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Uncertainties of stormwater characteristics and removal rates of stormwater treatment facilities: Implications for stormwater handling

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ABSTRACT

Stormwater runoff is a major contributor to the pollution of receiving waters. This study focuses at characterising stormwater in order to be able to determine the impact of stormwater on receiving waters and to be able to select the most appropriate stormwater handling strategy. The stormwater characterisation is based on determining site mean concentrations (SMCs) and their uncertainties as well as the treatability of stormwater by monitoring specific pollutants concentration levels (TSS, COD, BOD, TKN, TP, Pb, Cu, Zn, *E.coli*) at three full scale stormwater treatment facilities in Arnhem, the Netherlands. This has resulted in 106 storm events being monitored at the lamella settler, 59 at the high rate sand filter and 132 at the soil filter during the 2 year monitoring period.

The stormwater characteristics in Arnhem in terms of SMCs for main pollutants TSS and COD and settling velocities differ from international data. This implies that decisions for stormwater handling made on international literature data will very likely be wrong due to assuming too high concentrations of pollutants and misjudgement of the treatability of stormwater. The removal rates monitored at the full scale treatment facilities are within the expected range, with the soil filter and the sand filter having higher removal rates than the lamella settler. The full scale pilots revealed the importance of incorporating gross solids removal in the design of stormwater treatment facilities, as the gross solids determine operation and maintenance requirements.

1. Introduction

Separate sewer systems are widely applied in economically developed countries. Storm sewers are known to contribute significantly to the annual pollutant loads into the receiving waters and to cause severe degradation of urban receiving waters (House et al., 1993). In the United States, stormwater runoff is the major contributor to pollution of receiving waters (Lee et al., 2007). The European Water Framework Directive (WFD) (2000/60/EC, 23 October 2000) aims at achieving a good status for all European water bodies. In order to be able to comply with the WFD, local water authorities in member states have to develop stormwater management strategies able to enhance local receiving water quality to the desired

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level. In practice, this means that total pollutant load to the receiving waters has to be reduced to a level that sustains the required ecological status. Stormwater runoff contributes to a large extent to this total pollutant load of a receiving water, especially in smaller urban waters (Beenen et al., 2011).

Consequently, water authorities have to assess the impact of stormwater discharges on the receiving waters and, if the receiving water quality does not comply with the standards, to select appropriate measures for stormwater treatment. This requires knowledge of local stormwater characteristics in order to be able to assess the relative contribution of the stormwater pollution to the overall load of the receiving waters and to assess the treatability of the stormwater.

Local stormwater characteristics can be derived by:

1. scrutinizing available monitoring data from literature for catchments with comparable characteristics
2. stormwater quality modelling
3. local monitoring campaigns

1.1. *Available monitoring data*

The stormwater concentration levels found in literature are summarized in Table 1. The data from the Dutch STOWA database (Boogaard and Lemmen, 2007) show that stormwater monitored in the Netherlands has relatively low suspended solids, BOD and COD concentrations compared to international data, whereas the nutrient and toxic metal concentrations are within the international range. Given the lack of data on the monitoring site characteristics, monitoring set up and the broad range of concentration levels (Fuchs et al., 2004), it is impossible to explain the difference with respect to TSS, BOD and COD concentrations by available literature data only. The large differences between the stormwater characteristics in the Dutch and international databases make it very difficult to select the appropriate stormwater management strategy.

1.2. *Stormwater quality modelling*

The pollutant level of stormwater is a function of the pollution associated with rainfall itself, the pollutants taken with the flow during the rainfall runoff process, from illicit (or wrong) connections (Salvia-Castellvi et al., 2005) and in-sewer processes.

Data on the pollution associated to the rainfall (wet deposition) is generally widely available from long term monitoring programmes (e.g. Swaluw et al., 2010). Data on the level of pollutants taken with the stormwater during the runoff process on roofs and streets is sparsely available in literature (Gromaire-Mertz et al., 1999; Förster, 1996), whereas data on the contribution of in sewer stocks (sediment, biofilm) and illicit connections to pollutant levels in storm sewers is even more sparse (Pitt et al., 1993). However, much research effort has been invested in modelling of stormwater quality (Mourad et al., 2006). Despite this effort, it is still not possible to apply stormwater quality models to predict the stormwater quality at a given stormwater outfall (Bertrand-Krajewski, 2007): Model calibration and verification appear to dramatically depend on the data sets used for their calibration and verification. As a consequence, additional monitoring is required to be able to characterise stormwater locally.

This paper aims at characterisation of stormwater by a monitoring campaign in order to be able to determine the impact of stormwater on receiving waters and to be able to select the most appropriate stormwater handling strategy.

2. Materials and methods

The stormwater characterisation is based on determining site mean concentrations (SMCs) on three locations in Arnhem, the Netherlands, for specific pollutants by monitoring stormwater concentrations and on determining the treatability of

Table 1 – Stormwater concentration levels for principal pollutants.

		Boogaard and Lemmen (2007)[a]	Bratieres et al. (2008)[b]	Salvia-Castellvi et al. (2005)[c]		Fuchs et al. (2004)[d]	Daligault et al. (1999)[e]	
		Dutch data mean (median–90 percentile)	Worldwide and Australian	Mean EMC St. Quirin (min–max)	Mean EMC Rte d'Esch (min–max)	Median (25–75 percentile)	Mean Brunoy (min–max)	Mean Vigneux (min–max)
TSS	mg/l	49 (20–150)	150	592 (30–2500)	131 (30–300)	141 (74–280)	158 (11–458)	199 (25–964)
BOD	mg/l	6.7 (4.0–14)	–	335 (8–1300)	30 (5–90)	13 (8–20)	10 (3–29)	17 (4–168)
COD	mg/l	61 (32–110)	–	1152 (30–4800)	138 (25–400)	81 (5–113)	68 (18–299)	121 (26–561)
TKN	mg N/l	2.8 (1.7–5.2)	2.1	7.4 (1–24)	2.3 (0.6–7.8)	2.4 (2.1–5.8)	2.8 (1–12)	4.7 (1–50)
TP	mg P/l	0.42 (0.26–0.97)	0.35	3 (0.3–12)	0.7 (0.2–2)	0.42 (0.24–0.70)	0.56 (0.3–4.7)	1.1 (0.3–19.1)
Pb	μg/l	33 (12–75)	140	80 (20–130)	50 (20–90)	118 (46–239)	52 (2–210)	69 (4–404)
Zn	μg/l	194 (95–450)	250	3330 (80–11700)	1170 (500–4100)	275 (128–502)	607 (210–2900)	146 (30–640)
Cu	μg/l	26 (10–47)	50	170 (40–500)	70 (30–200)	48 (28–110)	23 (7–59)	24 (6–52)
E. coli	#/100 ml	3.4E+4 (1E+4–1E+5)	–	–	–	–	–	–

a Dutch STOWA database (version 2.6, 2007), based on data of 10 monitoring projects in the Netherlands, residential and commercial areas, with n ranging from 26 (SS) to 169 (Zn).
b 'Typical' pollutant concentrations based on review of worldwide (Duncan, 1999) and Melbourne (Taylor et al., 2005) data.
c 2 monitoring locations in Luxembourg, residential areas, $n = 11$ per location. Location St. Quirin is reported to have significant illicit connections to the storm sewer.
d ATV database, like Duncan (1999) partly based on the US EPA nation wide runoff programme (NURP), with n ranging from 17 (TKN) to 178 (SS).
e Brunoy: 55% educational and sporting infrastructures, 45% residential, Vigneux, residential, $n = 30$ per location.

stormwater by monitoring three stormwater treatment techniques in full scale pilots. The number of locations is limited to three given the available resources in the research project.

2.1. Selection of monitoring locations and treatment techniques

The southern part of the city of Arnhem, developed between 1960 and 2000, comprises 300 ha of separate sewer systems, with over 300 storm sewer outfalls (SSOs). In the selection of the monitoring locations the following aspects were taken into account:

- connected impervious area derived from simulations with a full hydrodynamic model; outfalls serving less than 2 ha will have small flows during smaller storm events, thus resulting in unrealistic accuracy requirements for monitoring equipment, outfalls serving more than 10 ha will have high design flows, requiring relatively expensive monitoring equipment as well as treatment facilities;
- water quality data available from quick scan with grab samples at stormwater outfalls (Vermulst et al., 2002);
- representativeness in terms of catchment characteristics, such as types of houses (single dwellings, terraced houses, high rise apartment buildings, construction period, number of inhabitants, average income, type of roads (quiet-busy), planned reconstruction of roads;
- local conditions: safety (traffic conditions), accessibility, available space for stormwater treatment and monitoring equipment, underground infrastructure (e.g. water and gas mains).

Table 2 summarizes the main characteristics of the selected catchments.

The selection of the treatment techniques was based on the following criteria:

- treatment efficiencies based on literature review
- investment and operational costs
- operational requirements in terms of man hours and level of complexity
- space requirements as stormwater treatment facilities had to be fitted in an existing urban environment.
- nuisance due to noise or odour emissions
- treatment processes involved.

This resulted in the following stormwater treatment techniques to be applied in full scale pilots at three locations:

- lamella settler in order to test the treatability with settling as main treatment process at location Dordrechtweg.
- high rate sand filter in order to test filterability as main treatment process at location Brabantweg
- soil filter in order to test sorption and filtering as combined treatment processes at location Matsersingel.

2.2. Design parameters, monitoring set up and data collection

2.2.1. Design parameters of stormwater treatment facilities

2.2.1.1. Lamella settler. The lamella settler has been installed in line in the storm sewer, protected from hydraulic overloading by a flow control structure comprising an overflow weir installed in a new manhole constructed at the former SSO location and a small diameter (250 mm) sewer (Fig. 1). This structure limits the flow to the lamella settler to 250 m^3/h, subsequently limiting the hydraulic surface loading to maximum 1 m/h. The lamella settler has a nominal design capacity of 50 m^3/h, at which the hydraulic loading is equivalent to a surface loading of 0.2 m/h.

2.2.1.2. Soil filter. The soil filter is installed off line and is fed by a pump with a capacity of 25 m^3/h (Fig. 2). The pump starts operating as soon as the flow in the storm sewer exceeds 50 m^3/h. The soil filter, with a surface of 300 m^2, is located at the banks of the receiving water. The filter layer consists of sand, with a design hydraulic permeability of 1.5 m/d, resulting in an infiltration capacity of 18.75 m^3/h. During long storm events the water level in the soil filter will rise. In order to prevent overtopping of the banks, an overflow weir has been constructed at a level of 0.3 m above ground level, resulting in a storage capacity of 90 m^3. At a depth of 60 cm, well above the groundwater table, drains collect the treated stormwater and discharge via a sampling manhole to the receiving water.

2.2.1.3. Sand filter. The sand filter has a design capacity of 25 m^3/h. The sand filter is installed off line and fed by a pump located near the SSO Brabantweg (Fig. 3). This pump starts operating as soon as the flow in the storm sewer exceeds 50 m^3/h.

The sand filter is designed at a surface loading of 10 m/h, a rate normally applied for rapid sand filtration of WWTP effluent (Nieuwenhuijzen, 2002). The sand filter consists of two parallel pressure tanks. As soon as the hydraulic resistance of the sand bed exceeds the threshold, the filter is backwashed automatically. The back wash, containing the retained pollutants, is discharged to a nearby foul sewer.

Table 2 – Site descriptions.

Site	Land use	ha impervious area connected	Period of development	Type of housing
Dordrechtweg	Medium density residential	3.8	1970	Mixed terraced and town houses, 90% owned by housing corporation
Brabantweg	Medium density residential	5.6	1980	Town houses, 40% owned by housing corporation, 60% privately owned
Matsersingel	Low density residential	4.0	1980–2000	Privately owned semi detached

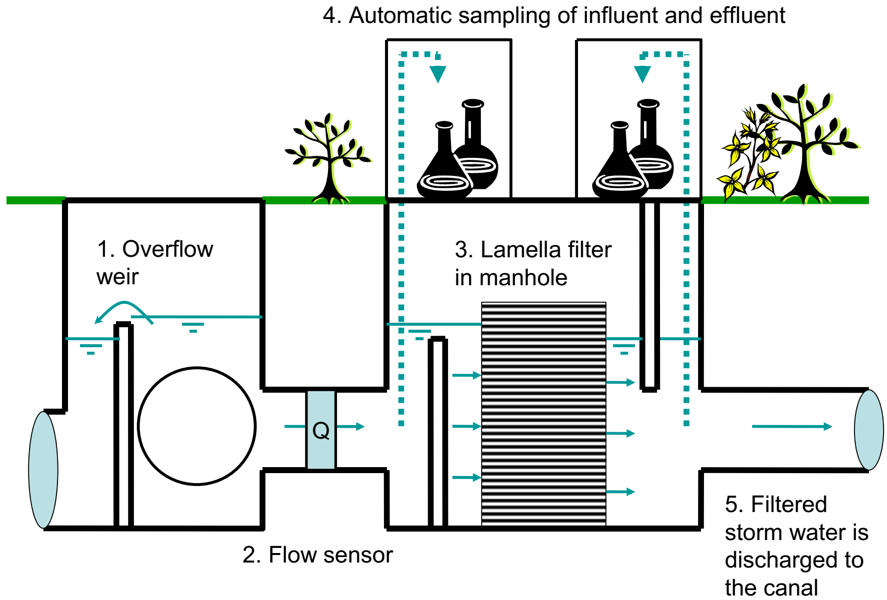


Fig. 1 – Schematic of lamella filter. The lamella filter is equipped with MPak® Coalescing Plates, http://www.facetinternational.com/pdfs/environ/cplatetech.pdf.

2.2.2. *Monitoring set up*

At each monitoring location, the measured flow is used to control the automatic sampling system. An automatic sampling system starts when flow above a threshold is measured. The strategy applied is time proportional sampling, as this is required to be able to monitor the efficiency of the pumped stormwater systems: the soil filter and sand filter. These facilities receive a constant flow (Q_{pump}) and consequently, flow proportional sampling of the inflow (Q_{pump}) to the facilities results in time proportional sampling of the stormwater ($Q_{stormwater}$) in the storm sewer. For reasons of comparability of the data, time proportional sampling has been applied at all three locations. The impact of this sampling design on the uncertainties for the SMC is discussed further in Section 3.1.1.

2.2.2.1. *Location lamella settler*. The flow to the lamella settler is measured at 1 min intervals by an ultrasonic flow sensor (Endress + Hauser PROMAG 50W), using a Doppler shift to determine the velocity in the fully submerged sewer Ø 250 mm. The automatic sampling system of the influent and effluent of the lamella settler is switched on when the flow is above the threshold of 30 m^3/h. The influent and effluent of the lamella settler are sampled automatically at a 5 min interval. The samples, with a volume of 250 ml, taken are stored at 4 °C in the Efconomy sampler system in 1 l bottles, containing up to 4 samples each. As soon as a sample is taken, an SMS signal is sent to the operator, who takes care of collecting the samples for subsequent analysis in the laboratory of Waterboard Rivierenland in Tiel. This procedure also applies to the other facilities.

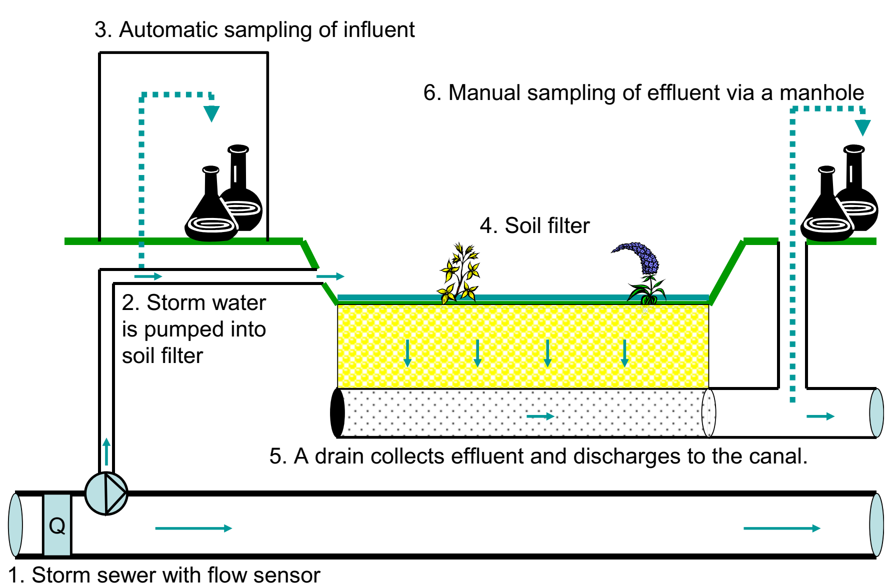


Fig. 2 – Schematic of soil filter.

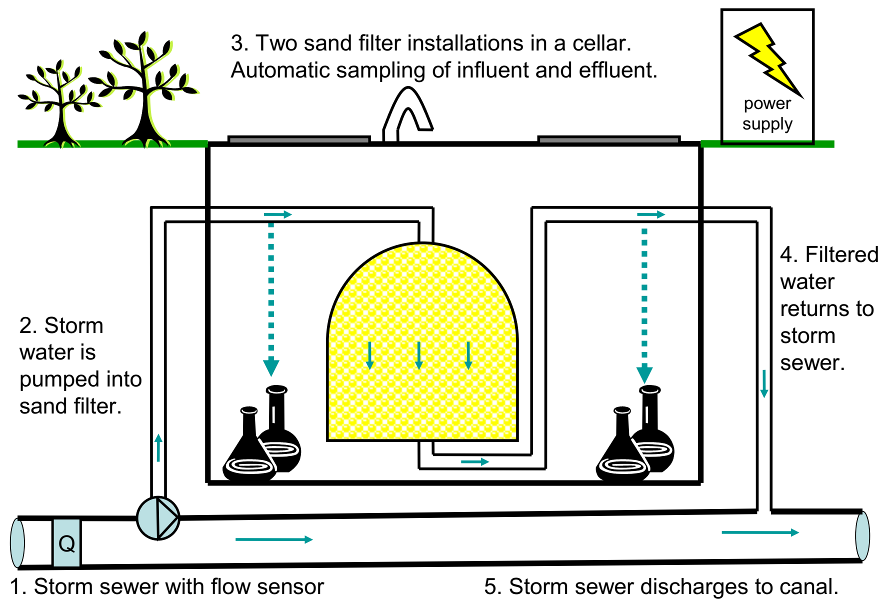


Fig. 3 – Schematic of sand filter. The sand filter is placed subsurface in the banks of the receiving water.

2.2.2.2. *Location soil filter*. The flow sensor at location soil filter is an ultrasonic flow sensor (Endress + Hauser PROMAG 50W), using a Doppler shift to determine the velocity in a 400 mm contraction in a 800 mm pipe. The hydraulic performance of the soil filter is monitored by two water level sensors, type ATM/N pressure gauges, at a 1 min interval, located in the soil filter. The influent of the soil filter is sampled at an interval of 5 min as long as the influent pump is running, using the same type of sampler as applied at the lamella filter. The effluent of the soil filter is manually taken at the sampling manhole, as automatic sampling from the drains is too difficult due to the long and varying retention time of the stormwater in the soil filter. The sampling manhole provides a completely mixed sample per storm event.

2.2.2.3. *Location sand filter*. The flow sensor at location sand filter is a flow sensor (OCM PRO), with ultrasonic velocity measurement based on acoustic reflection correlation to recognize reflecting particles and to determine their travelled distance in time (Solliec and Teufel, 2010). The flow sensor is installed in a 700 mm diameter sewer. The measuring range of the sensor is adjusted to 0–200 m^3/h in order to guarantee stable operation of the feeding pump. Stormwater and effluent samples were taken at an interval of 5 min from the influent and effluent pipes of the sand filter during operation of the sand filter.

2.2.3. *Data collection*

The used sensors are connected to a Campbell Scientific CR200 logger at the pilot locations. These loggers are equipped with a GSM/GPRS transmitter for data transport, including an alerting service via SMS. The data transmission is managed from the office with the Campbell software LoggerNet. The transmitted data are added to a data file per location on the connected computer. After the analysis of the obtained measurement data, it is decided how any taken samples will be analysed.

2.2.4. *Water quality sample collection and analytical methodology*

The samples taken by the automatic samplers were collected within 24 h after the storm event by Waterboard Rivierenland. The water quality parameters analysed are selected to cover the main water quality problems related to stormwater discharges, see Table 3. The water quality samples have been analysed after being completely mixed in the laboratory of Waterboard Rivierenland, according to standard methods and standard quality control/assurance procedures, see Table 3.

In addition, for 13 storm events monitored at the lamella settler settling velocities have been determined for 2 grab samples, resulting in 26 settling curves. The settling velocities have been determined using a column of 1500 mm height and 42 mm diameter. The column was filled with a fully mixed homogeneous sample, without further sample preparation. Sampling of water took place at desired moments via the lowest sampling point, 50 mm from the bottom of the column. This method is comparable to the multi port method (Pisano, 1996). The suspended solids concentration was determined using a laboratory turbidity meter HACH 2100N and subsequent lab analysis.

2.3. *Data analysis*

2.3.1. *Data validation*

The validation procedure applied to guarantee the quality of the measurement data obtained in the monitoring project in Arnhem is described in detail by Liefting and Langeveld (2008). Actuality and verifiability have been secured by keeping logbooks and archiving all relevant information digitally. Reliability, accuracy and completeness have been analysed by automated logical and statistical tests, including exceedance of boundary values, absence of data, equidistance of data, drift, autocorrelation and cross correlation checks. The main problems discovered were installation faults of the stormwater treatment facilities and software induced errors in flow

Table 3 – Water quality parameters analysed and analytical uncertainty.

Water quality problem related	Parameter	Reference method	Analytical uncertainty u (%)[a]
General parameter	TSS	NEN-EN 872	12
Oxygen depletion	Biochemical Oxygen Demand (BOD)	NEN-EN 1899 1&2	5.2
	Chemical Oxygen Demand (COD)	NEN 6633:2006	10.7
Eutrophication	Total Kjeldahl Nitrogen (TKN)	NEN-ISO 5663:1993	16.8
	Total Phosphorus (TP)	NEN 6663	1.9
Toxicity	Lead (Pb)	NEN-EN-ISO 17294-2:2004	1.3
	Zinc (Zn)		3.8
	Copper (Cu)		0.4
Microbiological quality	*E. coli*	NEN 6571:1982	1

a Specification of laboratory Waterboard Rivierenland 2011.

monitoring. E.g. on location Dordrechtweg the flow sensor gives a flow signal every 10 s. This signal was to be averaged per minute. However, the signals were totalized per minute, causing the flow registration to be six times too high.

2.3.2. *Calculating SMC and associated uncertainties*

The SMC applied is the weighed mean, with event volumes as weights (Mourad et al., 2005, 2006)

$$\mathrm{SMC} = \frac{\sum_{i=1}^{n} \mathrm{EMC}_i V_i}{\sum_{i=1}^{n} V_i} \quad (1)$$

where EMC_i is the EMC of event i and V_i the volume of event i.

The standard uncertainty $u(Y)$ of the SMC is calculated by means of the Law of Propagation of Uncertainties (LPUs):

$$u(y)^2 = \sum_{i=1}^{N} u(x)^2 \left(\frac{\delta f}{\delta x_i}\right)^2 + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} R(x_i, x_j)\ u(x_i)u(x_j)\frac{\delta f}{\delta x_i}\frac{\delta f}{\delta x_j} \quad (2)$$

where $R(x_i,x_j)$ is the coefficient of correlation between the quantities x_i and x_j (Bertrand-Krajewski et al., 2003).

The LPU enables calculating the total uncertainty from its individual sources. The individual sources taken into account are (Fig. 4):

- Sampling uncertainty. This uncertainty is due to the concentration at the sampling location being not representative for the concentration. The sampling uncertainty of the TSS concentration can be as large as 15–20% (Ahyerre et al., 1998; Bertrand-Krajewski and Bardin, 2002). However, dissolved substances and fine particles may be supposed to be mixed well (Martin et al., 1992; McCarthy et al., 2008). The sampling uncertainty of TSS is defined at 20%; the sampling uncertainty of other parameters is neglected as most pollutants are typically associated with fine particles (Brunner, 1998).
- Storage uncertainty. As the samples have been stored in a refrigerator at 4 °C for a maximum of 2 days, the microbiological activity and subsequent storage uncertainties can be regarded as non-significant (Kotlash and Chessman, 1998).
- Analytical uncertainty. The samples have been analysed by the laboratory of Waterboard Rivierenland. The uncertainties are given in Table 3.
- Uncertainties due to the sampling regime. The time proportional sampling regime introduces an error in the EMC. The volumetric weighted EMC is described by

$$\mathrm{EMC} = \frac{\int_T q_t c_t}{\int_T q_t} \quad (3)$$

where q_t and c_t are the respective flow and concentration at time t and T is the event period.

With a volume proportional sampling regime, the EMC is estimated with the discrete sample concentrations and their associated volumes (Shuster et al., 2008):

$$\mathrm{EMC_{VP}} = \frac{\sum v_t c_t}{\sum v_t} \quad (4)$$

With the applied time proportional sampling regime and combined/mixed samples, the EMC is estimated with the concentration of the mixed sample.

$$\mathrm{EMC_{TP}} = \frac{\sum c_t}{n} \quad (5)$$

The error introduced by the chosen time proportional sampling regime consists of two individual sources: the difference $\mathrm{EMC_{TP}} - \mathrm{EMC_{VP}}$ and the uncertainty due to the limited number of samples per event. The first error has been estimated from 18 events at location Dordrechtweg with the samples individually analysed for TSS. For each event both the $\mathrm{EMC_{TP}}$ and the $\mathrm{EMC_{VP}}$ have been calculated. Second order uncertainties (uncertainties in $\mathrm{EMC_{VP}}$ due to uncertainties in the flow measurements) are neglected.

- The uncertainty due to the limited number of samples per event is estimated using the bootstrap method (McCarthy et al., 2008) applied at the separately analysed samples from the aforementioned 18 events from location Dordrechtweg.
- Pipe radius uncertainty. The pipe radius was assumed to have an uncertainty of 0.002 m (Bertrand-Krajewski and Bardin, 2002).
- Velocity uncertainty. The uncertainty in the velocity measurement of the flow sensor at location Brabantweg is

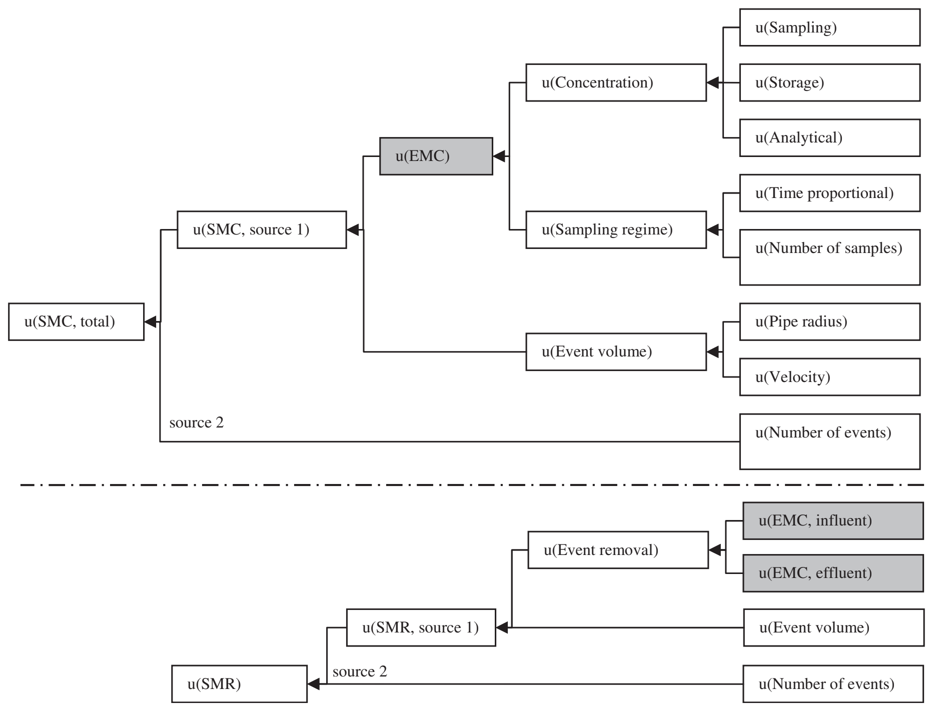


Fig. 4 – Dendrograms of the individual sources of uncertainties that contribute to the combined uncertainty of the Site Mean Concentration (SMC, upper) and the Site Mean Removal rate (SMR, lower). The EMC uncertainties in both dendrograms are shaded.

derived from Brauw et al. (2010), who tested the same measuring principle (acoustic reflection correlation) in similar conditions. The uncertainty in the velocity measurement of the electromagnetic flow sensors at locations Dordrechtweg and Matsersingel is derived from the manufacturer's specifications. Table 4 gives the errors of the three flow sensors.

- Uncertainty due to the number of events. The uncertainty in the estimation of the SMC due to the limited number of EMCs is estimated using the aforementioned bootstrap method applied for each parameter at each location. This method has only been used to calculate the uncertainty due to the specific number of events per parameter analysed and not to predict the uncertainty at higher number of events.

2.3.3. *Calculating removal efficiencies*

The overall removal efficiency per parameter per treatment facility is calculated as the weighed mean with event volumes as weights, as this best reflects the long term efficiency which is relevant to the reduction of pollution of receiving waters.

Table 4 – Characteristics of flow monitoring equipment.		
Location	Device	Measurement error
Brabantweg	OCM-PRO	5% + 0.01 m/s
Dordrecht	Promag 50W	0.5% + 0.001 m/s
Matsersingel	Promag 50W	0.5% + 0.001 m/s

$$\eta_x = \frac{\sum_{i=1}^{n} \eta_{x,i} V_i}{\sum_{i=1}^{n} V_i} \tag{6}$$

where η_x is the overall removal efficiency of parameter x, $\eta_{x,i}$ the removal efficiency for storm event i, with $\eta_{x,i}$ defined as:

$$\eta_{x,i} = \left(1 - \frac{EMC_{effluent,i}}{EMC_{influent,i}}\right) \cdot 100\% \tag{7}$$

3. Results and discussion

The stormwater treatment facilities have been monitored from August 2006 till August 2008. This has resulted in 106 storm events being monitored at the lamella settler, 59 at the sand filter and 132 at the soil filter. The number of sample concentrations in Table 5 may differ from these numbers, as some small events yielded too little sample to enable all analyses and for a number of events, multiple samples have been individually analysed. The high number of events (compared to the minimum number of 5–7 events required to give an estimate of the SMC (May and Sivakumar, 2009; Leecaster et al., 2002)) allows characterisation of the stormwater with a limited relative uncertainty due to the number of events used (McCarthy et al., 2008).

3.1. *SMC and EMCs*

The statistics of the stormwater characteristics measured in Arnhem are summarized in Table 5. The monitoring data

Table 5 – Statistics of monitoring results. Values in bold indicate exceedance of MAC of receiving waters.

Parameter		'SS'	'BOD'	'COD'	'TKN'	'TP'	'Pb'	'Cu'	'Zn'	'*E. coli*'	'Coli total'
Unit		mg/l	mg/l	mg/l	mg/l	mg/l	μg/l	μg/l	μg/l	#/100 ml	#/100 ml
Limit of quantification		2	1	10	0.5	0.05	5	5	5	20	25
MAC					2.2	0.15	220	3.8	40	200	
Dordrechtweg (Lamella settler)	*n* (*n* above detection limit)	428 (410)	24 (21)	81 (75)	81 (80)	80 (75)	88 (74)	88 (83)	88(88)	15 (14)	20 (20)
	Median	14	2.8	22	1.3	**0.14**	**7**	**14**	**85**	**5.70E+02**	2.90E+04
	10%-percentile	4.4	1.8	15	0.6	0.06	2	**6**	**50**	4.60E+01	2.20E+03
	90%-percentile	50	14	45	**2.8**	**0.37**	**24**	**32**	**180**	**4.40E+03**	5.00E+05
Brabantweg (sand filter)	*n* (*n* above detection limit)	57 (56)	11 (9)	46 (44)	42 (39)	39 (36)	47 (44)	47 (45)	47 (47)	12 (12)	12 (12)
	Median	16	4.8	22	1.1	0.13	**13**	**16**	**55**	**4.80E+03**	4.00E+04
	10%-percentile	5.4	1.4	13	0.6	0.06	**8**	**8**	24	**3.70E+02**	7.70E+03
	90%-percentile	57	30	70	**4.1**	**0.42**	**60**	**34**	**130**	**9.80E+03**	2.50E+06
Matsersingel (soil filter)	*n* (*n* above detection limit)	149 (143)	35 (33)	141 (130)	137 (125)	135 (135)	136 (122)	136 (130)	136 (133)	26 (26)	31 (31)
	Median	10	3.2	20	1.1	**0.24**	**8**	**21**	**70**	**1.20E+04**	9.00E+04
	10%-percentile	4	1.6	12	0.6	0.11	4	**9**	**44**	**2.80E+03**	1.70E+04
	90%-percentile	39	10	59	**2.6**	**0.42**	**24**	**42**	**145**	**3.50E+04**	5.90E+05

show a large range between the minimum and maximum concentrations, illustrated by the 10 percentile and 90 percentile in Table 5. The same phenomenon was observed in a comparable research project in Luxembourg (Salvia-Castellvi et al., 2005). The stormwater quality exceeds the maximum acceptable concentration (MAC) for receiving waters (NW4, 1998) for nutrients (TKN and TP) and toxic metals. In addition, the microbiological parameters show that stormwater exceeds by far the standards of 200 *E.coli*/100 ml for swimming water.

3.1.1. *Uncertainties in SMC*

3.1.1.1. *Uncertainty due to sampling regime*

- The relative error ($EMC_{TP} - EMC_{VP}$)/EMC_{VP} from discrete TSS concentrations from 18 events at location Dordrechtweg has an average magnitude of 8%. The resulting uncertainty due to the sampling regime is applied at all parameters.
- Fig. 5 shows the impact of the number of samples per event on the uncertainty. The actual number of samples differs for each event and each location. At the locations Dordrechtweg and Brabantweg the median event duration is somewhat more than 60 min (12 samples); at location Matsersingel with the largest connected area most events last slightly longer, 100 min (20 samples), which is a sufficient number according to (Leecaster et al., 2002). The uncertainty due to the number of samples per event for locations Dordrechtweg and Brabantweg is estimated at 15% and for location Matsersingel at 12%.

3.1.1.2. *EMC uncertainty*. The calculated EMC uncertainty ranges between 25 and 30% for the different parameters analysed.

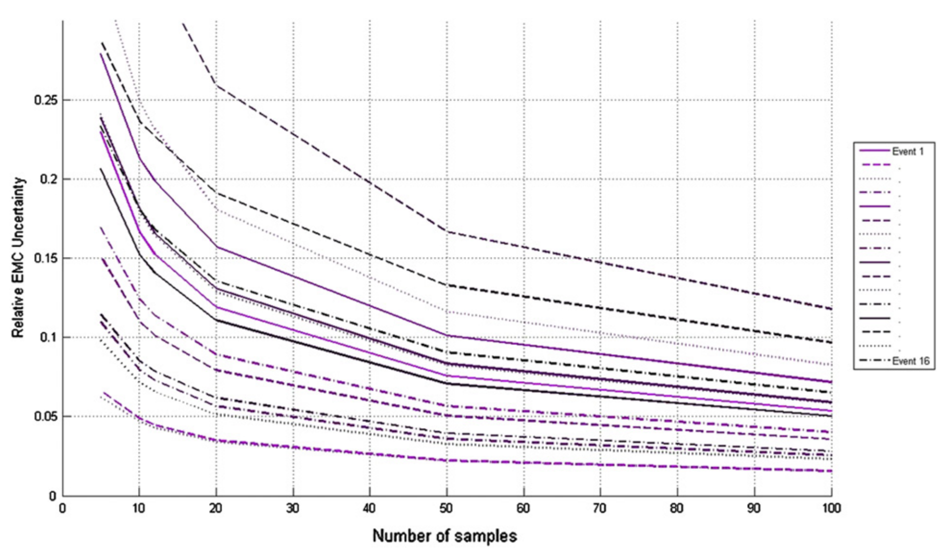


Fig. 5 – Estimation of *u*(Number of samples).

3.1.1.3. *Uncertainty due to number of events*. Fig. 6a and b shows the impact of the number of events on the relative SMC uncertainty for *E.coli* and TSS.

3.1.1.4. *Combined uncertainties in SMC*. Table 6 summarises the results of the uncertainty analysis. The combined uncertainties vary between locations and per parameter, with uncertainties as low as 5% for TP, Pb and Zn at location Matsersingel and as high as 47% for *E. coli* at the Dordrechtweg. These uncertainties reflect the strong influence of the number of events on the SMC uncertainty.

The lower and upper limits of the 95% confidence interval are calculated as $2 * u(x_i)$ (Bertrand-Krajewski and Bardin, 2002).

3.1.2. *Comparison of calculated SMCs with international and national data*

The upper limits of the 95% confidence intervals of the SMC for TSS and COD at the three locations are well below the values reported in international literature and summarized in Table 1, whereas they are within range of the Dutch data

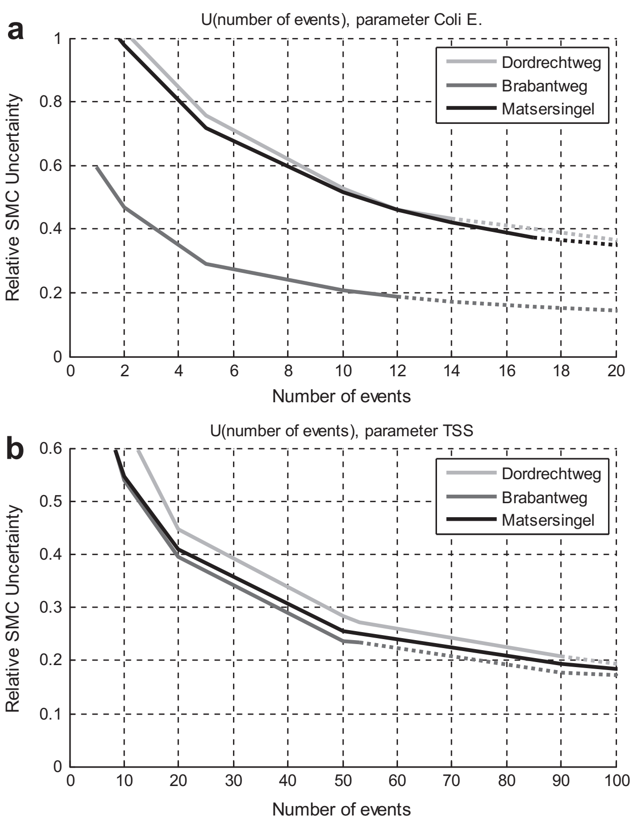


Fig. 6 – a. Relative uncertainty due to the number of events used to estimate the SMC for *E. coli*. For $n \le n_{monitored}$ the lines are solid, for $n > n_{monitored}$ the lines are dashed to illustrate the limitation of the applied method to calculate the relative SMC uncertainty. The number of events *n* can be found in Table 6.The range of SMC uncertainties for $n = 14$ is in the same range as reported in McCarthy et al. (2008). b. Relative uncertainty due to the number of events used to estimate the SMC for TSS. For $n \le n_{monitored}$ the lines are solid, for $n > n_{monitored}$ the lines are dashed to illustrate the limitation of the applied method to calculate the relative SMC uncertainty.

Table 6 – Combined uncertainties, SMCs and 95% SMC confidence limits (n = number of events per parameter).

Parameter	Dordrechtweg					Brabantweg					Matsersingel				
	n	Combined uncertainty (%)	SMC	95% SMC confidence limits		*n*	Combined uncertainty (%)	SMC	95% SMC confidence limits		*n*	Combined uncertainty (%)	SMC	95% SMC confidence limits	
				Lower	Upper				Lower	Upper				Lower	Upper
TSS (mg/l)	90	25%	72	36	108	53	28%	38	17	59	142	13%	27	20	34
BOD (mg/l)	21	19%	6.7	4.1	9.3	8	32%	11.9	4.2	19.6	33	17%	5.3	3.5	7.1
COD (mg/l)	75	14%	41	30	52	43	20%	35	21	49	129	6%	28	24	32
TKN (mg/l)	79	8%	1.9	1.60	2.20	38	22%	1.7	0.94	2.46	124	6%	1.5	1.32	1.68
TP (mg/l)	75	14%	0.26	0.19	0.33	35	19%	0.20	0.12	0.28	132	5%	0.24	0.21	0.27
Pb (μg/l)	81	23%	29	16	42	44	32%	30	11	49	121	13%	20	15	25
Zn (μg/l)	86	11%	152	119	185	46	22%	76	43	109	132	5%	97	87	107
Cu (μg/l)	81	23%	33	18	48	44	19%	22	14	30	127	5%	22	20	24
E. coli (MPN/100 ml)	14	54%	3200	0	6656	12	32%	5800	2088	9512	17	41%	3,300,000	594,000	6,006,000

monitored at other locations in the Netherlands (Boogaard and Lemmen, 2007). This indicates that the stormwater characterization in Arnhem revealed that Dutch stormwater apparently has other characteristics than international stormwater data.

A possible explanation for this difference could be the design philosophy applied. Most of the Dutch SSOs discharge below the level of the receiving waters and, given the lack of gradient in the catchments, up to 100% of the storm sewers draining a catchment are continuously surcharged. Consequently, the storm sewers act as settling basins during smaller storms, only being flushed at strong storm events. This is likely to affect the SMC for TSS, whereas the SMCs for nutrients and heavy metals, which are partly dissolved and typically attached to the finer particles (Boogaard et al., in preparation), are less impacted by the implications of the hydraulic design for sediment transport in storm sewers. In addition, this is likely to affect the total removal efficiency of stormwater treatment. Stormwater treatment facilities are normally equipped with a bypass for high flows in order to limit the hydraulic design capacity (Rombout et al., 2007). Bypasses typically only operate during strong storm events. If during strong storm evens, high flows coincide with a flush of TSS and associated pollutants, the total removal efficiency will be lower as a part of the pollutant load bypasses the treatment facility.

This explanation is supported by the settling velocities measured at the Dordrechtweg for 13 storm events, with settling velocities being determined for 2 grab samples per event, resulting in 26 settling curves (Fig. 7). The results show a significant variation between events. For the majority of events, the percentage of particles with settling velocities lower than 0.2 m/h ranges between 65% and 95%. Only in the storm event of 11 January 2007, an event with high flows and TSS concentrations during the event of up to 2000 mg TSS/l, the percentage of particles with lower settling velocities than 0.2 m/h is approximately 50%, a value found in comparable studies (Gromaire-Mertz et al., 1999; Daligault et al., 1999). These results support the hypothesis that the Dutch surcharged storm sewers act as settling basins during smaller storms, being flushed out during larger storms. Further research on sediment transport in storm sewers is required to be able to reject or confirm this hypothesis.

3.2. *Performance of stormwater treatment facilities*

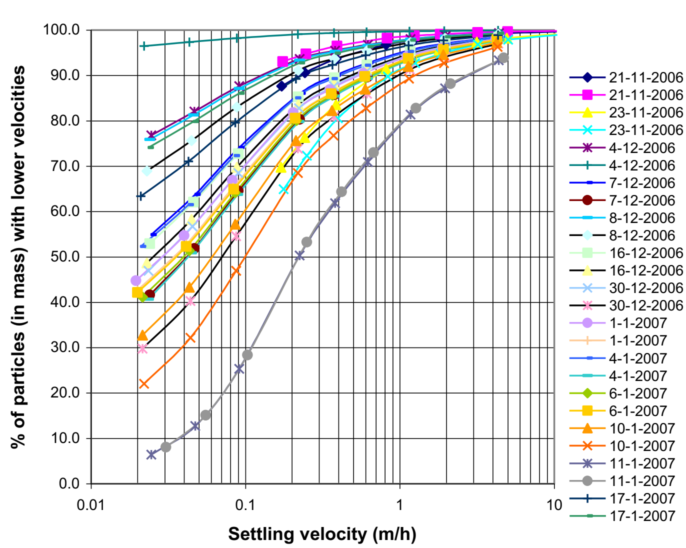
The performance of the stormwater treatment facilities is expressed in terms of removal rates and long term operational aspects.

3.2.1. *Uncertainties in removal rates*

Table 7 summarises the results of the uncertainty analysis for the removal rates of the stormwater treatment facilities. The number of storms with available data is lower than for the SMC due to missing effluent data. The combined uncertainties in the removal rates are as low as 5% for TP, Pb and Cu and as high as 30% for *E. coli* at the soil filter (Matsersingel). The uncertainties at the sand filter and the lamella settler are higher than at the soil filter. For the sand filter, this can be explained by the lower number of events, whereas the higher combined uncertainties at the lamella settler are due to uncertainties in the flow measurements.

3.2.2. *Comparison of calculated removal rates with international data*

Table 8 summarises the volume weighed calculated removal rates. The removal rates of the lamella settlers are around the lower limit reported by (Daligault et al., 1999), which was to be expected given the stormwater characteristics discussed in Section 3.1 and the design surface loading. According to the Dutch design guideline (Rombout et al., 2007), lamella settlers are to be designed at an hydraulic surface loading of 1 m/h at maximum design flow. This design value has been derived from international literature. The monitoring results obtained in this project showed stormwater characteristics to deviate



	Duration [hh:mm]	Max. intensity [mm/5min]	Total rainfall [mm]
21-11-2006	6:15	0.3	7
23-11-2066	21:10	0.2	14
4-12-2006	5:55	0.1	3
7-12-2006	14:35	0.3	16
8-12-2006	4:20	0.1	3
16-12-2006	6:55	0.2	7
30-12-2006	9:10	0.2	7
1-1-2007	1:55	0.3	4
4-1-2007	4:35	0.3	5
6-1-2007	12:55	0.2	11
10-1-2007	5:40	0.2	4
11-1-2007	9:30	0.8	14
17-1-2007	4:30	0.4	10

Fig. 7 – Settling velocities of suspended solids in stormwater.

Table 7 – Combined uncertainties in removal rates of stormwater treatment facilities (n = number of events per parameter).

Parameter	Lamella settler			High rate sand filter			Soil filter		
	n	Removal rate (%)	Combined uncertainty (%)	n	Removal rate (%)	Combined uncertainty (%)	n	Removal rate (%)	Combined uncertainty (%)
TSS (mg/l)	75	40%	15%	53	75%	10%	68	70%	8%
BOD (mg /l)	17	20%	16%	7	28%	14%	16	61%	12%
COD (mg/l)	65	18%	9%	43	36%	9%	64	63%	5%
TKN (mg/l)	71	17%	6%	38	38%	9%	64	58%	6%
TP (mg/l)	66	29%	7%	35	53%	7%	66	44%	4%
Pb (μg/l)	66	36%	10%	44	68%	7%	60	87%	5%
Zn (μg/l)	79	23%	6%	46	78%	6%	64	93%	4%
Cu (μg/l)	74	21%	8%	44	17%	7%	63	81%	4%
E. coli (MPN/100 ml)	14	−46%	136%	12	−39%	34%	8	68%	38%

Table 8 – Removal rates of stormwater treatment facilities.

Parameter	Soil filter	High rate sand filter	Range literature data soil filters	Lamella settler	Range literature data
	Removal rate (%)	Removal rate (%)	Rombout et al. (2007)	Removal rate (%)	Daligault et al. (1999)
TSS	70	75	70–90	34	30–54
BOD	61	28		20	28–31
COD	63	36		18	30
TKN	58	38	50–90	15	
TP	44	53	30–80	29	
Pb	87	68	80–90	36	28–44
Zn	93	78	80–90	23	−38 to +27
Cu	81	17	80–90	21	29–40
E. coli	68	−39		−46	

from the international literature, thus making the design guideline inappropriate for Dutch stormwater.

The removal rates of the soil filter are in accordance with rates reported in literature, such as the BMP reports of the Daywater project (Rombout et al., 2007). The sand filter shows lower removal rates than the soil filter, and much lower for Cu, which might be explained by a lack of binding capacity of the sand applied in the sand filter.

Overall, the removal efficiencies obtained reflect the dominant removal processes. The removal of pollutants in the lamella settler is based on settling, whereas the sand and soil filters rely on filtration and the soil filter additionally on possible adsorption of pollutants.

3.2.3. *Long term operational aspects*

The monitoring of the full scale pilots also had to reveal long term performance and robustness for e.g. high loads of gross solids (Smith, 2010). The soil filter and sand filter are fed by a pump. After a few weeks of operation these pumps were blocked by gross solids. Installing a 20 mm screen proved to be a good solution to this problem.

Fig. 8 shows the measured water levels above the soil filter between November 2006 and February 2010. The slope of these plots characterise the infiltration rate of the soil filter. The average infiltration rate is almost constant throughout the period at approximately 1.7 m/d, which is just above the design permeability of 1.5 m/d. Hence, the hydraulic performance of the soil filter still suffices.

The lamella settler, placed in line, was designed without a screen for gross solids, causing the filter to be fully clogged within 6 months of operation. Consequently, the gross solids rather than the retained settleable solids showed to be the key factor determining the required cleaning frequency. These

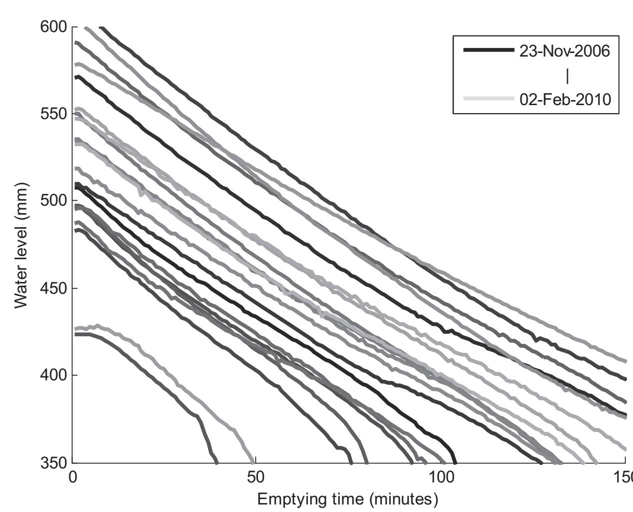


Fig. 8 – Measured water levels above soil filter during the emptying phase after large storm events. The infiltration rates, characterized by the slope of the plots, do not decline during the monitoring period.

findings show that more attention has to be paid to gross solids when designing stormwater treatment devices for existing SSOs.

4. Conclusions

The period of 2 year monitoring of stormwater combined with the assessment of the performance of three types of stormwater treatment facilities at three locations in Arnhem has resulted in a detailed dataset, including site descriptions, operational data, continuous monitoring data and results from sampling. This enabled characterisation of stormwater at three locations in SMCs and treatability. The following conclusions and recommendations for further research are made:

1. Stormwater characteristics in Arnhem in terms of SMCs for main pollutants TSS and COD and settling velocities differ from international data. This implies that decisions for stormwater handling made on international literature data will very likely be wrong due to assuming too high concentrations of pollutants and misjudgement of the treatability of stormwater. The latter will result in ineffective designs of stormwater treatment facilities.
2. SMCs of stormwater exceed the MAC for chemical receiving water quality for phosphate, zinc and copper at all locations. This indicates that stormwater treatment might be necessary to be able to meet the water quality requirements. For phosphate and zinc it is possible to meet the MAC with treatment of stormwater with a sand or soil filter. The removal efficiency of a lamella settler is insufficient to meet this standard. For copper it is not possible to prevent exceedance of the MAC in stormwater with any of the three treatment techniques monitored.
3. Although flow proportional sampling is widely advocated in literature, high frequent time proportional sampling is a good alternative for determining SMCs with relative uncertainties as low as 5% for Cu and Zn after approximately 130 events. The relative uncertainty strongly depends on the number of events sampled.
4. The available extensive dataset is a source for future sampling design of urban stormwater monitoring.
5. Sediment transport in storm sewers is likely to exert a strong influence on stormwater pollutant levels and characteristics. More research on this issue is needed to be able to quantify the contribution of sediment transport to stormwater pollutant levels and to be able to quantify the impact of design criteria on the performance of storm sewers. In this respect, the design of surcharged sewers with SSOs discharging below the water table of receiving waters needs to be evaluated.

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