VA-teknik
CHALMERS

CHALMERS UNIVERSITY OF TECHNOLOGY
Department of Sanitary Engineering
S-412 96 GÖTEBORG
Sweden
Telephone Nat 031 - 772 10 00
Int +46 31 772 10 00

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LICENTIATE THESIS

Pollution Reduction in Stormwater Detention Ponds

Field study and modelling experiments

THOMAS JR PETTERSSON

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element program, FIDAP, for one storm event. A 3-dimensional flow field was calculated with a turbulence model applied. With the particle trace function, included in FIDAP, three different sizes were released in the flow field at the inlet and particle removal was calculated. Results from the particle removal calculations showed good agreement for the larger particles but poor agreement for the smallest particles compared to observed removal rates. However the particle characteristics need to be more investigated to get more accurate results from the FIDAP modelling.

Sammanfattning

Figurer, tabeller och ekvationer presenterade i denna avhandling refereras i denna svenska sammanfattning på samma sätt som avhandlingen i övrigt med det undantaget att även benämningen är översatt till svenska (ex tabell 3.1 istället för Table 3.1).

Syfte
Arbetet som redovisas i denna avhandling är en undersökning av ett öppet utjämningsmagasins förmåga att avskilja dagvattenföroreningar. Målet med arbetet har varit att få en bild av hur ett öppet utjämningsmagasin för dagvatten fungerar och hur dess förmåga är som föroreningsavskiljare under enskilda tillfällen. Även långtidseffekter för magasinet bör studeras där funktionen för flera på varandra följande regn skall undersökas. Ett framtida mål är att kunskaper om ett magasins uppträdande skall kunna användas till att skapa en modell till att förutsäga föroreningsavskiljningen för olika dagvattenmagasin med varierande geometrier och storlekar. Finita element beräkningar med FIDAP avses att genomföras för ett befintligt magasin där flödesförhållanden och partikelavskilning kommer att simuleras.

Introduktion
Regn som faller på exploaterade områden i urban miljö blir till förorenat dagvatten som är skadligt för miljön. Föroreningar som ofta förekommer i dagvatten är suspenderat material (SS), partiklar, tungmetaller, polyaromatiska kolväten (PAH) och närsalter såsom kväve och fosfor (tabell 1.1). Vatten är ett bra lösningsmedel för flertalet föroreningar och blir därmed ett av dess viktigaste transportmedel. Modellering av föroreningstransport i dagvatten över urbana markytor påbörjades redan under 1970-talet och är något man idag har god kunskap om.

Då en betydande del av dessa föroreningar är kopplade till partiklar av olika slag, kan en stor del av föroreningarna avskiljas genom sedimentering och därmed minska belastningen på recipienten. Detta kan åstadkommas genom att t ex anlägga någon form av dagvattenmagasin innan vattnet når recipienten.

Öppna utjämningsmagasin har uteslutande använts till att *utjämna stora dagvattenflöden* men på senare tid har de även uppmärksammats som en *alternativ reningsmetod* för dagvatten, eftersom utjämningsmagasinen bromsar upp vattenhastigheten och möjliggör sedimentering av partiklar. Undersökningar har visat att belastningen av SS och tungmetaller minskade med 45-65 % då dagvattnet passerade igenom ett öppet utjämningsmagasin, med ständig vattenspegel. Resultaten har medfört att dessa magasin idag är en vanlig reningsmetod för dagvatten. Dock har undersökningarna rörande öppna utjämningsmagasins föroreningsreducerande funktion ofta gjorts som stickprovsanalyser på inkommande och utgående dagvatten. Sällan har mer än ett par regntillfällen i följd studerats varför dess långtidsverkande effekter ej är välkända. Under vinterförhållanden minskar syrehalten, på grund av isläggning, i magasinet vilket i sin tur påverkar bottensedimentens löslighet t ex. tungmetaller löses i vattnet. Detta är inte väl känt. Detta faktum ger vid handen att det finns ett behov av ytterligare undersökningar av långtidseffekter och vinterförhållanden i dessa utjämningsmagasin.

Ingenjörsmässiga uppskattningar av föroreningsreduktionen i dagvatten då det passerar igenom ett öppet utjämningsmagasin baseras på enkla beräkningar av partikelavskiljningen. Beräkningar av uppehållstider i magasinet förutsätter ofta "pluggflöde" samt laminära och stationära strömningsförhållanden, vilka är ovanliga i naturliga vatten (ekv 1.1). Enkla sedimenteringsmodeller, t ex Stokes lag (ekv 1.2), används för att beräkna partiklarnas sjunkhastighet som tillsammans med uppehållstiden ger de olika partiklarnas avskiljningsgrad. För att kunna beräkna partikelavskiljningen under turbulenta föhållanden krävs mer grundläggande ekvationer såsom Navier-Stokes lag med medelvärdesbildade tryck- och hastighetskomponenter (ekv 1.3; 1.4). Dessa ekvationer kan endast lösas numeriskt men detta är tidskrävande och eftersom magasinet måste delas upp i många små element, används oftast finita differensmetoden (FDM) eller finita elementmetoden (FEM). Ett exempel på FEM-program är FIDAP som har använts som modelleringsverktyg i denna avhandling.

Utjämningsmagasinet vid Järnbrott

Undersökningar och mätningar som presenteras i denna studie är från ett öppet utjämningsmagasin för dagvatten i Järnbrott beläget 5 km söder om Göteborgs centrum. Magasinet har en volym av 420 m^3 och tillhörande avrinningsområde har en hårdgjord yta på 2,6 ha som består av parkeringsytor, en medeltrafikerad väg, en restaurang och en bensinstation (figur 2.1; tabell 2.1). Magasinet har försetts med kontinuerlig flödes- och turbiditetsmätning vid inlopp och utlopp. Två flödesproportionella provtagare, med 24-flaskor vardera som styrs av instrumenten för flödesmätning har också placerats vid magasinets in- och utlopp. Halten löst syre i magasinet och nederbördsmängden har också mätts kontinuerligt. Alla mätdata har kontinuerligt lagrats i en datalogger tillsammans med information om tid för provtagning och flasknummer (figur 2.2).

Analyser som gjorts på de flödesproportionella dagvattenproverna är följande:

- halten suspenderat material, total och organisk halt (TSS och VSS)
- partikelstorleksfördelning (med ett partikelräknarinstrument)
- halten tungmetaller (zink, koppar, bly och kadmium)
- halten närsalter (kväve och fosfor)

Mätprogrammet påbörjades i juli 1995 och pågår fortfarande.

Analys och mätresultat från Järnbrottsmagasinet

Totalt har 18 regntillfällen analyserats helt eller delvis vilket är redovisat i appendix A. Analyser av SS och partikelstorleksfördelning har gjorts på inkommande och utgående dagvatten för samtliga regntillfällen med några undantag. Totalt tungmetallinnehåll har analyserats för sju regntillfällen och löst tungmetallhalt har analyserats för ett av dessa. Totala kväveinnehållet har analyserats för tre regntillfällen och fosforhalten som fosfatfosfor (PO_4-P) för två regntillfällen. Halten lösta tungmetaller i magasinet under vinterförhållanden har också mätts.

I denna avhandling har detaljstudier av Järnbrottsmagasinets förmåga att avskilja föroreningar för enstaka regntillfällen gjorts där i huvudsak tre regntillfällen har studerats för halterna SS och tungmetaller, redovisade i appendix B, och två regntillfällen för kväve och fosfor, redovisade i appendix C. In- och utflöden har tillsammans med föroreningshalter under regntillfällena redovisas i diagramform. Långtidseffekter av utjämningsmagasinets förmåga att avskilja föroreningar har också gjorts där flera, på varandra följande, regn har sammanställts. För SS och tungmetaller har effekter av 5-7 regntillfällen ställts samman och för kväve och fosfor har två regntillfällen ställts samman. Detta redovisas i form av ackumulerade föroreningsmängder som funktion av ackumulerad dagvattenvolym som passerat igenom magasinet.

I figur 3.1, där en avrinningshydrograf för regntillfället 5 oktober visas, ser man det typiska mönstret för ett utjämningsmagasin med en utjämnad hydrograf för utgående flöde. Detta är förutsättningen för att partiklar skall kunna sedimentera i magasinet. I figur 3.2 ser man att inkommande föroreningshalter är tydligt flödes- och tidsberoende. Man ser också att utgående föroreningshalter är mycket lägre men att halterna ökar konstant under hela regntillfället. Partikelytan av det suspenderade materialet har beräknats genom att dagvattenpartiklarna antagits vara sfäriska (se kapitel 3.3). I figur 3.2 visar det sig att de minsta partiklarna (1-5 µm) i inkommande dagvatten förekommer främst i början av regntillfället. I det utgående dagvattnet uppträder dessa partiklar mer jämnt fördelat under hela regntillfället, och "halten" små partiklar är mycket lägre än för inkommande dagvatten. Detta visar att även de små partiklarna avskiljs i utjämningsmagasinet. I figur 3.3, där föroreningshalterna för (TSS) och totalt bly är presenterade för tre olika regntillfällen, ser man en markant skillnad i halter för de båda regnen. T ex är halterna TSS och totalt bly i inkommande dagvatten högre för regntillfället 17 oktober än 15-16 november trots att inflödet är högre för 17 oktober än för 15-16 november. Denna avvikelse kan till viss del förklaras med att regnmängden var större för 15-16 november än för 17 oktober (tabell 3.1). I tabell 3.2, där avskiljningen SS och tungmetaller för dessa regntillfällen är redovisade, ser man att avskiljningsgraden för regntillfället 15-16 november är mycket lägre än för 17 oktober. I tabell 3.1 ser man att torrperioden, tiden från föregående regntillfälle, är mycket längre för 17 oktober (10 dygn) än för 15-16 november (0.5 dygn). Tiden mellan regntillfällena inverkar tydligen starkt på utjämningsmagasinets förmåga att reducera inkommande föroreningar.

I figur 3.4, där föroreningsavskiljningens långtidseffekter är uppritade, varierar den inkommande ackumulerade föroreningskurvan märkbart för alla redovisade föroreningar men för den utgående belastningen är kurvan relativt rak, med ett litet undantag för koppar och zink. Som väntat är det de partikelbundna föroreningarna (TSS, VSS, bly och kadmium) som avskiljs mest, dvs de kurvor som divergerar mest i figur 3.4. Detta blir även uppenbart i tabell 3.3 där siffrorna visar att dessa föroreningar avskiljs till ca 50 %. Koppar och zink däremot avskiljs till 20 % respektive 28 %.

Kväve- och fosforavskiljningen i utjämningsmagasinet har analyserats för tre respektive två regntillfällen, se tabell 3.4 (karakterisering av regntillfällen) och tabell 3.5 (avskiljning). Kväve uppvisade väldigt varierande resultat för de olika regnen och verkar vara beroende av regnmängd till viss del men mer beroende av torrvädersperioden som föregått, där längre torrvädersperiod ger kvävet möjlighet att avgå som kvävgas. För fosfor ser tidsberoendet inte ut att vara lika stort medan regnmängden däremot har stor inverkan.

I kapitel 3.5 har en jämförelse gjorts mellan den partikulära och lösta halten tungmetaller i dagvatten i förhållande till TSS-halten där kvoten kallas för "partition coefficient" K_D och har enheten (µg/l). Högt K_D-värde anger att metallerna i stor utsträckning är partikelbundna medan ett lågt K_D-värde anger att den lösta fasen dominerar. Från analyser av regntillfället 17 oktober uppvisar alla metaller, med undantag för bly, låga K_D-värden i inkommande dagvatten vilket innebär att de till stor del uppträder i löst fas. Bly däremot visar höga K_D-värden i inkommande dagvatten vilket visar på hög partikulär förekomst som tidigare nämnts. I utgående dagvatten visar alla metaller med undantag för koppar lågt K_D-värde i början av regntillfället som efterhand ökar för att sedan återigen minska.

Undersökningar av syrehalten och halten lösta tungmetaller i utjämningsmagasinet under vinterförhållanden gjordes vintern 1995-1996 då magasinet var täckt med is. Resultaten visar att syrehalten sjönk dramatiskt då isen lagt sig (figur 3.9) och att halten lösta tungmetaller ökat flerfalt under ett par månader (tabell 3.7).

Modellering

Vid en jämförelse mellan beräknad (enligt en metod rekommenderad av EPA, 1986) och observerad partikelavskiljning, för regntillfället den 17 oktober, för partiklar med storleken 1-45 μm visar det sig att den observerade avskiljningen av mindre partiklar är bättre än den teoretiskt beräknade. Samma jämförelse mellan beräknad (med FIDAP) och observerad partikelavskiljning för regntillfället den 15-16 november, visar på motsatsen (tabell 4.4.1). Orsaken till denna skillnad kan sökas i att de två olika regntillfällena föregåtts av olika långa torrperioder. För de större partiklarna ger de två teoretiska metoderna ungefär samma resultat trots att medelfödena från de båda regntillfällena som använts skiljer sig åt markant.

Diskussion

Noggrannheten i analysresultaten är i hög grad beroende av hur proverna är tagna och hur mätinstrumenten är placerade. Turbiditetsmätningarna fungerade dåligt på grund av bristande noggrannhet i kalibreringen. Provtagningsutrustningen vid inloppet och utloppet har fungerat väl men det bör påpekas att intagningsslangen vid utloppet är relativt lång, 14 m, och har en sughöjd på 3 m. Risken att större och tyngre partiklar avskiljes och inte når provflaskorna finns men dessa partiklar når i allmänhet ej utloppet varför detta ej har beaktats. Instrumentet för analys av partikelinnehåll i vatten har visat vissa tveksamma resultat då totala partikelinnehållet överstigit 10 000 partiklar/ml. Därför har proverna spätts till des att 4 000-7 000 partiklar/ml har uppnåtts. Detta har medfört stabilare resultat.

Resultaten från kapitel 3 visar att avskiljningen av dagvattenföroreningar i ett öppet utjämningsmagasin i stor utsträckning är beroende av nederbördsmängd och den torrperiod som föregått regntillfället. Man kan även dra slutsatsen att det inte går att förutsäga hur stor avskiljningsgraden av dagvattenföroreningar i ett magasin blir för en längre period bara med kunskap om avskiljningen för några enstaka regntillfällen. Avskiljningsgraden som har observerats i detta arbete gäller för 5-7 på varandra följande regntillfällen och det kan anses som en relativt god indikation på hur detta magasin fungerar över en längre period. Resultaten visar att ungefär 50 % av de föroreningar som är partikulärt bundna (SS, bly och kadmium) avskiljs och att 20-30 % av de mer lättlösliga föroreningarna (koppar och zink) avskiljs.

Slutsatser som kan dras för det utgående dagvattnet i magasinet är att de låga K_D-värdena (kapitel 3.5) i början av regnet beror på att de partikulärt bundna föroreningarna har sedimenterat sedan föregående regn och att det enbart finns lösta föroreningar i vattnet. Den kraftiga ökningen under regntillfället tyder på att de lätta organiska partiklarna som sedimenterat åter slammats upp vartefter de spolats ut ur dammen. Resultaten från mätningar av tungmetallinnehållet i magasinet som gjorts under vintern, indikerar att dessa typer av utjämningsmagasin bör tömmas på förorenat bottensediment före varje vinterperiod.

Fortsatta studier

De fortsatta studierna inom detta område bör inriktas på att skapa en modell som kan förutsäga ett godtyckligt utjämningsmagasins förmåga att avskilja föroreningar. Denna modell bör vara enkel i sitt utförande och skapas av noggranna simuleringar för olika typer av hypotetiska utjämningsmagasin. Simuleringarna som skall ligga till grund för den enklare modellen kan t ex vara fortsatta FEM-beräkningar med FIDAP. Partikelbanor och därmed sedimenteringen av olika partiklar skall simuleras för flera olika teoretiska utjämningsmagasin med varierande geometri och storlek. Kompletterande mätningar och analyser av dagvattenpartiklar bör också ingå och knytas samman med de FIDAP-simuleringar som kommer att utföras.

Det fortsatta forskningsarbetet inom detta projekt kan sammanfattas under följande två rubriker:

- Att fortsätta modellera partikelavskiljning med FIDAP för Järnbrottsmagasinet för olika regntillfällen, med förbättrade ingångsvärden för dagvattenpartiklar (storlek och densitet), till dess beräknad och observerad partikelavskiljning överensstämmer. Därefter bör olika magasinstyper (geometri och storlek) modelleras.

- Att fortsätta studera tungmetallers förekomst i magasinet för inkommande och utgående dagvatten för att undersöka vilka partiklar (storlek och material) som olika tungmetaller sitter häftade vid.

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1 INTRODUCTION

1.1 Stormwater pollution

In urban areas the natural water cycle is affected by an infrastructure, such as surfaces impervious to water, that concentrate flow and hinder infiltration. This causes higher stormwater velocities, thereby allowing the transport of pollutants attached to particles. Rain water 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 (1). Since raindrops have an erosive feature and water is a good solvent for different substances and compounds it will carry them through the urban area until they reach the receiving water with or without any stormwater clarification. Stormwater transport capacity of particles, solids and other materials, over urban areas, depends on topology, runoff intensity and urban-surface character. Models to predict pollutant transport in stormwater have been developed since the early 1970s (2) and the knowledge of this matter is rather good. After particles and sediment leave the urban surfaces, their transport continues through the sewer system where temporary sediment storage can build up in the pipe bottom by low stormwater velocities and later on be eroded by high velocities (3).

Stormwater in urban areas is polluted (Table 1.1) with heavy metals (*e.g.* lead, copper, cadmium and zinc) which are present in the particulate and dissolved phase. Other pollutants include organics such as poly-aromatic hydrocarbons (PAH) that are mostly attached to particles. Furthermore total and organic suspended solids (TSS and VSS) such as sand and clay together with nutrients, for example nitrogen and phosphorus compounds are present in urban stormwater (1, 4, 5).

It has been demonstrated that atmospheric fallout is the dominant source of nitrogen and phosphorus and an important source of zinc, lead and copper. Corrosion products from buildings are an important source of zinc and copper. Vehicular traffic is the dominant source of lead (up to the 1990s when lead-free petrol was introduced in Sweden) and an important source of zinc and nitrogen (1).

Table 1.1 Concentration of pollutants in urban stormwater (11).

Pollutant	Mean (mg/l)	Min-Max (mg/l)
COD	65	5 - 100
Nitrogen -total	2	1.3 - 3.6
Phosphorus -total	0.3	0.1 - 0.76
SS -total	200	30 - 1750
Zinc -total	0.3	0.005 - 0.95
Copper -total	0.1	0.0015 - 1.33
Lead -total	0.2	0.005 - 0.84
Cadmium -total	0.001	0.0005 - 0.003

PAH´s are formed during incomplete burning of *e.g* coal, oil and gas and do not occur alone in the environment but occur attached to solids (7).

1.2 Impact of stormwater on receiving water

Pollutants, included in the stormwater, are recognized as nonpoint-source pollution and are a threat to the receiving water ecosystem if no treatment, concerning stormwater improvement, is made. 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, which are available for organisms and can be taken up rapidly, such as dissolved heavy metals.

Heavy metals are to a great extent attached to particles that will accumulate in the receiving water sediment and run the risk of dissolving in the water during anoxic conditions or low pH conditions (1, 2, 6, 8). Anoxic conditions appear for example when oxygen demanding matter is discharged to the receiving water. Other short term damages are bacteria that is harmful to living organisms and solids causing turbidity conditions. Long term effects are damage originated from the stormwater content of nutrients and heavy metals. 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 (6). Poly-aromatic hydrocarbons have caused tumours in animals in laboratory studies when they have been exposed to PAH´s for a long period (7).

1.3 Improving stormwater quality; in general

Abation of the impact of stormwater runoff on receiving waters can be done through pollutant removal (4). Stormwater flows are highly variable, as well as the pollutant concentrations and therefore conventional treatment plants are not suitable for the treatment of stormwater due to the difficulties in taking charge of these high flow intensities during a rain event and also because of the high load of heavy metals in the stormwater that contaminate the sludge and makes it impossible to be used as a fertilizer on farmlands.

Prevention of stormwater from being polluted can be done by removing or decreasing the pollutant sources. In Table 1.2 important sources of stormwater pollution are shown and graded according to its relative influence. One heavy metal source is for example buildings plated with copper and zinc surfaces. A measure that could protect them against corrosion is, for example, painting the surfaces (1).

Another possibility to solve the problem at the source 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 (9).

Stormwater infiltration in soil is another method to dispose of stormwater but this will of course charge the soil with heavy metals and also run the risk to contaminate the ground water (10).

A more 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 but since the reduced flow prevents erosion and allows for the sedimentation of suspended materials in the pond they are being increasingly used also to improve stormwater quality (11, 12, 13). Detention ponds also have an ability to reduce nitrogen and phosphorus through algal growth and vegetation in the pond (14).

Table 1.2 Important pollutant sources on stormwater quality (15). (Translated from Swedish)

Source	COD	Nitrogen	Phosphorus	Zinc	Lead	Copper
Traffic	major	intermediate	minor	intermediate	major	intermediate
Corrosion, erosion	intermediate	minor	intermediate	major	minor	major
Rain, dust fallout	intermediate	major	intermediate	major	intermediate	intermediate
Local activities	minor	intermediate	major	minor	minor	minor

1.4 Improving stormwater quality; by open detention ponds

Open detention pond that are used to detain stormwater and reduce flow peaks can either be designed as dry detention basins that temporarily detain stormwater or as wet detention ponds that maintain a permanent pool of water (16).

Since it is known that a lot of the pollutants are attached to particles in the stormwater (6), open stormwater detention ponds remove pollutants through sedimentation. Quality measurements made on open detention ponds do not usually consider samples distributed over the whole storm event from both the inlet and outlet. It is more usual for samples to be taken only during a part of the storm event. Also during several successive storm events only a part of the storm event is analysed. Published results from such measurements in detention ponds show that the pollutant removal efficiency of solids and particulate heavy metals are in a range between 40-65 % (11, 12).

Engineering methods to design open detention ponds with respect to stormwater pollutant removal, are based on estimates of suspended solids removal. Assumptions that often are made when to calculate the stormwater flow through the pond are based on quiescent conditions, laminar flow and flow through the pond considered as "plug-flow". If the detention pond has a crested weir overflow at the outlet the continuity equation describing the change in reservoir storage volume (Eq. 1.1) can be used to form an idea of the water masses movements in the pond considered as a black box. Some, however, simple models, based on this continuity equation, have been developed in order to calculate the total pond volume at time t and then calculate the detention time that varies during the rain event (17, 18, 19). The continuity equation (Eq. 1.1) can only be solved numerically (*e.g.* with a

Runge Kutta or Euler technique), which implies a solution consisting of discrete time steps that does not take viscosity or turbulence effects into account.

$$\frac{d V_T(t)}{d t} = Q_i(t) - Q_{out}(t) = Q_i(t) - C_d L \left(\frac{V_T(t) - V_P(t)}{A_S(t)} \right)^{3/2} \tag{1.1}$$

where
$V_T(t)$ = total pond volume
t = time
$Q_i(t)$ = influent flow
$Q_{out}(t)$ = effluent flow
C_d = coefficient of discharge
L = length of weir
$V_P(t)$ = stormwater storage volume
$A_S(t)$ = the surface area of the pond

The sedimentation of particles is often described by the classical sedimentation theory such as Stoke´s law (Eq. 1.2), that calculates the settling velocity for a spherical particle. When calculating the particle settling in stormwater in an open detention pond a critical sedimentation velocity is defined as the ratio of pond depth and detention time (that previously has been calculated). Sedimentation velocities greater than the critical assume an applied particle distribution of that size completely removed from the pond and velocities equal or less only partly removed (17).

$$v_s = \frac{g}{18}(\rho_s - \rho_f)\frac{d_p^2}{\eta} \tag{1.2}$$

where
v_s = settling velocity
g = gravitational constant
ρ_s = particle density
ρ_f = fluid density
η = dynamic viscosity
d_p = particle diameter

Quiescent laminar flow condition is a rare phenomenon which seldom occurs in natural situations where turbulent flow and short-circuiting occur. These turbulent conditions mean that sedimentation calculations, at high Reynolds numbers (20), in an open detention pond, differ from observed values of sedimentation. To manage this situation adjusted sedimentation velocities are applied (19) through settling constants (16).

The US Environmental Protection Agency suggested in 1986 a method for the analysis and design of detention basins, EPA (21). A method that have been designed for the control of urban runoff pollution is also recommended by Urbonas and Stahre (16). Solids removal is calculated both for dynamic conditions and quiescent conditions based on settling velocities of the particles, pond surface load and pond performance. Any storm event may be used to calculate the outlet sediment concentration, knowing the inflow intensity and sediment concentration, the particle size distribution and the pond geometry. Turbulence or short circuiting is adjusted by a constant (mentioned above) which describes the performance in a range from poor to very good.

It would seem that simulations of water movements in an open detention pond is difficult to model accurately without having an equation that pays attention to viscosity and turbulence effects.

A more accurate way to model water movement is to solve the Navier-Stokes equation. This is the water momentum equation that takes into account molecular viscosity but not turbulence effects (22). Equation 1.3 shows the Navier-Stokes equation in vector form.

$$\frac{\partial \boldsymbol{U}}{\partial t} + (\boldsymbol{U} \cdot \nabla)\boldsymbol{U} = \boldsymbol{g} - \frac{1}{\rho}\nabla p + \nu \nabla^2 \boldsymbol{U} \qquad (1.3)$$

where
- $\mathbf{U}$ = velocity vector (u, v, w) in the x, y and z direction
- t = time
- ∇ = differential operator ($\partial/\partial x$, $\partial/\partial y$, $\partial/\partial z$)^t
- $\mathbf{g}$ = gravity vector
- ρ = fluid density
- p = hydrodynamic pressure
- ν = fluid kinematic viscosity

The solution of the Navier-Stokes equation is precise only in infinitesimal control volumes, where the smallest turbulence scales do not appear. Practical calculations demand larger scales but then one has to pay attention to the turbulent stresses that affect the solution which is not onsidered in the original Navier-Stokes equation. To overcome this difficulty, an eddy viscosity is introduced and added to the molecular viscosity (22). Turbulent flow is recognized as small fluctuations of the pressure and velocities in all directions (u, v, w). A statistical approach suggested by Reynolds separates the velocities and pressures into mean and fluctuation quantities (23); this is shown in equation 1.4.

$$U_i = \overline{U} + u_i, \quad P_i = \overline{P} + p_i \qquad (1.4)$$

where
- U_i, P_i = velocity and pressure in the i direction
- $\overline{U}_i$, $\overline{P}_i$ = average velocity and pressure in the i direction
- u_i, p_i = velocity and pressure fluctuation in the i direction

Transferring equation 1.4 into the Navier-Stokes equation provides the Reynolds averaged Navier-Stokes equation. It is impossible to solve this equation analytically and numerical solutions are very time consuming. Applicable techniques to solve this equation are for example the finite difference method (FDM) and the finite element method (FEM). There are commercial computer programs available to model fluid dynamics that solve this equation and consider turbulence effects *e.g.* FIDAP and PHOENICS (24, 25). Sedimentation models can be applied on these flow-models and can, for example, be a simple model like Stoke´s law.

FDM techniques have been used to simulate water movements and mass fluxes in open detention ponds, for example with a vertical integration of the Navier-Stoke´s equation (26, 27).

1.5 Discussion and aim of the study

Knowledge of pollutant removal efficiency in an open stormwater detention pond is not enough since investigations concerning long term effects and seasonal changes are missing. Until now most of the published investigations are based upon grab sample surveys during storm events where only a part of the storm event volume was analysed. Usually the analysis of the "first flush" from the pond outflow has been omitted. Since the pollutant removal is calculated as the difference in concentration of the "first flush" from the inflow to the pond and concentration of the last volume discharged from the outlet of the pond, only an indicatiom of detention pond removal efficiency is obtained. Long term effects have not been considered. Assumptions of long term effects are often made from knowledge of single storm event behaviour. A more accurate method of calculating pollutant removal is to take the difference of the accumulated pollutant loads between the stormwater inflow and the pond outflow during several 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. Different rain intensities will affect the flow pattern, the turbulence behaviour in a detention pond and accordingly the sedimentation, but these effects are not well known.

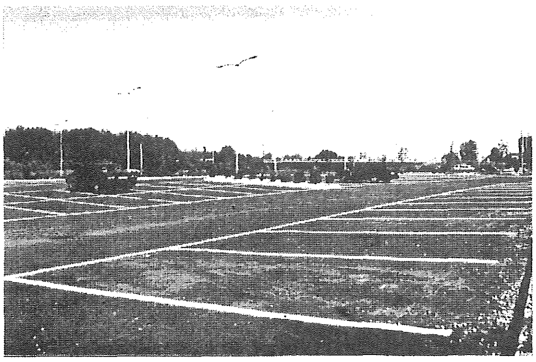
The aim of this study has been to investigate the ability of an open detention pond to remove pollutants in stormwater. Also an investigation of different modelling approaches for detention ponds were considered. The method of doing this has been to observe an existing detention pond for a longer period of time. Measurements and analyses of the detention pond stormwater were made both for the inflow and the outflow. The purpose of this has been to collect information to be able to predict the pollutant removal for this type of detention pond. A final goal has been to develop a model able to predict the pollutant removal efficiency for detention ponds with arbitrary geometries and sizes. Investigations of these variables can be made by a finite element method (FEM) program to evaluate the particle paths and consequently the removal of particle pollutants.

2. JÄRNBROTT EXPERIMENTAL POND

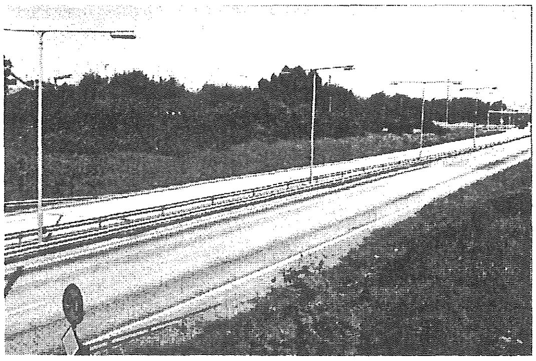
2.1 Details of the detention pond and the catchment area

An experimental detention pond has been built in Järnbrott by the Göteborg Water Works. The pond was constructed to investigate the possibility of improving stormwater quality for different conditions such as different rain intensities, rain durations and varying dry spells including winter periods with no discharge to the pond. The inlet of the pond consists of a 400 mm concrete pipe, with a slope of 4.1 ‰. The pipe enters at a level 10 cm above the lowest pond water level. The outlet consists of a weir that is also used to measure the effluent discharge. Pond geometries are: a surface area of 350 m^2, a volume of about 420 m^3 and an average depth of about 1.2 m when there is no discharge to the pond. Maximum depth allowed in the pond is about 1.7 m which implies a detention volume of about 175 m^3. This detention volume corresponds to a 2-year rain with a duration of 15 minutes. Maximum inflow for this event is about 300 l/s. An exchange of the total pond volume, i.e. 420 m^3, occurs at a rain depth of 16 mm (*e.g* a 2-year rain event with a duration of 62 min). The slope surrounding the pond has a ratio of 1:3.

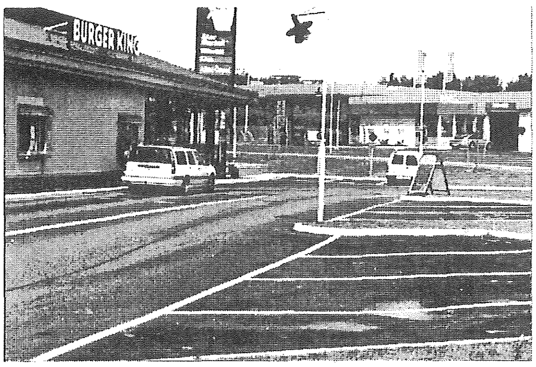
The Järnbrott catchment area consists of a parking lot, a petrol filling station, a restaurant and also a part of a city highway. The city highway has an annual mean traffic load of 24000 vehicles/day (Figure 2.1). Total impervious areafeeding the pond is 2.6 ha (Table 1). The location of the catchment is 5 km south of the Göteborg city centre.



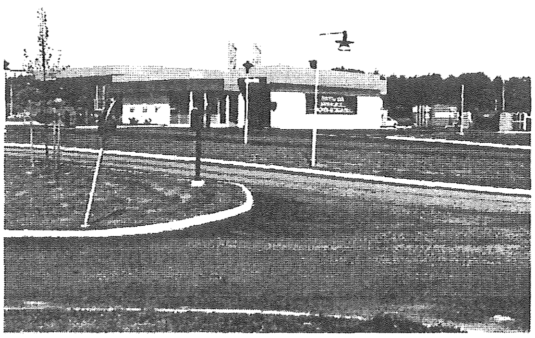
a) parking lot



b) city highway



c) restaurant



d) petrol filling station

Figure 2.1 Catchment area of the Järnbrott detention pond.

Table 2.1 Characteristics of the Järnbrott catchment area.

Catchment	Area		Mean surface
Type	ha	% of total	slope, ‰
Parking lot	0.35	14	25
Industrial area	0.73	28	20
Highway	1.5	58	15

2.2 Measuring equipment

General

The aim of the measurements was to investigate the ability of the detention pond to reduce pollutants that are carried by the stormwater. The ability has been determined by calculating the difference between the pollutant load of the inflow and the outflow. To make this effort possible, the treated stormwater as well as the untreated stormwater had to be characterized and analysed. The detention pond has been equipped with continuous measuring devices for precipitation, flow, turbidity and dissolved oxygen. To analyse the pollutant load as suspended solids (total and organic phase), particle size distribution and heavy metals concentrations two samplers were installed; one at the inlet and the other at the outlet of the detention pond. Samples were analysed in laboratory.

Instruments and samplers were connected to a data logger which stored data continuously. The data logger and the instruments were located in a container close to the pond. Data from the logger has been available for down loading through telecommunication. A schematic describing the connections of the equipment is shown in Figure 2.1.

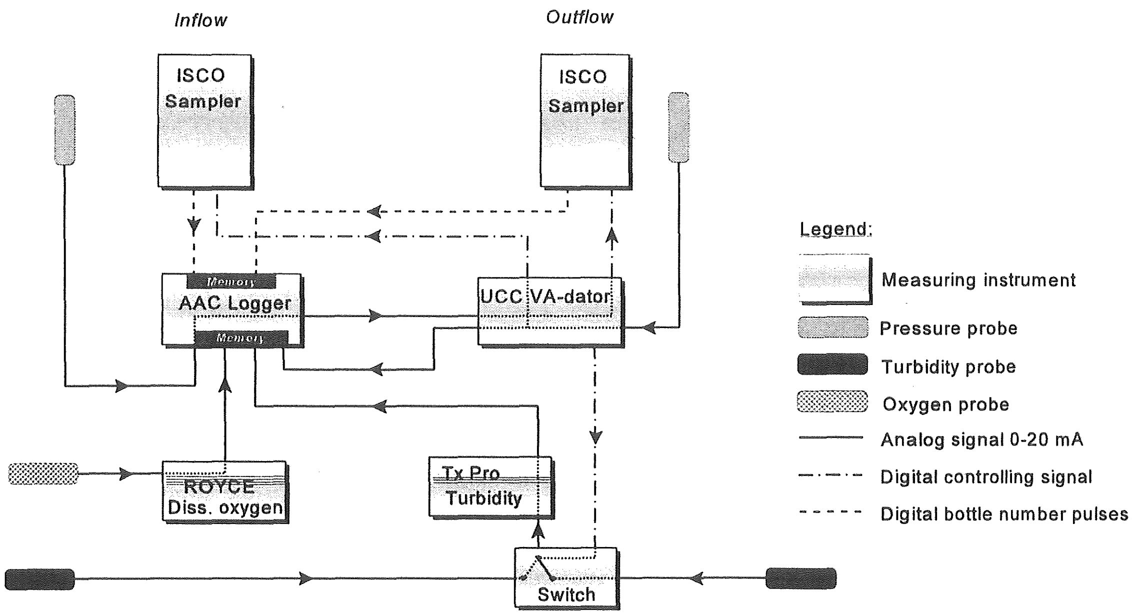


Bild 5

Figure 2.2 Schematic for the measuring equipment at the Järnbrott detention pond.

The concrete pipe supplying the detention pond with stormwater has a manhole placed at the end of the pipe containing instrument probes for measuring the inflow parameters and a sampler. The outlet consists of a 90-degree V-notch (Thompson´s spillway crest) and the effluent discharges to the river Stora Ån. Next to the pond and the outlet facility another manhole was placed containing instrument probes for the outlet measurements and another flow sampler.

Precipitation
Rainfall intensity and depth were observed with a tipping bucket rain gauge that gives a pulse signal at 0.2 mm rain depth intervals. The signals were transferred to the data logger which continuously stored the pulse signals as an accumulated sum in a digital counter. The rain gauge has been placed close to the pond.

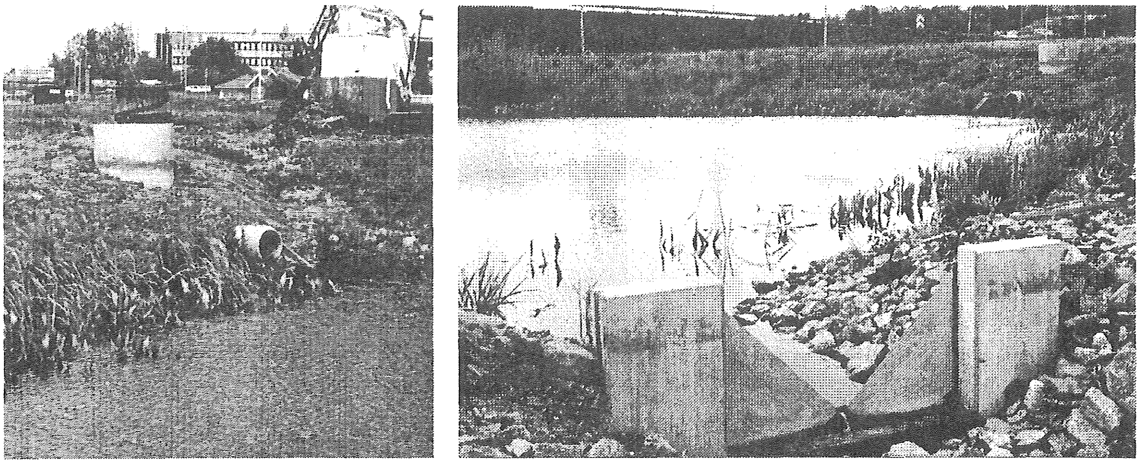
Flow
To allow the calculation of loads of pollutants into and out of the pond, the inflow and the outflow discharges were measured separately since the two hydrographs differ a lot from each other due to the detention effect. At the inlet manhole a pressure probe was mounted vertically on the wall in order to measure the water level in the pipe. At the end of that probe, located at the bottom of the inlet pipe, the pressure sensor was submerged, since the water level was at least 2 to 5 cm above the bottom even at zero inflow discharge. The inflow intensity has been calculated with the Manning discharge formula (Eq. 2.1); slope 4.1 ‰ and roughness M = 70.

$$Q = M A R^{2/3} S^{1/2} \tag{2.1}$$

where Q = discharge
M = Mannings number
A = cross section area
R = hydraulic radius
S = slope

The UCC instrument (28) transforms the water level, in the inlet pipe, recorded by the pressure probe to flow intensity by a built in microprocessor. The instrument is capable of calculating the discharge from any arbitrary formula. The instrument is equipped with 4 analog input channels and 1 analog output channel. It also has 16 digital input channels and 8 digital output channels to control other measurement equipment. Calculating the flow intensity in this manner needs a calibration. Therefore a calibration with known discharges, from two fire hydrants was made in a range of 0-35 l/s. Flow intensity was determined by a volume-time method and compared to the theoretical calculated inflow. The calibration showed that the deviation was less than 5 %. The data logger recorded all data from the UCC instrument.

The water level at the outlet V-notch was assumed to be equal to the water level in the pond since the slope of the water surface is very small. The pond was connected to the outlet manhole with a submerged pipe and the observed water level in the manhole was used to calculate the discharge at the outlet. The flow was calculated with the equation of Thompson´s spillway crest. A pressure probe was located in the outlet manhole and connected directly to the data logger that stored the current water level in the pond. Calculation of the discharge was made on the down loaded data.



Inlet Outlet

Figure 2.3 Inlet and outlet facilities at the Järnbrott detention pond.

Suspended solids - turbidity
Variations of suspended solids in the stormwater may be traced by measurements of turbidity at the inlet and at the outlet since the suspended solids concentrations, analysed in the laboratory, were calibrated to turbidity. The turbidity instrument, TxPro (29), has only one analog input but two probes were needed. To make it possible to measure the inlet turbidity and the outlet turbidity with one instrument, the probes were connected to a time controlled switch with a period of 5 minutes. The time switch was controlled by a digital signal from the UCC instrument. The two turbidity probes were located in the manholes in the same manner as the pressure probes. The instrument was placed in a container and, like the rest of the instruments, connected to the data logger. The logger stored turbidity data into one analog data channel switching between inflow and outflow every 5 minutes. To be able to separate the turbidity values from the inflow and the outflow, the logger stored a digital signal as well, telling when the switch was in the position for inlet turbidity and when the switch was in the position for outlet turbidity.

Dissolved oxygen
An instrument, ROYCE (30), adapted to measure the contents of dissolved oxygen in the pond was used. The oxygen probe was placed in the middle of the pond about 10 cm from the bottom. A temperature sensor was included in the probe which made it possible to measure the water temperature as well. The oxygen sensor in the probe needs moving water in its surroundings to be able to measure the content of dissolved oxygen accurately. In the pond and especially close to the bottom the water mostly becomes quiescent. This requirement of moving water was solved with a pump that circulates water close to the oxygen probe.

Samplers
Two samplers were used to collect flow weighted samples from the inlet and outlet. They

were both equipped with: 24 polyethylene bottles, a vinyl tubing and a submerged polypropylene strainer.

Inside the inlet manhole a portable sampler, ISCO 3700 (31), was placed. The strainer was located at the bottom of the inlet pipe and connected to a tubing with a suction length of 2 m and a suction height of 1 m. At the outlet a refrigerated sampler, also an ISCO 3700, was placed inside a small shed on the top of the outlet manhole. This sampler had its strainer located in the detention pond about 3 m upstream the outlet and about 30 cm below the water surface. The suction length of the tubing was 14 m and the suction height was 3 m.

The samplers were forced to take flow weighted samples when the discharge, at the inlet and at the outlet, exceeded predicted levels. The UCC instrument controlled samplers (Figure 2.2) by digital signals, where the sampling was stopped when the discharge was below the starting discharge. When samples were taken, each sampler delivered a number of discrete digital pulses equal to the number of current bottle being filled. The digital pulses were transferred to the data logger which continuously stored the bottle number pulses as an accumulated sum in two digital counters. Afterwards, it was easy to evaluate the occurrence of each sample.

Data logger
An AAC-2 data logger (32) was used and equipped with 8 analog input channels, 8 digital input/counter channels and 4 digital output channels. The logger stored arithmetic means from every connected analog input every 30 seconds with a scanning period of one second and data was stored together with current time. Data stored in the logger are current intensities in a range of 0-20 mA which corresponds to minimum or maximum probe deflection. Stored data could be down loaded to a laptop computer, directly at the site, or to a computer at the office via a connected modem and a cellular phone.

2.3 Observation programme

Flow intensity and turbidity were continuously measured from the inflow and the outflow of the pond. Dissolved oxygen in the pond was also continuously measured and stored in the data logger. At the beginning of a storm event samples were taken when the inflow intensity and the outflow intensity exceeded 8 l/s and 2 l/s respectively. During the whole storm event the samplers took flow weighted samples. When the discharges were below these determined flow intensities the samplers became inhibited. Collected stormwater samples were transported to the laboratory where they were directly prepared or analysed.

Stormwater quality measurements in the Järnbrott detention pond began in July 1995 and are still running (September 1996). In October, the catchment area was extended since the constructing of the restaurant and gas filling station were concluded.

Parameters that were always investigated were as follows: content of suspended solids (total and organic), contents and size distribution of particles and total content of heavy metals. On some occasions the stormwater content of heavy metals was analysed in both the particulate and dissolved phase. Also the stormwater content of total nitrogen and phosphorus were analysed for selected events. During the winter period when the pond was covered with ice, manual samples were taken in the pond. These samples were analysed with respect to the content of dissolved heavy metals.

2.4 Chemical analyses

Suspended solids

Stormwater content of suspended solids were determined according to a Swedish standard method (33). The stormwater was filtered through a GF C glass fibre filter. The filter was weighed before and after filtration. Content of organic material was determined as the residue on ignition. This were made through heating the GF C filter in a muffle furnace at 550 °C for one hour. The GF C filters were once again weighed.

Particles

Particle size distribution in stormwater was analysed by a Met One particle analyser, WGS 260 (34), that uses a light-blocking sensor technique (sensor LB1010) to determine the content of particle numbers for each size in a range of <1.0, 1.5 up to 282 µm, in steps of 0.5 µm. During the counting cycle, that lasts for 30 seconds, the continuously stirred stormwater sucks in to the sensor through a tubing. 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. The particle analyser generates an ASCII-file containing numbers of particles for each size. Three to six counting cycles were made on every sample.

Heavy metals

Heavy metals (zinc, copper, lead and cadmium) were determined by differential pulse anodic stripping voltammetry, Metrohm VA-processor (35), at a hanging mercury drop electrode, Metrohm VA-stand. Decomposition of the samples were made in a UV-digester, Metrohm 705, that decomposes 5 samples in two 10 ml quartz test tubes each for 3 hours at a temperature of about 90 °C. Before decomposition 50 µl 30 % hydrogen peroxide and 50 µl suprapure concentrated nitric acid were added to each test tube. After decomposition the 20 ml sample volume was transferred to the voltammetric cell, after which 200 µl sodium acetate buffer (pH 4.6) was added.

Samples were frozen in 100 ml polyethylene bottles directly after arriving at the laboratory. The frozen samples were thawed in a warm water bath for half an hour. Analyses of heavy metals were made for total content and for dissolved phase (<0.45 µm, cellulose acetate filter).

Nitrogen and phosphorus

Total content of nitrogen in the stormwater was determined through a Dr. Lange cuvette test method (LCK 238), in the measuring range 1-25 mg total-N/l. Phosphorus was determined as the content of phosphate (PO_4^{3-}) through HACH test method (8048), in the measuring range 0-2.5 mg PO_4^{3-}/l. The phosphate (PO_4^{3-}) concentration is then converted to phosphate-phosphorus (PO_4^{3-}-P).

3 RESULTS FROM THE JÄRNBROTT DETENTION POND

3.1 Introduction

The results from the observations at the Järnbrott detention pond and the analyses of laboratory data from sampled stormwater are reported in this chapter. Behaviour of several storm events and long term effects are included. Reasons for different behaviour concerning pollutant removal are examined by continuous measurements of flow intensity and pollutant concentrations in the stormwater inflow and the pond outflow. Flow weighted samples have been taken for several successive storm events. The studied pollutants are: suspended solids and heavy metals (zinc, copper, lead and cadmium). The particle size distribution has also been analysed for all events. A partition coefficient is introduced for one storm event and considers the partitioning between the particulate and dissolved phase of heavy metals in stormwater. Seasonal variations and winter conditions are also taken into account.

The measuring program started in the summer of 1995, and is still running (September 1996). A total of 18 storm events were completely or partially analysed. In Appendix A there is a survey of analyses made for each storm event including the storm event characteristics. Appendix B and C show the results of analyses that are used in this thesis to describe the event behaviour.

Turbidity measurements, described in chapter 2.2, were not made due to inaccurate calibration. Due to this, no results of stormwater turbidity from the inlet or the outlet of the detention pond are presented in this thesis.

This chapter is divided into five headings beside this introduction as: flow, suspended solids and heavy metals, nitrogen and phosphorus, partition coefficients and finally winter conditions. Parts three and four, concerning pollutants behaviour, are subdivided into two additional headings: storm event behaviour and long term effects. The former deals with the detention pond's behaviour during a single storm event and the latter deals with the long term effects based upon several successive storm events that were put together to get an accurate picture of the pond behaviour and to include the processes that occur between two storm events.

3.2 Flow

As seen from Figure 3.1, the hydrographs from the inlet and outlet of the Järnbrott open stormwater detention pond show the typical pattern for a detention pond for a single storm event. The stormwater influent is affected during the passage through the detention pond which is recognized as a smooth outlet hydrograph, which means no sharp flow peaks and longer duration. This well known fact is a necessary condition to allow for sedimentation of solids and other particles. The hydrographs and hyetograph in Figure 3.1 were drawn for 5 minute mean values.

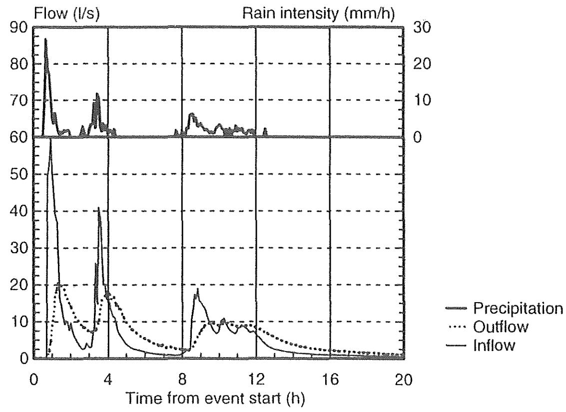


Figure 3.1 Hydrographs and hyetograph from storm event October 5 1995.

Observations of pollutant removal efficiency (Figure 3.2), during a storm event in the Järnbrott detention pond show that the influent pollutants are flow and time dependent. At the inlet, pollutants occur in a high concentration at the beginning of a storm event, often called the "first flush", but also if the hydrograph peaks later in the event. Effluent pollutant loads are usually low in the beginning of a storm event and then increase constantly during the event.

3.3 Suspended solids and heavy metals

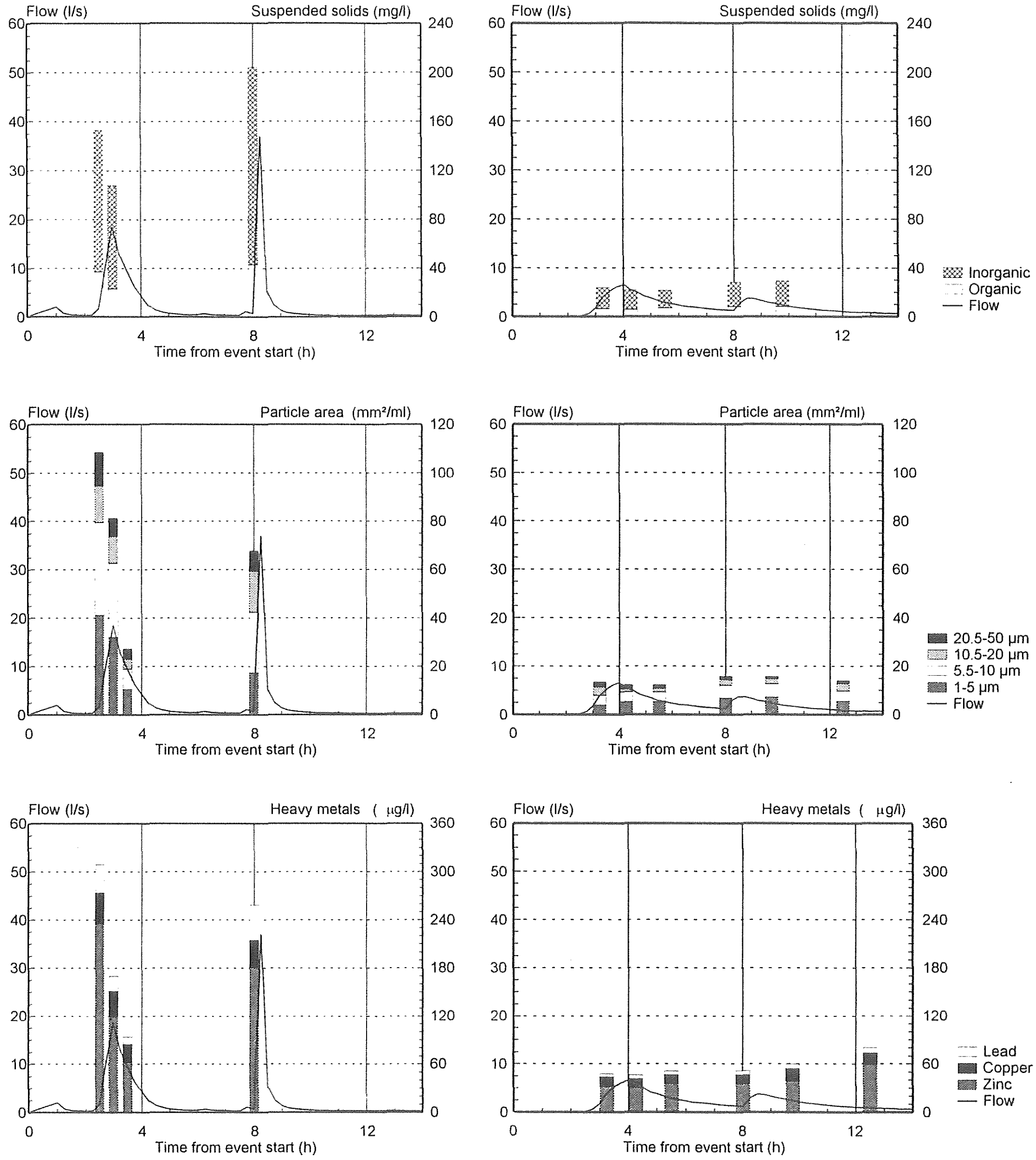
Storm event behaviour
Three selected storm events, October 5, October 17 and November 15-16 1995 are used to describe the suspended solids' concentration and specific particle area and the heavy metal concentration. The rain characteristics of these three events are described in Table 3.1.

Table 3.1 Characteristics of three selected storm events.

Date	Dry spell (d)	Rain depth (mm)	Duration (h)	Mean intensity (mm/h)	Max intensity (mm/h)
October 5	8	24.2	12.0	2.03	36.0
October 17	10	6.0	8.0	0.75	24.0
November 15-16	0.5	22.0	10.9	2.03	12.0

From one of the storm events, October 17 1995, see Figure 3.2, the hydrograph has two peaks and shows that the concentration of pollutants such as content of suspended solids and its particle area follow the idea about flow and time dependence. It is also seen that the attached heavy metals occur at high concentrations in the beginning of the event and at flow peaks.

The graphs showing particle areas (Figure 3.2) are calculated from results obtained from particle counting analysis. Since the particles in the stormwater to a great extent can be assumed to have a spherical shape (36) the area of one particle can be determined at every particle size. Multiplying the numbers of particles at every sizes (1-50 μm were considered) with its specific particle area to obtain total particle area for each particle size. In the graph, the particle areas for the stormwater inflow and outflow are separated into four size ranges.



a) b)

Figure 3.2 Flow intensity, suspended solids concentration, particle concentration and total heavy metals concentration during the storm event October 17 1995 for a) the inflow b) the outflow.

Figure 3.2 shows that the inflow concentration of suspended solids (SS) are highly reduced in the pond, which means that the SS, also the volatile SS (VSS) to a great extent, are settled in the pond. If a comparison between the SS and the total heavy metal concentrations are made one can show that there is a good correlation between these to pollutants. Lead concentration seemed to best follow the SS concentration, which confirm the SS powerful influence on the lead concentrations in stormwater. Copper does not seem to have as strong correlation to the SS concentration as lead and it is also known that copper is more soluble in water than lead (see chapter 3.5).

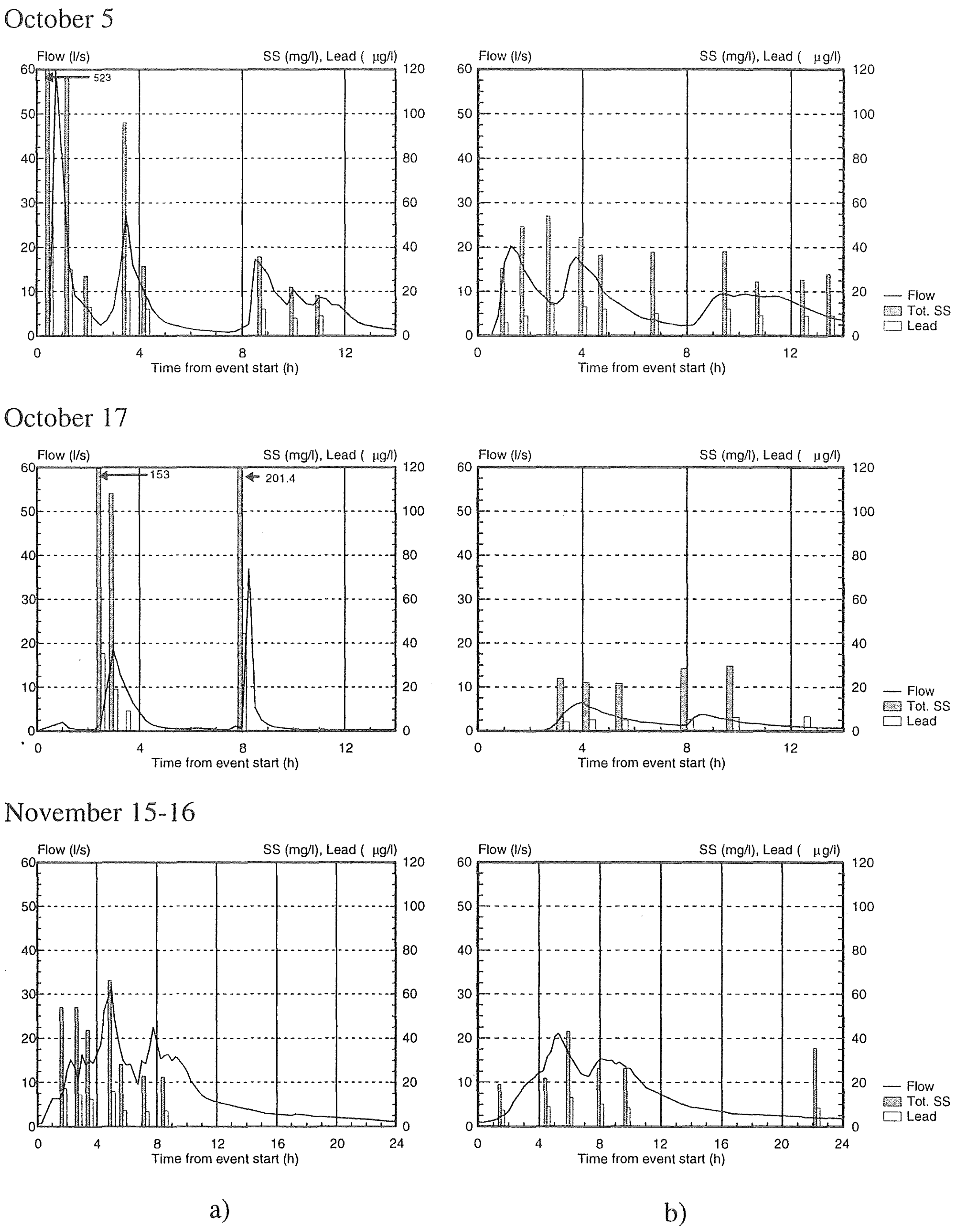


Figure 3.3 Flow intensity, total suspended solids concentration and total lead concentration during three storm events, October 5, October 17 and November 15-16 1995 for a) the inflow b) the outflow.

From the specific particle areas in Figure 3.2 it is seen that most of the small particles (1-5 µm) are present in the inflow stormwater at the beginning of the storm event and decrease during the event, except for the late high flow peak. In the outflow the specific particle area of the small particles are quite constant during the storm event and it is obvious that a considerable amount of the small particles were removed. Large particles that were discharged in the outflow can be interpreted as light organic particles that have flocculated in the pond since prior storm events and now were flushed out.

Table 3.2 Pollutant removal rate of heavy metals and SS for three single storm events (%).

Storm event	Zinc	Copper	Lead	Cadmium	TSS	VSS
October 5	39	-	49	40	59	47
October 17	67	54	78	47	81	74
November 15-16	-23	-3	16	47	19	20

In Figure 3.3 the total SS and total lead concentrations are shown for three different storm events and the strong connection between the two pollutants in the inflow and the outflow of stormwater are confirmed. It is also seen that the inflow stormwater concentration of SS and total lead was higher for the storm event of October 17 than for the storm event of November 15-16 in spite of lower inflow discharge to the pond for October 17 than for November 15-16. In Table 3.2 it is also seen that the removal efficiency for November 15-16 was much lower than for October 17, which to a certain degree could be explained as low rain depth during the October 17 event (Table 3.1). But the removal efficiency for the November 15-16 event also got lower than for October 5 although it had a larger rain depth than November 15-16. This last assertion could be derived from the preceded dry spell period of each storm event. Storm events October 5 and October 17 both not longer dry spell periods than the November 15-16 event that only got 0.5 days antecedent dry period (Table 3.1), which affects the detention pond pollutant removal capacity in not getting time enough to settle the smallest particles or to conclude possible chemical reactions.

Long term effects

Long term effects of the pond behaviour concerning suspended solids (TSS, VSS) and heavy metals (Zn, Pb, Cd) were investigated using data from 7 of the 18 storm events. Long term effects concerning copper (Cu) were based on five storm events. Measurements of inflow and outflow and analyses of pollutants from seven successive storm events, October 5 until November 15-16, were compiled in two types of graphs. The first one considers accumulated pollutant mass, in the inflow and the outflow from the pond, as a function of accumulated stormwater volume passing through the pond, and is shown in Figure 3.4. This graph includes five of the seven successive storm events and are from October 17 until November 15-16 1995 but does not concern the events occurrence in time. The other type of graph considers accumulated pollutant mass as well but as a function of event occurrence in time. This graph includes all the seven successive storm events from October 17 until November 15-16 1995 and is shown in Figure 3.5.

The accumulated mass of heavy metals was calculated as the product of stormwater volume and its heavy metal concentration in steps determined when samples were taken. The last inflow volume from the last sample were taken until the storm event was ended (when the flow was almost zero) was multiplied with half the concentration from the last sample to simulate the decreasing concentrations of heavy metals down to zero at the end of the event. When the cadmium concentrations were below the limit of detection (0.05 μg/l, for this analysis method) half that concentration was used in the calculations.

Values from these graphs have been used to determine the long term pollutant removal efficiency of the pond. It is obvious that higher pollutant removal efficiency (Table 3.3) is valid for pollutants that are mainly associated with particles (*e.g.* TSS, lead) than more soluble pollutants, *e.g.* copper. In Figure 3.4 the inflow accumulated pollutant graphs fluctuated rather much. The outflow graphs were quite straight for TSS, VSS, lead and cadmium which could be expected since these pollutants are strongly particulate associated. For copper and zinc, which are less particulate associated, the outflow graphs fluctuated a bit. Table 3.3 is based on data from the seven successive storm events October 5 until November 15-16 1995. During these events a stormwater volume of 1800 m^3 passed through the pond.

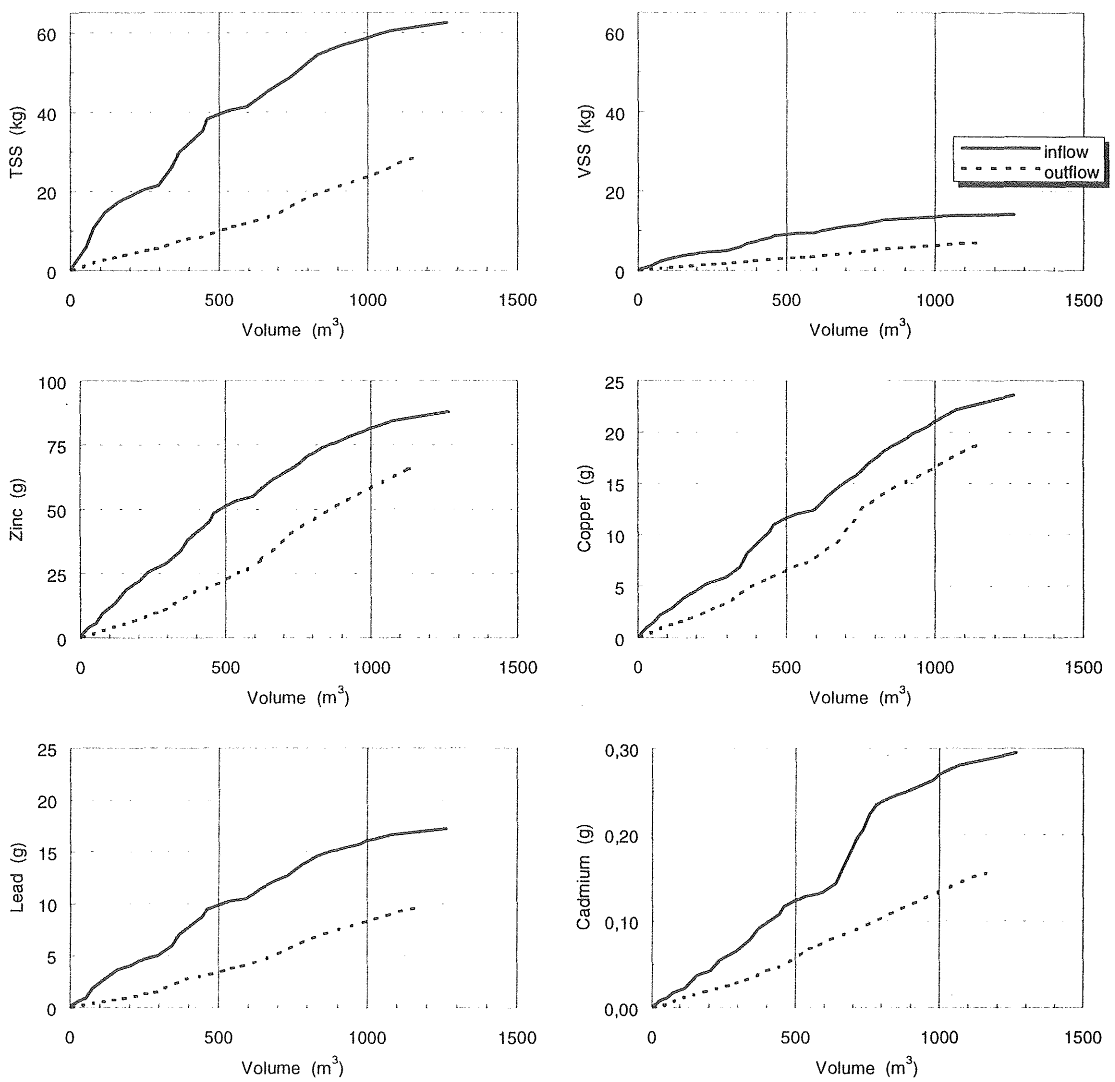


Figure 3.4 Accumulated pollutants at the inflow and the outflow as a function of stormwater volume passing through the pond during five storm events, October 17 until November 15-16 1995.

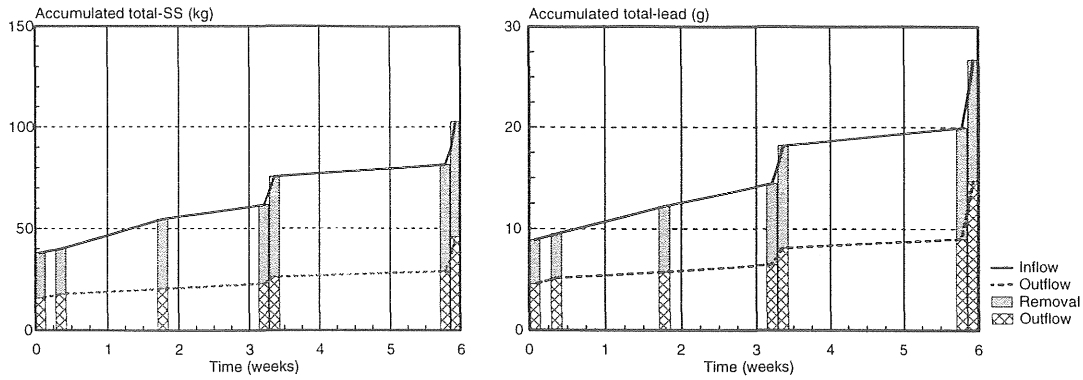


Figure 3.5 Accumulated total suspended solids and total lead at the inflow and the outflow as a function of event occurrence in time for seven storm events, October 5 until November 15-16 1995.

In Figure 3.5 the strong correlation between total lead and TSS was shown again.

Table 3.3 Pollutant removal efficiency of the Järnbrott detention pond concerning suspended solids and heavy metals.

	Zinc	Copper	Lead	Cadmium	TSS	VSS
Removal (%)	28	20	45	44	55	47

3.4 Nitrogen and phosphorus

Storm event behaviour

Nitrogen and phosphorus removal were analysed for three storm events, September 12, September 14 and October 5 (where only nitrogen was analysed) 1995. The rain characteristics of these three events are described in Table 3.4. The behaviour of the detention pond, during a storm event, concerning nitrogen and phosphorus removal is based upon one storm event September 12 and shown in Figure 3.6.

Table 3.4 Characteristics of three selected storm events.

Date	Dry spell (d)	Rain depth (mm)	Duration (h)	Mean intensity (mm/h)	Max intensity (mm/h)
September 12	6	6.4	8.9	0.76	7.2
September 14	2.5	22.8	19.1	1.19	9.6
October 5	8	24.2	12.0	2.03	36.0

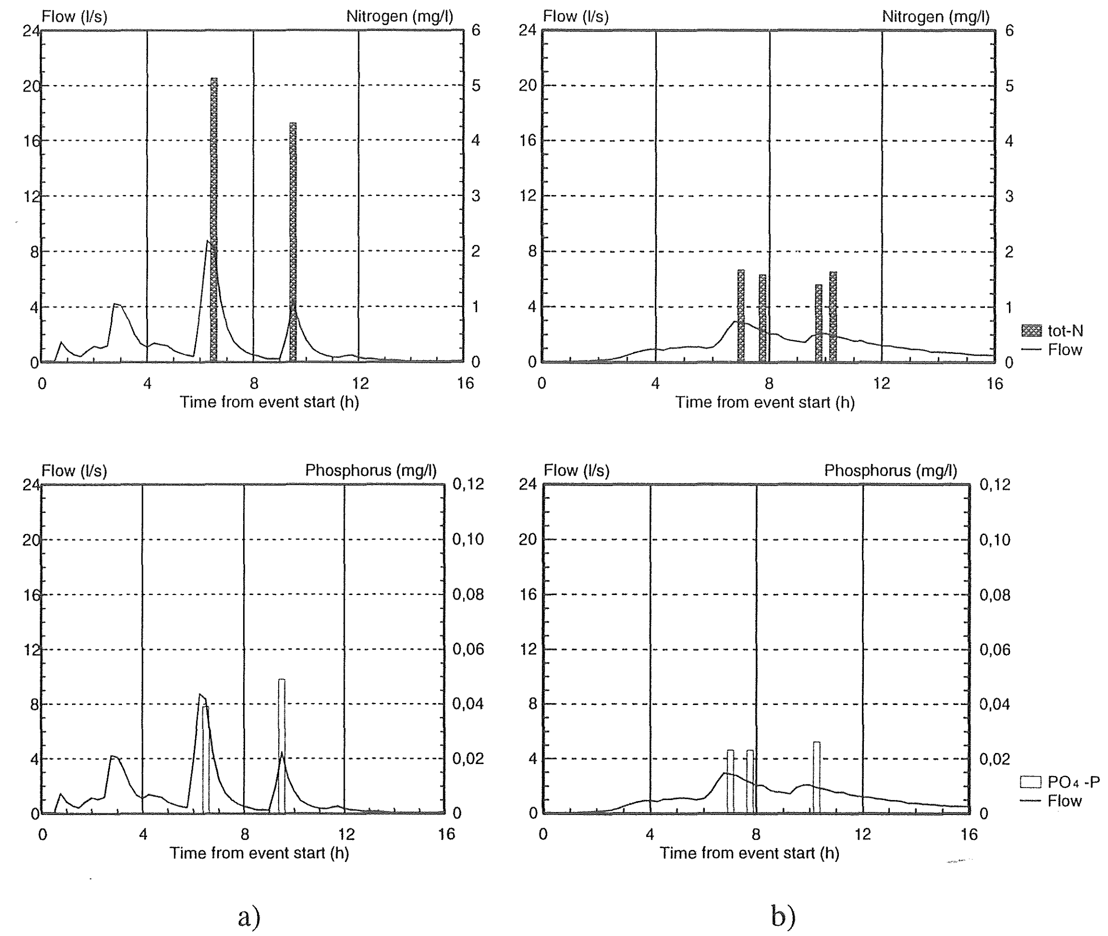


Figure 3.6 Flow intensity, nitrogen concentration and phosphorus concentration during storm event September 12 1995 for a) inflow b) outflow.

In Table 3.5 the removal efficiency for each storm event is shown. It should be mentioned that the removal capacity seemed to be dependent on rain depth and dry spell duration. Event September 12 got a high removal capacity (73 %) in spite of a large rain depth due to the longer dry spell. Storm event September 14 has a negative reduction (-16 %) and this can be related to the short dry spell which could be explained by the fact that nitrogen is released from the pond during the dry spell and is pretty time dependent.

Phosphorus seemed to be less time dependent but is certainly dependent on the rain depth during an event similar to the other pollutants described above.

Table 3.5 Pollutant removal rate of nitrogen for three single storm events and of phosphorus for two single storm events (%).

Storm event	Total nitrogen	Phosphate-phosphorus
September 12	73	53
September 14	-16	9
October 5	30	

Long term effects
Long term effects of nitrogen and phosphorus removal in the Järnbrott detention pond is based upon two successive storm events, September 12 and September 14 1995. In Figure 3.7 the accumulated masses of nitrogen and phosphate-phosphorus are shown. Nitrogen had a low removal capacity and a bit better for phosphorus (Table 3.6). One direct conclusion of these results is that phosphorus are more attached to particles in stormwater than nitrogen.

Table 3.6 Pollutant removal efficiency of the Järnbrott detention pond concerning total nitrogen and phosphate-phosphorus.

	Total nitrogen	Phosphate-phosphorus
Removal (%)	8	20

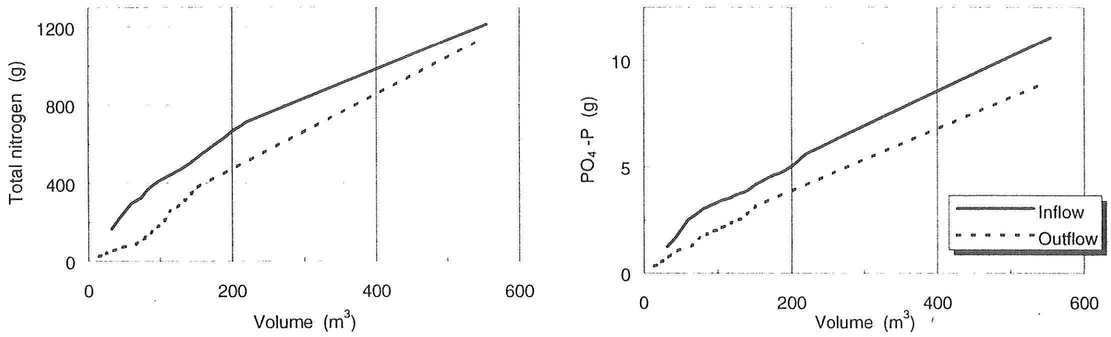


Figure 3.7 Accumulated total nitrogen and phosphate-phosphorus as a function of stormwater volume passing through the pond during two storm events, September 12 and September 14 1995.

3.5 Partition coefficient

Heavy metal analysis of storm event October 17 1995 (see Figure 3.2), also included the dissolved phase of heavy metals. This storm event had an antecedent dry period of 10 days. Consideration of particulate and dissolved phase of heavy metals together with the content of TSS gives a partition coefficient K_D (l/g) (37). K_D is usually defined as the ratio between the TSS-associated heavy metal concentration (µg/l) and the TSS concentration (g/l) over the dissolved heavy metal concentration (µg/l). K_D gives information on how the heavy metals are associated with TSS. High K_D means that the heavy metals are to a high extent associated with particles, while low K_D mean that the heavy metals to a high extent are in the dissolved phase.

In Figure 3.8 one can distinguish, for the stormwater at the inflow, that zinc, copper and cadmium had constantly low K_D-values. This means that a large amount of these heavy metals were in the dissolved phase. The opposite was valid for lead that had a high K_D, which consequently means that lead was highly associated with suspended solids. From the pond outflow the K_D fluctuated in a range from high to low values for all metals except copper which had a constant value of about 20, which was the same value as for the inflow.

Copper was accordingly constant displaced to the dissolved phase during the whole storm event as well for the inflow as for the outflow. It is interesting to study the variation of the K_D in the stormwater outflow for the entire storm event and to find that there were very low values in the beginning and that the values increased rapidly after which the values slowly decreased to the same order of magnitude as the initial K_D. The K_D decreased subsequently with time and reached almost the same values as in the beginning of the storm event.

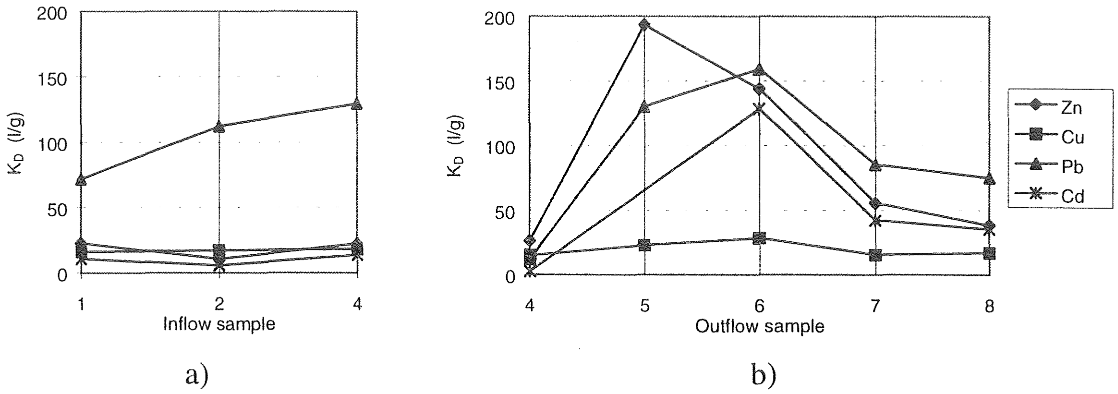


Figure 3.8 K_D-values of storm event October 17 1995 for a) inflow b) outflow.

3.6 Winter conditions

Winter conditions were investigated during the winter period of 1995-1996, when the pond was ice covered.

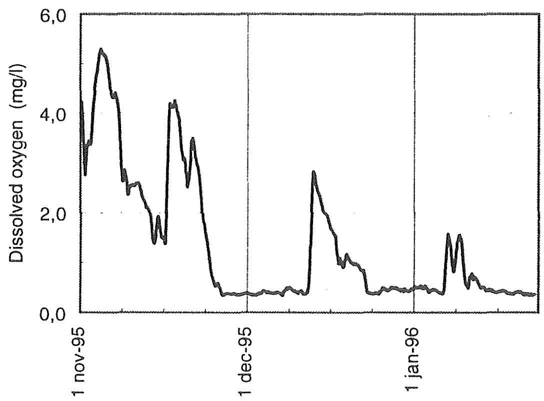


Figure 3.9 Dissolved oxygen concentration in the Järnbrott detention pond during winter conditions 1995-1996.

Measurements of dissolved oxygen were made during the autumn, winter and spring 1995-1996. This shows that the oxygen concentration decreases during the winter period (Figure 3.9) when the pond for a longer period of time is covered with ice. No inflow or outflow of stormwater took place in the pond during the winter. Two months of winter conditions have been investigated where the heavy metals concentration in the pond were analysed beside the dissolved oxygen concentration. Here the analyses shows that the winter conditions affects the dissolved phase of heavy metals in the detention pond to be dramatically increased when the dissolved oxygen concentration decreases (Table 3.7).

Table 3.7 Mean concentration of heavy metals (μg/l) and dissolved oxygen (mg/l) in the Järnbrott detention pond during quiescent winter conditions 1995-1996.

Sample date	Zinc	Copper	Lead	Cadmium	Diss. Oxygen
December 7	23	3.5	1.0	0.1	0.38
January 12	89	7.5	3.0	0.8	0.69

4 MODELLING

4.1 Introduction

This chapter (chapter 4) includes two conference articles, accepted for presentation, concerning modelling of pollutant removal for open stormwater detention ponds. In these articles, tables and figures are consecutively numbered but they are in this thesis considered as a chapter plus number (4.2.1, 4.2.2 etc.). This convention is also applicable for the final chapter, (4.4).

4.2 Modelling of open stormwater detention ponds

This chapter consists of a conference article titled : Modelling of open stormwater detention pond. This article is accepted for presentation at 7:th International Conference on Urban Storm Drainage (ICUSD) in Hanover, Germany, September 9-13, 1996. The main purpose of this article was a comparison between an engineering method in modelling sedimentation of solids in an open stormwater detention pond and observed sedimentation for two storm events including a particle distribution and associated heavy metal concentrations. Also a partitioning of particulate and dissolved heavy metals was included.

(Presented at the ICUSD '96, Hanover, Germany)

MODELLING OF OPEN STORMWATER DETENTION PONDS

Thomas J R Pettersson and Gilbert Svensson
Dept. of Sanitary Engineering, Chalmers University of Technology
S-412 96 Göteborg, Sweden

KEYWORDS: Stormwater, detention ponds, solids, heavy metals, finite element method, FIDAP

INTRODUCTION AND AIM OF THE STUDY

In urban areas the natural water cycle is affected through an infrastructure that hinders infiltration and concentrates flow. Urban areas are a part of the global hydrological cycle and stormwater in urban areas is today heavily polluted with heavy metals (Pb, Cu, Cd, Zn), organics (PAH, hydrocarbons), suspended material (sand, clay) and substances causing eutrophication (N and P), Larm(1994). The sources of these substances are local, regional and global.

Stormwater pollution must be approached by working on the stormwater system. The long term goal for research and development within stormwater will be to use stormwater as a useful resource in urban areas. But even if this direction is clear it will take time to reach the long term goal. It is therefore necessary to work on technical solutions in the stormwater system which reduce or eliminate the problems as well. The stormwater flows are highly variable, as well as the pollutant concentrations, why conventional treatment plants are not applicable for stormwater. One way of improving stormwater quality is to use detention ponds. Due to the composition of stormwater, only mechanical and/or chemical treatment methods are applicable.

Making use of urban stormwater in open ponds and creeks, running water and water mirrors can be created to the benefit of both the environment and the social welfare of the inhabitants. The art of doing this is not well established, though it has been tested in some places in Sweden. The performance of open detention ponds with respect to pollution reduction is not very well known. Knowing the particle size distribution of the transported solids and also knowing the the extent of attachment to particles by different pollutants, it will be possible to design detention ponds for maximum pollution reduction. However, designing for pollution reduction also calls for better hydrodynamic models for detention ponds. Models which are capable of describing the velocity distribution of any detention pond, irrespective of the pond geometry.

DESIGN PROCEDURES FOR DETENTION PONDS

The US Environmental Protection Agency suggested in 1986 a metod for the analysis and design of detention basins, EPA (1986). The method have been used for the control of urban runoff pollution and is also recommended by Urbonas and Stahre (1993). The solids removal is calculated for both dynamic conditions and quiescent conditions from settling velocities of the particles, pond surface load and pond performance. The dynamic conditions are calculated by the following formula.

$$E_d = 1 - (1 + w \cdot A / n \cdot q)^{-n} \qquad ...(1)$$

where
E_d is the dynamic sediment trap efficiency,
w is the particle fall velocity,
q is the average inflow,
A is the surface area of the pond,
n is the pond settling performance constant.

Any storm event may be used to calculate the outlet sediment concentration, knowing the inlet discharge and sediment concentration, the particle size distribution and the pond geometry.

DETAILS OF THE JÄRNBROTT CATCHMENT AND DETENTION POND

The Järnbrott catchment is 2.6 ha and includes a part of a city highway and a parking area. The catchment is located 5 km south of the Göteborg downtown area. An experimental detention pond has been built by the city with a surface area of 350 m^2. The maximum inflow has been estimated to 150 l/s. The purpose of the experimental pond is to investigate the performance for different conditions including winter periods with no discharge to the pond. Later the City of Göteborg will build a larger pond to take care of stormwater from the city highway.

Continously measurements of inflow and outflow is performed in the Järnbrott detention pond. The inlet facilities are: a pressure probe measuring the water level in the 400 mm inlet pipe, a turbidity probe measuring turbidity and a 24-bottle sampler. The instruments are all placed in one manhole at the inlet. The flow calculations are based on the Manning formula. A calibration with known discharge from two fire hoses confirms the accuracy. At the outlet a V-notch weir is used to measure the outflow from the pond. A 24-bottle sampler and a turbidity probe are also installed. All probes and samplers are connected to and controlled by a central unit located to a container close to the pond. The central unit includes a data logger that has an on-line connection via modem to the university. Rainfall intensity is observed with a tipping bucket rain gauge also connected to the central unit. The samplers are flow-paced and start taking samples when the flow intensity exceeds a predicted level. Analysis of samples from a storm event are made with respect to the contents of suspended solids (TSS and organic SS), particle size distribution and the contents of heavy metals (Zn, Cd, Pb, Cu) both total and dissolved phase.

PERFORMANCE OF THE JÄRNBROTT EXPERIMENTAL POND

The performance of the detention pond has been estimated with eq. 1 for the expected surface loads and for particle sizes up to 50 μm. Figure 1 shows the calculated removal efficiencies for the experimental pond with n=1 and a density 1300 kg/m^3. As seen from Figure 1, particle sizes larger than 10 μm will be removed to a large extent even for high surface loads. Figure 2 displays the performance for one of the observed storms, OCT-A. For this storm event the pond tends to remove smaller particles than 10 μm as well. The agreement between the observed values and the calculated is good for particles larger than 10 μm.

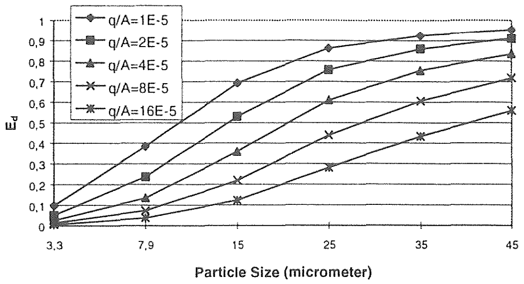


Figure 1 Removal efficiency.

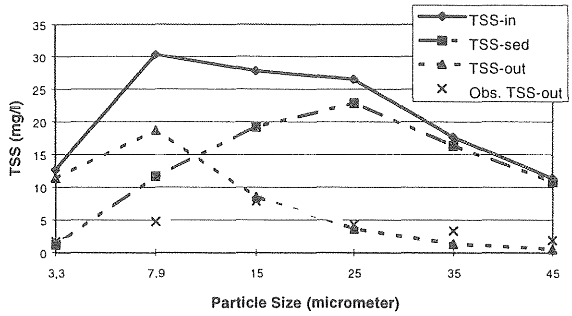


Figure 2 Calculations for OCT-A

The results presented here are from two successive storm events in October 1995, called OCT-A and OCT-B. Flow hydrographs and accumulated rainfall from these events are shown in Figure 3. The OCT-A event consists of two sharp peaks and the OCT-B event consists of several lower peaks.

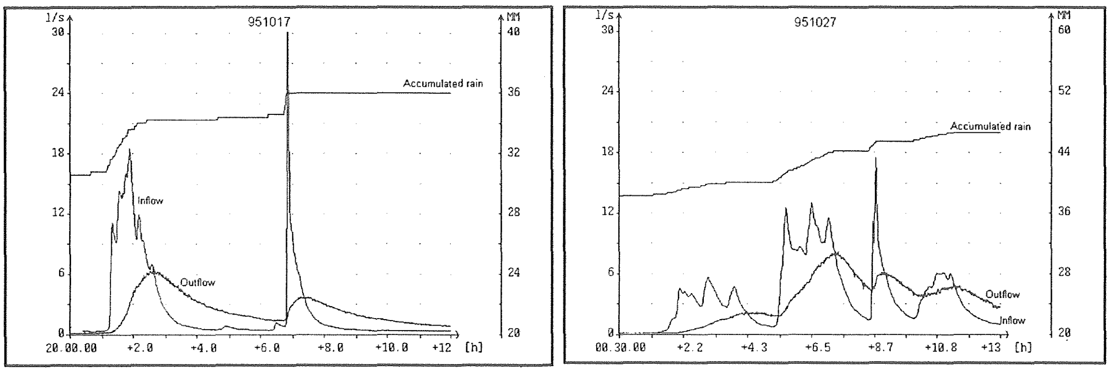


Figure 3 Flow hydrographs and accumulated rainfall for OCT-A and OCT-B events.

One way of getting a picture of the ponds ability to reduce pollutants is to draw an accumulated graph for each pollutant on accumulated inflow and outflow volume. These graphs are shown in Figure 4. It is obvious that the pond reduces the high pollutant load from the incoming stormwater to a lower load at the outlet for these two rain events. The average pollutant concentrations of the inflow and outflow are shown in Table 1. Most of the heavy metals are associated with particles and other suspended solids in the stormwater. The essential purpose of treating stormwater in an open detention pond is simply to give the suspended solids a possibility to settle and hence to reduce the pollutant load of the outflow. From Table 1 it is also seen that the highly variable pollutant load at the inlet is reduced to a rather constant load at the outlet.

A deeper analysis of rain event OCT-A, where also the dissolved concentrations of the heavy metals are determined, gives together with the concentration of TSS the partition coefficient K_d (l/g), Pankow et al (1991). The K_d is usually defined as the ratio between the TSS-associated heavy metal concentration (µg/l) and the TSS concentration (g/l) over the dissolved heavy metal concentration (µg/l). The K_d gives information on how the heavy metals are associated with TSS. High K_d mean that the heavy metals are to a high extent associated with particles, while low K_d mean that the heavy metals to a high extent are in dissolved phase.

Table 1 Average pollutant load during two rain events.

	IN		OUT	
	OCT-A	OCT-B	OCT-A	OCT-B
Zn (mg/m³)	114.3	86.7	37.3	35.9
Cu (mg/m³)	24.8	16.5	11.3	10.7
Pb (mg/m³)	23.6	12.5	5.1	4.8
Cd (mg/m³)	0.20	0.24	0.10	0.09
TSS (g/m³)	126.3	37.8	23.9	15.8
Organic SS (g/m³)	27.2	9.9	6.9	4.9

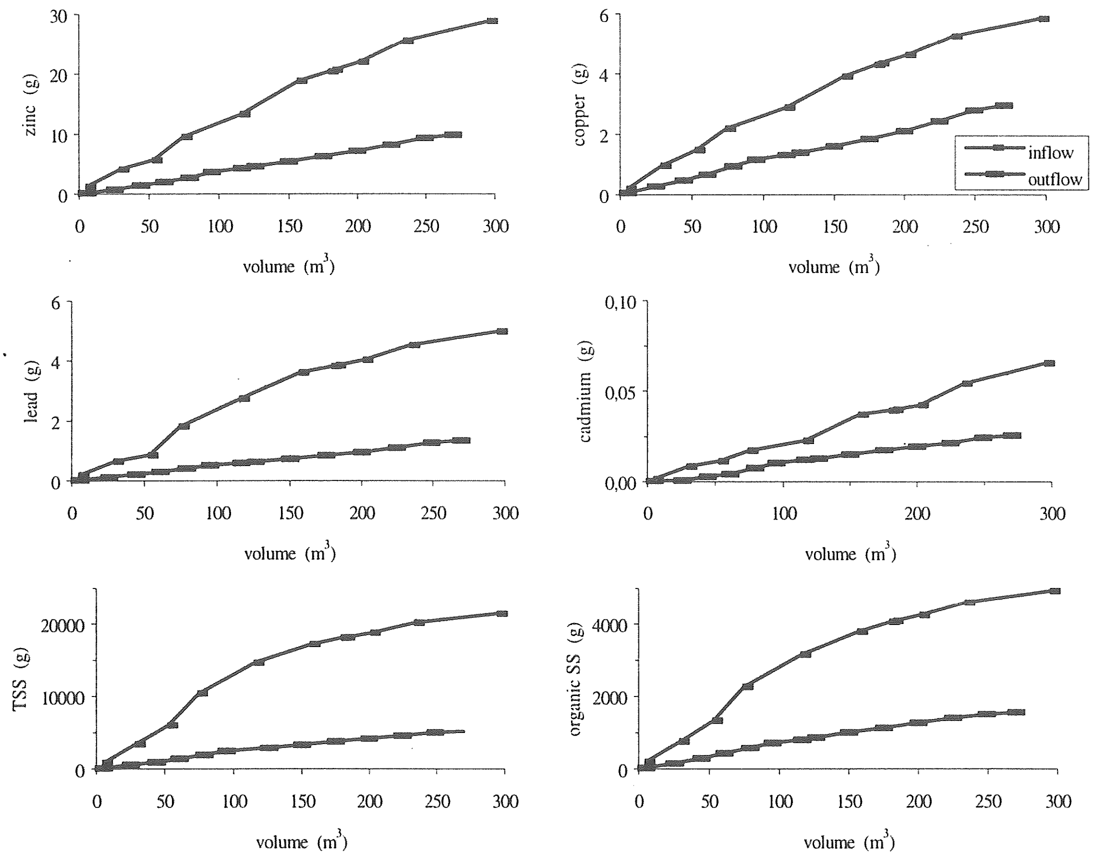


Figure 4 Pollutant accumulation on accumulated inflow and outflow volume.

In Figure 5 one can distinguish, for the inflow, that zinc, copper and cadmium has constantly low K_d-values. This means that a large amount of these heavy metals are in dissolved phase. The opposite is valid for lead that has a high K_d, which hence means that lead is highly associated with suspended solids. At the outlet the K_d fluctuates in a range from high to low values for all metals than copper that have a constant value of about 20, which is the same as at the inlet. Copper is hence constantly displaced to the dissolved phase during the whole rain event. It is interesting to study the variation of the K_d at the outlet for the entire rain event and to find that there are very low values in the beginning and that the values increase rapidly after which again the values slowly decrease to the same order of magnitude as the initial K_d. This can be interpreted as that almost all of the heavy metals are in dissolved phase from the beginning of the rain event because it has been quiesent conditions in the pond since the latest rain event. The big increase of the K_d is probably affected by the resuspension of the low density organic particles from the bottom which are washed out. The K_d decreases subsequently with time and reaches almost the same values as in the beginning of the rain event.

A closer study on the particles with a particle counter shows that the particle size distribution of the inflow is highly varied considering particle volume and area in a range from > 2 µm to about 50 µm. Calculating particle areas and volumes assumes spherical particles. This have been confirmed with SEM investigation of solids in stormwater. The total particle area decreases for the inflow during the whole rain event, Figure 6. At the outflow the particle area increases to a top value in the middle of the event and then decreases a bit at the end. In the outflow the particle area, for the small particle size range, is almost constantly large which indicates organic particles.

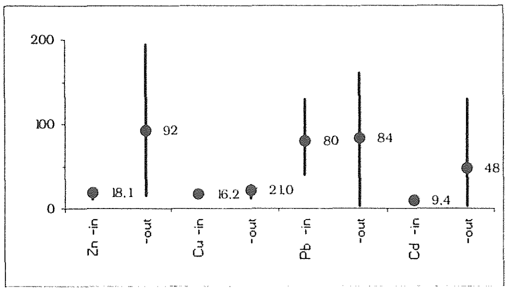


Figure 5 Range of inflow and outflow K_d-coefficients

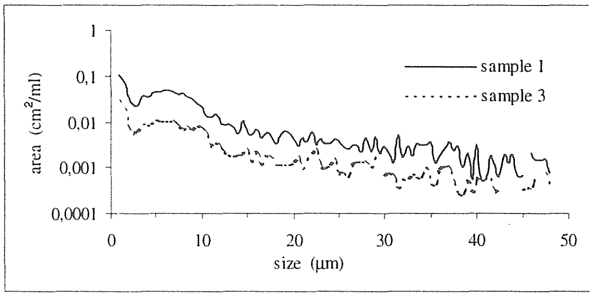


Figure 6 Particle area distribution on OCT-A event

HYDRODYNAMIC MODELLING WITH FIDAP

Having all the initial values on the incoming stormwater and knowledge of the reduction process in the pond the modelling work begins. As mentioned before todays methods to design open detention ponds are much of empiric character. Effects as turbulence in the pond and in the inflow are parameters that often neglects because of its difficulties to model. Plug flow and quiesent conditions are rare phenomena which seldom appear in nature. To be able to model the flow and sedimentation in a pond with turbulence taking into account a FEM-program called FIDAP is used, FIDAP (1993). This tool of fluid mechanics is equipped with different turbulence models built in together with sedimentation models too.

MODELLING EXPERIMENTS WITH FIDAP

Calcualtions with FIDAP in 2D, with a k-ϵ turbulence model applied for the Järnbrott detention pond, show a short-circuited flow pattern. A speed contour plot is shown in Figure 7. The interpretation of the plot is that small particles and organic low density particles only may settle ouside the main stream from the inlet to the outlet. Sediment samples from the bottom verifies this explanation. A 3D-model with the sediment process included will have the ability to simulate the solids transport and removal. With the aid of K_d-values it will also be possible to model heavy metal transport and removal.

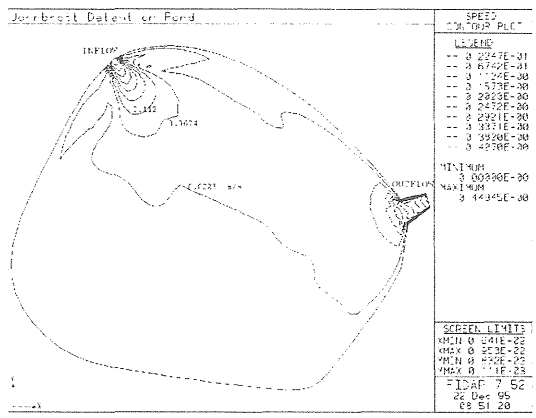


Figure 7 Velocity contour plot calculated with 2D FIDAP-model.

CONCLUSIONS

The observed storm events show that the detention pond removes between 50 % and 70 % of the solids and the metal contents discharged to the pond.

Low density solids that have settled in the pond may easily be eroded and resuspended by succeeding storm events.

The outflow from the pond has a larger fraction of organic SS than the inflow has, which indicates easily eroded low density organic flocs. The design of the pond has to take into account the critical surface load, causing erosion of the bed and resuspension of solids.

The metal transport and removal may be calculated from TSS concentrations and K_d-values for each metal.

ACKNOWLEDGEMENTS

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4.3 FEM-modelling of open stormwater detention ponds

This chapter consists of a conference article titled: FEM-modelling of open stormwater detention pons. This article is accepted for presentation at the Nordic Hydrological Conference (NHK-96) in Akureyri, Iceland, August 13-15, 1996. The main purpose of this article was the evaluation of a finite element model concerning flow and sedimentation. Particle removal modelled with FIDAP, for three different particle sizes, was compared with particle removal for one storm event.

(Presented at the NHK´96 in Akureyri, Iceland)

FEM-MODELLING OF OPEN STORMWATER DETENTION PONDS

Thomas J.R. Pettersson Dept. of Sanitary Engineering, Chalmers Sweden

ABSTRACT

Stormwater in urban areas is polluted with suspended materials which transport heavy metals and degrade the quality of the receiving waters. Since open detention ponds improve water quality, an investigation of the Järnbrott detention pond in Göteborg has been carried out. Measurements of inflow and outflow were performed and two flow-weighted samplers were used to collect representative samples for suspended solid and heavy metal analysis. The particle size distribution was analysed to allow an estimation of the settling of suspended solids. The occurrence of settling means that heavy metals are removed.

A FEM-program called FIDAP is used to calculate the three dimensional velocity flow field. A sedimentation approach is applied to the flow field where a couple of particle sizes is compared with the inflow sample analysis.

INTRODUCTION

In urban areas the natural water cycle is affected by an infrastructure that hinders infiltration and concentrates flow. Rain is polluted during transport over urban surfaces (*e.g.* roads and parking lots) and is termed stormwater when leaving the surface. Stormwater in urban areas is polluted with heavy metals (*e.g.* lead, copper, cadmium and zinc) and suspended solids (SS) such as sand and clay (Larm, 1994). These pollutants are recognized as nonpoint-source pollution and are a threat to the receiving water ecosystem.

A cost-effective strategy is to treat polluted stormwater in open detention ponds. Open stormwater detention ponds reduce flow, prevent erosion and allow the sedimentation of suspended materials in the pond. They are therefore increasingly being used also to improve stormwater quality (Mesure and Fish, 1989). Since the greater proportion of heavy metals are attached to particles in stormwater, the essential purpose of treating stormwater in an open detention pond is simply to give the particles a possibility to settle and thereby reduce the pollutant load at the outflow.

At present, methods for the design of open detention ponds are generally empirical. Effects such as turbulence in the pond and in the inflow are parameters that are often neglected because of the difficulties in modelling these variables. Plug flow and quiescent conditions are rare phenomena which seldom appear in nature.

Different rain intensities will affect the flow pattern, the turbulence behavior in a detention pond 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, from which the settling of suspended solids and hence the reduction of heavy metals is highly dependent. Investigations of these variables can be made through a finite element method (FEM) program to evaluate the particle paths and consequently the removal of particulate pollutants.

The work reported in this paper is a FEM-modelling of a small open stormwater detention pond in Göteborg (Järnbrott detention pond). Flow-weighted samples have been taken at the inlet and outlet of the detention pond for a number of rain events. Analysis of the samples includes the content of suspended solids (total and organic), heavy metals and the particle size distribution. The three-dimensional (3-D) velocity flow field in the Järnbrott detention pond was calculated with FIDAP (FIDAP Theory, 1993), which is a FEM-program.

A sedimentation approach was applied in a 3-D flow field solution. This was made by a particle tracing function that is included in the FIDAP post-processor (FIDAP Fipost, 1993). The flow distribution for a set of particles in three different size ranges equal to the analysed inflow samples was investigated.

MATERIALS AND METHODS

Experimental pond

The Järnbrott catchment is a 2.6 ha area including a part of a city highway and a parking lot. The catchment is located 5 km south of Göteborg. An experimental detention pond was built by the Göteborg water authority with a surface area of 350 m^2 and a depth of about 1.5 m.

The purpose of the experimental pond was to investigate pollutant removal mainly through sedimentation for different conditions (Pettersson and Svensson, 1996). Continuous measurements of inflow and outflow were performed in the Järnbrott detention pond. At the inlet a pressure probe, measuring the water level in the 400 mm inlet pipe, was installed and the flow calculations were based on the Manning formula. At the outlet a V-notch weir was used to measure the outflow from the pond. Two flow-weighted 24-bottle samplers were installed, one at the inlet and the other at the outlet. Analysis of samples was made with respect to the content of suspended solids, particle size distribution and the content of heavy metals (Zn, Cd, Pb, Cu).

Model assumptions

Data from one single rain event, 15-16 Nov 1995, were used to model the performance of the detention pond with respect to flow field and particle removal through sedimentation. Total rain depth was 22 mm with a duration of 10 h and 20 min (Fig. 1), with an average rain intensity of 2.1 mm/h and a maximum intensity of 12 mm/h over 3 min. Averaged particle distribution for the inlet and outlet for three different sizes was used to calculate the particle removal in the pond (Table 1).

The 3-D flow-model in the detention pond was built up with the boundary conditions described below. Numerical calculations with FIDAP solved the Reynolds averaging of Navier-Stokes equations. To solve the turbulence at the inlet the k-ϵ model was used, which is a two-equation model for isotropical turbulence at high Reynolds numbers.

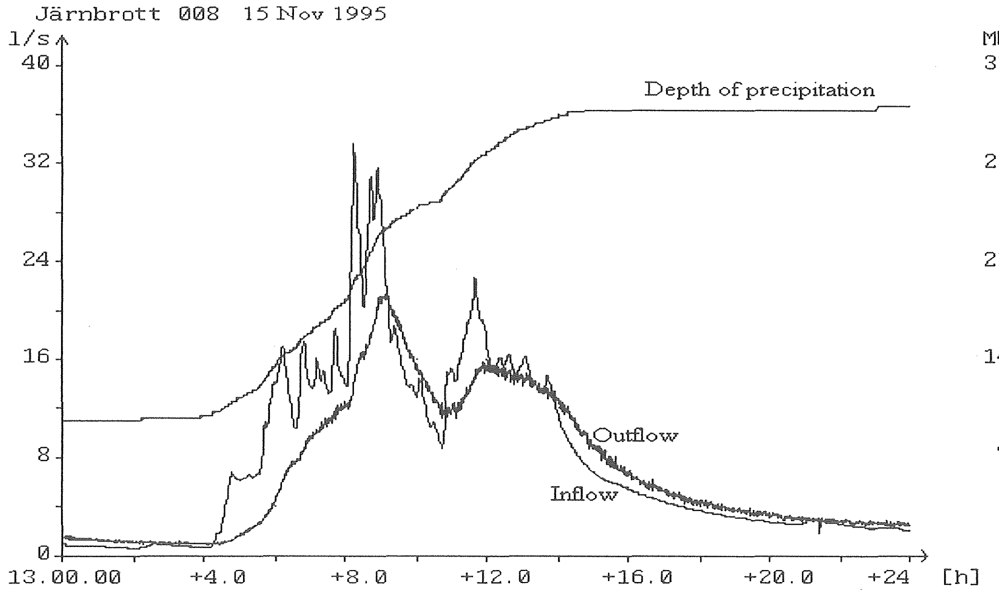


Fig.1 Hydrograph and cumulative hyetograph for the rain event 15-16 Nov 1995.

Table 1 Averaged data, during the rain event, used in the FEM-model.

Particles	Inlet (numbers/ml)	Outlet (numbers/ml)	Removal (%)
1.5 μm	287 x 10^3	213 x 10^3	26
20 μm	1380	840	48
40 μm	360	60	83

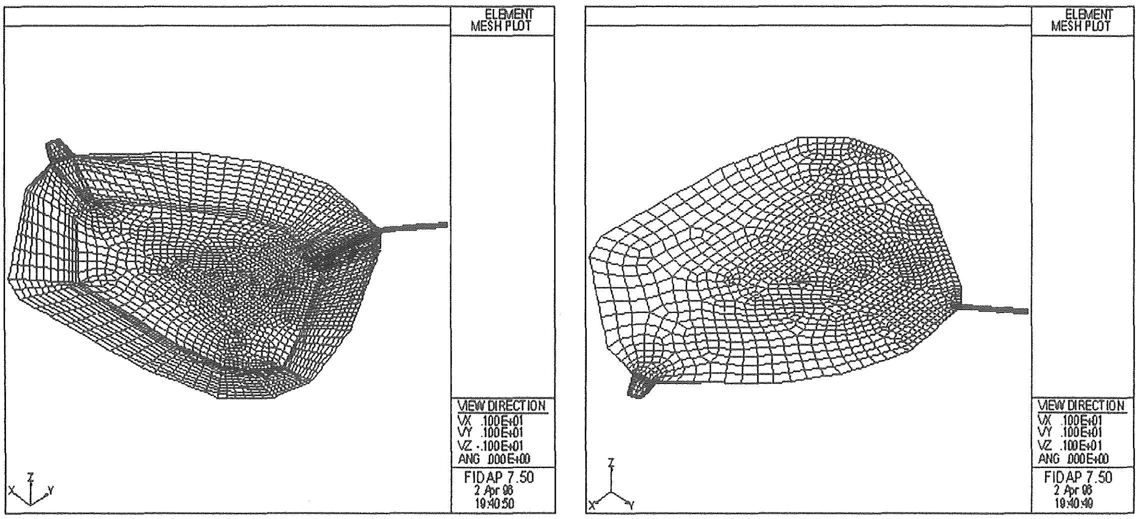
In the FEM-model an average inflow during the whole event was used and set to 22.4 l/s. On the converged 3-D solution of the flow the FIDAP particle tracing function was used. The theoretical particle removal was calculated as the difference between particle characteristics (size and numbers) given for the inlet and the simulated characteristics for the outlet. The particle trace function considers the particle density, gravity, size and distribution. To model the sedimentation, three sets (1.5, 20 and 40 μm) of 24 particles were released just before the pond, at the end of the inlet pipe, in 4 different levels and from 1 mm above the bottom of the pipe to 1 mm below the water surface.

Calculated particle sizes and volumes assume spherical particles. This was confirmed through a SEM (scanning electronic microscope) investigation of solids in stormwater (Pettersson and Svensson, 1995).

Element geometry

The element model of the inlet pipe was given a length of 5 m in order to obtain an appropriate boundary condition at the inlet of the pond. A rectangular shaped inlet pipe with a height to width ratio of 0.120m /0.127m represents the inlet pipe. Since the measurements indicate low velocities at the outlet the weir was modelled as a free boundary.

Calculations were performed on a detailed model of the detention pond. A total number of 21512 elements were created. The model was constructed so that large velocity gradients were discretised with smaller elements in order to resolve the velocity field (see fig. 2). For each node in the mesh (element grid system) the following degrees of freedom were calculated: velocity (in x, y and z), pressure and turbulent kinetic energy (k) and decay (ϵ).



a) b)

Fig. 2 FEM mesh of the detention pond fluid domain seen from a) below and b) above.

Boundary conditions

Boundary conditions of velocity, turbulent kinematic energy (k) and turbulent kinematic energy decay (ϵ) were set upstream of the inlet pipe. The velocity was calculated at 0.7065 m/s from a flow of 0.0224 m^3/s. Values for k and ϵ were calculated at 0.0025 and 0.0125 respectively (FIDAP Tutorial, 1993).

In the numerical scheme, the computational domain was extended to the physical boundary and the full set of equations was solved all the way to the wall. A one-element thick layer of special elements was employed in the near-wall region between the fully turbulent outer field and the physical boundary. In these special near-wall elements, special shape functions were used to accurately capture the sharp variations of the mean velocity in the viscosity-affected near-wall region. The k and ϵ equations were not solved in this layer; instead the variation of the turbulent diffusivities of momentum was modelled using a van Driest mixing length approach (van Driest, 1956). The roughness of the different walls that were used in these calculations and implemented as Moody's sand roughness are presented in table 2.

Table 2 Roughness of different walls.

Entity	Roughness [m]
outlet wall	0.01
inlet pipe	0.001
pond bottom	0.01
pond slopes	0.04

The velocity at the outlet was free and is modelled as a rectangular crest. The free surface of the detention pond was fixed 150 mm above the bottom of the outlet in order to minimise the number of equations to be solved. The velocity component perpendicular to the surface was set at zero and the tangential components were given slip conditions.

The water density was constant equal to 1000 kg/m^3, which is the density at a temperature of 5°C and the dynamic viscosity, μ which was used in the momentum equation was equal to $1.519*10^{-3}$ Ns/m^2, which is the viscosity at a temperature of 5°C.

Particle density was estimated as an average at 1300 kg/m^3 since it includes both organic and inorganic particles.

RESULTS AND DISCUSSION

Results presented here are from the FEM-calculated flow field in the detention pond from one single rain event, 15-16 Nov 1995, with an inflow of 22.4 l/s. The vector plot of flow velocities shows two swirling motions at a plane 0.10 m below the surface (Fig. 3). One swirl (the larger one) is controlled by the inlet and the other by the outlet.

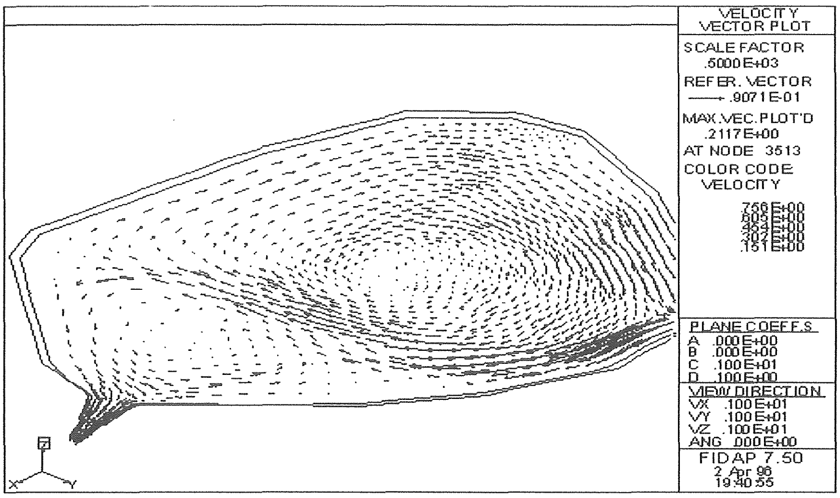


Fig. 3 Vector plot of flow velocities at a plane 0.10 m below the surface.

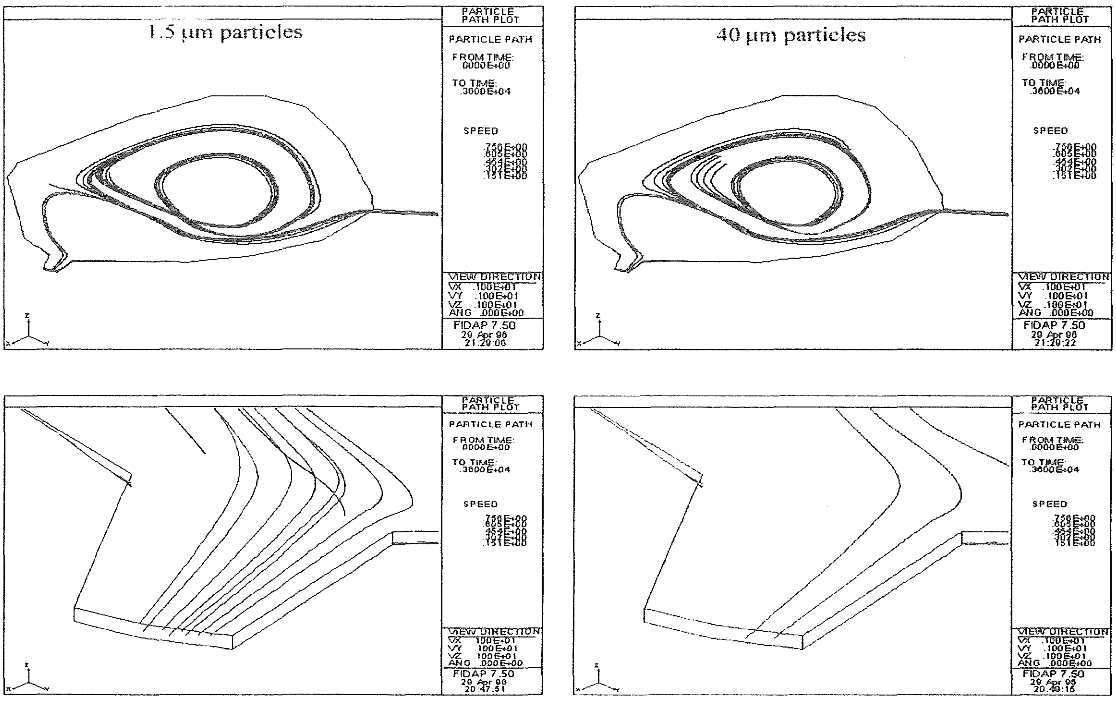


Fig. 4 Paths for 1.5 μm and 40 μm particles respectively in the pond and at the outlet.

Results of the sedimentation approach by particle tracing (Fig. 4) show that of 24 particles with a size of 1.5 μm, 8 will pass through the pond, which gives a removal capacity of 67 %. Of the 24 particles of sizes 40 μm, only 2 will pass through the pond, which corresponds to 92 % removal. For the 20 μm particles, 7 will pass through and corresponds to 71 % removal. These theoretical removal capacities should be compared to observed removal. In table 3 it can be seen that the agreement between calculated and observed particle removal is satisfactory for the 40 μm particles, not as good for the 20 μm and poor for the 1.5 μm particles. An appropriate explanation could be that these smaller particles are highly organic and that the density used in the calculations was too high. Particles in Fig. 4, seem either to go directly out through the outlet or follow the main swirl and remain in the swirl until the particles have settled.

It is shown here that FIDAP is a tool to predict flow and particle removal for detention ponds with different geometry, if the particle sizes and the density at different sizes of particles are known. Further, if heavy metal attachment to specific particle sizes is known, then it is possible to predict the removal efficiency of each heavy metal in a stormwater detention pond during a rain event.

Table 3 Theoretical and observed particle removal (in %).

Particles	FIDAP	Observed
1.5 μm	67	26
20 μm	70	48
40 μm	92	83

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Address: Thomas J.R. Pettersson
Chalmers University of Technology
Dept. of Sanitary Engineering
S-412 96 Göteborg
Sweden
E-mail: thomas@sani.chalmers.se

4.4 Comparison between theoretical and observed particle removal

The inflow discharges accounted for in the calculations were 3.5 l/s for the EPA-method (Chapter 4.2) and 22.4 l/s with FIDAP FEM-program (Chapter 4.3) and an assumed particle density of 1300 kg/m^3 were considered for both the methods.

A comparison between the two methods for modelling particle removal shows an agreement for the larger particles even when different inflow discharges are considered but deviates a lot for the smallest particles, 1.5-3.3 μm (Table 4.4.1). Modelling small particles is difficult since the characteristics, such as density and particle size, are not well known.

Storm event October 17 1995, modelled with the EPA-method, is preceded by a long antecedent dry period which leads to a low initial concentration of suspended particles in the detention pond water that causes the high observed particle removal which is seen in Table 4.4.1 explained in Chapter 3.3. The storm event November 15-16 1995, modelled with FIDAP, is preceded by a short antecedent dry period which leads to a high initial concentration of suspended particles in the detention pond water which causes the lower observed removal capacity which is seen in Table 4.4.1 and explained in Chapter 3.3. The removal capacity for the larger particles seemed to be independent of the preceded dry period.

Table 4.4.1 Two methods of calculating the particle removal (%), for different particle sizes (μm), compared with observations from two storm events.

	EPA		FIDAP	
Particle size (μm)	Observed October 17	Theoretical	Observed November 15-16	Theoretical
1.5			26	67
3.3	87	10		
7.9	84	38		
15	72	69		
20			48	70
25	84	86		
35	81	92		
40			83	92
45	83	95		

5 DISCUSSION

Measurements and analysis

Analysis results are based on measurements that were made in the Järnbrott detention pond and their accuracy depends to a great extent on the operation of the measurement equipment and the installation of the intruments in the pond. Results from flow and dissolved oxygen measurements in the pond were accurate but the turbidity measurement failed due to an inaccurate calibration. Samples taken at the outlet were transported through a 14 m tubing with 3 m suction height before the stormwater reached the sample bottle. It is debatable if there were any losses of heavier large particles during the sampling cycle when the sample volume was transported in the tube. But this has been neglected since most of the heavier large particles were settled in the pond before they reached the sampler intake at the outlet. The accuracy of the results from particle counting analysis has been difficult to validate. The samples, according to the manual, have to be diluted with nanopure water until a particle concentration less than 14 000 particle counts/ml were reached. One problem was found. When a sample was analysed and the resulting total number of particles were about 10 000 counts/ml a further dilution to half the particle concentration, gave about 7 000 counts/ml, not 5 000 as expected. The total counts/ml and the dilution degree seemed to be a non-linear system when the particle concentration was 10 000 particles/ml or more. To make the particle counting analysis as accurate as possible the dilution of samples were made until the total particle counts/ml were in a range of 4 000-7 000. This procedure made the results of different samples comparable.

Performance of the detention pond

From Tables 3.1 and 3.2 it is seen that the removal efficiency of suspended solids and heavy metals vary a lot and that they were strongly dependent on rain depth and the antecedent dry period. A long antecedent dry period combined with a small rain depth gives a high pollutant removal efficiency and the opposite gives a low pollutant removal. To predict the pollutant removal capacity for an open detention pond during a single storm event, the storm event characteristics have to be known for the current catchment area. It is also seen here that it is not possible to predict the pollutant removal for a longer period of time with data from only a few single storm events. It has to be a cumulative analysis, concerning long term effects, made upon several successive storm events to make a more accurate prediction of the detention pond pollutant removal capacity, (Chapter 3.3). In figure 3.4 graphs of the accumulated pollutant load are shown for five successive storm events. The difference between accumulated pollutants in the inflow and the outflow for five successive storm events is also shown. The inflow graphs fluctuate a lot while the outflow graphs are quite straight which can be interpreted as the detention pond not only smooths out the inflow discharge, but also the pollutant concentration in the inflow. These five successive storm events were limited to a period of about one month which was too short to be able to predict the pollutant removal for a longer period, such as a year, since the seasonal variations have not been analysed. Differences in the detention pond removal capacity for different pollutants are obvious in Figure 3.4 (SS and heavy metals) and in Figure 3.7 (nitrogen and phosphorus) where the removal capacity for TSS, VSS, lead and cadmium are about 50 % but for zinc 28 % and for copper only 20 %. The analyses of the removal capacity for nitrogen and phosphorus, where only two successive storm events were analysed, shows very low values but should not be used to predict the removal for a longer period, such as a year. Nevertheless, the result could be considered as an indication of the detention pond removal capacity of nitrogen and phosphorus if being aware of the rain characteristics for these storm events.

Partitioning of the total heavy metal concentration into the particulate and the dissolved phases and the metal attachment to total suspended solids concentration (Chapter 3.5) shows that the inflow distribution of K_D were almost constantly low for the heavy metals except lead that had an increasing K_D during the storm event (Figure 3.8). Since high K_D is equivalent to displacement to the particulate phase, the increased values for lead should be interpreted as lead was displaced more to the dissolved phase in the beginning of the storm event but became more displaced to the particulate phase during the storm event. Zinc, copper and cadmium were for the inflow stormwater constantly displaced to the dissolved phase. The outflow K_D-values show that copper was almost constantly low and of the same magnitude as for the inflow. For zinc, lead and cadmium, the K_D-values were low at the event start but increased during the storm event and decreased again at the end of the event. Low K_D-values in the outflow at the beginning could be interpreted as that almost all of the heavy metals were in the dissolved phase at the beginning of the storm event. The obvious reason is that the particulate heavy metals were settled since it is quiescent conditions in the pond between storm events. The high increase of the K_D was probably affected by the resuspension of the settled low density organic particles from the bottom which were washed out. An interpretation of the almost constant copper K_D-values could be a preferential association of copper with the colloidal phase, which is not reflected by the present K_D-value.

Measurements of dissolved oxygen concentration in the detention pond showed a dramatically decrease during the winter (Figure 3.9) which caused an increased heavy metals concentration in the dissolved phase (Table 3.7) since the heavy metals attached to the bottom sediments were dissolved.

Operation

The problem of release of heavy metals that often appear in a detention pond during winter conditions (Table 3.7), in Scandinavia, would yield a consideration of cleaning up the pond bottom from sediments before the winter condition appears. And if this is made it has to be considered where to store the polluted sediments, that no further damages occur.

Modelling

In the modelling chapter (Chapter 4) it has been clearly shown that the initial values of the stormwater characteristics were of great importance for the accuracy of the modelling of the detention pond pollutant removal. A complete model to be used to calculate the pollutant removal of an arbitrary open stormwater detention pond would be a composite model that consists of mainly three submodels, namely:

1) A quality model that models the inflow stormwater intensity and quality should include catchment area, dry spell, pollutant load, particle size distribution, and rain depth etc.

2) A hydrodynamic model that calculates the flow pattern and the sedimentation in the detention pond with input such as flow intensity, particle size and density and pollutant content from the quality model. This model should be based on calculations by, for example a FEM-program such as FIDAP that calculates possible pollutant removal for

different pond geometries and flow intensities. Results from these calculations should yield a simpler model that is easy to use and is based on tables and equations that may be extrapolated to further geometries.

3) A pond bottom process model that is modelling the pollutant processes in the bottom sediment and sediment accumulation with inputs from the hydrodynamic model such as settled particles with attached pollutants, flow intensities at the bottom layer to calculate possible erosion and the build up of the bottom sediments. Also vegetation should be considered. These calculations should also be based on an accurate model that yields a simpler model.

Design

Results presented in this thesis are not enough to give strict advice on how to design an optimal detention pond concerning maximum pollutant removal, but some guidelines should be pointed out. First of all, it is a fact that the rain depth is of great importance for the removal capacity. Therefore the volume of the detention pond should be larger than the storm event volume in acceptable limits. On the other hand should the volume of the detention pond not be too large, since the aeration of the pond could be too small and the pond will then run the risk of dissolving the heavy metals attached to the bottom sediments into the pond water and then the risk to wash them out at the next storm event. An open detention pond should also have a design that prevents the appearance of a short-circuiting of flow since this will wash out the lightest flocculated particles. Finally the bottom of the detention pond should consist of some hard material such as a concrete slab to make it possible to empty the bottom from accumulated sediment before the next winter period. This will be made to prevent that the heavy metals will be dissolved during anoxic winter conditions.

6 FURTHER RESEARCH

In the discussion chapter (Chapter 5) the need of a more complete model was discussed that simply could be applied on an arbitrary open detention pond predicting its capacity of removing inflow pollutant loads. To be able to develop such a model it has to be divided into three main submodels: a quality inflow model, a hydrodynamic model and a pond bottom process model.

The quality inflow model should be an existing pollutant transport model since there already exists several such models.

The hydrodynamic model has to be developed through continued modelling with the FEM-program FIDAP. Continuous FEM-calculations of the Järnbrott detention pond should be made until satisfying results concerning particle removal for different flow intensities compared to corresponding observations in the detention pond are obtained. This modelling work requires improved initial values of the stormwater particle characteristics, such as particle densities of different particle sizes and the heavy metals attachment to particles of different sizes, that also will be a subject of further investigations. A validation of the FEM-model should be made on another existing detention pond. After this validation, FIDAP will be used to model the particle removal (as in Chapter 4.3), consequently also the pollutant removal, for different pond geometries and sizes. The intention of this FEM-modelling work is that the received knowledge (data bank) from different geometries will create a basis for developing a simpler pollutant removal model that consists of tables and simple equations and may be extrapolated to further geometries and sizes.

The pond bottom process model mainly concerning long term effects will include the processes that appear in bottom sediments and in the pond water and also the flow intensities at the bottom layer for the calculation of possible erosion of settled particles. This model will use, as for the hydrodynamic model, an accurate FEM-program, like FIDAP, to calculate the bottom shear stresses that will affect the erosion and build up of the bottom sediments. These calculations should be the basis of building up another data bank consisting of data of the physical behaviour of a bottom in a detention pond, to again develop a simpler model. The modelling of chemical processes in the detention pond have to be based on knowledge gained from measurements. The model should also include the vegetation impact on the pollutant removal and therefore the removal of nitrogen and phosphorus during summer conditions, with high vegetation, should be a subject of further investigations.

The particle sizes of the bottom sediments together with the particles heavy metal content should be further investigated and linked to the FEM-calculations of particle removal through sedimentation.

Further research planned for this project have three main goals:

- to be able to model the flow pattern and the sedimentation of particles in an arbitrary detention pond with FIDAP

- to investigate and extend the knowledge of the densities of different particle sizes in urban stormwater

- to investigate and extend the knowledge of the attachment of heavy metals to particles of different sizes in urban stormwater

These three goals are closely linked together and the result from the coming work will form the basis of an accurate model to predict stormwater pollutant removal, principally heavy metals, in open detention ponds with arbitrary geometries and sizes.

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Appendix

Appendix A	List of rain characteristics and an analysis survey
Appendix B	Analysis values for suspended solids and heavy metals
Appendix C	Analysis values for nitrogen and phosphorus

Appendix A

Rain characteristics and analyses, July - November 1995.

Date	Rain depth (mm)	Duration (h)	Mean intensity (mm/h)	Max intensity (mm/h)	Total volume (m^3)	Analyses carried out				
						SS	Heavy metals	Particle counting	Nitrogen	Phosphorus
July 31	16.5					√		√		
August 25a	5.6 [1)]	6.2 [1)]	0.90 [1)]	9.6 [1)]	34	√		√		
August 25b					4	√		√		
September 3	6.4	2.0	3.20	12.0	41	√		√		
September 5a	2.0	2.5	0.79	2.4	24	√		√		
September 5b	1.6	1.0	1.57	4.8	12	√		√		
September 12	6.4	8.9	0.76	7.2	74				√	√
September 14	22.8	19.1	1.19	9.6	481				√	√
September 16	21.8	21.2	1.03	2.4	400					
September 26	4.6	2.6	1.76	12.0	77			√		
September 27	14.2	25.1	0.57	26.4	174					
October 5	24.2	12.0	2.03	36.0	440	√	√	√	√	
October 7	3.0	2.5	1.20	4.0	107	√	√	√		
October 17	6.0	8.0	0.75	24.0	116	√	√	√		
October 27	8.4	10.0	0.84	8.0	180	√	√	√		
October 28	5.6	5.8	0.97	20.0	148	√	√	√		
November 15	6.6	9.8	0.67	4.0	149	√	√	√		
November 15-16	22.0	10.9	2.03	12.0	673 ?	√	√	√		

[1)] Includes storm event August 25b

Appendix B

Characteristics of storm event: October 5 1995 - *Inflow*

Event start 09:50

Sample	Time	Rain time (h)	Total volume (m^3)	Heavy metals (µg/l) Zinc	Lead	Cadmium	Suspended solids (mg/l) TSS	VSS	Particle area (mm^2/ml) 0-5 µm	5.5-10 µm	10.5-20 µm	20.5-50 µm	tot 1-50 µm
1	10:31	0.68	0.4	240	65	0.7	523	73	43.4	63.1	37.6	22.9	167.1
2	10:40	0.83	26	230	56	0.5	291	54	33.2	43.0	21.4	13.2	110.8
3	10:47	0.95	49	200	55	0.6	291	53	39.0	44.2	19.0	9.2	111.3
4	10:55	1.08	73	180	56	0.8	259	42	34.1	34.6	15.4	5.2	89.3
5	11:06	1.25	98	80	30	0.4	117	21	22.1	17.8	5.6	1.4	46.9
6	11:25	1.58	122	30	14	0.3	43	9.5	13.5	7.9	5.7	2.1	29.2
7	11:48	1.95	134	20	13	1.7	27	7.5	8.5	4.2	2.3	0.9	15.8
8	13:03	3.22	155	40	20	0.4	41	6.7	6.9	6.0	4.0	1.1	18.0
9	13:22	3.53	179	60	20	0.5	96	15	10.4	12.3	6.9	4.2	33.8
10	13:35	3.73	202	30	19	0.3	65	13	10.6	9.5	3.8	1.6	25.5
11	13:59	4.13	226	50	12	0.2	32	8.0	6.7	3.0	1.2	0.3	11.2
12	18:19	8.47	269	50	16	0.2	104	14	6.8	7.2	2.8	1.8	18.6
13	18:44	8.88	293	40	12	0.2	36	12	6.7	5.7	2.4	0.8	15.6
14	19:12	9.37	317	20	8	0.2	21	7.0	5.2	3.2	1.1	1.1	10.6
15	19:50	10.00	335	30	8	0.2	22	7.2	4.0	2.2	0.9	0.4	7.4
16	20:21	10.50	353	25	8.5	0.2	20	9.0	4.5	2.3	0.8	0.3	7.9
17	20:50	11.00	366	20	9	0.2	18	< 5	3.1	1.7	0.6	0.3	5.7
18	21:19	11.47	380	10	8	0.2	18	< 5	3.5	2.0	1.2	0.4	7.1

Characteristics of storm event: October 5 1995 - *Outflow*

Event start 09:50

Sample	Time	Rain time (h)	Total volume (m^3)	Heavy metals (µg/l)			Suspended solids (mg/l)		Particle area (mm^2/ml)				
				Zinc	Lead	Cadmium	TSS	VSS	0-5 µm	5.5-10 µm	10.5-20 µm	20.5-50 µm	tot 1-50 µm
6	10:51	1.00	3.8	10	6	0.2	30	12	3.4	4.2	2.7	0.7	11.1
7	11:14	1.40	27	10	7	0.2	41	7.7	2.7	4.8	4.2	1.0	12.7
8	11:34	1.72	49	10	9	0.2	49	12	4.0	6.7	4.4	1.4	16.6
9	11:59	2.15	72	10	11	0.2	49	11	8.4	10.6	5.5	1.2	25.7
10	12:37	2.78	95	20	14	0.2	54	12	11.9	13.4	4.0	1.1	30.3
11	13:24	3.55	117	10	11	0.2	39	14	8.5	11.2	2.5	2.6	24.8
12	13:47	3.95	140	20	13	0.2	44	12	13.5	11.3	2.7	0.1	27.6
13	14:10	4.33	163	30	13	0.2	40	10	11.4	9.7	2.9	0.0	24.2
14	14:37	4.78	185	20	12	0.2	36	10	10.6	9.3	3.5	6.6	29.9
15	15:19	5.47	208	10	13	0.6	30	5.3	8.9	6.1	2.4	0.6	18.0
16	16:31	6.68	230	20	10	0.2	38	11	10.0	6.8	2.1	1.3	20.2
17	18:37	8.77	252	30	12	0.3	37	6.4	8.5	5.8	2.1	0.4	16.7
18	19:23	9.53	274	30	12	0.2	38	8.4	8.4	5.1	2.0	1.0	16.4
19	20:03	10.22	297	20	10	0.2	26	6.0	7.7	5.4	2.5	0.8	16.4
20	20:44	10.88	319	20	9	0.1	24	8.0	7.8	5.7	2.6	1.0	17.1
21	21:26	11.58	341	30	10	0.2	36	8.3	7.8	5.6	2.8	1.2	17.4
22	22:11	12.33	364	20	9	0.1	25	5.0	6.3	4.3	2.1	1.2	13.9
23	23:12	13.35	386	40	9	0.2	28	5.0	4.9	3.4	2.2	0.6	11.1

Characteristics of storm event: October 17 1995 - *Inflow*

Sample	Time	Rain time (h)	Total volume (m^3)	Heavy metals (µg/l)				Suspended solids (mg/l)		Particle area (mm^2/ml)				
Event start	18:45			Zinc	Copper	Lead	Cadmium	TSS	VSS	0-5 µm	5.5-10 µm	10.5-20 µm	20.5-50 µm	tot 1-50 µm
1 tot.	21:18	2.55	5.5	235.8	37.75	35.36	0.26	153	37	41.2	38.3	15.1	13.9	108.6
diss.				52.56	10.84	2.95	0.10							
2 tot.	21:50	3.07	29	119.3	31.46	19.01	0.29	108	23	32.1	30.5	11.4	7.3	81.3
diss.				56.12	11.01	1.45	0.18							
3 tot.	22:22	3.62	53	62.36	22	9.16	0.12			10.5	8.5	4.2	4.1	27.3
diss.				22.12	9.05	1.7	0.07							
4 tot.	02:49	8.07	75	181	33.1	44.4	0.27	204	43	17.4	25.1	17.0	8.3	67.8
diss.				32.41	7.01	1.62	0.07							

Characteristics of storm event: October 17 1995 - *Outflow*

Event start	18:45													
Sample	Time	Rain time	Total volume	Heavy metals (μg/l)				Suspended solids (mg/l)		Particle area (mm^2/ml)				
		(h)	(m^3)	Zinc	Copper	Lead	Cadmium	TSS	VSS	0-5 μm	5.5-10 μm	10.5-20 μm	20.5-50 μm	tot 1-50 μm
4 tot.	22:02	3.27	5.4	31.73	12	4.15	0.09	24	6.8	4.0	4.1	3.5	2.1	13.6
diss.				19.49	8.81	3.22	0.08							
5 tot.	23:01	4.25	25	30.72	10.61	5.1	< 0.05	22	6.0	5.3	4.0	1.5	1.6	12.4
diss.				5.85	7.06	1.32	< 0.05							
6 tot.	00:18	5.55	44	35.82	10.73	4.93	0.10	22	7.2	5.4	4.0	1.6	1.4	12.4
diss.				8.72	6.66	1.11	< 0.05							
7 tot.	02:46	8.00	61	35.53	11.03	5.24	0.10	28	8.4	6.8	5.4	2.3	1.5	16.0
diss.				13.78	7.67	1.53	0.05							
8 tot.	04:24	9.65	79	38.88	15.11	6.32	0.18	30	8.4	7.2	5.6	2.1	1.0	15.9
diss.				18.22	10.05	1.96	0.09							
9 tot.	07:19	12.6	95	59.35	14.28	6.66	0.17	-	-	5.6	4.3	3.1	1.1	14.1
diss.				15.7	7.82	3.0	-							

Characteristics of storm event: November 15-16 1995 - *Inflow*

Event start	16:54													
Sample	Time	Rain time (h)	Total volume (m^3)	Heavy metals (μg/l)				Suspended solids (mg/l)		Particle area (mm^2/ml)				
				Zinc	Copper	Lead	Cadmium	TSS	VSS	0-5 μm	5.5-10 μm	10.5-20 μm	20.5-50 μm	tot 1-50 μm
5	18:40	1.75	28	106.7	27.3	17.2	0.22	54	17	24.7	17.8	6.4	12.5	61.5
6	19:06	2.18	47	83.67	32.63	23.38	0.23							
7	19:34	2.65	71	79.59	24.53	14.45	0.73	54	15	17.9	13.9	6.9	16.7	55.3
8	20:02	3.13	95	63.48	22.53	15.87	0.71							
9	20:30	3.58	119	69.12	20.06	12.49	0.69	44	10	10.9	8.2	2.5	5.1	26.7
10	20:56	4.02	142	60.65	16.44	10.99	0.45							
11	21:17	4.37	167	86.53	24.66	22.44	0.78							
12	21:32	4.63	191	100.0	27.97	21.43	0.47							
13	21:47	4.88	215	67.76	21.29	15.99	0.16	66	14	14.7	12.9	6.0	4.7	38.3
14	22:01	5.10	239	76.61	24.88	19.13	0.15							
15	22:18	5.40	263	39.72	17.45	9.83	0.14							
16	22:42	5.80	287	39.55	16.71	7.3	0.10	28	5.1	9.0	5.6	3.2	1.1	18.8
17	23:11	6.28	311	49.26	17.02	7.55	0.15							
18	23:49	6.90	334	51.63	20.16	8.24	0.15							
19	00:16	7.37	359	41.3	13.76	6.83	0.15	23	5.1	5.7	4.8	2.2	2.3	15.1
20	00:38	7.72	383	42.73	15.65	8.05	0.15							
21	00:58	8.05	407	50.5	20.32	12.98	0.29							
22	01:23	8.47	431	38.29	15.19	7.12	0.15	22.5	< 5	5.6	4.2	2.8	7.0	19.6

Characteristics of storm event: November 15-16 1995 - *Outflow*

Event start	16:54														
Sample	Time	Rain time	Total volume	Heavy metals (µg/l)				Suspended solids (mg/l)		Particle area (mm^2/ml)				
		(h)	(m^3)	Zinc	Copper	Lead	Cadmium	TSS	VSS	0-5 µm	5.5-10 µm	10.5-20 µm	20.5-50 µm	tot 1-50 µm
9	18:30	1.60	8.8	76.7	13.5	7.5	0.15	19	5.6	6.8	4.4	2.1	1.7	15
10	20:22	3.47	54	82.8	19.1	8.1	0.15							
11	21:26	4.52	101	89.2	21.6	9	0.13	22	6.8	7.2	4.3	2.9	2.1	16.5
12	22:09	5.23	149	104.4	32.2	12.9	0.15							
13	22:51	5.95	197	75.5	40.4	13.2	0.15	43	10	11.0	10.4	4.2	1.7	27.4
14	23:48	6.90	244	74.8	18.6	12.9	0.15							
15	00:49	7.90	291	69.8	17.3	10.3	0.15	26	6.4	8.5	6.0	2.6	0.9	18.1
16	01:41	8.77	338	55.9	15.3	9	0.15							
17	02:36	9.68	385	59.8	14.1	8.5	0.15	26	5.2	8.8	6.2	3.7	1.3	20.0
18	03:40	10.75	431	57.9	15.7	8.7	0.15							
X [1)]	15:09	22.25	595	205.4	18.7	8.6	0.15	36	5.6	4.9	2.9	1.7	0.9	10.4

[1)] Manual sample

Appendix C

Characteristics of storm event: September 12 1995 - *Inflow*

Sample	Time	Rain time (h)	Total volum (m^3)	Nutrients (mg/l)	
Event start	04:15			Total nitrogen	PO_4 -P
1	10:26	6.18	32		
2	10:37	6.37	38	5.13	0.04
3	10:48	6.55	44		
4	10:50	6.57	45		
5	13:35	9.33	58		
6	13:40	9.40	61	4.31	0.05

Characteristics of storm event: September 12 1995 - *Outflow*

Sample	Time	Rain time (h)	Total volume (m^3)	Nutrients (mg/l)	
Event start	04:15			Total nitrogen	PO_4 -P
1	10:42	6.45	14		
2	11:01	6.77	17		
3	11:18	7.05	20	1.67	0.023
4	11:36	7.35	23		
5	11:55	7.67	26	1.58	0.023
6	12:16	8.02	29		
7	12:40	8.40	32		
8	14:07	9.87	40	1.40	
9	14:30	10.25	43	1.63	0.026

Characteristics of storm event: September 14 1995 - *Inflow*

Event start		15:05			
Sample	Time	Rain time	Total volum	Nutrients (mg/l)	
		(h)	(m^3)	Total nitrogen	PO_4 -P
1	17:14	2.15	7.1	4.99	0.026
2	17:21	2.27	13	3.08	0.013
3	17:29	2.40	19	2.95	0.02
4	17:37	2.53	25	2.49	0.016
5	17:45	2.67	31	1.90	0.016
6	17:52	2.78	37	1.86	0.01
7	17:57	2.87	43	1.95	0.01
8	18:04	2.98	49	1.99	0.02
9	18:14	3.15	55	1.90	0.013
10	18:26	3.35	61	2.80	0.013
11	18:36	3.52	67	2.27	0.016
12	18:44	3.65	73	2.99	0.026
13	18:50	3.75	79	2.58	0.023
14	18:56	3.85	85	2.72	0.02
15	19:00	3.92	91	2.63	
16	19:05	4.00	97	3.17	0.016
17	19:10	4.08	103	2.36	
18	19:14	4.15	109	2.76	0.013
19	19:20	4.25	115	2.63	
20	19:26	4.35	121	3.26	0.02
21	19:33	4.47	127	2.81	
22	19:39	4.57	133	2.17	0.029
23	19:46	4.68	139	2.22	0.029
24	19:54	4.82	145	2.99	0.033

Characteristics of storm event: September 14 1995 - *Outflow*

Event start		15:05			
Sample	Time	Rain time	Total volume	Nutrients (mg/l)	
		(h)	(m^3)	Total nitrogen	PO_4 -P
4	17:58	2.88	6.1	2.27	0.033
5	18:10	3.08	10		
6	18:21	3.27	13	3.63	0.02
7	18:31	3.43	17		
8	18:40	3.58	20	3.72	0.02
9	18:49	3.73	24		
10	18:56	3.85	28	2.49	0.013
11	19:03	3.97	31		
12	19:08	4.05	35	3.4	0.016
13	19:14	4.15	39		
14	19:19	4.23	43	5.85	0.016
15	19:24	4.32	48		
16	19:29	4.40	52	2.2	0.02
17	19:33	4.47	56		
18	19:38	4.55	60	2.99	0.016
19	19:43	4.63	64		0.01
20	19:48	4.72	68	3.85	0.029

Characteristics of storm event: October 5 1995 - *Inflow*

Event start	09:50			
Sample	Time	Rain time (h)	Total volum (m^3)	Total nitrogen [1] (mg/l)
1	10:31	0.68	0.4	1.72
2	10:40	0.83	26	1.72
3	10:47	0.95	49	1.72
4	10:55	1.08	73	1.72
5	11:06	1.25	98	1.72
6	11:25	1.58	122	1.72
7	11:48	1.95	134	1.45
8	13:03	3.22	155	1.45
9	13:22	3.53	179	1.45
10	13:35	3.73	202	1.45
11	13:59	4.13	226	1.45
12	18:19	8.47	269	1.45
13	18:44	8.88	293	1.18
14	19:12	9.37	317	1.18
15	19:50	10.00	335	1.18
16	20:21	10.50	353	1.18
17	20:50	11.00	366	1.18
18	21:19	11.47	380	1.18

[1] Three composite samples (1-6, 7-12, 13-18)

Characteristics of storm event: October 5 1995 - *Outflow*

Event start	09:50			
Sample	Time	Rain time (h)	Total volume (m^3)	Total nitrogen [2] (mg/l)
6	10:51	1.00	3.8	0.5
7	11:14	1.40	27	0.5
8	11:34	1.72	49	0.5
9	11:59	2.15	72	0.5
10	12:37	2.78	95	0.5
11	13:24	3.55	117	0.5
12	13:47	3.95	140	0.8
13	14:10	4.33	163	0.8
14	14:37	4.78	185	0.8
15	15:19	5.47	208	0.8
16	16:31	6.68	230	0.8
17	18:37	8.77	252	0.8
18	19:23	9.53	274	1.4
19	20:03	10.22	297	1.4
20	20:44	10.88	319	1.4
21	21:26	11.58	341	1.4
22	22:11	12.33	364	1.4
23	23:12	13.35	386	1.4

[2] Three composite samples (6-11, 12-17, 18-23)