Selection of monitoring locations for storm water quality assessment

Sélection des points de mesure pour évaluer la qualité des eaux pluviales

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RÉSUMÉ

Les systèmes d'assainissement séparatifs sont largement employés dans les pays économiquement développés. Il est désormais connu que les égouts pluviaux contribuent largement aux charges polluantes annuelles dans les milieux récepteurs et provoquent une grave dégradation des milieux récepteurs en zone urbaine. Les caractéristiques des eaux pluviales peuvent varier de manière importante d'un lieu et d'un événement à l'autre. Par conséquent il faudrait, pour chaque lieu donné, une campagne de mesure bien conçue avant de choisir la stratégie appropriée de gestion des eaux pluviales. Le défi pour la conception d'une campagne de mesure avec un budget donné est d'équilibrer des mesures détaillées dans un nombre limité de points de mesure et des mesures moins détaillées dans un nombre plus important de points de mesure. Cet article propose une méthodologie pour la sélection de points de mesure pour le suivi de la qualité des eaux pluviales, basée sur la (pré)sélection, une campagne de mesure d'évaluation rapide et une sélection finale d'un point de mesure et d'un concept pour le dispositif de suivi. Les résultats montrent que la méthodologie facilite la conception d'un réseau de mesure. De plus, l'évaluation rapide a fourni un premier ensemble de données utiles sur la qualité des eaux pluviales et une forte indication de connexion illicite sur l'un des points de mesure, ce qui a été confirmé en utilisant des capteurs de température distribués pour détecter les connexions illicites.

ABSTRACT

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 Storm water characteristics may vary significantly between locations and events. Hence, this would necessitate for each given location a well-designed monitoring campaign prior to selection of an appropriate storm water management strategy. The challenge for the design of a monitoring campaign with a given budget is to balance detailed monitoring at a limited number of locations versus less detailed monitoring at a large number of locations. This paper proposes a methodology for the selection of monitoring locations for storm water quality monitoring, based on (pre-)screening, a quick scan monitoring campaign and final selection of a location and design of the monitoring set up. The results show that the methodology facilitates the design of a monitoring network. In addition, the quick scan resulted in a first useful data set on storm water quality and a strong indication of illicit connection at one of the monitoring locations, which was confirmed using Distributed temperature sensing to detect illicit connections.

KEYWORDS

Experiment set up, Monitoring, Monitoring location, Sampling strategy, Storm water quality

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 a major contributor to pollution of receiving waters (Lee et al. 2007). The European Water Framework Directive (WFD) (2000/60/EC) 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 level. 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 to the receiving waters and knowledge of the impact of storm water strategies.

Storm water characteristics may vary significantly between locations and events (see e.g. Langeveld et al., 2012 for a range of values from literature). Hence, this would necessitate for each given location a well-designed monitoring campaign prior to selection of an appropriate storm water management strategy. Time and budget constraints, however, prevent local authorities from monitoring all storm sewer outfalls (SSOs) in their area as the number of SSOs in an area can be very large. For instance, the storm sewer systems in the city of Utrecht, the Netherlands, serve an impervious area of 160 ha with 43 outfalls (i.e. 1 outfall per 4 ha). The challenge for the design of a monitoring campaign with a given budget is hence to balance detailed monitoring at a limited number of locations versus less detailed monitoring at a large number of locations, as discussed by Lee et al. (2007).

The design of a storm water monitoring campaign involves the selection of the monitoring setup, the selection of the number of storm events to be monitored and the selection of the monitoring location. Bertrand-Krajewski et al. (2003) discussed the uncertainties associated with the monitoring setup at a specific location and sampling. More recently, Rossi et al. (2011) developed the “samplinghelper”, a web-based tool that can be used to design the monitoring set up given the acceptable uncertainty level. The selection of the minimum number of storm events to be monitored is discussed in detail by Leecaster et al. (2002), Mourad et al. (2005) and May and Sivakumar (2009).

The selection of the monitoring locations, on the other hand, has hardly received attention in literature on storm water monitoring. For groundwater monitoring, the selection of monitoring locations has received much attention, resulting in well established design methods for monitoring networks for e.g. detection of groundwater pollution (Bierkens et al. 2006; Cieniawski et al. 1995). These methods balance the costs of increasing the number of monitoring locations versus the additional information of one additional monitoring location. Clemens (2001, 2002) introduced these methods to develop monitoring networks for the calibration of hydrodynamic sewer models.

This paper proposes a methodology for the selection of monitoring locations for storm water quality monitoring. The paper first describes the case Almere and the OSAL monitoring project which is used to test and evaluate the methodology. Secondly, the proposed methodology itself is presented. Then, the results of application of the methodology on the sewer system in Almere are discussed. In a last paragraph quick scan results are compared to an additional data source (DTS monitoring) and the assumed catchment categorization is verified using some of the quick scan data results.

2 MATERIAL AND METHODS

2.1 System description

Almere (194.500 inhabitants) is a young municipality, founded in 1975 after the realisation of the Flevopolder in order to accommodate for the increase of population in Amsterdam. In 1995, the municipality counted nearly 75.000 inhabitants, which had doubled by the year 2000. The main type of sewer system applied in Almere is the separate system, with foul sewers discharging to the wwtp and storm sewers discharging via storm sewer outfalls to the receiving waters. The quality of the receiving waters is to a large extent determined by nutrient rich seepage (Almere is situated 4 m below mean sea level or NAP) and the outflow from the SSOs.

The sewer system of Almere comprises 680 km of storm sewer, 625 km of foul sewer, 700 SSOs and 2125 ha contributing area. The municipality has divided the catchment in three categories (see figure 2):

I. Storm sewers dating from before 1985, a period associated with the use of traditional building materials

II. Storm sewers dating from 1985, a period associated with the use of sustainable building material

III. Special areas with a high risk of pollution, i.e. industrial zones.

The municipality of Almere and regional water authority Zuiderzeeland have launched a comprehensive research project OSAL (Optimisation Study Almere). The objective of the OSAL project is to quantify the emission from SSOs as well as the impact of the SSOs on the receiving water quality. The project also looks into strategies/measures to improve the receiving water quality in order to be able to comply with the ecological water quality standards.

The OSAL project comprises 7 pilot projects, shown in figure 1.

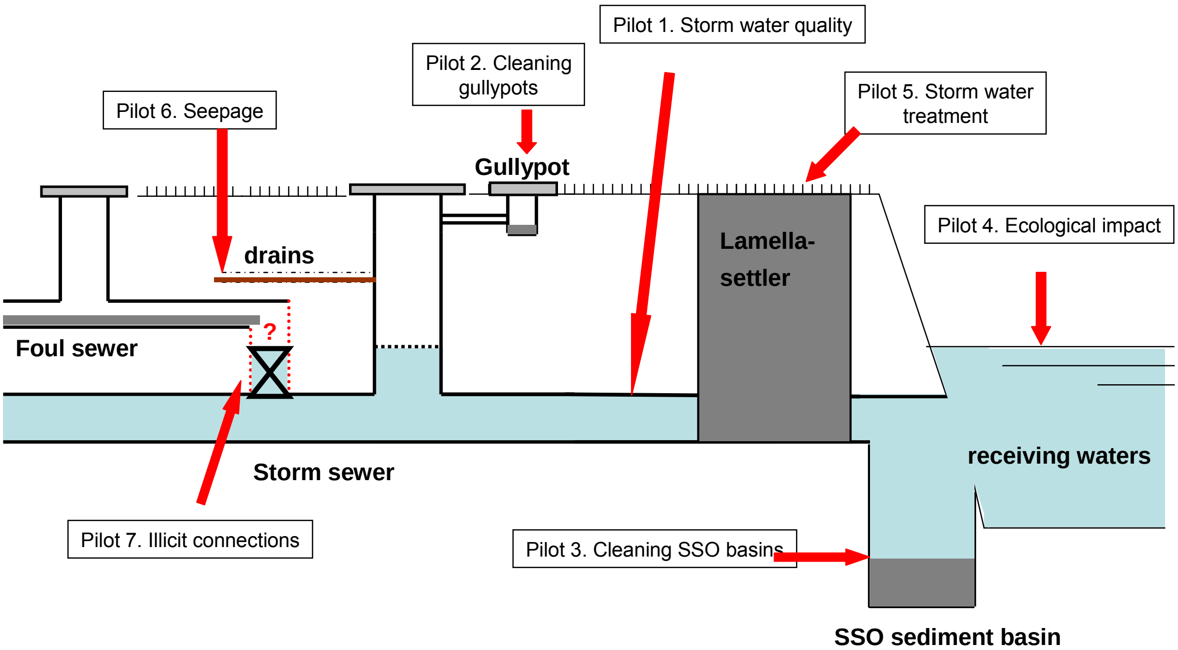

Figure 1. Pilots in OSAL research project

Pilot 1 involves long term monitoring of the storm water quality at 3 SSOs. Pilot 2 analyses the impact of gully pot cleaning on the storm water quality at the SSOs. Pilot 3 studies the impact of cleaning of the outflow structure of the SSOs on storm water quality. Pilot 4 assesses the impact of SSOs on the receiving water quality. Pilot 5 monitors the efficiency of a lamella settler for storm water treatment purposes. Pilot 6 measures the quality of ground water in the drains connected to the storm sewers. Finally, pilot 7 quantifies the impact of illicit connections on the storm water quality at the SSOs. The monitoring project started in January 2013 and will last for 2 years. The monitoring set up per location comprises sensors for continuous monitoring of flow, water level, temperature, turbidity and conductivity and an automated sampler for taking time proportional samples during at least 30 storm events per location. Samples will be send to the laboratory and analysed on nutrients, metals, micropollutants and general parameters such as Cl and TSS.

During the preparatory phase of the OSAL project, out of a total of 60 SSOs in Almere, 3 locations have been selected to implement the monitoring set-up. The method that has been used for this selection procedure is presented in the next paragraph.

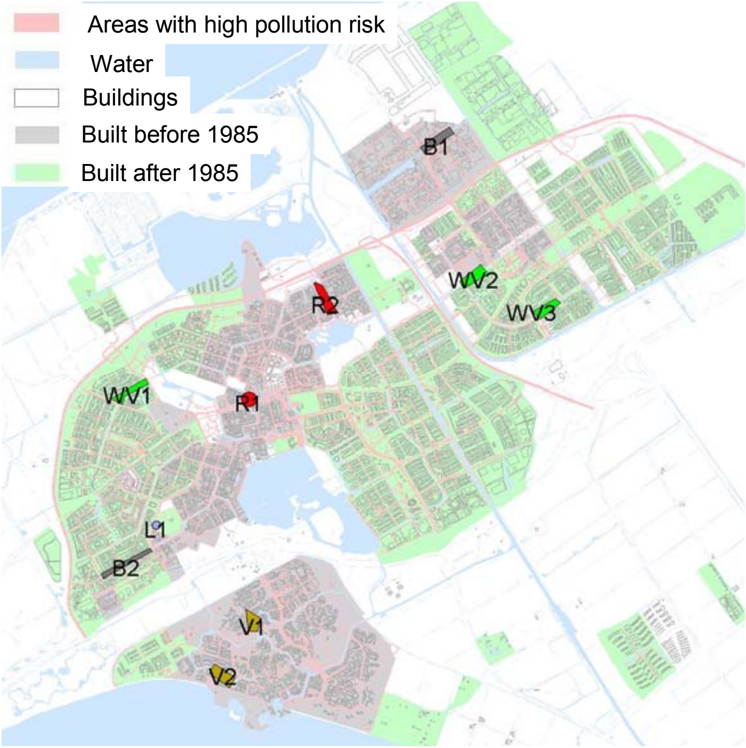

Figure 2. Catchment and categories

2.2 Method for selection of monitoring locations

The method for the selection of monitoring locations comprises 4 steps:

1. Pre-screening
2. Screening
3. Quick scan
4. Final selection

1. Pre-screening. The pre-screening stage limits the total number of potential monitoring locations by applying the following criteria:

- General suitability for research, with the connected impervious area per SSO as criterion. 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;
- Representativeness in terms of catchment characteristics, such as construction period, number of inhabitants, average income, type of roads (high/low traffic intensity), planned reconstruction of roads, surcharged/non-surcharged storm sewers;
- Coverage of the three categories of catchments areas in the city of Almere
- Geographic coverage of the total research area

The pre-screening has been based on information that was already available from municipality registers. If no information is available for a location, this will not be taken into account. The receiving water quality has not been taken into account in the selection procedure, as uniquely linking the local receiving water quality to the discharges of any of the 700 SSOs is not possible given the lay out of the receiving waters.

2. Screening. The screening stage further limits the total number of monitoring locations by assessing practical aspects such as:

- safety (traffic conditions, criminality , vandalism);
- accessibility and available space for storm water treatment and monitoring equipment;
- planned reconstruction of sewers;

The screening has been based partly on available information and partly on information from a site visit. During the site visit also parameters like observed pollution, such as gross solids and toilet paper, are documented. This data can later be used to select appropriate monitoring equipment and to initiate a detailed search for illicit connections.

3. Quick scan. The quick scan aims at gathering information on (1) the water quality to be expected at a potential monitoring location and (2) on the system dynamics. This information is gathered using a very simple and relatively cheap approach:

1. Installation of a CTD diver in the manhole just upstream of the SSO that continuously measures water level, temperature and conductivity at a 1 minute time interval.
2. Use local radar weather forecast to timely detect significant storm events (i.e. storms > 4 mm of precipitation as smaller storms might not result in runoff depending on the state of the catchment at the onset of the storm event)
3. For significant storm events, send a team for grab sampling of storm water.
4. Laboratory analyses of samples.
5. After having successfully sampled and analysed 3 events, relocate the divers to the next monitoring location until all locations have been observed.

The quick scan results in a data set with grab sample results for at least 3 storm events per location and at least 1 month of continuous data on water level, temperature and conductivity. The latter can be used to identify the occurrence of significant illicit connections and other irregularities that might interfere with the monitoring.

4. Final selection of monitoring locations. The results of the quick scan, combined with information on the criteria related to the representativeness of the monitoring locations used in the pre-screening phase, are used to select the final monitoring locations.

3 RESULTS AND DISCUSSION

3.1 Selection of locations

3.1.1 Pre-screening

In Almere, the pre-screening has resulted in 60 of the 700 locations being selected. As the Almere sewer systems mostly have meshed network configurations, the use of a full hydrodynamic model has been necessary to link specific parts of the catchments to specific SSOs. The 60 locations are spread evenly over the three catchment categories and over the city.

3.1.2 Screening

Using a dedicated inventory form, the screening stage involved collecting information on all 60 locations:

- general information: manhole number, address, pictures of manhole and surroundings, building period, type of housing)
- site characteristics: safety issues, accessibility, position (road, green areas), available space, accessibility of manhole, geometry of manhole, diameter of sewer, visual observations (toilet paper, gross solids).

After the screening stage, 40 locations were considered potential monitoring locations. Of these 40, the most interesting 30 have been selected for the quick scan, mainly based on covering the 3 categories indicated in figure 2 and on the relative easy to place monitoring equipment.

3.1.3 Quick scan

The quick scan has been applied at 30 locations, in batches of 10 locations. Using this approach, it was possible (given the geographical distribution) to sample 10 locations (near-) simultaneously during selected storm events with one team. Figure 3 shows a schematic representation of the installation of the CTD diver in the storm sewer. As the water level monitoring was only intended to give an indication of the system dynamics, there was no need to place the sensor at a known level. Consequently, a simple set-up using wooden rods sufficed to quickly install the sensors.

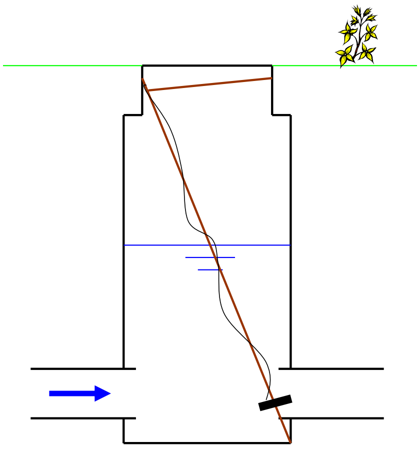

Figure 3. Left: Schematic of installation of sensor (water level, temperature and conductivity), right: picture of installed sensor in manhole (please note gross solids in manhole)

The quick scan has resulted in a dataset of 100 grab samples from the 30 locations (some locations have been sampled more than 3 times) and 30 time series of sensor data. The storm water quality of the grab samples is summarized in table 1. Apart from PAH and Cl, which are rather high in Almere, the median of the samples in Almere is comparable to the median of the Dutch database on storm water quality (Boogaard, 2012).

Table 1. Storm water quality. in **bold** if number exceeds Maximum Acceptable Concentration (MAC), (NW4, 1998)

parameter	MAC	100 samples Almere, 30 locations		STOWA Database (Boogaard, 2012)	
		Median	10 and 90 percentiles	Median	10 and 90 percentiles
TP (mg/l)	0.15	**0.18**	0.1-**0.5**	0.25	0.05 – **0.96**
TKN (mg/l)	2.2	1.3	0.7-**3.4**	1.1	0.38 **-3.3**
Pb (µg/l)	220	9.5	3.5-25	6.5	1.8 – 46.6
Zn (µg/l)	40	**89**	27.8-**262**	60	7.5- **280**
Cu (µg/l)	3.8	**5.6**	2.5-**20.1**	11	3.8-**34.7**
Benz(a)anthracene (µg/l)	30	20	9-**145**	20	7.5-**90**
Benzo(a)pyrene (µg/l)	200	19	7-106	20	7.5-196
Cl (mg/l)	200	34	7-116	11	3.3-33

Figure 4 and 5 give examples of the observed dynamics using the continuous measurements. Figure 4 shows that at location Wipmolenweg during the storm event of 18/05/09, the water level increases 10 cm, indicating that the sewer (and in fact the receiving water, as the surcharged sewers discharge below the water level of the receiving water) has a clear hydraulic response to the storm event. In addition, the conductivity at this location decreases from 1.000 µS/cm (a normal value in the receiving waters in Almere) to 300 µS/cm during the first storm event and to 150 µS/cm during the second storm event, which are normal values for storm water (Göbel et al. 2007). The temperature stows distinct peaks at the onset of the storm event and decreases afterwards. This most likely demonstrates that during the onset of the storm event, the impervious area is relatively warm, thus warming the first part of the runoff. This location is relatively clean, as on average per sample only 2 of the 29 assessed parameters exceeds the MAC.

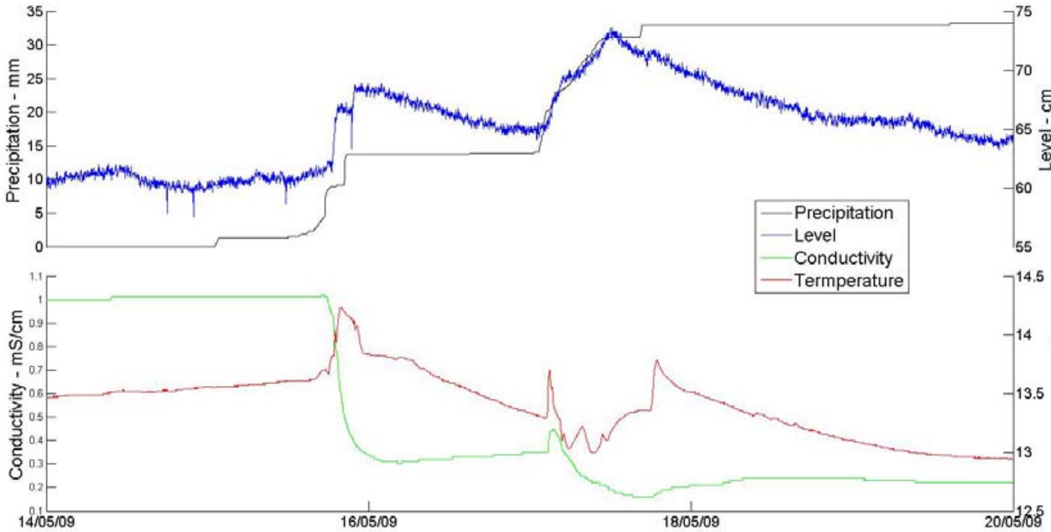

Figure 4. Measured precipitation, conductivity, water level and temperature from 14-20 may 2009 at location Wipmolenweg.

At location Sluis, see figure 5, the fluctuations in the water level have the same order of magnitude as at location Wipmolen. The conductivity at location Sluis shows the same dilution effect as at location Wipmolenweg during storm events, but both the conductivity and the temperature show frequent peaks during dry weather, indicating illicit connections. In addition, on average 4.7 parameters per sample exceed the MAC, indicating that location Sluis is relatively polluted.

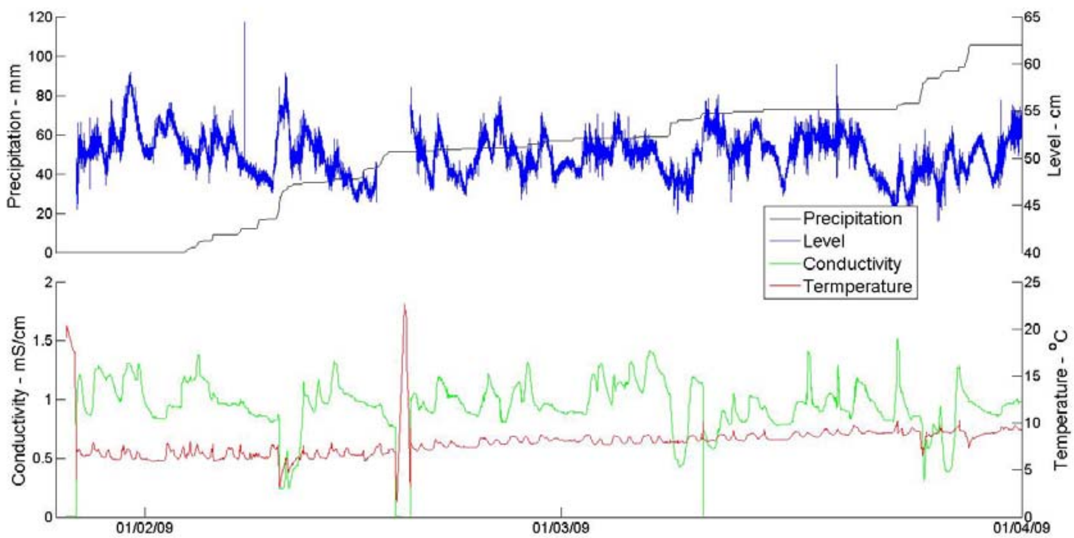

Figure 5. Measured precipitation, conductivity, water level and temperature from 26 January-1 April 2009 at location Sluis

3.1.4 Final selection

Based on the results of the quick scan and the available information on site characteristics, three locations have been selected. The site characteristics are summarized in table 2.

Table 2. Site characteristics

Location	Land use	Ha impervious area connected	Period of development	Comment
Baljuwstraat	City center	7.1	Before 1985	Exceedance of MAC for nutrients, Cu, Zn and PAHs, high conductivity in winter due to road de-icing with salt
Sluis	Medium density residential	10	Before 1985	Exceedance of MAC for nutrients, Cu and Zn, suspicion of illicit connections
Palembangweg	Medium density residential	2.5	After 1985	Exceedance of MAC for phosphate and sulphate

3.2 Additional results

3.2.1 Illicit connections: DTS versus quick scan results

At location Sluis distributed temperature sensing (DTS) has been applied to detect illicit connections (Hoes et al., 2009), as these were expected given the temperature and conductivity data from the quick scan, shown in figure 5. Figure 6 gives an example of the DTS results at location Sluis. A clear diurnal pattern in the temperature was observed in the storm sewer, indicating two adjacent illicit connections. In total 8 house connections have been identified to be connected directly to the storm sewer. These illicit connections have been confirmed on site and subsequently restored.

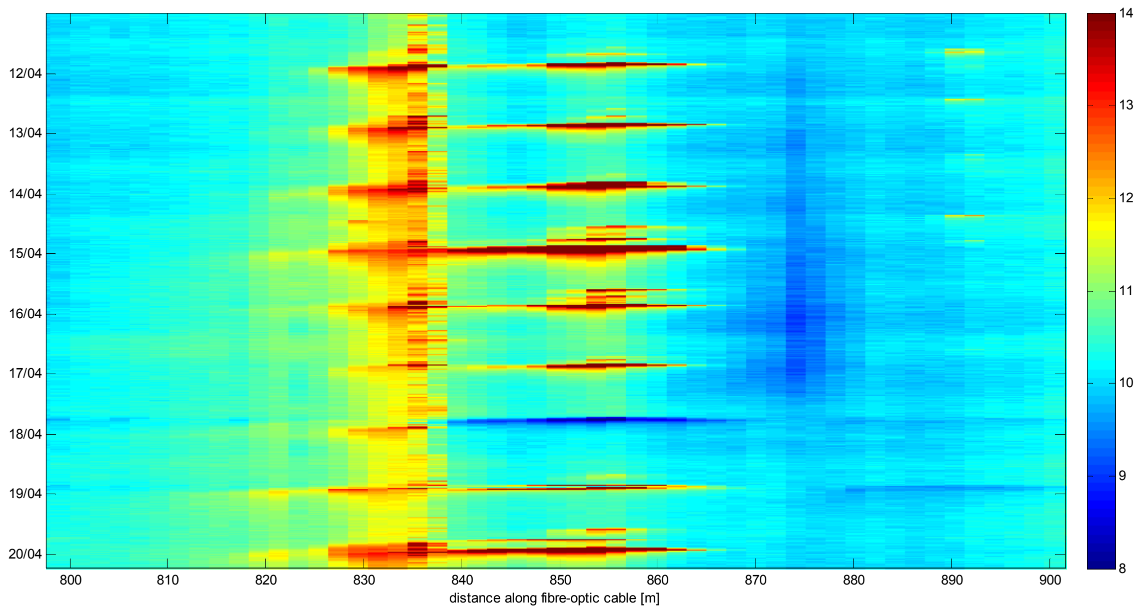

Figure 6. Results of DTS for detection of illicit connections

3.2.2 Verification of assumed catchment categorization

The catchment categorization as presented in paragraph 2.1 was conceived assuming a large impact on storm water quality following a change in the use of building materials around 1985. More specifically, the municipality of Almere assumed that sewer catchments developed before 1985 would be more polluted with zinc than sewer catchments developed after 1985. A Kolmogorov-Smirnov test applied on the monitoring data from the quick scan confirmed that the zinc concentration in all samples from catchments developed before 1985 was significantly higher (95% confidence) than in the samples from catchments developed after 1985, see table 3 for details. In addition, the catchments before 1985 also showed a significantly higher average number of exceedances of the MAC. Apparently, the catchments developed before 1985 (and of course after 1975, given the development of Almere) result in a generally higher pollutant level than the catchments developed after 1985.

Table 3. Comparison of pollution level in sewer catchment developed before and after 1985

	Zn (μg/l)		Number of exceedances of MAC (n)	
	Catchments before 1985	Catchments after 1985	Catchments before 1985	Catchments after 1985
Mean	404	161	3.6	2.3
Standard deviation	800	513	2.08	1.57
Number of samples	29	46	29	46

4 CONCLUSIONS AND OUTLOOK

This paper describes a methodology to select a number of suited monitoring locations for storm water quality assessment from a large number of potential SSOs in an area. It hence assists researchers to improve their design of monitoring networks for storm water quality. As a result, the chance of failure of the subsequent research or monitoring project decreases significantly, as especially the quick scan reveals the on-site system dynamics. This not only enhances the selection of appropriate monitoring locations, but also the subsequent detailed design of the monitoring equipment and sampling strategy. The investment necessary for the (pre-) screening, quick scan and selection amounted in the case of Almere to approximately 10% of the overall research budget for the OSAL project.

Applying the method has shown to result in the following additional benefits:

- Well described set of meta data on the project locations and sewer system.
- The laboratory results of the samples taken during the quick scan already contain information on the pollutant level of the storm water at the SSOs.
- Direct action is possible if the quick scan indicates erroneous system behaviour, such as the occurrence of illicit connections.

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