1996). There is a toxic threat to the receiving water ecosystem and the biological life if no treatment, concerning stormwater improvement, is undertaken (Hall and Anderson, 1988; Wei and Morrison, 1992); therefore stormwater pollutant reduction is a key issue. A significant proportion may be present as dissolved and then bioavailable species (Sansalone and Buchberger, 1997b). These species, such as dissolved heavy metals, are available for organisms and can be taken up rapidly.

It is important to distinguish between short-term damage (*e.g.* acute toxic effects) and long-term damage. The acute toxic effects are soluble substances, in the urban runoff, which during a storm event reach very high concentrations and thus are directly bioavailable. Other short-term damage is caused by bacteria that are harmful to living organisms, as well as by solids causing turbidity conditions.

Long-term damage appears when particulate-bound pollutants to a great extent accumulate in the receiving water sediments and then dissolve out into the water during unfavourable conditions, such as anoxic or low-pH conditions (Malmqvist, 1984; Svensson, 1987; Wei, 1993). Anoxic conditions may appear, for example, when oxygen-demanding matter is discharged to the receiving water in excess of the aeration rate.

Various types of damage to organisms in lakes due to heavy metal discharges that have been observed are: lethal effects on the aquatic ecosystem, reduced biological diversity, and bio-accumulation in fish and aquatic birds. PAH have caused tumours in animals in laboratory studies when they have been exposed to PAH for a long period of time (ATSDR, 1990).

Source control and stormwater quality improvement

Prevention of stormwater pollution reaching the receiving waters can be achieved by removing or decreasing the pollutant sources (Field and Brown, 1994). One heavy metal source is, for example, buildings plated with copper and zinc surfaces, and one measure that could protect them against corrosion is, for example, painting the surfaces (Malmqvist, 1984).

Abatement of the impact of stormwater runoff on receiving waters can be achieved through pollutant removal (Ellis *et al.* ,1987). Measures to treat the polluted stormwater, before it is released to the receiving waters, can be of differing character. Stormwater flows are highly variable as are the pollutant concentrations. Consequently, conventional treatment plants are not suitable for treatment of stormwater due to the difficulties in taking care of these high flow intensities during a rain event, and to the high load of heavy metals in the stormwater that contaminate the sludge and make it impossible to use as a fertiliser on farm lands.

In Maestri and Lord (1987), vegetative control, infiltration basins, wetlands and wet ponds are regarded as effective measures. These measures can be used alone or in combination to reduce the pollutant load from highway stormwater. Stormwater infiltration in soil is another method for disposing of stormwater, but will of course burden the soil with heavy metals. There is also a risk that the ground water will be contaminated (Mikkelsen *et al.*, 1994). Maestri and Lord (1987) also regarded street cleaning, dry detention ponds and porous pavements as ineffective measures, since they either show low pollutant reduction efficiency or cause big maintenance efforts. Street cleaning is sweeping of streets, since it is known that the dust and dirt from streets include heavy metals. One problem with street sweeping is that it is difficult to collect the smallest particles, to which most of the readily washed-off heavy metals are attached (Pitt, 1985).

A cost-effective strategy is to treat polluted stormwater in open detention ponds, before letting it out into receiving waters. Traditionally, open stormwater detention ponds are used to prevent flooding during heavy rain events. However, since the reduced flow prevents erosion and allows the sedimentation of suspended materials in the pond, they are increasingly being used on purpose to improve stormwater quality.

Treatment of stormwater in open ponds

Open stormwater detention ponds were originally used for flood control in the sewage pipe system, to reduce flow peaks. Investigations have, however, shown a risk of unwanted flow effects when detention ponds in sub-catchments are coupled together, since this can result in increased effluent flow rate of the total catchment (Boyd, 1993). Therefore, these effects should be carefully studied before establishing such ponds. Open detention ponds detain stormwater, reduce flow peaks, prevent erosion and allow the sedimentation of suspended materials in the pond. The ponds can be designed either as dry detention ponds that temporarily detain stormwater or as wet detention ponds that maintain a permanent pool of water (Urbonas and Stahre, 1993).

Using open detention ponds is a cost-effective strategy for the treatment of polluted stormwater. Investigations have shown a significant improvement of urban stormwater quality in open detention ponds (Randall, 1982; Martin, 1988a; Mesuere and Fish, 1989; Rushton, 1992; Yousef and Wanielista, 1993; Van Buren *et al.*, 1997). Due to these favourable water quality effects, open ponds have, in recent years, been increasingly used solely for stormwater treatment (Pettersson, 1996; Johansson, 1997), and are nowadays named stormwater ponds. One important mechanism for pollutant reduction in stormwater ponds is through sedimentation (Whipple and Hunter, 1981) since a considerable proportion of the pollutant load is attached to solids (Svensson, 1987;

Sansalone and Buchberger, 1997a), although chemical and biological processes are also included (Mayer *et al.*,1996).

Detention ponds are inexpensive to construct but require a significant surface area per treated volume (Culp and Doering, 1995). On the other hand, the investigation costs for accurate flow-weighted stormwater sampling in these ponds are considerable. Consequently, calculations of the pollutant removal efficiency are in many cases performed only with grab samples from the inlet and the outlet (Cutbill, 1993). In some studied ponds, time-dependent samples have been collected during a storm event (Watt and Paine, 1993), while other samples have been collected as non flow-weighted composite samples.

To be able to determine the removal efficiency in stormwater ponds, pollutant removal assessments based on an accurate measuring strategy are demanded. This means that during a storm event, flow measurements and a series of flow-weighted samples should be performed, at the inlet and the outlet, during the whole storm event to achieve samples that represent the total stormwater volume entering and leaving the pond. For accurate mass balance calculations involving multiplication of concentrations by flow rates, the importance of a precise determination of flow is evident (Watt and Paine, 1993). With this procedure it is possible not only to follow pond behaviour during a storm event but also to gain knowledge of the processes between two events (dry period). Several successive storm events should be measured to determine removal efficiency for the studied pond (Johansson, 1997). A further, more accurate, method to determine the pollutant removal is to consider the event mean concentration of the stormwater inflow and the pond outflow during several successive storm events. This method requires flow-weighted samples from the stormwater inflow and the pond outflow during the whole storm event. However, there are only a limited number of investigations available where long-term pollutant removal efficiency has been examined. It is important that the investigation consists of several successive storm events since the pollutant removal efficiency to a great extent depends on the rain volume and antecedent dry period (Hvitved-Jacobsen and Yousef, 1988).

Properly designed ponds trap polluted sediments but, if unfavourable chemical conditions arise, retained metals might be transformed into mobile forms (Marsalek *et al.*, 1997). Particle size distributions are of great importance when the pollutant mechanisms in stormwater ponds are studied. Several investigations show that the main part of the particulate-bound pollutants is associated with the smallest particles (Sansalone and Buchberger, 1997a). Fine primary particles aggregate, naturally, to larger flocs in a stormwater pond. It has been shown that these flocs, in sizes between 5-15 μm and with a fall velocity around 0.1 m/h, settle faster than both smaller and larger flocs and that large flocs (>100 μm) remain in suspension (Marsalek *et al.*, 1998). One investigation shows, however, very high settling velocities for small stormwater particles (< 50 μm) in a downstream storm sewer, with fall velocities around 4 m/h (Chebbo and Bachoc, 1992). This diversity in fall velocities would reflect the difference between primary particles and aggregated flocs. Smaller primary particles (< 2 μm) are difficult to remove, but necessary since the particulate-bound pollutants to a great extent are attached to these particles (Greb and Bannerman, 1997). Differences in stormwater particle characteristics have been found in different parts of the world, which also demands different types and sizes of wet ponds to remove the desired particle sizes.

During winter periods, in the northern part of the Northern Hemisphere, low temperatures often result in an ice layer that covers the pond during a certain time in the winter (Marsalek *et al.*, 1998). This may cause inhibition in surface aeration, which often leads to anoxic conditions in the pond (Pettersson, 1996) and an increase in the soluble content of the pollutants, because the sediment-bound pollutants dissolve out in the pond water (Striegl, 1987). Most of the sediment metals are found in the first few centimetres of the bottom sediment layer (Nightingale, 1987). However, some of the soluble metal increase, during winter periods, is related to the fact that vegetation, such as algae, has strong affinity to Cu and other metals (Wang and Wood, 1984), which are then released during this decaying period.

To achieve high pollutant removal efficiency, open stormwater ponds need to be designed properly, promoting a favourable flow regime and sufficient residence time during storm events. Unfavourable pond geometry results in short-circuiting of flow, or dead zones. To remedy this drawback, in an already existing pond, there is a need to prolong the flow path, which can be achieved by using baffles that alter the flow in the pond and thereby increase the residence time (Gain, 1996; Van Buren *et al.*, 1996). Another phenomenon that affects the flow in the pond and consequently the residence time is stratification of the water body, which occurs when water densities vary vertically. This is caused by vertical variations in the temperature and salinity profile (Scanlon *et al.*, 1998).

<u>Modelling of pollutant reduction in open ponds</u>

Design tools for developing and constructing stormwater ponds for stormwater treatment are often limited to empirical or simplified methods, such as spreadsheet-based models (Felstul and Montgomery, 1991), which often assume quiescent or laminar conditions and do not consider turbulent effects (Amandes and Bedient, 1980). In the literature, many of the methods for the design of detention ponds with respect to sedimentation refer to surface loads (Curtis and McCuen, 1977; US EPA, 1986) in a way similar to the design of sedimentation tanks (Hazen, 1904; Ellis *et al.*, 1995). The transport of particles in the detention pond is important for the accumulation of sediment in the pond (Mesuere and Fish, 1989).

Usually, a lot of simple models for the prediction of pollutant removal in ponds do not take the internal flow paths into account. They consider the flow either as completely mixed or as a non-mixed plug flow regime where calculations of pollutant removal efficiency are considered for different ponds (Yu *et al.*, 1993; Medina *et al.*, 1981). Simulations by a simple one-dimensional model, based on mass balance calculations in the pond, show that the volume of a water quality pond would be larger than 200-300 m^3/ha (reduced area) to achieve a pollutant removal efficiency above 50% for suspended solids (Toet *et al.*, 1990). Hydrological models that mainly consider rain characteristics and stormwater volume are also used as guidelines for effectively sizing these stormwater treatment ponds (Sear and van Ravenswaay, 1992). Also, statistical models for pollutant removal are available (Duncan, 1998) where data from several Australian and overseas investigations of water quality improvements are used to establish relationships between quality improvement performance and a number of pond and rain variables.

It is of great importance to study the hydraulic performance in open ponds so that they can be designed to promote satisfactory flow conditions, *i.e.* well distributed flow in the pond without short-circuiting currents and recirculation or dead zones, with no water exchange during storm events. Ponds with different geometric shapes exhibit different flow regimes (Persson, 1999), with two extremes: (a) completely mixed flow and (b) plug flow, which seldom appear in nature. Usually, flow regimes in stormwater ponds are somewhere in between. Completely mixed flow is favourable when a reduction in inflow pollutant peak concentration is desired. Plug flow is preferable when capturing stormwater volumes less than the pond volume. Determination of the flow regime and current residence time in a pond during inflow can be carried out through tracer studies (Martin, 1988b). Other factors that affect the flow regime in a pond are wind intensity and direction (Thackston *et al.*, 1987).

Different rain intensities will affect the flow pattern, the turbulence behaviour in a detention pond during a rain event and accordingly the sedimentation, but these effects are not well known. When designing an open detention pond it is important to create a geometry that prevents high velocity gradients, on which the settling of suspended solids and hence the reduction of heavy metals are highly dependent. Investigations of these variables can be made through 3-D computational fluid dynamic (CFD) models, such as the finite element method (FEM) models (Pettersson, 1996), or finite volume method models (Adamsson *et al.*, 1999).

PART 2 EXPERIMENTAL

2.1 Site locations

In Sweden, a number of ponds aimed at stormwater treatment have been built during the last ten years to remedy further contamination of the receiving waters. In this PhD project three different stormwater ponds have been studied, where field measurements of water quality and flow pattern have been performed. Two ponds were located in the city of Göteborg (south-west of Sweden) and one pond in the city of Örebro (central part of south Sweden), Figure 2.1.

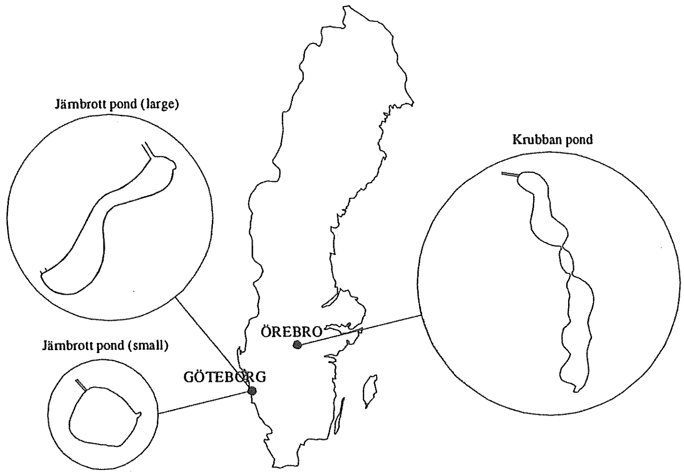


Figure 2.1 Site locations for the three ponds in Sweden (two in Göteborg and one in Örebro) studied in this project

The small Järnbrott pond is an experimental pond constructed for the purpose of investigating pond performance and studying the pollution reduction effects. The two other studied ponds were originally constructed to remedy the receiving waters from stormwater pollution.

2.2 Pond descriptions

The three ponds studied have different specific pond areas (pond area over impervious catchment area, m^2/ha), shape and geometry. All three ponds are off-stream ponds, *i.e.* no significant base flow appears between rain events.

The small Järnbrott pond

The pond, which was constructed in 1993, is located 5 km south of Göteborg city centre and is aimed at investigating the effects on pollutant reduction of stormwater in open ponds. During dry weather conditions the pond has a surface area of 530 m^2 and a pond volume of 500 m^3. Average water depth, at dry weather, is 1.2 m. Pond slopes, with 30% gradients surrounding the pond and bottom, consist of clay. An impervious catchment area of 2.6 ha supplies the pond with urban runoff, Table 2.1. The inlet consists of a 400 mm concrete pipe, which enters the pond 0.1 m above the dry weather pond water level, and the outlet consists of a 90° V-notch weir, which was also used to measure the outflow discharge. An exchange of the dry weather pond volume occurs at a rain depth of 19 mm.

Table 2.1 Pond and catchment data for the three studied sites

		Pond site	
	Järnbrott (small)	Järnbrott (large)	Krubban
Catchment area -total (ha)	4.2	480	40
- impervious (ha)	2.6	160	17
Pond size - surface area (m^2)	530	6 200	11 800
- volume (m^3)	500	6 000	11 300
- depth (m)	1.2	0.5 - 1.6	1.0 - 1.5
Specific pond area (m^2/ha)	200	40	730/240
Pond slope (%)	30	30	25
Year of construction	1993	1996	1996

The large Järnbrott pond

The large Järnbrott stormwater pond is also located 5 km south of the city centre of Göteborg, adjacent to the small Järnbrott pond, Figure 2.2. The pond was constructed in 1996 and has a water surface area of 6200 m^2 and a pond volume of 6000 m^3 at dry weather. An impervious catchment area of 160 ha is connected, Table 2.1. The pond slopes consist of clay and have a gradient of about 30%. The inlet consists of a submerged Ø1000 mm steel tube, originating from an upstream overflow, leading all inflow stormwater volumes off to the pond until the inflow intensity exceeds about 700 l/s. When it does, the overflow starts diverting the exceeding part of the stormwater directly to the river Stora Ån. Maximum inflow intensity to the pond is estimated to 1100 l/s when the total inflow to the overflow reaches the maximum of about 8 m^3/s. Due to the overflow, about 80% of the annual stormwater load is treated in the pond before reaching the river. The outlet consists of an 8 m broad concrete crest. An exchange of the dry weather pond volume occurs at a rain depth of about 4 mm.

The bottom topography varies in the pond due to local variation in soil strength. From the inlet to the outlet in the pond the depth varies from about 0.5 m to 1.6 m at dry weather. At the inlet section, the depth is about 1.5 m and the bottom consists of a concrete bottom slab. Accumulated sediments are prepared to be removed by a wheel-mounted loader, through a concrete descent connected to the slab, when the sediment layer becomes too thick. At the middle section the bottom consists of penetration macadam and the depth is about 0.5 m. The last section in the pond consists of a clay bottom overgrown with reeds and with a corresponding depth of about 1.6 m. The outlet consists of an 8 m wide concrete crest. The pond has a narrowing middle macadam section.

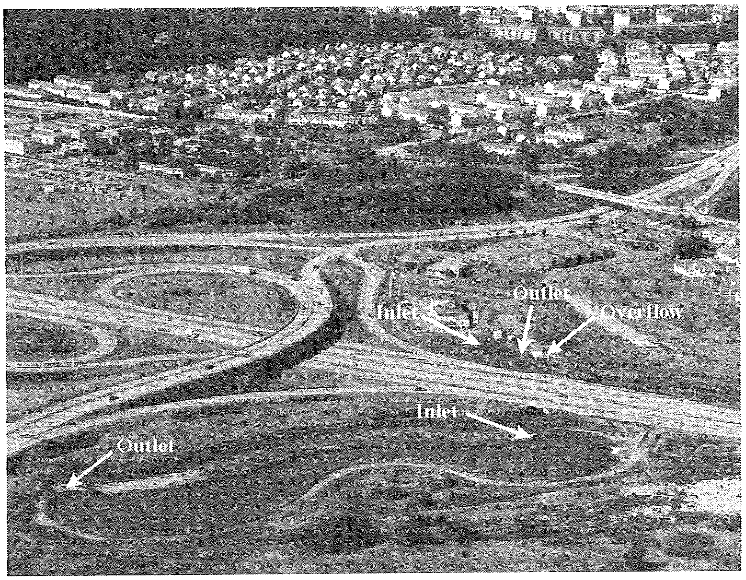


Figure 2.2 Photo over the two Järnbrott ponds with inlets and outlets indicated

The Krubban pond

The third stormwater pond included in this project is the Krubban pond, constructed in 1996 and located in Örebro, 3 km north of the city centre. The pond consists of a system with three serial connected ponds, seen in Figure 2.3, which have a total water volume of about 11 500 m^3 and a surface area of 11 800 m^2 (Table 2.1) divided into 4 100, 600 and 7 100 m^2 respectively. The connected catchment has an impervious area of 17 ha. Also this pond has slopes consisting of clay with a gradient of about 25%. and the depths vary between 1.0 m and 1.5 m at dry weather. The inlet consists of a partly submerged (70% submerged at dry weather) Ø1200 mm concrete pipe throttled to a Ø590 mm steel tube with a length of 7 m. This is to increase the inflow velocity to ensure flow measuring at lower discharges. The flow is conveyed between the ponds by means of a Ø800 mm concrete pipe The outlet of the pond system consists of a 2 m wide rectangular weir. An exchange of the pond system volume during dry weather conditions occurs at a rain depth of about 70 mm.

The bottom topography in the first pond varies, where the first part has a depth of about 1.0 m and the last part about 1.5 m separated by a shallow part with only 0.1 m depth and a couple of metres in length. The second (small) pond has a depth of 1.5 m and the last pond (largest) a water depth of 1.2 m at dry weather conditions.

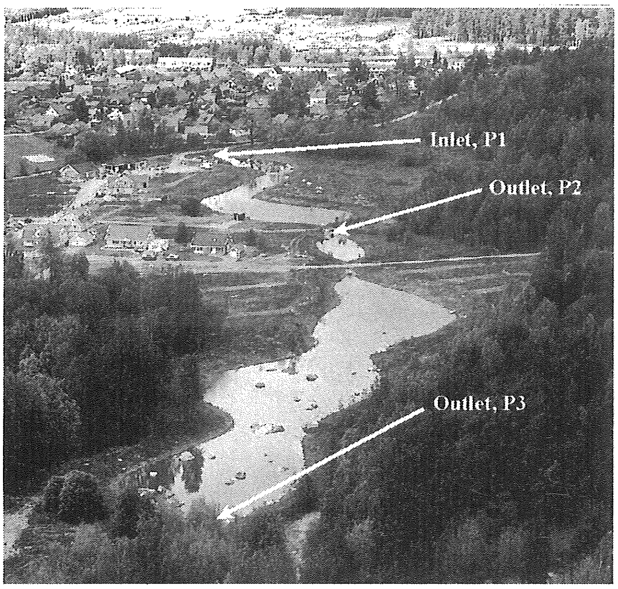


Figure 2.3 Photo over the Krubban pond with measuring points indicated

2.3 Measuring equipment

All water quality measurements in this project were performed on stormwater samples collected identically within the three pond sites. Automatically stormwater samplers (ISCO models) provided with peristaltic pumps and forced to take only flow-weighted samples during storm events have been used.

Flow velocity measurements were made in the large Järnbrott pond by drogue tracking. The drogue consists of a submerged aluminium drag device, connected to a luminous tape covered float (Ø 120 mm) by a nylon cord at fixed depths, Figure 2.4. Flow velocities at three different depths, surface-layer (0.12 m), 0.5 m and 1.0 m below current water level were investigated. A geodetic instrument determined the positions of the floats. Current flow velocities in the pond were calculated as moved distance from two position measurements over corresponding difference in time, usually 5-10 seconds. Three drogues were released in the pond near the end of the inlet pipe during the events.

The small Järnbrott pond
Stormwater quality was characterised by analysing samples collected by two automatic samplers (ISCO 3700), which were installed at the inlet pipe and at the outlet, Figure 2.5. Inflow and outflow discharges were measured using two pressure probes. The first one was installed in the inlet pipe measuring the water table, and by using Mannings formula

the discharge was calculated. The second pressure probe was installed in the pond, and the outlet discharge was monitored by measuring the water level in the pond and using the discharge formula for the 90° V-notch weir. Flow weighted samples were collected by the samplers, which were forced by the flow meters.

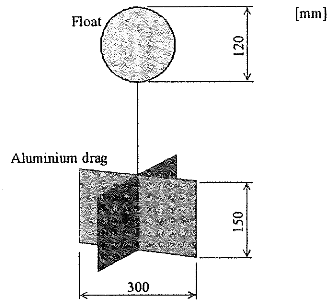


Figure 2.4 Drag device used at flow velocity measurements by drogue tracking

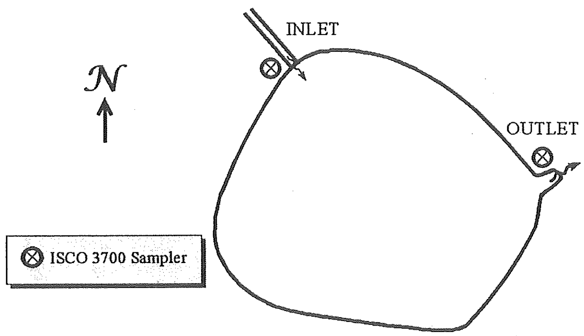


Figure 2.5 The small stormwater pond in Järnbrott, Göteborg

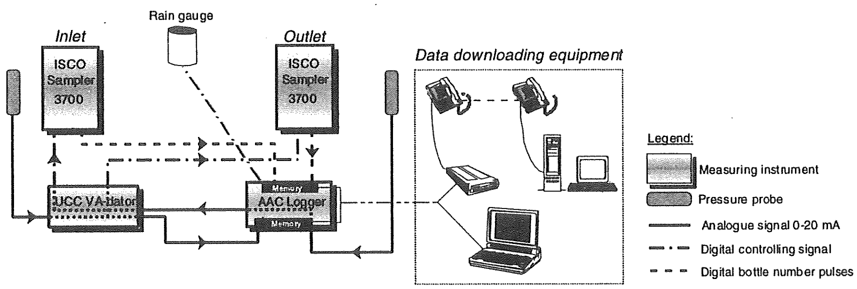


Figure 2.6 Schematic of the ISCO 3700 samplers, flow meters and other equipment at the small Järnbrott pond

All field data were stored in a logger and downloaded by an on-line connection (modem and a cellular phone) to a computer at the university or directly to a laptop computer at the pond site. In Figure 2.6, a schematic of the instruments, samplers and logger is shown.

The large Järnbrott pond

The pond is equipped with automatic stormwater samplers at the inlet and outlet of the pond. The samplers were of a portable ISCO 6700 model, provided with: 24 polyethylene bottles, vinyl tubing and a submerged polypropylene strainer. The strainers were located 10 cm above the bottom of the inlet pipe as well as about 2 m upstream the outlet weirs and 0.3 m below the dry weather water level. The strainers were connected to the tubing and have a suction length and a height of 4 m and 2 m respectively at the inlet and 4 m and about 1 m respectively at the outlet.

Each sampler had a flow meter installed, Figure 2.7, which forced the sampler to take flow-weighted samples. At the inlet the sampler was provided with a so-called V-H flow meter (ISCO 750 Area Velocity Module), calculating the discharges from measurements of water table and water velocity in the inlet pipe. At the outlet, a pressure probe (ISCO 720 Submerged Probe Module) calculated the discharge from measurements of the pond level above the outlet weir. At the site a rain gauge (ISCO 674) was installed. During a period of six months a "multi-probe" (YSI 600 Multi Parameter Water Quality Monitor) was installed and connected to the outlet sampler, monitoring the contents of effluent dissolved oxygen, pH, specific conductivity and water temperature.

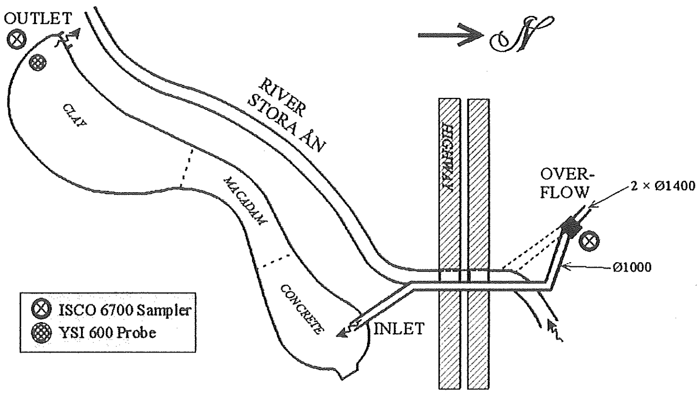


Figure 2.7 The large stormwater pond in Järnbrott, Göteborg

All field data were stored in the samplers by a built in data logger from which data were "downloaded" after each storm event by a laptop computer. In Figure 2.9, the principle of the inlet and outlet instrumentation is shown.

The Krubban pond

In the pond system, three measuring locations were provided; at the inlet (P1), the outlet of the first pond (P2) and the outlet of the last pond in the pond system (P3), which is seen in Figure 2.3 and Figure 2.8. The samplers were all of an automatic portable model (ISCO 6700), provided with: 24 polyethylene bottles, vinyl tubing and a submerged polypropylene strainer. The strainers were located, for the inlet (P1) and in the midpoint (P2), 10 cm above the bottom of the pipes and, at the outlet, about 2 m upstream the weirs and 0.3 m below the dry weather water level. The strainers were connected to the tubing and have a suction length and height of 2 m and 1.5 m respectively at P1 and P2 and 4-5 m and about 1 m respectively at P3.

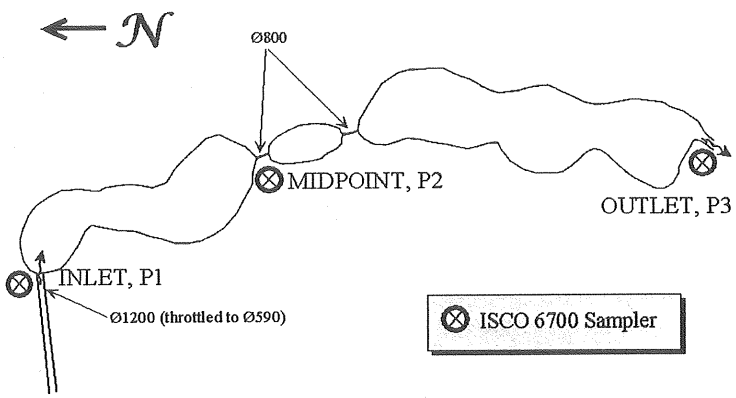


Figure 2.8 The stormwater pond in Krubban, Örebro, consists of three serial connected ponds with three measuring points

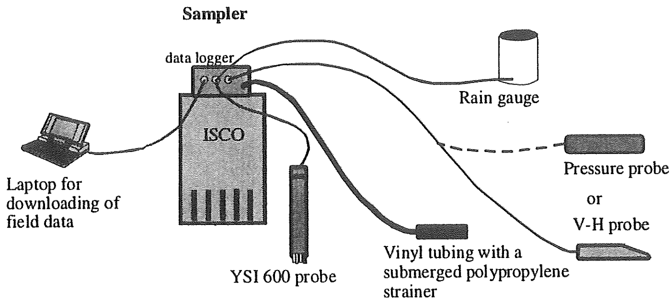


Figure 2.9 Schematic of the ISCO 6700 sampler and provided equipment at the large Järnbrott pond and Krubban pond

Each sampler has a flow meter installed, which forces the sampler to take flow-weighted samples. At P1 and P2 the samplers were provided with so-called V-H flow meters (ISCO 750 Area Velocity Module), monitoring discharges from measurements of water table and water velocity in the pipes. At P3, a pressure probe (ISCO 720 Submerged

Probe Module), measuring the pond level above the outlet weir, monitored the discharge. At the site a rain gauge (ISCO 674) was installed. All field data were stored in the samplers by a built in data logger from which data were "downloaded" after each storm event by a laptop computer. In Figure 2.9, the principle of the instrumentation is shown.

2.4 Observation programme

Before each sample was taken, the sampler automatically performed one rinse cycle of the tubing.

The measuring programme in this study was designed to include single storm events and several successive events during a longer period of time, in this case between three and six months. A series of successive storm events has to be studied to be able to calculate the long-term removal efficiency for current ponds. To ensure that the long-term effects will be included, it is important with continuity and to study not only single events. If only single events are studied, the pollutant removal rates will appear in a wide range, from negative values (more pollutants out than in) up to almost 100%, depending on rain volume and antecedent dry period. Therefore, it is important to cover a longer period of time, where a number of successive events are included, to average out these effects that strongly affect the pollutant removal rate.

Table 2.2 Sampler setup for forced flow-weighted samples being taken at the three pond sites; start and stop discharge levels, predetermined stormwater volumes per sample and number of samples per bottle

Measuring point		Start/stop levels for the samplers (l/s)	Stormwater volume passed between sampling (m^3)	Number of samples per bottle
Järnbrott (small)				
	-inlet	8	6	4
	-outlet	2	6	4
Järnbrott (large)				
	-inlet	60	500	3
	-outlet	60	500	3
Krubban	-inlet, P1	15	150	3
	-midpoint, P2	10	150	3
	-outlet, P3	5	150-200	2

Each storm event includes one or more flow-weighted samples (up to 24 bottles containing three flow-weighted samples each) at the inlet and at the outlet respectively, depending on current stormwater volume, Table 2.2. In the beginning of a storm event, the sampler was started when the inflow and outflow discharges exceeded predetermined levels and stopped when the discharges fell below these levels, Table 2.2. During the sampling period of the storm event, samples were taken every time a predetermined water volume passed the measuring point. Collected stormwater samples were transported to the laboratory, within 8-12 hours after the events, where they were directly prepared or analysed.

Stormwater quality measurements in the small Järnbrott pond include a period from July 1995 to June 1996. In the large Järnbrott pond, two measuring periods, from August 1997 to February 1998 and from April 1998 to July 1998 were included. In the Krubban pond, measurements were made from May 1998 to July 1998. These observation periods and number of analysed storm events for the three ponds are presented in Table 2.3.

Table 2.3 Observation periods of field measurements in the three studied ponds

Pond site		Observation period	Number of storm events
Järnbrott (small)		July 1995 - June 1996	21
Järnbrott (large)	autumn-97	Aug 1997 - Feb 1998	16
	summer-98	April 1998 - July 1998	17
Krubban	P1* and P2*	May 1998 - July 1998	10
	P3*	May 1998 - July 1998	5

* measuring points

2.5 Laboratory analyses

Laboratory analysis of the stormwater samples included content of suspended solids, total (TSS) and organic (VSS), heavy metals (zinc, copper, lead and cadmium), and nutrients (total nitrogen and phosphate-phosphorus). The pollutant concentrations in the stormwater were determined according to Swedish standard methods, which are shown in Table 2.4. The content of total suspended solids (TSS) was analysed by filtering the stormwater through a GF/C glass fibre filter. Heavy metal concentrations (zinc, copper, lead and cadmium) were determined in an atomic absorption spectrophotometry instrument for the large Järnbrott pond and the Krubban pond but, for the small Järnbrott pond, by a differential pulse anodic stripping voltammetry. Nutrients (total nitrogen and phosphate phosphorus) were analysed by spectrophotometry methods.

Detection limits, indicated in Table 2.4, are the values that refer to the guaranteed laboratory limits. Lower concentrations (instrument readings) than this have been used in the scope of this research work.

Particle size distribution in the stormwater was analysed by a Met One particle analyser, WGS 260, which uses a light-blocking sensor technique to determine the content of particle numbers for each size in a range of <1.0, 1.5, up to 282 μm. The stormwater samples were diluted until the count of total number of particles was in a range of about 4000-7000 particles/ml, to get an accurate result.

Table 2.4 Methods of stormwater analysis used and their limits of detection

Pollutant	Method of analysis*	Detection limit
Suspended solids		
- total	SS-EN 872-1 / SS 02 81 12	5 mg/l
- residue on ignition	SS 02 81 12	5 mg/l
Heavy metals		
- zinc	SS 02 81 52-2	20 µg/l
- copper	SS 02 81 84-1	3 µg/l
- lead	SS 02 81 84-1	3 µg/l
- cadmium	SS 02 81 84-1	0,1 µg/l
Nutrients		
- total nitrogen	SS 02 81 31-1	0,08 mg/l
- phosphate phosphorus	SS 02 81 26-2	3 µg/l

* Swedish Standard Method

2.6 Data processing

All data that have been downloaded from the loggers were processed with the computer software, Analys95©, developed at the department of Sanitary Engineering, Chalmers. From the loggers (AAC and ISCO) data were downloaded, and then rawdata were exported to text files by their own softwares. Analys95 reads these text files and then calculates rain intensity, flow volumes from the discharge data and pollutant masses, when stormwater quality data are added.

Analys95 calculated pollutant masses that enter and leave the pond, during a storm event, according to the principle in Figure 2.10a.

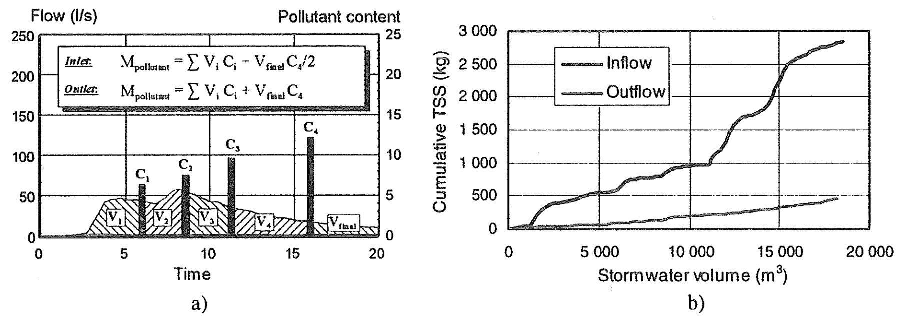


Figure 2.10 Principle of pollutant mass calculation during one storm event (a) and several successive storm events (b)

The total amount of pollutants ($M_{pollutant}$), registered at a measuring location during one storm event (Figure 2.10a) was calculated by multiplying the concentration (C_i) for each sample with the associated stormwater volume (V_i) from the corresponding hydrograph. Then, the sub masses were summed up to a total pollutant mass for all pollutants during a storm event. To calculate the mass for the outlet hydrograph tail (*i.e.* the volume after the samplers stopped taking samples, V_{final}), the last sample concentration (here C_4) from the event is used. For the inlet, half the corresponding concentration ($C_4/2$) is used since the inflow pollutant concentrations constantly decrease at the end of a storm event.

When the pollutant masses for all storm events have been calculated, cumulative pollutographs as a function of stormwater volume are created for the inlet and outlet, as shown in Figure 2.10b.

PART 3 PAPER OVERVIEW

In this part of the thesis, the different published papers enclosed in the appendix are summarised. The research work is divided into two parts: one water quality part and one modelling part. The water quality part deals with the investigation of stormwater quality improvement due to treatment effects in open stormwater ponds. The modelling part addresses modelling work of flow pattern in existing ponds and idealised model ponds. Also particle removal processes in the pond, during storm events and during antecedent dry periods, are modelled.

3.1 Water Quality Investigations

Paper I Water quality improvement in a small stormwater detention pond

Paper I deals with the variations in pollutant removal performance in the small Järnbrott pond (530 m^2, 500 m^3), derived from the mechanisms in pollutant transport. The measuring points are located at the inlet and the outlet where automatic samplers are taking flow-weighted samples. Three single and seven successive storm events are examined. The single storm events are studied in more detail to find the pollutant transport mechanisms that affect the pollutant removal rate of a stormwater pond. The long-term removal efficiency of the pond is studied by creating cumulative pollutographs from the successive storm events. Studied pollutants are total suspended solids (TSS), where also the specific surface area (SSA) is studied from particle size analyses, and heavy metals such as zinc, copper, lead and cadmium. Analyses are made for 21 storm events, of which seven events are studied in this paper.

The pollutant removal rates vary between single events from negative removal (*i.e.* more pollutants are transported out than enter the pond) to very high removal. TSS, lead and zinc has removal rates in a range of 14 - 82%, 10 - 82% and -32 - 74%, which are derived from antecedent dry period length and rain depth. Long dry periods and low rain depths result in a high pollutant removal rate for most of the pollutants while the opposite, short, dry periods and high rain depths, causes low removal rates or even a negative rate. Appropriate pollutant removal efficiency can not be determined based on results from a single storm event.

Cumulative pollutographs from seven successive storm events with inflow and outflow data will smooth out the single storm event variations. The gap between the inflow and outflow curve (see principle in Figure 2.10b) describes the long-term pollutant removal efficiency of the pond and would be used if an estimation of the annual pollutant reduction was aimed at. The TSS associated pollutants show an almost linear relationship with stormwater volume, and the linear regression slopes of those curves are the outflow load coefficients. For calculation of annual pollutant loads from the pond to the receiving waters load coefficients are useful.

Physical mechanisms and chemical processes during one single storm event are studied by a partial event mean concentration (PEMC) approach of the inflow and outflow stormwater. The total stormwater volume during this event was about 420 m^3 (less than total pond volume). The outflow PEMC graphs exhibit a top value at different volumes for different pollutants, which can be interpreted as the pollutant residence time in the pond at that particular storm event. For TSS, maximum PEMC occurs at 120 m^3, which demonstrates that TSS is connected to a short-circuiting flow. Lead occurs at 200-400 m^3, which is also valid for the smallest stormwater particles (0-5 μm), indicating a close relationship between them and more mixed internal pollutant transportation conditions in the pond.

Conclusions from Paper I
The most important finding in Paper I is that the pollutant removal efficiency needs to be calculated on several successive storm events rather than a single event, since the removal rate varies in a wide range for different events.

Paper II   Pollutant removal efficiency in two stormwater ponds in Sweden

In Paper I the pollutant removal rates and pollutant transport mechanisms during single storm events as well as long-term pollutant removal efficiency during several successive events were investigated in the small Järnbrott pond. In this paper the long-term removal efficiency is further studied in two additional ponds. Analysed stormwater pollutants are the same as in Paper I, but extended with nitrogen and phosphorus analyses.

One of the ponds, the large Järnbrott pond, has measuring points at the inlet and the outlet, like the small Järnbrott pond in Paper I, but with the difference that the inlet originates from an upstream overflow that diverts a part of the stormwater during heavy events. Partially bypassing a pond has been shown as a measure to increase the pollutant removal efficiency in a heavy loaded pond (Clemens *et al.*, 1993). The other pond, the Krubban pond system, consists of three serial connected ponds. Three measuring points are located at: the inlet (P1), the outlet of the first pond (P2), and the outlet of the third pond (P3). Analysed storm events are 33 and 10 respectively for the two ponds. Also the effects of different specific pond areas (pond area over impervious catchment area) on the removal efficiency are investigated. The specific pond area for Järnbrott is 40 m^2/ha and for Krubban 240 m^2/ha (P1-P2) and 700 m^2/ha (P1-P3).

The pollutant removal efficiency for TSS, VSS and metals (except cadmium) is 70%, 60% and 30-50%, respectively, for the Järnbrott pond and 84%, 76% and about 80% for the Krubban pond (P1-P2). If the overflowed stormwater at Järnbrott (modelled by MOUSE-PIPE) is taken into account, the removal efficiency for TSS, VSS and metals become 42%, 39% and about 25%, respectively, which is the removal efficiency used when comparing different ponds. Total nitrogen has much lower removal efficiency, 7% for Järnbrott and 33% for Krubban.

Cumulative pollutographs are created for all pollutants, from which effluent pollutant load coefficients and pollutant removal efficiency are calculated for the two ponds. Using the effluent pollutant load coefficients together with average annual stormwater volumes entering the ponds, the extrapolated effluent annual pollutant loads to the receiving waters are calculated.

The pollutant removal efficiency for the two studied ponds is compared with results from the small Järnbrott pond in Paper I and an additional pond located in Växjö, Sweden (Johansson, 1997), where field measurements have been performed with the same method. Results from four investigated ponds with five specific pond areas in the range 40-700 m^2/ha are used. When studying the removal efficiency for each pollutant as a function of specific pond area, it becomes obvious that the removal efficiency curves flattens out for specific pond areas above 250 m^2/ha. The results from the small Järnbrott pond (200 m^2/ha) in Paper I clearly deviate from the other ponds. The pollutant removal efficiencies for all pollutants in the small Järnbrott pond are much lower, see Figure 3.1. The pond geometry, which is almost circular and the flow quite short-circuiting can explain this deviation. The other ponds have a large length to width ratio, which develops a more uniform flow distribution through the ponds and thus increases the retention time. All studied ponds are off-stream ponds, *i.e.* ponds without significant baseflow.

Conclusions from Paper II
The most important findings in Paper II are that the curve for the pollutant removal efficiency, as a function of specific pond area for stormwater ponds, flattens out above a certain specific pond area and that different pond geometry affects this significantly.

Paper III The effects of variations of water quality on the partitioning of heavy metals in a stormwater pond

In Paper III the heavy metal partitioning in a stormwater pond is investigated since the dissolved phase has importance for the bioavailability. The partitioning is derived from water quality parameters, such as oxygen, pH and conductivity.

From the field measurements in the large Järnbrott stormwater pond (Paper II), the heavy metal analyses also include the concentration of the dissolved phase, which is defined as the metal concentration after filtration of the stormwater sample through a 0.45 µm cellulose filter. At the outlet an ISCO 6700 sampler, a "multi-probe" YSI 600 Multi Parameter Water Quality Monitor, is installed measuring dissolved oxygen content, pH, specific conductivity and water temperature. All the data from the probe are stored in the logger since the YSI 600 probe is compatible with the ISCO system. Water quality parameters are continuously measured during 20 of the total of 33 analysed storm events, during an observation period from 28 October 1997 to 2 July 1998.

Two events are studied in this paper. The first one is a storm event, 30 November 1997, with a total stormwater volume of 13 000 m^3 (double the pond volume) and an antecedent dry period of 15 days, when flow-weighted samples were taken. The second one is a snow melting runoff event, 5 February 1998, with a total stormwater volume of 5 000 m^3, preceded by two and a half weeks of cold weather (average temperature -5 °C) when time-dependent samples were taken. From the YSI 600 measurements, pH remains unchanged, about 7.5, during the two events while small changes appear in the contents of dissolved oxygen and specific conductivity. During the storm event, the specific conductivity is quite low but a clear increase appears during the event (when about 3000 $m^3$of stormwater has passed through the pond) due to some salty stormwater inflow. From the snow melt event the specific conductivity appears at a ten time higher magnitude due to intensive road salt measures. The content of dissolved oxygen is a more sensitive parameter and shows a distinct oxygen sag in the beginning of the storm event but an immediate increase to a level above the initial level appears during the event. During the snow melt event, the oxygen content is quite high but with small variations.

The effluent heavy metal concentration, except lead, shows almost constant high levels during the snow melt event. During the storm event, the total metal concentration increases up to a peak level in the middle of the event (when 5 900 m^3 of stormwater has passed through the pond, *i.e.* the total pond volume) as the inflow stormwater starts to reach the outlet. At the second half of the storm event, the concentration starts to decrease, which is caused by the decreased inflow metal concentration that reaches the outlet. The dissolved part of the effluent metals also varies between the two events. Zinc and copper have higher dissolved components during the snow melt event (76% and 63%) compared to the storm event (61% and 58%). Lead and cadmium have lower dissolved components during the snow melt event (2% and 38%) compared to the storm event (11% and 64%). Similar seasonal variations in metal partitioning, as found in the studied ponds, are also shown for urban runoff (Sansalone and Buchberger, 1997a). The clear increase of the particulate partition of lead (fivefold) during the snow melt event, at high specific conductivity, is due to flocculation of smaller particles and colloids at high ionic strength. This is also reflected in the removal rate of the dissolved heavy metals during this snow melt event. For the dissolved fraction of the most soluble metals zinc and copper, the removal rate was -3% and -14% (negatives), respectively, but for the dissolved fraction of lead the removal rate was extremely high, 86%, which is shown in Table 3.1.

Table 3.1 Heavy metal removal rates (%) in the large Järnbrott pond during the storm event and snow melt event

	Storm Event 30 Nov -97		Snow Melt Event 5 Feb -98	
Metal	Particulated	Dissolved	Particulated	Dissolved
Zinc	59	33	66	-3
Copper	65	8	52	-14
Lead	61	-40	87	86
Cadmium	60	37	-22	-7

Conclusions from Paper III

The most important finding in Paper III is that the dissolved heavy metal fraction in the pond, in particular lead, to a great extent is affected by the specific conductivity in the pond.

3.2 Modelling

The modelling work was carried out on two existing ponds, the small and the large Järnbrott ponds. The surface area and dry weather volume of the small Järnbrott pond are 530 m^2 and 500 m^3, respectively. Unfortunately, wrong surface area and dry weather volume of the pond have been used in Papers IV - VI. However, this does not affect the conclusions of the modelling work.

Paper IV Particle removal in detention ponds modelled for a year of successive rain events

The field measurements described in Paper I give knowledge about the variation in pollutant removal rates at different storm events with various rain characteristics. With this in mind, it is of interest to see if a simple model can be used to predict the removal of solids in a stormwater pond during a longer period of time with various rain characteristics (rain depth, rain duration and dry period).

Data from a normal hydrological year in Göteborg, Sweden, and data from the catchment area of the small Järnbrott pond (2.6 ha impervious area) are used as input to a hydrological package (MOUSE). Inflow hydrographs to the pond are calculated for the normal year. Three different effective pond sizes (130, 260 and 520 m^2) with three different depths (0.6, 1.26 and 2.5 m) are considered, which gives nine different pond volumes (from 80 up to 1300 m^3). Pond slopes are assumed to be vertical, which gives the pond volume as the product of pond area and depth. For each pond the particle removal calculation is carried out at three different particle densities (1050, 1300 and 2000 kg/m^3), which then gives 27 cases to be modelled.

The removal calculations are performed for the TSS mass and the specific particle surface area, which is divided into four fractions, established from particle size analysis of four different storm events. A model for particle removal calculation in stormwater ponds (US EPA, 1986) is then used to calculate the TSS removal. One equation is used for the particle removal calculation during a storm event (phase one) and another for the removal in between events (phase two). The settling velocity is calculated using Stoke´s law for particle settling at laminar flow. Turbulent conditions that are normally the case in ponds are considered in the model using a performance factor. Stormwater particles are assumed to be spherical, as indicated in Pettersson and Svensson (1995). Modelled inflow stormwater volumes from each storm event are compared with the effective pond volume to determine if the pond volume is partly or fully exchanged. The MOUSE model is running with 4 h time steps and set to consider a mean flow exceeding 0.14 l/s as a storm event. This yields 159 events for this normal year with inflow volumes in a range from 2 to 220 m^3.

The modelling results for the smallest pond (80 m^3) show that, during 22 storm events out of 159, the pond volume is exceeded. With a particle density of 1300 kg/m^3, the TSS removal efficiency is 68%. For the largest pond (1300 m^3), with no storm event exceeding the pond volume and with the same particle density, the TSS removal efficiency is 95%. The particle removal rate is strongly dependent on specific pond area (m^2/ha) and particle density. It is also shown that the removal is not significantly improved when the specific pond area increases to a certain level. In this paper, 150 m^2/ha is indicated as that level, but after an extension of the modelled pond cases, shown in Figure 3.1, that level seems to appear at 200-250 m^2/ha. In Paper II, measured pollutant removal efficiency, in four ponds, shows a similar behaviour with flattened out curves above a specific pond area of 250 m^2/ha. Figure 3.1 shows a comparison between modelled TSS removal, for two different particle densities (1300 and 1050 kg/m^3), and observed TSS and lead removal. The observed TSS removal and lead (mainly particulate-bound) removal curves appear underneath the modelled TSS removal curves (different particle densities).

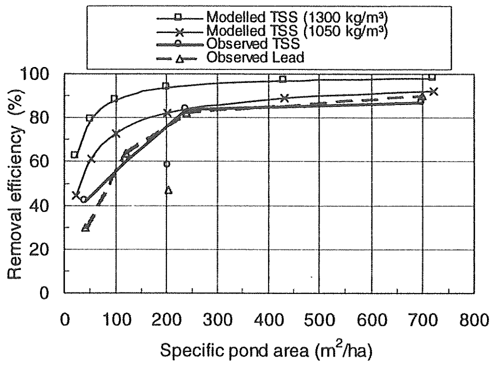


Figure 3.1 TSS removal efficiency as a function of the specific pond area; modelled removal for the particle densities 1300 and 1050 kg/m^3 and observed removal at five different specific pond areas from four existing ponds

Another effect from the simulation is that more than 90% of the TSS removal occurs during the dry periods, between storm events. Also seasonal variations affect the removal efficiency; especially periods with higher rain event frequency and short dry periods (autumn in Sweden) will reduce the removal efficiency.

Field measurements of TSS from seven successive storm events in the small Järnbrott pond, described in Paper I, are used to validate the model. One pond volume, 330 m^3 of the nine different pond volumes, corresponding to the small Järnbrott pond, is chosen, giving an effective pond volume of 65% since the total pond volume is 500 m^3. Stormwater volumes and TSS inflow concentrations from the field measurements are used as input data to the model. Modelled TSS removal efficiencies for three different particle densities, 1050, 1300 and 2000 kg/m^3, result in 48, 57 and 60% removal respectively. Measured removal is 56%.

This validation shows that the model is very useful when predicting TSS removal as well as particulate associated pollutant removal. Further investigations of the magnitude of effective pond volume for different pond geometry are necessary.

Conclusions from Paper IV
The most important findings in Paper IV are that the modelled TSS removal in a stormwater pond appears mainly during dry periods and that this simple model is useful for dimensioning stormwater ponds regarding particulate bound pollutant removal.

Paper V FEM-Modelling of open stormwater detention ponds

The work reported in this paper is modelling of a three-dimensional (3-D) velocity flow field and particle settling in the small Järnbrott stormwater pond during one of the seven storm events, reported in Paper I. Using a 3-D model is a more sophisticated way to calculate the particle removal, during the first of the two phases, compared to that used in Paper IV. Calculations are made with FIDAP, which is a finite element method (FEM) software package. The Navier-Stokes equations were solved with the Reynolds averaging over time, and the k-ε model was used to describe the turbulence. Calculations were performed on a detailed model of the detention pond with a total number of 21,500 8-node brick elements. Steady-state inflow is used and the average inflow during the event is set to 22.4 l/s. Results from the flow simulation show two whirls where the first one (larger) is controlled by the inlet and the other by the outlet. In between them a main stream flows, which is quite short-circuiting.

A sedimentation approach is applied in the 3-D flow field solution by a particle tracing function, included in the FIDAP post-processor, to simulate the TSS removal. A set of particles in four different size ranges (1.5, 10, 20 and 40 μm) is released at the inlet of the pond, with a used particle density of 1300 kg/m^3. Calculations of particle paths through the 3-D flow field are performed for a time period of 1 hour, since an extension of the calculation time does not affect the final particle position in the pond, probably due to the short-circuiting flow. Higher particle settling velocities than theoretical (Stokes) are another interpretation shown by Chebbo and Bachoc (1992). Some of the particles are transported through the pond out through the outlet, and the rest are considered as settled since the particle velocity approaches zero. The theoretical particle removal, from the particle tracing, was calculated as the ratio between remaining particles in the pond and released particles at the inlet.

Particle size distributions at the inlet and outlet from field measurements of that storm event are used to calculate the real particle removal for the four different sizes during the storm event. For the inlet, a sample from the beginning of the storm event is compared with a sample from the outlet in the middle of the event (250 m^3 have passed the outlet). Calculated particle removal rate and observed removal rate show very good agreement, Figure 3.2. Removal rates for the four particle sets vary from 60 up to 95% during this storm event.

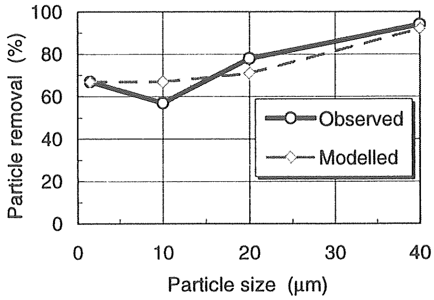


Figure 3.2 Modelled and observed particle removal rate during a storm event in the small Järnbrott pond

Conclusions from Paper V

The most important findings in Paper V are that FIDAP is a useful tool for modelling flow pattern and particle removal in a stormwater pond during storm events.

Paper VI Modelling of flow pattern and particle removal in an open stormwater detention pond

The objective of this paper is to study the flow behaviour in the large Järnbrott stormwater pond at different inflow intensities. This is carried out by a FEM-model (the same FEM-model as in Paper IV) and field measurements. Field measurements are designed to verify the FEM-modelled flow field. Measurements of flow pattern in the pond are performed by drogue tracking at three different depths; surface-layer, 0.5 m, and 1.0 m

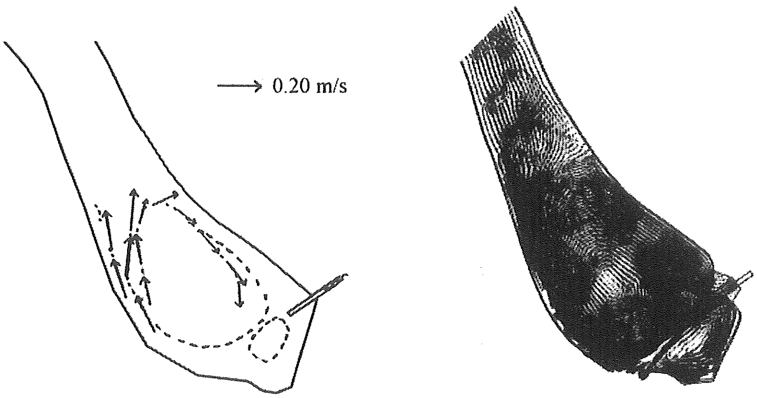
The pond is divided into three different sections with dry weather depth varying between 0.5 m and 1.6 m. At the inlet section the bottom, 1.5 m deep, consists of concrete, followed by a narrow and shallow section with a 0.5 m deep macadam bottom. The outlet section consists of clay and has a depth of 1.6 m.

Field measurements are performed during one very heavy storm event and during one base flow event. The inflow intensity of the storm event is about 800 l/s and for the base flow about 20 l/s.

The velocity vectors at the storm event show two whirls appearing at each side of the inlet pipe in the inlet. A smaller whirl appears to the left of the inflow pipe and a larger one to the right, over the whole inlet section extended to the boundary of the shallow macadam bed. After the boundary between the inlet section and the shallow macadam section, a transition of the flow pattern to a more distributed flow over the whole pond width with no return circuit appears, but the flow velocities tend to be a bit displaced to the right half of the pond. In the deeper outlet section of the pond, the reed vegetation made drogue tracking impossible since the aluminium drag got stuck. Due to this, no measurements were carried out in this section.

Since this is an off-stream detention pond, only a small base flow, mainly ground water, is present between storm events. The results are similar to the heavy storm event regarding flow patterns, but the flow velocities in the pond are of course much lower; however, the two whirls appear at the same positions.

Flow calculations are mainly performed on a detailed 3-D model consisting of 85 000 8-node brick elements, but also on a 2-D model consisting of 38 000 4-node elements. Inflow intensities in the pond that are modelled are 20, 100, 200, 400 and 800 l/s, where 20 l/s refers to the base flow event and 800 l/s to the heavy storm event. The results of the modelled flow pattern for the two events show very good agreement with the measured flow pattern, and the two whirls at the inlet also appear at the same positions and magnitudes, see Figure 3.3.



a) b)

Figure 3.3 Measured (a) and modelled (b) flow pattern in the inlet and middle section of the large Järnbrott pond during a heavy storm event.

It is seen that the outlet section consists of a quite large dead zone, with almost zero flow. This is an effect of the widening of the outlet section, which first decreases the effective pond volume and then the residence time in the pond, as discussed in Paper I and Paper V. Further, it is also seen that the position and shaping of the outlet affect the flow pattern and thus the effective pond volume.

A comparison between the results from the 2-D and 3-D modelling shows that the effects from the bottom topography do not appear in the 2-D modelling, *e.g.* the break off of the large inlet whirl. Because of this, 3-D modelling of stormwater ponds is desirable.

Conclusions from Paper VI

The most important findings in Paper VI are that the flow pattern should be modelled in 3-D to include the effects from the variations in bottom topography and that the pond outlet has to be designed properly to avoid dead zones and low effective pond volume.

PART 4 DISCUSSION AND CONCLUSIONS

Stormwater treatment in open ponds can be everything from very effective pollutant removal to poor performance. When studying ponds and removal efficiency it is important to consider the difference between different stormwater pollutants. Suspended solids and other particulate-bound pollutants are to a great extent removed in stormwater ponds by sedimentation processes, while dissolved pollutants are removed through chemical and biological processes.

It has been observed in field measurements (in Sweden) that pollutant removal rates vary from negative removal up to almost 100% removal of particulate-bound pollutants during single storm events, due to variation in rain characteristics. A pond should therefore not be classified as good or bad from a single event only. Long-term performance of the pollutant removal efficiency, determined for several successive storm events during a longer period of time is preferable. From field measurements, variations in pollutant removal efficiency between different ponds have been identified. This is caused by two major factors; first, difference in catchment load *i.e.* connected impervious area in relation to pond area, defined as specific pond area, and second, difference in pond geometry.

For heavy loaded ponds, the entire pond volume was usually exchanged, theoretically, during even minor storm events, 3-4 mm rain depths. In spite of this, pollutant removal efficiencies from 20% to 40% will be obtained. Ponds with low catchment loads where the pond volume is seldom exchanged, only at extreme rain depths of 50-100 mm, show pollutant removal efficiencies from 80% up to almost 100%. Stormwater ponds in between these extremes do not exhibit a linear relation in removal efficiency but a curve that flattens out at higher specific pond areas. It seems that above a certain level of specific pond area (250 m^2/ha), a further increase does not considerably affect the removal efficiency for most of the pollutants. Apparently, it is not necessary to over-size a low loaded stormwater pond since a doubling of the pond volume will only yield a marginal increase in pollutant removal efficiency. On the other hand, doubling the volume of a heavy loaded pond will cause a significant increase in removal efficiency. This finding is valuable for pond designers and has not been found in any of the other stormwater pond investigations that put a great emphasis on accuracy in stormwater sampling and flow measurement. Attempts to model and extrapolate metal and nutrient removal efficiencies, for different specific pond areas, have been carried out, but based only on results from measured TSS removal (Wu, 1989).

One criticism against the approach, of pollutant removal efficiency as a function of specific pond area, is that the created curves are valid only for ponds in southern Sweden, due to variations in hydrology in different climates. Consequently, the removal efficiency should be compared to a variable that takes both a hydrological and a pond size parameter into account, *e.g.* the pond surface area over the event mean volume. If this transformation is made, the approach will be applicable all over the world and not only in southern Sweden or other areas with similar rain characteristics. This new approach will occupy one of the studies to be carried out after the dissertation.

The occurrence of particle and particulate-bound pollutant removals in a stormwater pond, during a normal year, was 90% during dry periods, with no stormwater inflow. The captured stormwater volume in the pond is undergoing a water quality improvement during the dry period since the suspended particles and associated pollutants settle, from large particles that are settled down immediately, to, depending on the dry period length, smaller particles that flocculate and settle. Despite extensive dry periods, there is always a residue of small and light particles that will not be removed and that will be transported out through the outlet at the following storm event. These small particles of course transport other particulate-bound pollutants out through the pond. Cumulative pollutographs, pollutant mass as a function of stormwater volume, are created for influent and effluent stormwater pollutants. Effluent pollutants show an almost linear curve where the gradient is defined as an outflow pollutant load factor, which can be expressed in mg/l. This finding is very useful when the annual pollutant load from a stormwater pond to the receiving waters is to be determined, but further research is needed from more stormwater ponds to find out if there is any relation between pollutant load and specific pond area. For particulate-bound pollutants, the linear outflow pollutant curve is a confirmation that the outflow always contains small, not removable, particles. Therefore, 100% pollutant removal is an impossible goal to reach.

If a very heavy loaded stormwater pond is a result of limited available building area for the pond, one measure to reduce the load is to construct an upstream overflow that reduces the peak flows and thus the stormwater volume entering the pond. This measure prevents resuspension and erosion of the bottom sediment in the pond and, consequently, the pond outflow pollutant mass transport. However, field measurements show that the highest inflow pollutant concentrations appear at these heavy events and then divert untreated stormwater, with significant pollutant mass, directly to the receiving waters.

Problems with overloaded stormwater ponds lead to another important aspect of pond design, namely pond geometry. Pond geometry strongly affects the internal flow pattern and consequently the hydraulic performance of the pond. The internal flow pattern can be completely mixed, short-circuiting or plug-flow. Efforts to avoid short-circuiting flow, where a great part of the pond volume becomes inactive, with almost zero flow, cannot be overemphasised since the effective pond volume and pond area will be reduced. Reduced pond volume leads to overloaded ponds with decreased pollutant removal efficiency. For stormwater treatment purposes, ponds would be designed so that plug-flow regimes appear during storm events, in order to capture as large an inflow stormwater volume as possible simultaneously with the release of treated stormwater, from prior events, out from the pond.

From the literature, modelling of flow pattern in ponds with different geometry (square and rectangular) shows, for some types, short-circuiting flow, and for other types, plug-flow regimes (Persson, 1999). In practical pond design, pond geometry also needs to be aesthetic, why the selected shape is not only an isolated geometrical type, but a combination of several types or a completely irregular pond shape. If a non-standard pond geometry is chosen, it is necessary to examine the pond flow regime, with some

3-D flow modelling tool, to find out if the pond design is effective enough and yields sufficient effective pond volume.

The 3-D flow modelling of internal flow pattern in investigated stormwater ponds has been carried out by FIDAP, and the results show very good agreement with field measurements. This flow-modelling tool is useful for investigation of flow pattern and particle transportation in stormwater ponds, with arbitrary geometry. It has also been obvious that modelling of flow pattern in 2-D does not include bottom variations, why 3-D modelling is necessary. Since 3-D modelling is a quite time-consuming effort, which entails extra design costs (about 50 000 Swedish crowns), it is not used in pond design today. On the other hand, the investment costs for a stormwater pond construction are so high (a million Swedish crowns) that a flow modelling study certainly ought to be carried out.

A simple model for TSS removal efficiency calculation is created. TSS removal calculations are carried out for several ponds with various catchment loads (specific pond area) during a normal year of stormwater inflow. It was seen that the removal efficiency curves, for three different particle densities, flatten out above a specific pond area of 200 m^2/ha, like the observed TSS removal efficiency curve, which flattens out above 250 m^2/ha. It was also seen that the observed curve appears underneath the three modelled curves. As described earlier, effective and total pond area and pond volume normally differ in observed ponds, during storm events, depending on flow regime (short-circuiting flow and dead zones in the pond). The model ponds do not have these differences since they are theoretical, with 100% effective pond area and volume. The specific pond areas for the observed ponds must be corrected, as they suffer from short-circuiting and, consequently, the specific pond area should be reduced. This means that the observed curves should be moved to the left in the graph to fit the modelled curves better.

A final aspect of appropriate pond size is that large ponds, deep ponds in particular, run the risk of becoming anoxic near the pond bottom, especially during long dry periods, when no inflow stirs the pond water body, or during winter periods, when an ice layer covers the pond (Pettersson, 1996). From field measurements of effluent stormwater, it was seen that content of dissolved oxygen exhibit a distinct dip in the beginning of a storm event, which caused particulate-bound heavy metals to dissolve out into the pond water. Also high specific conductivity conditions in stormwater ponds, due to road salt, cause heavy metals to exclusively appear in a dissolved phase, except for lead where the effect is opposite. Lead then becomes more particulate-bound, up to 98%, due to favourable conditions for flocculation of colloids. The removal rates for the dissolved fraction during high specific conductivity are also affected; a deterioration of removal rates for dissolved zinc and copper since they decrease to negative values, -3% and -14% respectively but a distinct improvement of removal rate for dissolved lead, 86%.

Metals in soluble fraction not only appear after long dry periods, but also during more dynamic conditions (rainy periods with short dry periods). Zinc and copper mainly appear in the soluble fraction while lead, again, appears principally in the particulate-bound fraction. It has been shown that lead is associated with the smallest stormwater particles (0-5 μm). Lead seems to be more mixed in the pond and distributed out into more inactive parts of the pond, why the transport of lead out from the pond is not as rapid as, for instance, TSS that has a more short-circuiting behaviour. Zinc seems to spread out even more in the pond than lead due to the fact that the transport of zinc out from the pond is slow during a storm event. In spite of the retention of the dissolved pollutants in the pond, the removal efficiency of these pollutants is quite low.

This thesis has the focus on pollutant removal efficiency in stormwater ponds, where mainly solids and particle attached pollutants have been studied, especially metals. Nevertheless, nitrogen and phosphorus are two important nutrients that only briefly have been investigated in this work. They can cause a lot of trouble in the receiving waters when they are found in too high concentrations, but since stormwater only contains a smaller amount of nutrients, this is not a big issue for stormwater treatment in open ponds. If these pollutants appear in high concentrations, contrary to expectation, stormwater ponds only remove them to a certain degree. Nitrogen, in some ponds, even increases from inlet to outlet, shown in Ferrara (1982), which was also seen in the large Järnbrott pond during some storm events. A more effective way to reduce nutrients is to use wetlands since they hold more vegetation and promote biological uptake. A combination of stormwater ponds and wetlands is very effective when removal of solids, metals and nutrients is aimed at (Johansson, 1997).

From these investigations, the following conclusions can be drawn:

- A pond should not be classified as good or bad based on a single storm event only. Different pollutant removal rates in an open stormwater pond are obtained at different storm events derived from rain characteristics.

- The investigation showed that the pollutant removal efficiency varies depending on the specific pond area (the ratio of pond area and impervious catchment area) and that the removal efficiency does not noticeably improve above 250 m^2/ha for most of the pollutants.

- The pond volume should be large enough to catch most of the stormwater entering the pond and remain until the next event since more than 90% of the pollutant removal takes place during dry periods.

- The pond volume should not be so large that it becomes anoxic with particulate metals dissolving out in the bottom sediment.

- For very heavy loaded ponds, the removal efficiency for the pond itself may be improved by adding an upstream overflow that cuts off the peak flows and decreases the number of storm events exceeding the effective pond volume. The diverted stormwater contains, however, high pollutant concentrations that need to be stored or taken care of.

- Sediment associated pollutant load in the outflow, from a stormwater pond during storm events, shows an almost linear relationship to stormwater volume, independently of variation in inflow pollutant load. It seems that every stormwater pond has a unique outflow pollutant load coefficient. These load coefficients are useful when extrapolation of annual outflow pollutant loads to the receiving waters is intended.

- Pollutant removal efficiencies from some short-circuiting ponds clearly fall below the pollutant removal efficiency curve (as a function of specific pond area) created from investigated ponds. This deviation can be derived from pond geometry that strongly affects the effective pond volume. Circular ponds cause short-circuiting flow while ponds that have a large length to width ratio cause a more uniform flow distribution.

- At the outlet of stormwater ponds it has been seen that dead zones exist, due to widening of the pond and narrow outlet sections. The stormwater flow behaves, as a result of the canalisation at the outlet, as a short-circuiting flow. To find a remedy for this, additional outlets could help split up the main stream. Wider outlet or alternatively locations of the outlet could also yield a more uniform flow distribution. This would increase the effective pond volume.

- FIDAP is a 3-D flow-modelling tool that can be used to predict internal flow pattern and particle removal in open stormwater ponds with arbitrary geometry.

- When simulations of internal flow pattern are intended, it is important that the model takes account of the topography of the bottom. In this work it has been shown that 2-D models produce incorrect flow patterns while 3-D models produce satisfactory results.

- Dissolved pollutants diffuse out into the detention pond to the more or less hydraulically inactive parts. This means that the transport of dissolved pollutants out of the pond is even slower than for the smallest particles. However, the dissolved pollutant removal rates are low.

- Heavy metals are to a great extent in dissolved phase in a stormwater pond during high specific conductivity with the exception of lead, which increases its particulate-bound part due to flocculation of colloids. This is favourable under these conditions as well as improves the removal rate for dissolved lead.

- Contents of dissolved oxygen in the pond effluent exhibit a distinct dip in the beginning of a storm event followed by a clear peak. These effects are derived firstly from mixed up stormwater from the bottom layer of the pond with low oxygen content and secondly by a mixing of influent, aerated stormwater in the pond.

- It has been shown from field measurements that the behaviour of internal flow patterns, in each studied pond, in general does not change with various inflow intensities. Modelled flow pattern in 3-D also showed the same behaviour. This almost stable flow pattern, for different inflow intensities, has the advantage that it causes the inflow stormwater particles to be transported and thus settled in the same region of the pond. The risk of altering the flow pattern appearance is that a great deal of the bottom sediment (light particles) could be eroded.

- The inlet pond geometry would be designed so that the inflow whirls are reduced and forced to rotate in only one direction during storm events, to prevent resuspension.

- Nitrogen is only removed to a certain degree and occasionally increased in the pond, why wetlands are more suitable for nitrogen removal.

PART 5 REFERENCES

Abustan, I. and Ball, J. E. (1998). Modelling the export of phosphorus from urban catchments. In: *Proc. HydraStorm'98*, Adelaide, Australia, 45-50.

Adamsson, Å., Persson, J. and Lyngfelt, S. (1999). Numerical simulation and large-scale physical modelling of flow in a detention pond. In: *Proc.* 8th *Int. Conf. Urban Storm Drainage,* Sydney, Australia, vol 3, 1175-1183.

Akan, A. O. (1988). Derived frequency distribution for storm runoff pollution. *J. Env. Eng.*, **114**(6), 1344-1351.

Amandes, C. B. and Bedient, P. B. (1980). Stormwater detention in developing watersheds. *J. Env. Eng.*, **106**(2), 403-419.

ATSDR, (1990). Polycyclic aromatic hydrocarbons (PAHs). Agency for Toxic Substances and Disease Registry, Division of Toxicology. Atlanta, Georgia, USA. (Internet information; http://atsdr1.atsdr.cdc.gov:8080/ToxProfiles/phs9020.html).

Boyd, M. (1993). Effects of detention storage on downstream flooding. In: *Proc. 6th Int. Conf. Urban Storm Drainage*, Niagara Falls, Ontario, Canada, 1043-1048.

Chebbo, G. and Bachoc, A. (1992). Characterization of Suspended Solids in Urban wet Weather Discharges. *Wat. Sci. Tech.*, **25**(8), 171-179.

Chui, T. W., Mar, B. W. and Horner, R. R. (1982). Pollutant Loading Model for Highway Runoff. *J. Env. Eng.*, **108**(EE6), 1193-1210.

Clemens, F. H. L. R., van Mameren, H. J. and Kollen, J. (1993). Optimising the efficiency of storm water settling basins by means of bypassing. *Wat. Sci. Tech.*, **27**(5-6), 105-110.

Culp, D. E. and Doering, J. C. (1995). Urban Stormwater Treatment Pond Volume Optimization for a Horizontal Orifice Outflow Device. *International Water Resources Engineering Conference-Proceedings*, New York, USA, **2**, 1263-1267.

Curtis, D. C. and McCuen, R. H. (1977). Design efficiency of stormwater detention basins. *J. Wat. Res. Plan. Man. Div.*, ASCE, **103**, 125-140.

Cutbill, L. B. (1993). Urban stormwater treatment by artificial wetlands: A case study. In: *Proc. 6th Int. Conf. Urban Storm Drainage*, Niagara Falls, Ontario, Canada, 1068-1073.

Duncan, H. P. (1998). Urban stormwater quality improvement in storage. In: *Proc. HydraStorm'98*, Adelaide, Australia, 203-208.

Ellis, J. B., Revitt, D. M., Harrop, D. O. and Beckwith, P. R. (1987). The contribution of highway surfaces to urban stormwater sediments and metal loading. *Sci. Total Environ.*, **59**, 339-349.

Ellis, J. B., Hall, M. J. and Packman, J. C. (1995). Modelling water quality for urban flood storage reservoirs. *Envir. Int.*, **21**(2), 177-186.

Felstul, D. R. and Montgomery, J. M. (1991). Modeling the reduction of sediment-bound toxics by detention basins. *Aquatic Toxicology and Risk Assessment*, **14**, 294-304.

Ferrara, R. A. (1982). Stormwater detention and nonpoint source pollution control. *In Int. Symp. on Urban Hydrology, Hydraulics & Sediment Control*, Lexington, Kentucky Univ., USA.

Field R., Brown M. P (1994). Stormwater Pollution Abatement Technologies. U.S. Environmental Protection Agency, NJ, USA.

Gain, W. S. (1996). The effects of flow-path modification on water-quality constituent retention in an urban stormwater detention pond and wetland system, Orlando, Florida. Water-Resources Investigations Report 95-4297, U.S. Geological Survey, Tallahassee, Florida, USA.

Greb, S. R. and Bannerman, R. T. (1997). Influence of particle size on wet pond effectiveness. *Water Environ. Res.*, **69**(6), 1134-1138.

Hall K. and Anderson B. C. (1988). The toxicity and chemical composition of urban stormwater runoff from a commercial land use. *Can. J. Civ. Eng.*, **15**, 98-106.

Hazen A. (1904). On sedimentation. *Trans Am. Soc. Civ. Eng.*, **53**, 53-62.

Hvitved-Jacobsen, T. and Yousef, Y. A. (1988). Analysis of Rainfall Series in the design of Urban Drainage Control Systems. *Wat. Res.*, **22**(4), 491-496.

Johansson M. (1997). Separation of Stormwater Pollution - Study of the Bäckaslöv sedimentation basin and wetland. Master Thesis 1997:9, Dept. of Sanitary Engineering, Chalmers University of Technology, Göteborg, Sweden.

Lloyd, S. D., Wong, T. H. F., Liebig, T. and Becker, M. (1998). Sediment characteristics in stormwater pollution control ponds. In: *Proc. HydraStorm'98*, Adelaide, Australia, 209-214.

Lundberg, K., Carling, M. and Lindmark, P. (1998). Treatment of highway runoff - A study of three detention ponds. Submitted paper to *Sci. Tot. Envir.*

Maestri, B. and Lord, B. N. (1987). Guide for mitigation of highway stormwater runoff pollution. *Sci. Total Environ.* **59**, 367-376.

Malmqvist, P-A. (1984). Urban stormwater pollutant sources. PhD-thesis, Dept. of Sanitary Engineering, Chalmers University of Technology, Göteborg, Sweden.

Marsalek, J., Watt, W. E., Anderson, B. C. and Jaskot C. (1997). Physical and chemical characteristics of sediments from a stormwater management pond. *Water Qual. Res. J. Canada*, **32**(1), 89-100.

Marsalek, J., Krishnappan, B. G., Watt, W. E. and Anderson, B. C. (1998). Size distribution of suspended sediments in an on-stream stormwater management pond. In: *Proc. Novatech'98, 3rd Int. Conf. Innovative technologies in urban storm drainage*, Lyon, France, vol 1, 543-550.

Marsalek, P. M., Marsalek, J., Watt, W. E. and Anderson, B. C. (1998). Winter Regime of an On-Stream Stormwater Management Pond: (I) Physical Aspects. An interim report, Dept. of Civil Engineering, Queen's University, Kingston, Ont., Canada.

Martin, E. H. (1988a). Effectiveness of an urban runoff detention pond-wetlands system. *J. Env. Eng.*, **114**(4), 810-827.

Martin, E. H. (1988b). Mixing and residence times of stormwater runoff in a detention system. In: *Design of Urban Runoff Quality Controls - Engineering Foundation Conference*, Potosi, MO, 164-178.

Mayer, T., Marsalek, J. and Delos Reyes, E. (1996). Nutrients and metal contaminants status of urban stormwater ponds. *J. Great Lakes Res.*, **12**(3), 348-363.

Medina, M. A., Huber, W. C. and Heaney, J. P. (1981). Modeling stormwater storage/treatment transients: Theory. *J. Env. Eng.*, **107**(4), 781-797.

Mesuere, K. and Fish, W. (1989). Behavior of runoff-derived metals in a detention pond system. *Water, Air and Soil Pollution*, **47**, 125-138.

Mikkelsen, P. S, Weyer, G., Berry, C., Walden, Y., Colandini, V., Poulsen, S., Grotehusmann, D. and Rohlfing, R. (1994). Pollution from urban stormwater infiltration. *Wat. Sci. Tech.*, **29 (1-2)**, 293-302.

Morrison, G. M. P., Revitt, D. M., Ellis, J. B., Svensson, G. and Balmer, P. (1984). Variation of dissolved and suspended solid heavy metals through an urban hydrograph. *Envir. Technol. Letters*, **7**, 313-318.

Nightingale, H. I. (1987). Accumulation of As, Ni, Cu and Pb in retention and recharge basins soils from urban runoff. *Wat. Res. Bull.*, **23**(4), 663-672.

Nix, S. J., Heany, J. P. and Huber, W. C. (1988). Suspended solids removal in detention basins. *J. Env. Eng.*, **114**(6), 1331-1343.

Ota, J. J., Nalluri, C. and Perrusquia, G. (1999). Graded sediment transport- the influence of particle size on sediment transport over deposited bed in sewers. In: *Proc. 8th Int. Conf. Urban Storm Drainage*, Sydney, Australia, .

Perrusquia G. (1991). Bedload transport in storm sewer. PhD-thesis, Dept. Hydraulics, Chalmers University of Technology, Göteborg, Sweden.

Persson, J. (1999). The hydraulic performance of ponds of various layouts. Paper submitted to: *J. Urban Water*.

Pettersson, T. J. R. and Svensson, G. (1995). Utjämningsmagasin för dagvatten. *Bygg & Teknik*, **5**. (in Swedish).

Pettersson T. J. R. (1996). Pollution Reduction in Stormwater Detention Ponds - Field study and modelling experiments. Licentiate thesis, Dept. of Sanitary Engineering, Chalmers University of Technology, Göteborg, Sweden.

Pitt R. (1985). Characterizing and controlling urban runoff through street and sewerage cleaning. EPA/600/S2-85/038, U.S. Environmental Protection Agency, Water Engineering Research Laboratory, Cincinnati, Ohio, USA.

Randall, C. W. (1982). Stormwater detention ponds for water quality control. In: *Proc. Stormwater Detention Facilities - Planning, Design, Operation and Maintenance*, Henniker, New Hampshire, USA, 200-204.

Rushton, B. (1992). Water quality and hydrologic characteristics of a wet detention pond. In: *National Conference on Water Resources Planning and Management, Water Forum ´92*, Baltimore, MD, USA, 878-883.

Sansalone, J. J., Buchberger, S. G. and Koechling, M. T. (1995). Correlation Between Heavy Metals and Suspended Solid in Highway Runoff: Implications for Control Strategies. In: *Transp. Res. Rec.*, **1483**, 112-119.

Sansalone, J. J. and Buchberger, S. G. (1997a). Characterization of Solid and Metal Element Distribution in Urban Highway Stormwater. *Wat. Sci. Tech.*, **36** (8-9), 155-160.

Sansalone J. J., Buchberger S. G. (1997b). Partitioning and First Flush of Metals in Urban Roadway Storm Water. *J. Env. Eng.*, **123**(2), 1-10.

Scanlon, P., O'Neill, I., Hughes, R. and McMahon, T. (1998). Stratification and pollution control pond efficiency. In: *Proc. HydraStorm'98*, Adelaide, Australia, 215-219.

Schroeter, H. O. and Watt, W. E. (1989). Practical simulation of sediment transport in urban runoff. *Can. J. Civ. Eng.*, **16**, 704-711.

Schueler, T. R. (1987). Controlling urban runoff: A practical manual for planning and designing urban BMPs. Metropolitan Washington Council of Governments, Washington, D.C., USA.

Sear, T. R. and van Ravenswaay, B. (1992). Efficient sizing of storm water treatment ponds. In: *Proc. Water Resources Sessions at Water Forum '92*, 780-785.

Sharma, M., McBean, E. A. and Marsalek, J. (1997). Source characterization of polycyclic aromatic hydrocarbons in street and creek sediments. *Water Qual. Res. J. Canada*, **32**(1), 23-35.

Stahre, P. (1993). Assessment of BMP´s being used in Scandinavia. In: *Proc. 6th Int. Conf. Urban Storm Drainage*, Best Management Practices (1), Niagara Falls, Ontario, Canada, 939-944.

Striegl, R. G. (1987). Suspended sediment and metals removal from urban runoff by a small lake. *Water Res. Bull.*, **23**, 985-996.

Svensson, G. (1987). Modelling of Solids and Metal Transport from Small Urban Watersheds. PhD-thesis, Dept. of Sanitary Engineering, Chalmers University of Technology, Göteborg, Sweden.

Thackston, E. L., Shields, D. (Jr) and Schroeder, P. R. (1987). Residence time distribution of shallow basins. *J. Env. Eng.*, **113**(6), 1319-1332.

Toet, C., Hvitved-Jacobsen, T. and Yousef, Y. A. (1990). Pollutant removal and eutrophication in urban runoff detention ponds. *Wat. Sci. Tech.*, **22**(10/11), 197-204.

Urbonas, B. and Stahre, P. (1993). Stormwater: Best management practises and detention for water quality, drainage and CSO management. *Prentice-Hall, Inc.*, Englewood Cliffs, New Jersey 07632, USA. (ISBN 0-13-847492-3)

US EPA (1986). Methodology for analysis of detention basins for control of urban runoff quality. EPA440/5-87-001, U.S. Environmental Protection Agency, USA.

Van Buren, M. A., Watt, W. E., Marsalek, J. (1996). Enhancing the removal of pollutants by an on-stream pond. *Wat. Sci. Techn.*, **33**(4-5), 325-332.

Van Buren, M. A., Watt, W. E. and Marsalek, J. (1997). Removal of urban stormwater constituents by an on-stream pond. *J. Environ. Plan. Mgmt.*, **40**(1), 5-18.

Wang, H. K. and Wood, J. M (1984). Bioaccumulation of Nickel by algae. *Environ. Sci. Technol.*, **18**(2), 106-109.

Watt, W. E. and Paine, J. D. (1993). Instrumentation and monitoring of stormwater ponds: A case study. In: *Proc. 6th Int. Conf. Urban Storm Drainage,* Niagara Falls, Ontario, Canada, 1037-1042.

Wei, C. and Morrison, G. M., (1992). Bacterial enzyme activity and metal speciation in urban river sediments. *Hydrobiologia*, **235/236**, 597-603.

Wei, C. (1993). Metal speciation and toxicity in urban river sediments. PhD-thesis, Dept. Sanitary Engineering, Chalmers University of Technology, Göteborg, Sweden.

Whipple, W. (Jr) and Hunter, J. V. (1981). Settleability of urban runoff pollution. *J. Wat. Poll. Contr. Fed.*, **53**(12), 1726-1731.

Wren, C. D. and Bishop, C. A. (1996). Risk of chemicals in stormwater ponds and constructed wetlands to fish and wildlife. In: *Proc. 31st Central Canadian Symp. on Water Poll. Res.*, Burlington, Canada.

Wu, J. S. (1989). Evaluation of detention basin performance in the Piedmont region of North Carolina. Project No. 70077, Dept. of Civil Engineering, The University of North Carolina at Charlotte, Charlotte, North Carolina, USA.

Yousef, Y. A. and Wanielista, M. P. (1993). Runoff quality enhancement in wet detention ponds. In: *Proc. Symposium on Engineering Hydrology,* San Francisco, CA, USA, 665-670.

Yu, S. L., Li, D. and Hwang, B. G. (1993). Estimating detention pond efficiency by a derived distribution approach. In: *Proc. Symp. Engineering Hydrology*, San Francisco, CA., USA, 671-676.