Selection of monitoring locations for storm water quality assessment

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ABSTRACT

Storm water runoff is a major contributor to the pollution of receiving waters. Storm water characteristics may vary significantly between locations and events. Hence, for each given location, this necessitates 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 locations and design of the monitoring setup. The main advantage of the method is the ability to prevent the selection of monitoring locations that turn out to be inappropriate. In addition, in this study, the quick scan resulted in a first useful dataset on storm water quality and a strong indication of illicit connections at one of the monitoring locations.

Key words | monitoring location, monitoring setup, sampling strategy, storm water quality

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INTRODUCTION

Separate sewer systems are widely applied in economically developed countries. Storm sewers are known to contribute significantly to the annual pollutant loads of receiving waters and to cause severe degradation of urban receiving waters (House *et al.* 1993; Beenen *et al.* 2011). The European Water Framework Directive (WFD) (2000/60/EC) aims to achieve a good status for all European water bodies. To comply with the WFD, local water authorities in member states have to develop storm water management strategies to enhance local receiving water quality to the desired level. Sound knowledge of local storm water characteristics allows assessment of the relative contribution of the storm water pollution to the overall load of 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 the literature). Storm water characteristics are a function of rainfall and runoff processes (Göbel *et al.* 2007), the contribution of illicit connections (Pitt *et al.* 1993) and in-sewer processes. Despite much work, it is still not possible to adequately predict the storm water quality for a given location and event (see e.g. Mourad *et al.* 2005). Hence, a well-designed monitoring campaign is necessary for each given location 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. For instance, in the Netherlands each storm sewer outfall typically serves an impervious area between 2 and 5 ha. As a consequence, for a given city with a few hundred hectares of impervious area connected to storm sewers, the number of potential monitoring locations easily exceeds one hundred. 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 determination of the number of storm events to be monitored and the choice of the monitoring location in order to achieve a water quality assessment with the desired level of uncertainty. 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 setup given the required 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 & Sivakumar (2009). It can be concluded that the selection of an appropriate monitoring setup and number of storm events has sufficiently been dealt with in the literature.

The selection of monitoring locations, by contrast, has hardly received attention in the 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 the detection of groundwater pollution (Cieniawski *et al.* 1995; Bierkens 2006). These methods balance the costs of increasing the number of monitoring locations versus the additional information from 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 appropriate monitoring locations for storm water quality monitoring. The paper describes the case of Almere and the OSAL (Optimisation Study ALmere) monitoring project which is used to test and evaluate the methodology. Finally, the results of the application of the methodology on the sewer system in Almere are presented and discussed.

MATERIALS AND METHODS

System description

Almere, The Netherlands (with 194.500 inhabitants) is a young city, founded in 1975 after the realisation of the Flevopolder, in order to accommodate the increase of population in Amsterdam. The Flevopolder is a polder, or region of reclaimed land, drained between 1955 and 1968. In 1995, the municipality had 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 wastewater treatment plant 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) 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 2,125 ha of contributing area. The municipality has divided the catchment into three categories:

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

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

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

The municipality of Almere and Zuiderzeeland regional water authority launched a comprehensive research project, OSAL. The objective of the OSAL project is to quantify the emissions from SSOs as well as the impact of the SSOs on receiving water quality. The project integrates strategies/measures to improve the receiving water quality in order to be able to comply with ecological water quality standards. The OSAL project comprises seven pilot projects. Pilot 1 involves long-term monitoring of the storm water quality at three SSOs, using both continuous sensors and flow proportional sampling. 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 2014 and will last for 2 years. During the preparatory phase of the OSAL project, out of a total of 700 SSOs in Almere, three locations were selected to implement the monitoring setup. The method used for this selection procedure is presented in the next section.

Method for selection of monitoring locations

The method for the selection of monitoring locations comprises four steps (Figure 1).

1. **Pre-screening.** The pre-screening stage limits the total number of potential monitoring locations by checking for (1) the 'general suitability' for the planned research and (2) the 'representativeness' in terms of catchment characteristics. Both aspects are discussed below. The 'general suitability' for the planned research is evaluated, using as criteria the connected impervious area per SSO, anticipated works that might have an impact on the system dynamics (e.g. road reconstruction) and hydraulic design.

Based on experiences in other comparable research projects (Langeveld et al. 2012), the connected impervious area per SSO suitable to be used as a monitoring location ranges between 2 and 10 ha. Outfalls serving less than 2 ha have small flows during smaller storm events, thus resulting in unrealistic accuracy requirements for monitoring equipment when using flow proportional sampling. Outfalls serving more than 10 ha have high design flows, requiring relatively expensive monitoring equipment as well as treatment facilities, such as the lamella settler of Pilot 5.

Road works during the monitoring period can have an impact on the system dynamics as they alter the catchment. Catchments with road works of more than 5% of the connected length are excluded. The threshold value was set at 5% to prevent the selection of catchments with planned extensive roadworks, but to allow for small road repairs on an ad hoc basis.

The hydraulic design of the storm sewers (surcharged versus non-surcharged, the available head between the outfall and the receiving water level) determines the performance of the sewer. It also determines the required effort to accurately monitor flows and the ability to install a V-notch weir or other primary monitoring structure (flume, orifice, plate) for flow monitoring. Locations that do not allow affordable flow monitoring are excluded.

The 'representativeness' comprises catchment characteristics such as construction period, population density, average income and type of road (high/low traffic intensity). The selection of these criteria has a clear relation to the research objectives: only if the impact of one of these criteria is to be quantified should the criterion be selected.

The pre-screening should be based on information already available from municipality registers. Site visits are to be made in the second screening step for a reduced number of locations.

2. **Screening.** The screening stage further limits the total number of monitoring locations by setting a number of minimum practical requirements. The first requirement is safety, which involves traffic conditions, criminality and vandalism. As monitoring locations will be visited frequently, locations underneath busy roads are excluded. In addition, remote locations where crimes can be expected are to be avoided for safety of the research personnel. The second requirement is accessibility and available space for storm water treatment and monitoring equipment in public spaces. The third requirement is the absence of planned reconstruction of sewers. Reconstruction work on sewers during the monitoring project are unacceptable, as they will influence the monitoring results. In addition, the cleaning of sewers is to be avoided during the monitoring project. This aspect, however, should be negotiated with the sewer operator and should therefore not interfere with the selection of monitoring locations.

These practical aspects typically have a 'go' or 'no-go' character, as they cannot easily be adjusted by the research team. The screening is based partly on available information and partly on information from a site visit. During the site visit other parameters like observed pollution, such as gross solids and toilet paper, are documented. These 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 with respect to hydraulics and water quality. The combination of these two data sources gives information on the performance of the sewer system at the specific location.

Information on the local storm water quality is required to prevent the selection of locations with pollutant
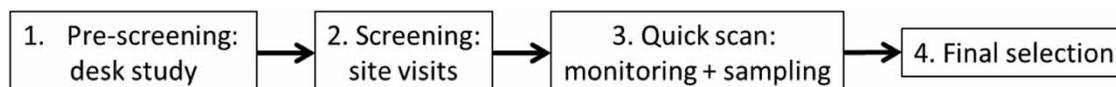

Figure 1 | Method for selection of monitoring locations.

concentrations far below or above the expected level (by at least a factor of 2), possibly indicating illicit connections or other problems. This information can be obtained by sampling a number of events and analysing for relevant water quality parameters. Given the objective of the quick scan, that is, indicating whether the pollutant concentrations are far below or above the expected level, grab sampling is considered sufficient, even though it introduces an additional uncertainty of 10% (Fletcher & Deletic 2007). Combination with continuous water quality sensors allows a check to be made to see if the grab sampling occurred during the extremes of the pollutograph, thus allowing potentially large errors to be avoided.

The minimum number of events to be sampled depends on the uncertainty that can be accepted. Monitoring three events per location will result in site mean concentrations (SMC) with a relative SMC uncertainty in the order of magnitude of 1 for total suspended solids (TSS), 0.4–0.55 for Zinc (Zn) and 0.4–0.55 for total Kjeldahl nitrogen (TKN) (see Figure 2). This order of magnitude allows comparing potential monitoring locations and identifying locations with significantly differing concentration levels which may be due to some location specific problem.

Information on dynamics might demonstrate differences between the system characteristics as recorded in the database of the sewer operator and the 'real' system characteristics as observed. Typical differences observed during recent monitoring projects are related to illicit connections, infiltration of groundwater, pipe diameters, the lay out of the sewer system with respect to location, and number of outfalls and connections between sewer systems in different catchments.

Information on dynamics can be obtained by installing sensors measuring relevant water quality parameters and hydraulics at a 1 minute interval. This 1 min interval is

necessary to be able to detect swift changes in water quality due to illicit connections (Nienhuis *et al.* 2013) and the very high dynamics in water quality typically observed during the onset of storm events (Langeveld *et al.* 2008).

For the purpose of the quick scan, these sensors should be robust and easy to maintain. Turbidity and conductivity sensors have been shown to be applicable in sewer systems (e.g. Krebs *et al.* 1999) and can be applied as surrogate measurements for the more complex direct parameters (Lombard *et al.* 2010), even with an acceptable uncertainty (Lepot *et al.* 2013). The dynamics in the hydraulics can be monitored using water level sensors, such as vented pressure transducers.

The quick scan results in a dataset with grab sample results for at least three storm events per location and at least 1 month of continuous data on water level and some relevant water quality parameters, such as turbidity, conductivity or temperature. The latter could indicate illicit connections (Hoes *et al.* 2009). This dataset can be gathered using a very simple and relatively cheap approach:

1. Installation of a water level and surrogate water quality sensor, in this case temperature and conductivity in the manhole just upstream of the SSO.
2. Use radar weather forecast to identify 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 three events, relocate the sensors to the next monitoring location until all locations have been observed.
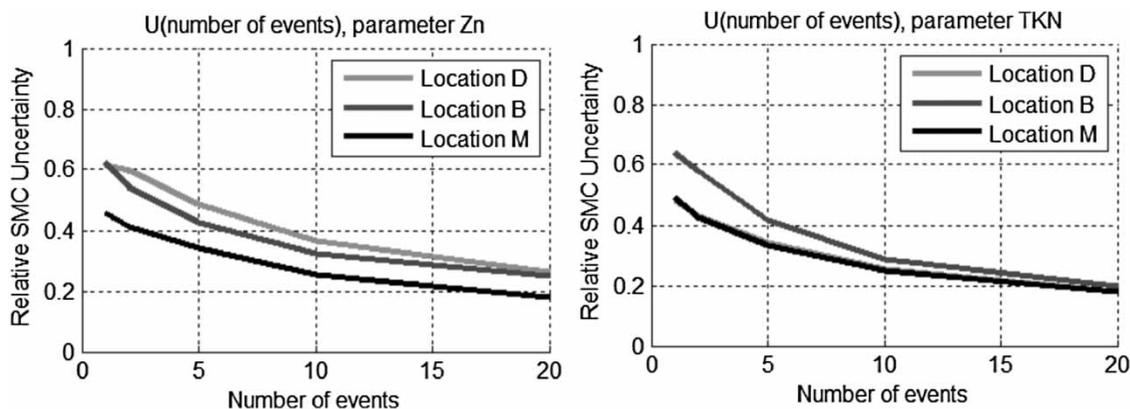

Figure 2 | Relative uncertainty in SMC for zinc (left) and Kjeldahl nitrogen (right) as a function of the number of measured events, derived from a dataset used in Langeveld *et al.* (2012), comprising nearly 300 storm events monitored at three locations D, B and M (abbreviations of the names of the locations in Arnhem, The Netherlands).

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 considered to select the final monitoring locations. The final selection itself is performed in two steps. First, inappropriate locations are removed from the list and second, the remaining locations are ranked based on expert judgement.

RESULTS AND DISCUSSION

Selection of locations

Pre-screening

In Almere, the pre-screening resulted in 60 of the 700 locations being selected based on general suitability and representativeness, the latter in terms of construction period of the catchment and the type of catchment (residential/non-residential). As the Almere sewer systems mostly have meshed network configurations, the use of a full hydrodynamic model was necessary to link specific parts of the catchments to specific SSOs. The 60 locations are spread evenly over the three catchment categories, dating from before 1985, after 1985, and special areas, and over the city. The 60 locations are shown on the map in the separate Appendix (available online at http://www.iwaponline.com/wst/069/134.pdf).

Screening

Using a dedicated inventory form, the screening stage involved collecting information on characteristics of all 60 locations: 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 were selected for the quick scan, mainly based on covering the three categories and the suitability of the location to place monitoring equipment.

Quick scan

The quick scan was 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 a CTD-diver® (http://www.swstechnology.com/groundwater-monitoring/groundwater-dataloggers/ctd-diver) in the storm sewer. The CTD-diver continuously measures water level, temperature and conductivity. 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 setup using wooden rods sufficed to quickly install the sensors.

The quick scan resulted in a dataset of 100 grab samples from the 30 locations (some locations being sampled more than three times) and 30 time series of sensor data. The storm water was analysed for nutrients (total phosphate and TKN), micro pollutants (polycyclic aromatic hydrocarbons (PAH)), metals (copper, zinc and lead) and chloride as an indicator of brackish seepage. These parameters were selected to cover the most relevant receiving water quality issues: eutrophication and toxicity. The storm water quality of the grab samples is summarized in Table 1. Apart from PAH and chloride, 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 et al. 2014). The pollutant level of metals in Dutch storm water is relatively low compared to the international literature (Bratieres et al. 2008), whilst for nutrients they are within the same range.

Figures 4 and 5 give examples of the observed dynamics using the continuous measurements. Figure 4 shows that at Wipmolenweg during the storm event of 15–16/05/09, the water level increases 10 cm, indicating that the sewer (and in fact the receiving water, as the sewer discharges below the

Figure 3 | Picture of an installed sensor in a manhole. The CTD-diver is in a protective tube (note the gross solids in the manhole).

Table 1 │ Storm water quality. Numbers in bold denote values exceeding maximum acceptable concentration (MAC) (NW4 1998)

Parameter	MAC	Almere: 100 samples, 30 locations		STOWA database (Boogaard et al. 2014)		Worldwide and Australian (Bratieres et al. 2008) 'typical' levels
		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**	**0.35**
TKN (mg/l)	2.2	1.3	0.7–**3.4**	1.1	0.38–**3.3**	2.1
Pb (µg/l)	220	9.5	3.5–25	6.5	1.8–46.6	140
Zn (µg/l)	40	**89**	27.8–**262**	**60**	7.5–**280**	**250**
Cu (µg/l)	3.8	**5.6**	2.5–**20.1**	**11**	3.8–**34.7**	**50**
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	
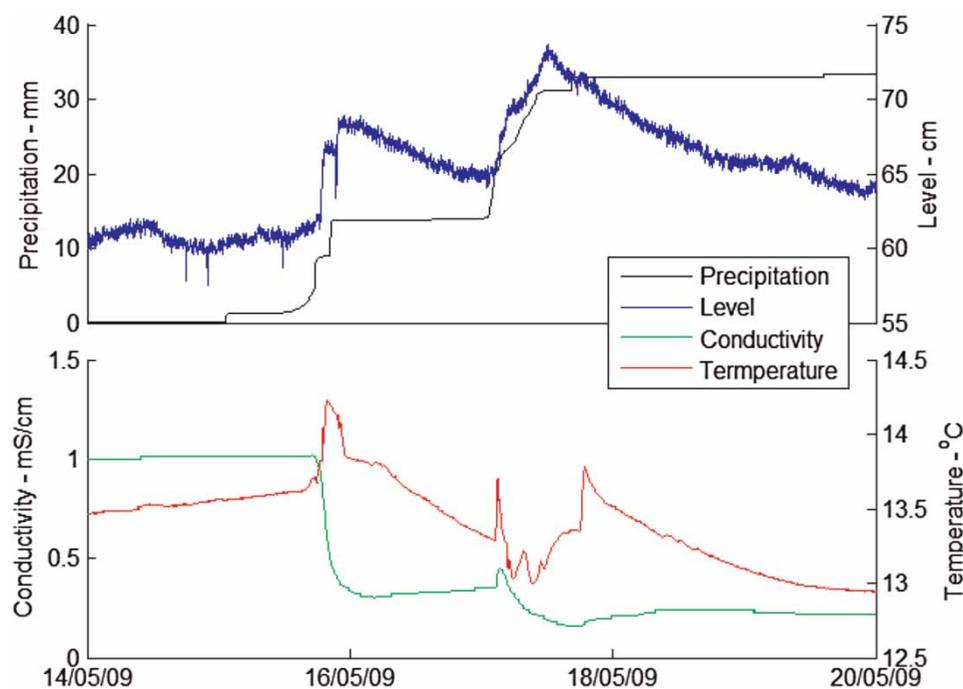
Figure 4 │ Measured precipitation (cumulative), conductivity, water level and temperature, 14–20 May 2009 at Wipmolenweg.

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 shows 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 two of the 29 assessed parameters exceed the maximum acceptable concentration (MAC).

At Sluis (Figure 5) the fluctuations in the water level have the same order of magnitude as at Wipmolenweg. The conductivity at Sluis shows the same dilution effect as at Wipmolenweg during storm events, but both the conductivity and the temperature show frequent peaks during dry weather, indicating illicit connections. In total, eight house connections have been identified in a subsequent project to be
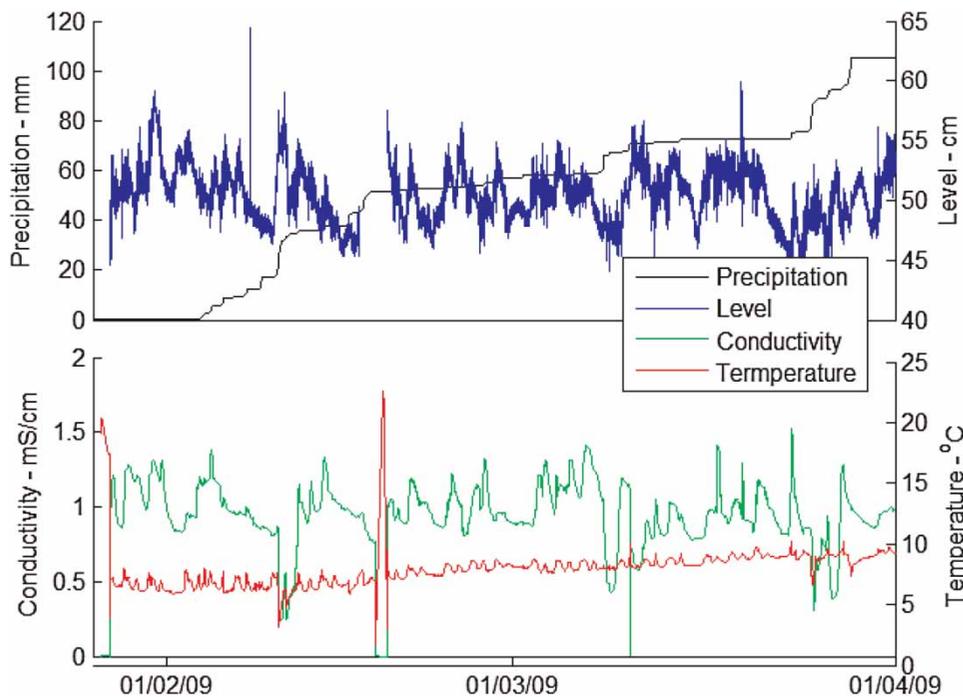
Figure 5 | Measured precipitation (cumulative), conductivity, water level and temperature 26 January–1 April 2009 at Sluis.

wrongly connected directly to the storm sewer. These illicit connections have been confirmed on site and subsequently removed before the detailed monitoring campaign. In addition, on average 4.7 parameters per sample exceed the MAC, indicating that Sluis is relatively polluted.

Final selection

The selection of three locations out of the 30 quick scan locations was mainly based on the following criteria: lack of dynamic response in water quality on storm events, accessibility, suitability for installing a flow sensor and coverage of the three categories. The characteristics of the selected locations, shown on the map in the separate Appendix (available online at http://www.iwaponline.com/wst/069/134.pdf), are summarized in Table 2.

### Additional result: verification of assumed catchment categorization

The catchment categorization 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, as after 1985 the use of leachable zinc was prohibited for roof drainage. A Kolmogorov–Smirnov test applied on the monitoring data from the quick scan confirmed that the zinc concentration in storm water runoff samples from category I catchments, developed before 1985, was significantly higher (95% confidence) than in the samples from category II catchments, developed after 1985; see Table 3 and Figure 6 for

Table 2 | Location characteristics

Category	Location	Land use	Ha impervious area connected	Comment
Category III, special area	Baljuw-straat	City centre	7.1	Exceedance of MAC for nutrients, Cu, Zn and PAHs, high conductivity in winter due to road salt (de-icing)
Category I, dating before 1985	Sluis	Medium density residential	10	Exceedance of MAC for nutrients, Cu and Zn, suspicion of illicit connections
Category II, dating after 1985	Palem-bangweg	Medium density residential	2.5	Exceedance of MAC for phosphate and sulphate

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

	Zn (µg/l)		Number of exceedances of MAC (n)	
	Cat. I. catchments before 1985	Cat. II. catchments after 1985	Cat I. catchments before 1985	Cat II. 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
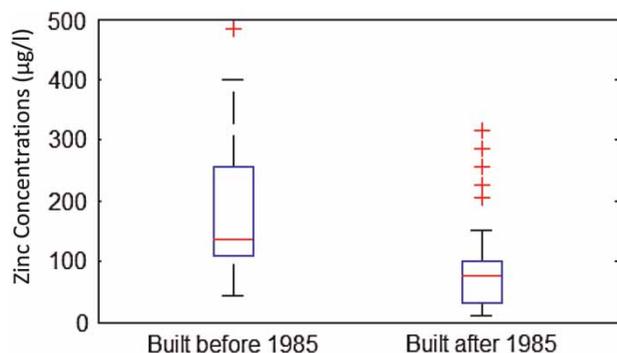
Figure 6 │ Boxplot of measured zinc concentrations in category I catchments (before 1985) and category II catchments (after 1985). The y-axis has been cut off at 500 µg/l in order to enhance readability, cutting off three data points >500 µg/l for category I catchments and one data point for category II catchments.

details. In addition, the catchments before 1985 showed a significantly higher average number of exceedances of the MAC for all pollutants. 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.

DISCUSSION

The method for selecting monitoring locations has been shown to be applicable for the selection of locations appropriate for monitoring of storm sewer outfalls. In a few steps, three monitoring locations were selected from the 700 potential monitoring locations. The criteria used to pre-screen and screen the locations aim to be able to select locations suitable for a monitoring campaign from a practical point of view and to ensure that the processes that are to be studied indeed occur.

The main advantage of the method is being able to prevent the selection of monitoring locations that turn out to be inappropriate, with the main cause being differences between design drawings and the actual sewer system lay out and structure. It is quite hard to find evidence in the literature for this, as failures in monitoring projects are hard to publish. Veldkamp & Kluck (2005) describe the results of a monitoring campaign on the efficiency of a storm water settling tank. During the monitoring project, it was discovered that in an adjacent street an additional CSO was located with a lower weir level and, as a consequence, during the first part of the monitoring project no CSO events could be monitored. Gamerith *et al.* (2013) describe the results of a comprehensive monitoring campaign designed to monitor the impact of CSOs on receiving water quality, stating 'Despite the fact that stormwater and combined sewage (from CSO structures) is discharged into the river stretch, no severe effects regarding physical water quality parameters (oxygen deficit, NH_4-N peaks) were observed during large rainfall events at the downstream measurement station.' In both cases, a quick scan could have revealed the lack of dynamic response of the CSO and the river, respectively, to rainfall events and thus have prevented wasting monitoring efforts as well as funds.

Unlike design methods for monitoring networks in groundwater (Bierkens 2006) and sewers (Clemens 2001), the developed method does not allow the costs of increasing the number of monitoring locations versus additional information to be balanced. This is due to the fact that these design methods determine the amount of information that any monitoring network configuration could deliver on one single system within its well defined boundaries, whether this is an aquifer or sewer system. Storm sewer outfalls, by contrast, turn out to serve individual catchments that are not a part (in hydraulic and hydrologic terms) of one large system.

To address the issue of representativeness, ongoing research in the Netherlands aims at creating a database with well described monitoring locations, including meta data.

CONCLUSIONS AND OUTLOOK

This paper describes a methodology to select a number of suitable monitoring locations for storm water quality

assessment from a large number of potential SSOs in a watershed. 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 projects decreases substantially, as 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 been 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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REFERENCES

2000/60/EC Directive of the European Parliament and of the Council establishing a framework for Community action in the field of water policy (2000/60/EC). 23 October 2000, http://europa.eu.int/eur-lex/.

Beenen, A. S., Langeveld, J. G., Liefting, H. J., Aalderink, R. H. & Velthorst, H. 2011 An integrated approach for urban water quality assessment. *Water Science and Technology* **64** (7), 1519–1526.

Bertrand-Krajewski, J.-L., Bardin, J.-P., Mourad, M. & Béranger, Y. 2003 Accounting for sensor calibration, data validation, measurement and sampling uncertainties in monitoring urban drainage systems. *Water Science and Technology* **47** (2), 95–102.

Bierkens, M. F. P. 2006 Designing a monitoring network for detecting groundwater pollution with stochastic simulation and a cost model. *Stochastic Environmental Research and Risk Assessment* **20** (5), 335–351.

Boogaard, F. C., van de Ven, F., Langeveld, J. G. & van de Giesen, N. 2014 Stormwater quality characteristics in (Dutch) urban areas and performance of settlement basins. *Challenges* **2014** (5), 112–122.

Bratieres, K., Fletcher, T. D., Deletic, A. & Zinger, Y. 2008 Nutrient and sediment removal by stormwater biofilters: a large-scale design optimisation study. *Water Research* **42** (14), 3930–3940.

Cieniawski, S. E., Eheart, J. W. & Ranjithan, S. 1995 Using genetic algorithms to solve a multiobjective groundwater monitoring problem. *Water Resources Research* **31** (2), 399–410.

Clemens, F. H. L. R. 2001 A design method for monitoring networks in urban drainage. In: *Urban Drainage Modeling. Proceedings of the specialty symposium held in conjunction with the World Water and Environmental Resources Congress, May 20–24, 2001* (R. W. Brashaer & C. Maksimovic, eds).Orlando, Florida.

Clemens, F. 2002 Evaluation of a Method for the Design of Monitoring Networks in Urban Drainage. In: *Global Solutions for Urban Drainage. Proceedings of the Ninth International Conference on Urban Drainage. Portland, Oregon, USA. 8–13 September 2002* (E. W. Strecker & W. C. Huber, eds). CD-ROM, 17 pp. ASCE Publications, Reston, VA.

Fletcher, T. D. & Deletic, A. 2007 Statistical evaluation and optimisation of stormwater quality monitoring programmes. *Water Science and Technology* **56** (12), 1–9.

Gamerith, V., Leonhardt, G., Hofer, T., Kinzel, C., Kleidorfer, M. & Rauch, W. 2013 Integrated assessment of receiving water quality based on validated high resolution data and water quality modelling. In: *Proceedings of 8th NOVATECH*, 9 pp.

Göbel, P., Dierkes, C. & Coldewey, W. G. 2007 Storm water runoff concentration matrix for urban areas. *Journal of Contaminant Hydrology* **91** (1/2), 26–42.

Hoes, O. A. C., Schilperoort, R. P. S., Luxemburg, W. M. J., Clemens, F. H. L. R. & van de Giesen, N. C. 2009 Locating illicit connections in storm water sewers using fiber-optic distributed temperature sensing. *Water Research* **43** (20), 5187–5197.

House, M. A., Ellis, J. B., Herricks, E. E., Hvitved-Jacobsen, Seager, J., Lijklema, L., Aalderink, H. & Clifforde, I. T. 1993 Urban drainage – impacts on receiving water quality. *Water Science and Technology* **27** (12), 117–158.

Krebs, P., Merkel, K. & Kühn, V. 1999 Dynamic changes in wastewater composition during rain runoff. *Proc. of 8ICUSD*, 30 August–3 September 1999, Sydney, Australia, pp. 920–927.

Langeveld, J. G., Liefting, H. J. & en Velthorst, H. 2008 Storm water sewers: pollution levels and removal rates of three full scale storm water treatment facilities in Arnhem. *Proceedings of 11th International Conference on Urban Drainage (11ICUD)*, Copenhagen, Denmark.

Langeveld, J. G., Liefting, H. J. & Boogaard, F. C. 2012 Uncertainties of stormwater characteristics and removal rates of stormwater treatment facilities: implications for stormwater handling. *Water Research* **46** (2012), 6868–6880.

Lee, H., Swamikannu, X., Radulescu, D., Kim, S.-J. & Stenstrom, M. K. 2007 Design of stormwater monitoring programs. *Water Research* **41** (18), 4186–4196.

Leecaster, M. K., Schiff, K. & Tiefenthaler, L. L. 2002 Assessment of efficient sampling designs for urban stormwater monitoring. *Water Research* **36** (6), 1556–1564.

Lepot, M., Bertrand-Krajewski, J.-L. & Aubin, J.-B. 2013 Accuracy of different sensors for the estimation of pollutant concentrations (total suspended solids, total and dissolved chemical oxygen demand) in wastewater and stormwater. *Water Science and Technology* **68** (2), 462–471.

Lombard, V., Toloméo, S., Bertrand-Krajewski, J.-L., Debray, R., Comte, C. & de Bénédittis, J. 2010 Conception et mise en place de stations de mesure des flux polluants dédiées à la gestion intégrée d'un système d'assainissement. *Proceedings of NOVATECH 2010*, 2–7 July 2010, Lyon, France.

May, D. & Sivakumar, M. 2009 Optimum number of storms required to derive site mean concentrations at urban catchments. *Urban Water Journal* **6** (2), 107–113.

Mourad, M., Bertrand-Krajewski, J. L. & Chebbo, G. 2005 Sensitivity to experimental data of pollutant site mean concentration in stormwater runoff. *Water Science and Technology* **51** (2), 155–162.

Nienhuis, J., Haan, C. J., de Langeveld, J. G., Klootwijk, M. & Clemens, F. H. L. R. 2013 Assessment of detection limits of fiber-optic distributed temperature sensing for detection of illicit connections. *Water Science and Technology* **67** (12), 2712–2718.

NW4 1998 *Fourth National Policy Document on Water Management*. Ministry of Transport and Water, The Netherlands (in Dutch).

Pitt, R., Field, R., Lalor, M., Adrian, D. D. & Barbé, D. 1993 Investigation of Inappropriate Pollutant Entries into Storm Drainage Systems: a User's Guide. Rep. No. EPA/600/R-92/238, NTIS Rep. No. PB93-131472/AS. US Environmental Protection Agency (EPA), Storm and Combined Sewer Pollution Control Program, Edison, N. J. Risk Reduction Eng., Lab., Cincinnati, Ohio.

Rossi, L., Rumley, L., Ort, C., Minkkinen, P., Barry, D. A. & Chèvre, N. 2011 Samplinghelper a web-based tool to assess the reliability of sampling strategies in sewers and receiving waters. *Water Science and Technology* **63** (12), 2975–2982.

Veldkamp, R. G. & Kluck, J. 2005 The effectiveness of a lamella separator in a storm water settling tank in Limmen (in Dutch: De effectiviteit van kokerafscheiders in de bergbezinktank van Limmen) STOWA report 2005-W02.