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Long-term simulation of the removal of pollutants in retention basins

ABSTRACT

The paper describes a method for the long-term simulation of the discharge of pollutants to the environment from storm sewer overflows in combined sewer systems, which has a connected retention basin. This study covers Cd, Cu, Ni, Pb, Zn and PAH. The method includes both the influence of the flow-dependant sedimentation and the variation of the settling velocity of the particles. The results show that including these effects lead to significant lower discharges of pollutants compared to conventional methods of estimation. As an example computations with a spectrum of basins which cover realistic sizes show that the long-term discharges of PAH are about half of the expected values without removal.

Keywords: Sewer systems; Retention basins; Storm water overflows; Pollutants removal.

1. INTRODUCTION

Natural waters like lakes and rivers receive more or less diluted sewage from combined storm sewer overflows during rain. As almost all dry-weather discharges now are sent to the treatment plants the major impact on the recipients now can be assigned to the overflows. A recent literature study (Larsen and Neerup-Jensen, 2000) has shown that simple causal relations between impacts and effects do not exist in this area. On the other hand there is a well-documented empirical experience that proofs that overflows in general have a negative influence on the water quality. Makepeace et al, 1995, give an overview of the data on urban water quality.

The most clear and best-understood influence on the biological system is the direct physical impact on the fauna of small animals living in streams and rivers. The drift or erosion of the animals caused by the increased flow can be registered quantitatively on the fauna index used for the biological characterization of the water quality.

For the time being no reliable causal relations have been established between the specific components in the storm water and the influence on the biological characterization of the receiving waters. On the other hand studies of the ecotoxic risk where a group of organisms are exposed to storm water rather clearly indicate that potential toxic effects exist (VanLoon et al, 2000). Despite this obvious lack of detailed knowledge it is a well-accepted idea to reduce the discharge of pollutants as one of the steps towards a better water quality in the receiving waters. This way of thinking corresponds well with the EU Water Framework Directive, which actually is under implementation in the EU countries.

Retention basins in connection with overflow structures will reduce the discharge of matter for 3 reasons:

- Most important is the basic idea that basins will accumulate a part of the storm water volume and send it to treatment.
- Basins primarily catch the first and most polluted part (first flush) of the storm flow. It has been shown that taking this effect into account reduces the computed discharges with more than 50 % compared to estimations based on a constant concentration during the rain (Larsen et al, 1998).
- A significant part of the pollution is connected with particles, which to some extent will sediment out in the basins. This effect is described in this paper.

In Denmark no well-documented investigations exist regarding the reduction of pollutants in basins based on direct measurements. German investigations (Michelbach and Weiss, 1996), which incorporated measurements on real retention basins designed according to the German guidelines A 128 (ATV, 1992), showed that basins have an important capability of removal of pollutants. The study summarized as follows:

- The concentration of settable particles (particles which will settle in a standard settling column after 2 hours) is reduced with more than 80 %.
- The concentration of suspended solids (measured by filtration) is reduced with 65 %.
- The concentration of organic matter (measured as COD) is reduced with 50 %.

So in general these field investigations clearly indicates that retention basins are rather efficient for solid and pollutant removal.

2. METHOD FOR ESTIMATION OF LONG-TERM POLLUTANT DISCHARGE

Estimations of annual pollutant loads from storm overflows have up till now most frequent been based on the assumption of a constant *event mean concentration (EMC)* of the actual component of pollutant. The annual overflow volume will often be found from a long-term simulation based on historical time series of rain. Then the load can easily be found as the product of concentration and volume.

The method presented in this study can be understood as a further development of the EMC-method. The method includes the sedimentation of particles taking into account that the settling characteristics of the particles vary over a broad spectrum of settling velocities and also taking into account that the settling conditions in basins vary with the varying hydraulic load on the basins during rain. Furthermore it is also included that the pollutant components (Cd, Cu, Ni, Pb, Zn and PAH) are attached to distinct fractions of particles with varying weight.

The method estimates the annual discharge of pollutants on the basis of the following information:

Rainfall data

The driving force of the storm water flow in the sewer system is the rain, and the rainfall data come from long historical time series of measured rainfall. The Danish National Rain Gage System (Spildevandskomitéen, 1999) includes 98 gages. The related database contains 15 to 30 years of data for each gage where rainfall intensity is stored with a temporal resolution of 1 minute.

Model of run-off

The mathematical model of the catchment was based on the well-known *time-area method*, which transforms the input of historical rainfall to time series of outflow hydrographs. Initial loss and so-called hydrological loss factor are included. (The hydrological loss factor, which often has a value of 0.8 to 0.9, is the slope of the regression line in a plot of discharge volumes against rain volumes).

Model of flow and particle removal

The description of the basin includes two conservation equations, the continuity equation for flow and the continuity equation for settable particles.

The flow description is a traditional quasi-stationary basin calculation based on a varying water depth, a free overflow dependant on the surface level and a constant forward transmission of water and mass to the treatment plant.

The mass balance for settable matter in the basin covers four terms. These are accumulation, inflow, outflow and removal. The removal is described by the *efficiency function* for the removal in a basin as shown in figure 1.

The efficiency E is here defined as

$$E = (1 - \frac{m}{m_0})$$

where m is the flux of matter over the overflow and m_0 is the potential flux of matter, which would have occurred if the matter had been fully mixed in the water column corresponding to that removal does not take place.

The relative (or dimensionless) settling velocity $w_s^{'}$ is defined as

$$w_s^{'} = \frac{w_s}{s}$$

As characteristic velocity for the scaling of settling velocity the so-called surface load s is applied. This is defined as $s = Q/A$, where Q is the inflow to the basin and A is the surface are of the basin.

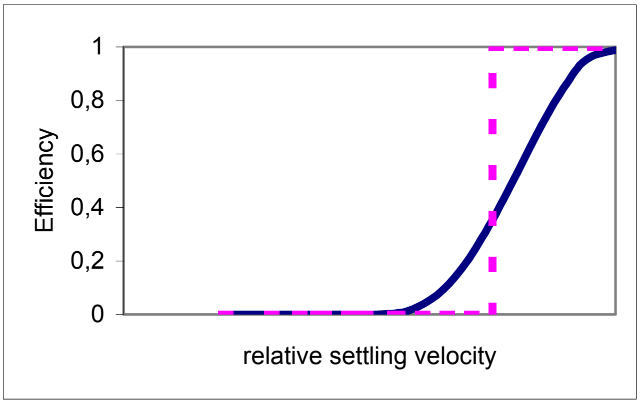

Figure 1: Principle of efficiency function for basin (full line is real function and dotted line is simplified function applied in this study)

The theoretical background for this removal function should not be given here, but the two key points are

1. The removal function depends on the geometry of the basin and can be assumed to be identical for geometrical similar basins.
2. The removal function in its dimensionless form can be assumed independent of the flow as long as the flow is turbulent with high Reynolds numbers.

As mentioned the efficiency function is specific for the basin. This means that the function has to be determined in each case. It can be determined either by experiments (laboratory or full-scale) or it can be found from numerical modelling as described by Neerup-Jensen et al, 1999. As the removal function is given as function of the relative (dimensionless) settling velocity the efficiency function this way covers the varying hydraulic load of the basin.

In this study the efficiency function has been further simplified to a step function as shown in figure 1. This was based on the well-know Hazen's formula for sedimentation tanks

$$T \geq \frac{h}{\alpha w_s}$$

where T is retention time necessary for the removal of particles with a settling velocity greater and equal than w_s, h is the water depth in the basin and α is a correction factor which can be estimated from the real removal function as shown in figure 1.

The α contains the information on the basin geometry and on the flow (turbulence and secondary currents). For an ideal basin (a long channel without turbulence and secondary currents) this factor is 1,0 but in the real world the value lies in the area of 0,2 to 0,5 and can, as already said, only be found from physical experiments or numerical modelling.

Data for settling characteristics of pollutants

The data for this study is taken from a comprehensive study carried out by UFT, Dr. Brombach GmbH. A resume of the investigation can be found in Michelbach and Weiss (1996). The data were obtain from the city Bad Mergentheim in the southern Germany having about 25.000 inhabitants and included catchments with reduced areas from 0.1 to 350 hectares.

The settling characteristics of the particles from the storm water were measured in a settling column as shown in figure 2.

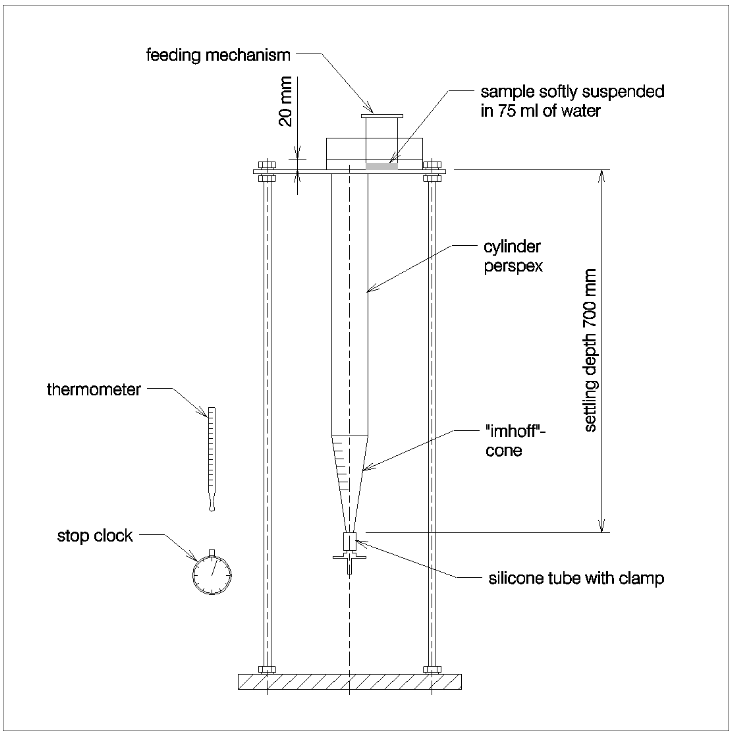

Figure 2: Settling column (from Michelbach et al, 1993)

The experiments take place as follows. First the sample was settled out during 2 hours in an Imhoff cone. Next, this sample was placed at the top of the column. At defined time steps samples were taken out from the bottom of the column and afterwards the sample was analysed. In each experiment 12 samples were taken out to cover a range of settling velocities from 0,001 to 17,5 cm/s. Totally 396 experiments were carried out and among those 101 were from combined sewer systems. The settling curves for suspended solids (SS) are shown in figure 3.

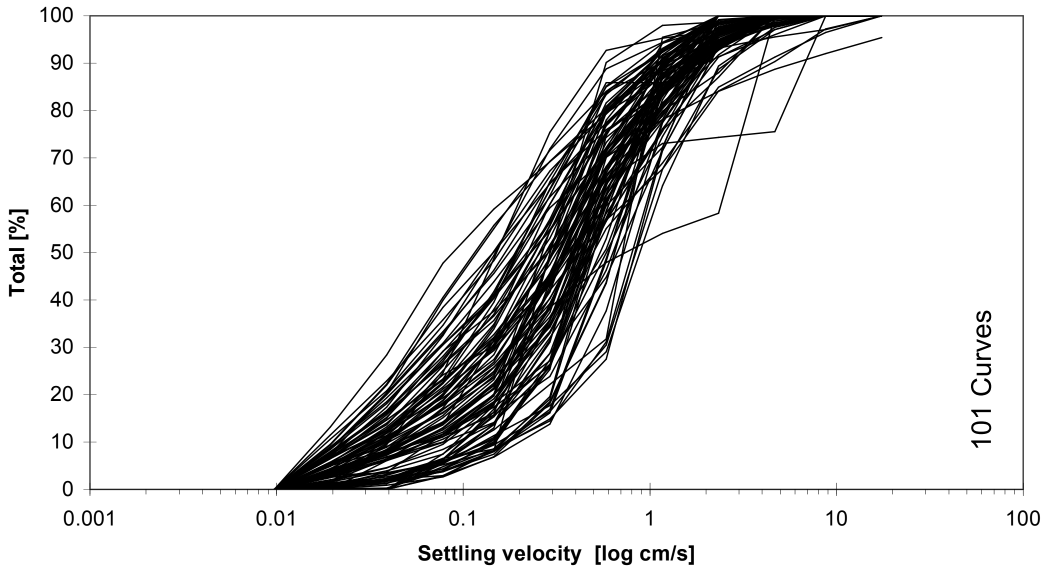

Figure 3: Settling curves for 101 samples of storm water from combined sewer systems (from Michelbach and Wöhrle, 1994)

All samples were analysed for water content, ignition loss and density. A selected number of samples were also analysed for chemical properties. The analyses covered organic matter (COD), Polly Aromatic Hydrocarbons (PAH), Zinc (Zn), Cadmium (Cd), Lead (Pb) and Copper (Cu) and Nickel (Ni). Unfortunately, the data of COD had to be excluded for the purpose described here.

3. ESTIMATION OF THE AVERAGE ANNUAL REMOVAL OF POLLUTANTS IN BASINS

As the estimation of the average annual removal of pollutants in basins depends on a large number of parameters it is not appropriate to present the results as table or graphs, which represent the total range of the parameters. Instead the result of a specific and typical case, which covers many standard situations, is shown in the next. The data for the case are given in table 1 shown below.

Table 1. Data for case study

Historical rain series: Kolding Forrenseanlæg,	18	years
Reduced catchment area	10	hectares
Time of concentration for flow in catchment	10	minutes
Initial loss in run-off	0,06	mm
Hydrological reduction factor	1,0	-
Volume of basin	400, 650, 1000, 1500 and 2000	m^3
Water depth in basin	3	m
Dry weather flow	1	l/s
Flow conveyed to treatment	10	l/s

With the model and these data the overflow volumes were calculated and the results are summarized in table 2. The table also gives the total removal of the settable particles.

Table 2. Calculated average balance of water and particles in the basins

Volume of basin mm rain	**Number of over-flows per year**	**Inflow of water 10^3 m^3 per year**	**Overflow of water 10^3 m^3 per year**	**Removal of water dis-charges %**	**Annual inflow of settable particles kg**	**Annual overflow of settable particles kg**	**Removal of parti-cles %**
20	3	75	2,2	97	48000	191	99,6
15	6	75	4,5	94	48000	450	99,0
10	13	75	8,8	88	48000	1200	97,5
6,5	21	75	14,5	81	48000	2600	94,5
4	34	75	21,5	71	48000	5200	89,1

In table 3 is given the computed further reduction of matter in the overflow because of sedimentation in the basins of the settable part of the matter. The numbers cover the average over 18 years.

Table 3. Long-term removal of pollutants connected to settable particles

Basin		**Removal [%]**					
Volume mm rain	**Overflows per year**	**Cd**	**Cu**	**Ni**	**Pb**	**Zn**	**PAH**
20	3	84	83	78	86	88	87
15	7	81	79	73	83	84	84
10	13	74	72	64	76	77	78
6,5	22	65	63	54	67	67	69
4	34	52	50	41	55	53	57

Finally an estimate of the overall removal of PAH including both settable and non-settable fraction is summarized in table 4. The dataset did not cover a complete series of measurements of both fractions so it has been assumed that the soluble part was 25 % of the total concentration of PAH and that the settable part accounted for 75 %.

Table 4. Estimate of the total removal of PAH (both settable and non-settable fraction)

Volume of basin mm	Number of overflows per year	Input to basin g PAH per year	Loss to recipient sedimentation not included g PAH per year	Loss to recipient sedimentation included g PAH per year	Additional removal %
20	3	1004	28	11	61
15	6	1004	55	24	56
10	13	1004	109	52	53
6,5	21	1004	180	96	47
4	34	1004	267	164	39

Last column of table 4 refers to additional removal of PAH in respect to loss to recipient, expressed in %, due to consideration of sedimentation in basin.

4. DISCUSSION AND CONCLUSION

As seen in table 4 the further reduction of the loss to the recipient because of sedimentation in the basins lies from 40 to 60 % although the size of the basins varies with a factor 5.

In this study all concentrations and settling characteristics of the particles and the pollutants have assumed to be constant during the rain events. This means that the first flush effects are not incorporated in the results. As mentioned earlier the first flush effects are known to cause a further reduction in the overflow of matter from basins. Often this reduction lies in the same order as the removal discussed in this paper. Accordingly one can from now allow on that estimates based on the assumption of a constant concentrations overestimates the overflows of pollutants considerably, probably with a factor 3 to 5.

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