Stormwater quality and removal efficiency rates of lamella filters

Qualité des eaux pluviales et efficacité des filtres lamellaires

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RÉSUMÉ

Aux Pays Bas, les décanteurs lamellaires constituent la méthode de traitement en sortie de procédé la plus appliquée pour répondre aux normes de qualité de l'eau stipulée dans la directive cadre sur l'eau. En quelques années, en raison des taux d'élimination attendus, des prix bas et de la faible emprise spatiale, ce système a été mis en œuvre dans 50% des municipalités néerlandaises. Toutefois, on constate peu de travaux de recherche sur les taux d'élimination obtenus avec les décanteurs lamellaires dans les réseaux d'assainissement pluvial. Cet article décrit les résultats d'une campagne de suivi de 2 ans à Arnhem ainsi que les essais en laboratoire subséquents destinés à expliquer et vérifier les résultats observés.

Les résultats montrent que les rejets des réseaux d'assainissement pluvial sont effectivement significatifs en termes de nutriments et de métaux lourds. Le rendement d'élimination des décanteurs lamellaires est inférieur aux attentes et le système doit être adapté pour améliorer les performances hydrauliques. En 2010-2011 une autre campagne de suivi de ces systèmes sera effectuée.

MOTS CLÉS

Suivi, traitement des eaux de pluie, caractéristiques des eaux de pluie, décanteur lamellaire, qualité des eaux de pluie, rendement d'élimination, suivi, eau de pluie, sédimentation.

ABSTRACT

In the Netherlands, lamella settlers are the most applied kind of end of pipe treatment to meet the Dutch surface and water frame work directive water quality standards. Due to high expected removal rates, low costs and a low spatial footprint, in a few years time this system has been implemented in more than 50% of Dutch municipalities. However, not much research has been done on removal rates of lamella settlers applied in storm sewers. This paper describes the results of a 2-year monitoring campaign in Arnhem and the subsequent laboratory testing to explain and verify the observed results.

The results show that the emission from storm water sewers is indeed significant with respect to nutrients and heavy metals. The removal efficiency of the lamella separator is less than expected and to improve the hydraulic performance the system should be adjusted. Further monitoring of these systems will take place in 2010-2011.

KEYWORDS

Monitoring, storm water treatment, storm water characteristics, lamella settler, storm water quality, removal efficiency, monitoring, storm water, sedimentation

INTRODUCTION

The urban water systems of many municipalities in the Netherlands are facing water quality problems that have to be addressed properly due to water frame work directive (WFD). To meet the Dutch surface water quality standards sustainable drainage systems (SUDS) have been implemented. Several research projects have been set up aiming to gain knowledge on the storm water quality, the ecological status of receiving urban waters and the cost effectiveness of end-of-pipe treatment facilities for treating urban runoff discharged by storm sewers.

Separated sewer systems are widely applied in Europe as well as in the United States. Storm sewers are known to contribute significantly to the annual pollution loads into the receiving waters. Measuring programs show that this annual pollution load per ha can easily exceed the load per ha discharged by combined sewer overflows. The pollution load discharged by storm sewers origins form the pollution associated with the rainfall itself, the pollutants taken with the flow during the rainfall runoff process and from illicit (or wrong) connections (Salvia-Castellvi *et al.*, 2005).

The available measurement data on the emission from separated sewer systems, however, is relatively sparse. Moreover, available data is often published without a good description of meta data, like measurement setup, sewer system and catchment characteristics. Even essential details on the monitoring itself, such as whether the data is derived from grab samples or flow proportional samples is often lacking (Boogaard and Lemmen, 2007).
In the context of the international study ‘Skills Integration and New Technologies (SKINT) for rainwater’, more than 7,500 monsters have been analyzed from runoff from roofs and roads in the urban area and added to the rainwater quality database (Stowa, 2007). The quality of runoff is affected by various factors: the composition of the roofing material and roads, location specific conditions (pollution, air quality), seasonal conditions (variations in air quality and rainfall/evaporation) and climatic conditions (dry periods, shower intensity).

The European Water Framework Directive (WFD) demands an enhanced protection of the aquatic environment. As a consequence, the WFD requires municipalities to address the emission from wastewater systems properly and to take action when these emissions whether they origin from storm water systems, combined sewer overflows or wastewater treatment plants, affect the water quality of receiving waters.

This article describes the available knowledge about the quality of storm water in the Netherlands and the monitoring results of a system which is used to meet Dutch quality standards which is widely discussed in the Netherlands: the lamella settler. Due to high expected removal rates and the limited available space in the densely populated areas of Holland, in a few years time (mostly from 2000-2009) hundreds of these systems have been implemented (see figure 1).

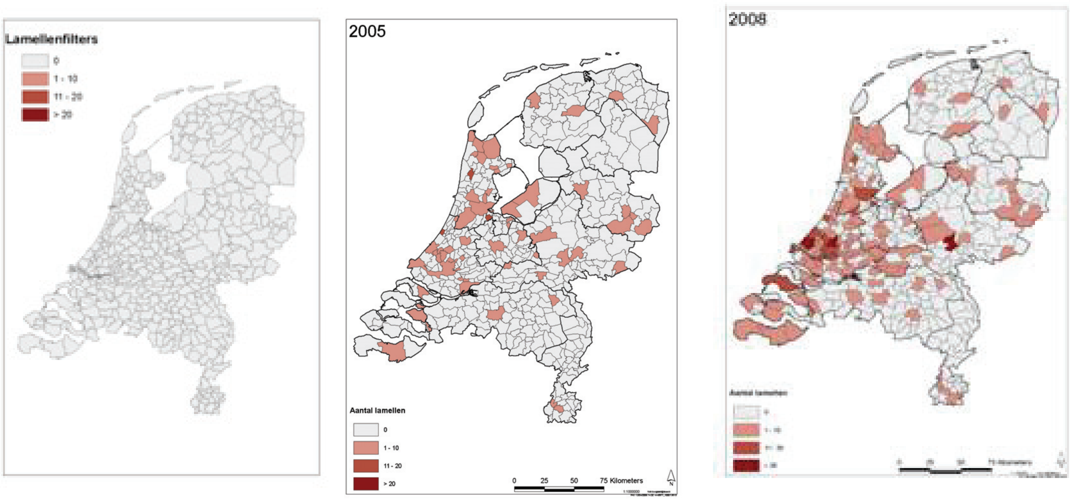

Figure 1: number of implemented lamella settlers (from 1999 to 2005 and 2008)

1 MONITORING LAMELLA SETTLER ON SITE: ARNHEM

1.1 Method: monitoring the lamella settler

The southern part of the city of Arnhem, developed between 1960 and 2000, comprises 300 ha of separated sewer systems, with over 300 storm water outfalls. At three of these outfalls, a full scale storm water treatment facility has been realized, fully equipped with monitoring devices in order to be able to determine:

- Event Mean Concentrations (EMCs) of major pollutants in storm water
- removal efficiencies under various loading conditions of the treatment facilities
- the impact of operation and maintenance on performance of the treatment facilities

The lamella settler is located at the Dordrechtweg. The contributing area comprises 3.8 ha, developed between 1970 and 1980. The majority of the houses are owned by a housing corporation Figure 1 gives a schematic of the lamella settler.

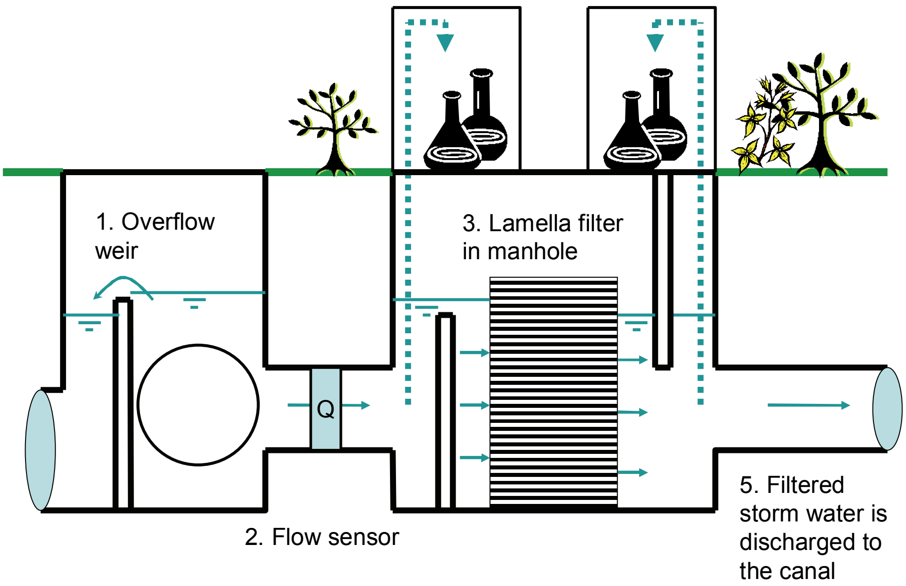

Figure 2. Schematic of lamella filter and method of measurement

Upstream of the lamella settler an overflow weir is installed in order to maximize the flow at 250 m^3/h to the lamella settler. This maximizes the hydraulic surface load at 1 m/h. The lamella settler has a nominal design capacity of 50 m^3/h, at which the hydraulic load is equivalent to a surface load of 0.2 m/h, according to the manufacturer.

1.2 Storm water characteristics: EMCs

Table 2 shows the storm water characteristics measured in Arnhem. For all parameters the mean of the EMCs is significantly higher than the median of the EMCs. This is due to the large variation in concentrations, with maximum EMCs that can be extremely high. The same phenomenon was observed in a comparable research project in Luxembourg (Salvia-Castellvi, 2005). In the Netherlands, STOWA has launched a project aiming at archiving all monitoring data on urban runoff quality. This resulted in a comprehensive database (Boogaard and Lemmen, 2007). Comparing the Arnhem data with the Dutch national database learns that the storm water in Arnhem is comparable with the average storm water quality in literature. This means that the loading of the treatment facilities in Arnhem was not exceptional, thus making the results more widely applicable. The microbiological parameters show that, though urban runoff is often considered 'clean', storm water exceeds by far the standards of 200 E.Coli/100 ml for swimming water. The PAH concentrations were in most storms below detection limits and therefore not listed in table 1.

Table 1. EMCs in storm sewers in Arnhem compared with median concentrations of all samples in the Dutch national stormwater quality database (Boogaard, 2009) (n = number of events in Arnhem)

	Dutch STOWA database, 2007	Influent lamella settler			Dutch SKINT database, 2009**
	Median	n	mean	median	Median
SS	20	*338**	*46**	*14**	
BOD	4.0	20	4.6	2.7	3,1
COD	32	56	29	22	20,0
NH_3-NH_4	-	27	0.5	0.3	
TKN	1.7	58	2.9	1.2	1,1
TP	0.26	55	0.24	0.14	0,3
Pb	12	63	19	7	6
Zn	95	63	128	80	60
Cu	10	63	22	12	11
E. Coli	1.E+4	15	3.E+03	5.E+02	6,7E+03
Tot. Coli	-	16	6.E+07	4.E+04	
Strep.faecalis	-	11	7.E+03	6.E+02	
Therm. Coli	-	15	4.E+03	8.E+02	

** the SS concentration of the influent of the lamella settler is the mean and median of all samples, rather than an EMC*

*** data 2009 update with several data including Arnhem.*

1.3 Removal efficiency lamella settler

Table 2 shows the removal efficiency of the lamella settler in Arnhem for a number of key parameters. The removal rates for potassium and chloride are almost equal to zero as is to be expected, thus indicating that the monitoring and sampling process did not introduce significant errors. The removal rate for suspended solids was overall 34%. This low removal rate is easily explained by the monitored settling characteristics of the pollutants in the stormwater in Arnhem, see figure 4. Based on this settling characteristics, a design curve has been derived which indicates the removal rate to be expected given a certain hydraulic loading.

Table 2 removal efficiency lamella settler

Parameter	***n***	*removal efficiency*
'COD'	66	18%
'Chloride (Cl)'	30	-4%
Suspended solids (SS)	380	34%
'Fosfor (P)'	67	29%
'Potassium (K)'	35	-1%
'Kjeldahl-N (N)'	73	15%
'Copper (Cu)'	76	21%
'Lead (Pb)'	68	36%
'Zinc (Zn)'	81	23%

1.3.1 Settling velocities

Van Geelen en Kloppenburg (2007) performed additional analyses on the settling velocities of pollutants in the influent of the lamella settler. 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 selected moments via the lowest sampling point, 50 mm from the bottom of the column. The suspended solids concentration was determined using a laboratory turbidity meter HACH 2100N and subsequent lab analysis.

For 13 storm events, the settling velocities have been determined for 2 grab samples, resulting in 26 settling curves as shown in figure 3. The results show a significant variation between events. For the majority of events, the percentage of particles with lower velocities than 0.2 m/h, the nominal design capacity of the lamella settlers, is at least 65%. Consequently, the removal rate of the lamella settler in Arnhem would be expected to be maximal 35%, which is in accordance with the observed removal efficiency of 37%. Only in the storm event of 11 January 2007 the percentage of particles with lower velocities than 0.2 m/h is approximately 50%, the value found in a comparable study in Le Marais, Paris (Gromaire-Mertz, 1999).

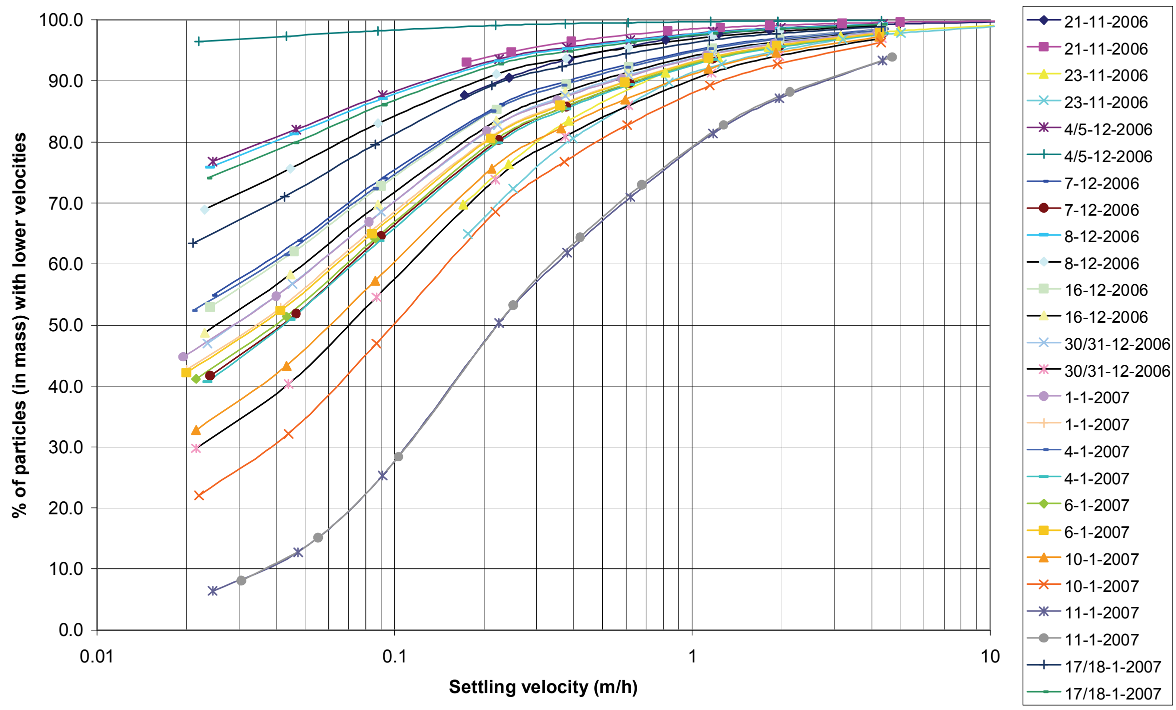

Figure 3. Settling velocities of suspended solids in the influent of the lamella settler, Arnhem. The settling velocities are based on grab samples at two stages per storm event.

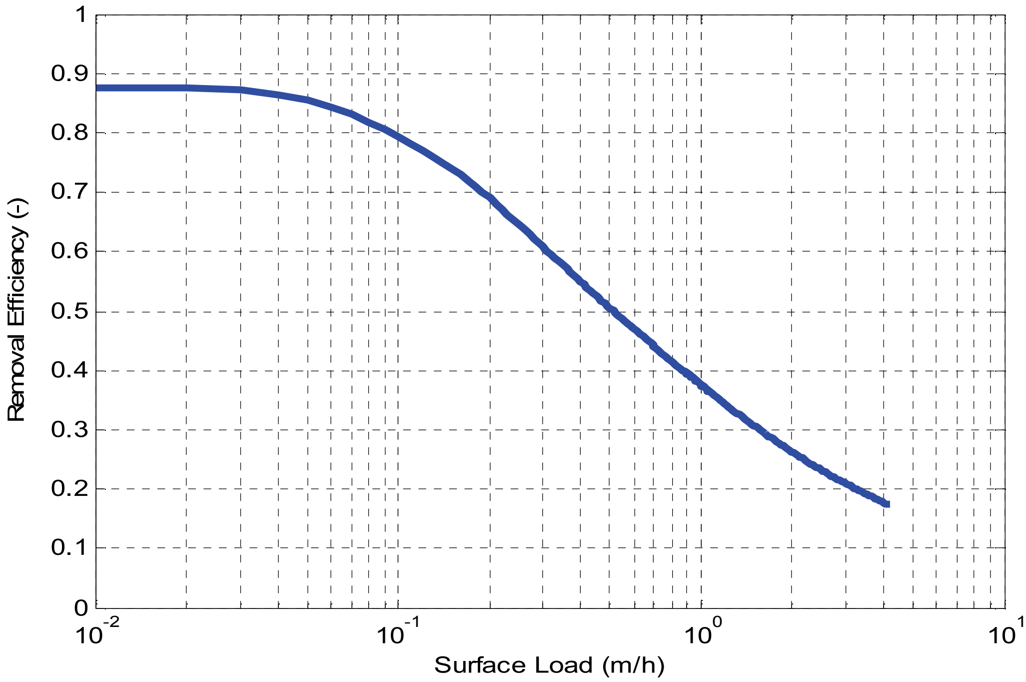

Figure 4. Design chart based on settling characteristics of storm water analyzed in Arnhem

2 MONITORING LAMELLA IN LABORATORY

In order to in detail investigate the removal efficiency of the lamella settler at different loadings and for different configurations, a full scale model was set up in the laboratory of the Technical University of Delft in 2009 (see figure 5).

Figure 5. Full scale model in the laboratory of the technical university of Delft

The full scale model of a lamella separator was used to answer the main research questions:

1. To which extent does the removal efficiency increase by placing lamellae in an empty basin?
2. What is the removal efficiency at different fractions of suspended solids at several surface loads and different lamella configurations (¾ inch, ½ inch, ¼ inch).
3. Can the removal ratio be predicted based on settling velocity and surface load.

In general it is accepted that particles settle sooner as the surface load decreases. The surface load is the hydraulic load in m^3/s divided by the area on which particles can settle. For a lamella separator the settling area should be the horizontal projection of the plates. The flow should be such that he load is equally spread between the different lamella. The removal ratio (R) is in theory equal to the ratio between settling velocity (v_s) and the surface load (s_o), but not larger than 100% [Kluck 1997].

2.1 Set up of measurements

The following tests have been carried out: The flow was either 5, 10, 14 or 20 l/s. Up to three packages of lamella could be placed in a row at the same time. The spacing between the lamella was: ¾ inch, ½ inch or ¼ inch. Most Dutch lamella separators (and also the one in Arnhem) have a number (mostly 2) of packages of ½ inches. These configurations and the above flow rates result in a surface load of respectively 0.42, 0.83, 1.25 and 1.66 m/h.

For these different configurations and loadings on the inflow and the outflow several samples were taken and analyzed in order to calculate the removal efficiency. During the test the turbidity was continuously measured to validate the results.

To simulate the suspended solids in storm water 'silicon-dioxide', which consisted of fractions from 0-100 µm, has been used. The research mainly focused on particles from 0.45 up to 63 µm, which, according to literature, bind most micro contaminants (Boogaard et all, 2007). These fractions result in settling velocities from 0.01 up to 13 m/h.

2.2 Results

According to the product specifications of the removal ratio before the tests, almost 100% of the fraction of 20 µm (settling velocity of 1,2 m/h for silicon-dioxide) would be captured. The measured removal ratios appeared however to be much smaller.

The measurements showed that the basin with a lamella settler gives a higher removal ratio than an empty basin (surface load 30 m/h for 10 l/s). The removal efficiency for 20 µm is doubled by placing lamella in the basin (2 packages ½ inch and ½ inch: surface load 0.83 m/h for 10 l/s) . However at the still only about 20% of particles is captured. Better results gave 3 packages of respectively ¾, ½ inch and ½ inch (surface load 0.61 m/h for 10 l/s) where about 40% of the fraction of 20 µm is captured. The removal efficiency at the several surface load are shown in figure 6.

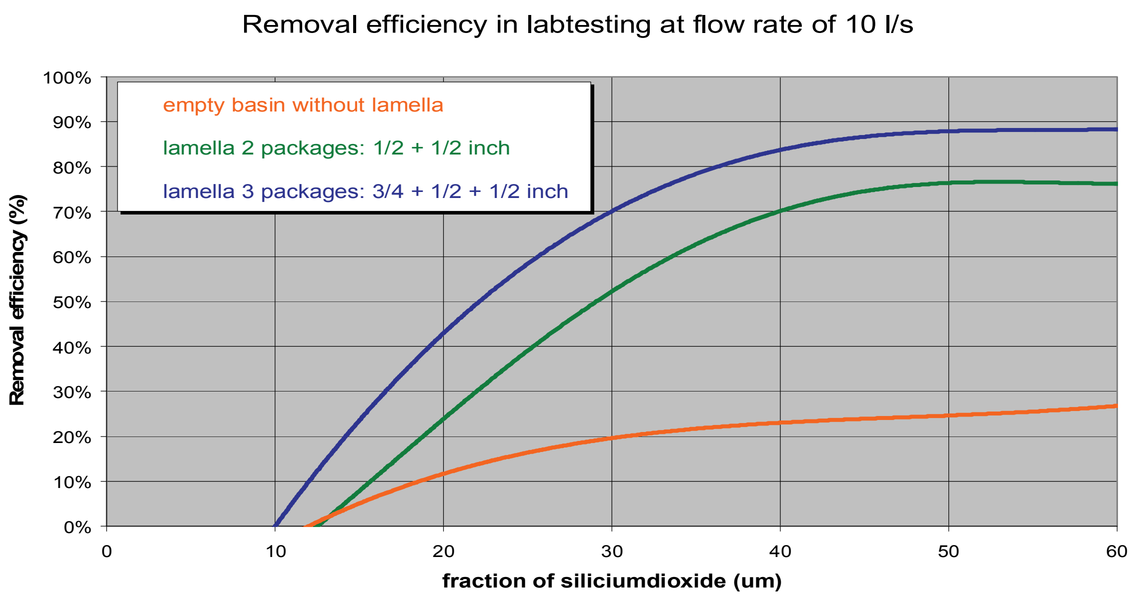

Figure 6. The removal efficiency at the several surface load (trend lines): 30 m/h (empty basin), 0.83 m/h (½, ½ inch) and 0.61 m/h (¾, ½ inch and ½ inch lamella package).

Figure 7 shows some measured removal ratios for the ½+½ inch configuration in a different way. The dots show the removal ratio for specific particle sizes, but the particle size has been transformed into a settling velocity based on Stokes and the physical characteristics of the water and the sand. The figure shows the measured removal ratios for 4 different loads. The x-axis is the settling velocity divided by the surface load. The points form more or less one line which could be used to predict within a reasonably narrow range the removal ratio for this configuration.

The lines in the figure represent different predictions of the removal ratio (based on the settling velocity and the surface load). The brown line near the bottom is the line for the situation without any lamella. The surface load is thus based on the tank bottom size. The lamella packages clearly improve the removal ratio.

The red line shows the removal ratio if the whole (horizontal projection of the) surface of the lamella is used to calculate the surface load. Clearly this is much higher than measured removal ratio and apparently the settling between the lamella is not as efficient as expected.

The other lines represent lines in which reasons why the settling is not as effective as for the red line have been incorporated. An important part of the theory is that particles that have settled onto a plate (lamella), will at certain point fall to the plate below. At that point the particles will have to cross the water flow and have to settle again. In the green line this was incorporated by assuming that the facility consists of 10 smaller facilities in series.

Finally it is possible that the current in the first package was so strong that settling was hindered by turbulence. The blue line represents the removal ratio for the situation with only settling in one package (e.g. because the turbulence in the first hinders settling), or because the flow is not evenly divided over the packages (which appeared to be true in a dye test. Figure 7b shows a photo of the dye test).

It seems to be a challenge to reach the red line. The package construction itself, like the poles to keep the lamella height on a stable level, has an impact on the hydraulic performance which can be visualized by adding color to the water (7b, purple lines shows the flow patern). Possibly the configuration can be optimized at this point to increase removal rates.

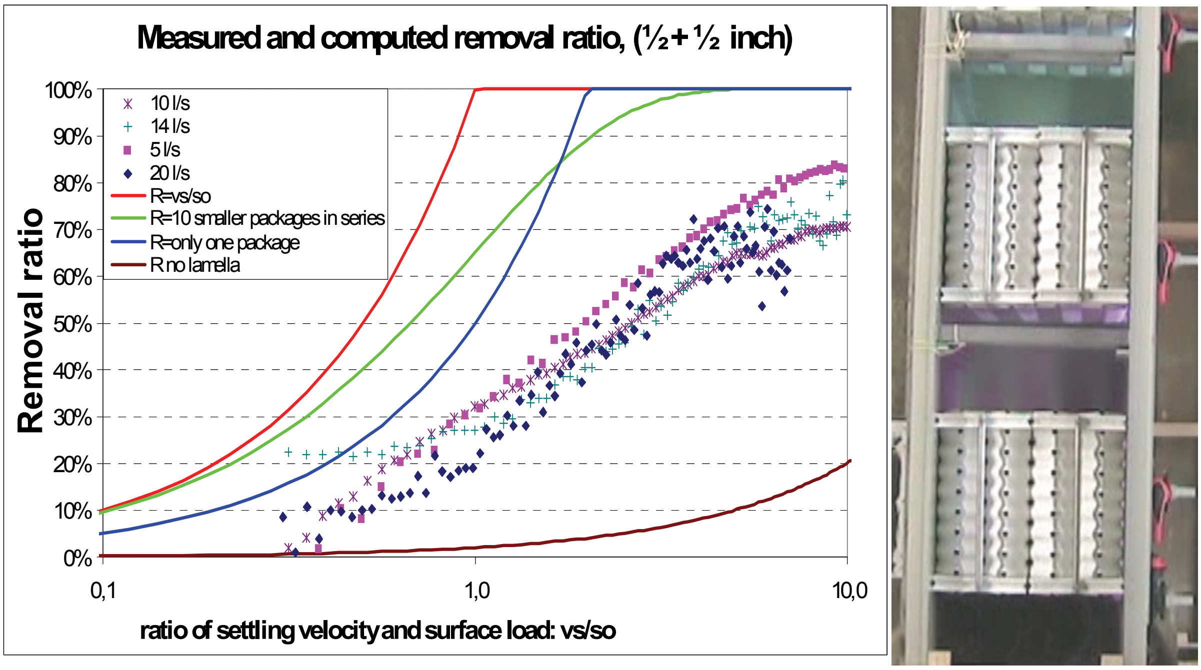

Figure 7a (left) Measured and estimated removal rates for test facility at Delft University of Technology. 7b top view lamella settler in laboratory technical university Delft (stream patterns) (right).

3 REMOVAL RATES OF LAMELLA SETTLERS

The removal efficiencies of lamella separators vary greatly due to the differences in the hydraulic load and the fact that micro-contaminants are generally bound to the smaller fraction of suspended solids

Due to differences in the hydraulic load and in settling velocities the removal efficiencies of lamella separators will vary greatly. With the monitoring in Arnhem and the test facility in Delft extra insight in actual removal rates is gained and in the function under better defined conditions. In literature can be found that Daligaut *et al*. (1999) reported a removal efficiency of 54% in a project in Brunoy and 30% in Vignuex. Mall GmbH measured a removal efficiency of 80% on sizes from 100-125 µm with a surface load of 18 m/h, and 90% on 1 m/h which is comparable with the results from the laboratory in Delft.

The removal efficiency of the lamella settler in Arnhem, based on the volume-averaged removal rate of 60 storm events, is 37% for suspended solids. The removal rates for heavy metals are also in the same range, e.g. for lead the rates are 44% in Brunoy and 28% in Vignuex, while the removal rate in Arnhem is 36%. The calculated removal rates are based on the total mass removed. The removal efficiency of these lamella settlers is with about 40% significantly lower than expected.

The measurements in Delft resulted in an estimation for the removal ratio based on the particle size. When we apply a measured (elsewhere) relation for the binding of pollutants to particles, we can derive an estimation of the removal ration of that pollutant.

The analyzed storm events in Arnhem showed a significant variation of settling velocities between and within storm events. Especially in storm events with low intensities and flows, the concentration levels of suspended solids remain low as well as the settleability. Only in larger storm events, the suspended solids concentration peaks with increasing settleabilty. This behavior indicates the availability of sediment in the storm sewer. As the storm sewers are always completely filled with water (fully submerged), they are likely to act as a settler itself. In order to account for this effect, the design curve of figure 4 has been made by weighing the settling curves by the suspended solids concentrations, thus yielding reliable results. It would be interesting to investigate whether the typical settling velocities of Arhnem are to be observed elsewhere.

Table 2 removal efficiency lamella settler (indicated comparisment, different products and dimensions are used)

Parameter	**Arnhem**	**Brunoy**	**Vignuex**	**TU Delft labtest**	**German labtest**
SS	37%	54%	30%		
Ro 100-125 µm S0= ca 30 m/h				Ca 40%	-
Ro 100-125 µm S0=18 m/h				-	80%
Ro 100-125 µm S0=9 m/h				-	85%
Ro 100-125 µm S0=1 m/h				85%	90%
cupper (Cu)	21%	44%	28%		

4 CONCLUSIONS

- The measurements in Arnhem and other locations in the Netherlands show that the concentrations in water from storm water sewers are indeed significant with respect to nutrients and heavy metals. In addition, storm water can be unsafe from a microbiological point of view.
- the removal rates of storm water treatment facilities like the lamella settler strongly depend on the characteristics of the storm water: on the settleability of specific pollutants and the ratio between dissolved and suspended material;
- Additional research is needed to establish a reliable database of typical settling velocities of storm water, possible related to catchment characteristics.
- The measurements in the test facility in Delft showed a lower removal ratio than expected given the design hydraulic loading and settling theory. There was however a significant better removal ratio with lamella separator than without.

- The settling velocities of the storm water samples in Arnhem and the research in the laboratory at Delft indicate that the standard Dutch design surface load of 1 m/h for a lamella settler will result in unsatisfactory removal efficiencies.
- In the next years additional monitoring will take place in Krimpenerwaard on 3 sites with 2 different type of lamella separators. On one site the most promising configuration from the TU Delft labtesting (3 packages of ¾, ½ inch and ½ inch) lamella will be monitored. The results are expected at the end of 2011.

5 ACKNOWLEDGEMENTS

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