An integrated approach for urban water quality assessment

Approche intégrée pour évaluer la qualité des eaux urbaines

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RÉSUMÉ

Cet article décrit d'une approche intégrée destinée à évaluer la qualité des eaux du milieu récepteur et de la contribution relative d'un système de drainage urbain en rapport avec les problèmes perçus de qualité des eaux du milieu récepteur. Cette approche combine des bilans massiques avec des modèles relativement simples d'impact sur les eaux du milieu récepteur.

Le projet de recherche nous a appris qu'un système de drainage urbain n'est qu'un des facteurs déterminants dans la problématique de la qualité des eaux du milieu récepteur. La morphologie des eaux du milieu récepteur et les sources de pollution hors assainissement – telles que les oiseaux, les chiens, ou les intrants d'eaux de surface extérieures - peuvent être tout aussi importants. Cette conclusion souligne la nécessité de changer l'approche actuelle basée sur les émissions et d'adopter une approche intégrale basée sur les immissions.

L'approche intégrée est illustrée par l'étude de cas d'Arnhem, où la qualité des eaux du milieu récepteur reste insatisfaisante même après transformation d'un système d'assainissement unitaire en système d'assainissement séparatif.

MOTS CLÉS

Qualité des eaux urbaines, politique et gestion, approche intégrée, étude d'impact

ABSTRACT

This paper introduces an integrated approach for the assessment of receiving water quality and the relative contribution of the urban drainage system to perceived receiving water quality problems. The approach combines mass balances with relatively simple receiving water impact models.

The research project has shown that the urban drainage system is only one of the determining factors with respect to receiving urban water quality problems. The morphology of the receiving waters and the non-sewer sources of pollution, such as waterbirds, dogs, or inflow of external surface water might be equally important. This conclusion underlines the necessity to change today's emission based approach and adopt an integral and immission based approach.

The integrated approach is illustrated by a case study in Arnhem, where the receiving water quality remained unsatisfactory even after retrofitting a combined sewer system into a separated sewer system.

KEYWORDS

Urban water quality, policy and management, integrated approach, impact assessment, emissions

1   INTRODUCTION

Within the North Sea Action Plan and Rhine Action Plan (1985) the contributing countries agreed to reduce the nutrient discharges from all sources within the Rhine catchment and to the North Sea by 50% compared to the 1985 pollution loads. In the Netherlands, this agreement resulted in stringent emission standards for combined sewer overflows (CSOs) and storm sewer overflows (SSOs). The emission reduction for CSOs is nearly achieved after two decades of major investments in sewer systems and wastewater treatment plants; the emission reduction for SSOs is yet to begin.

Nonetheless, the chemical quality of many receiving urban waters still does not meet the standards, such as the MAC (maximum acceptable concentration of pollutants) defined in the NW4 (Dutch 4th National Policy Document on Water Management, 1998). In addition, the ecological quality does not meet the water framework directive (WFD) derived standards for urban water systems.

The insufficient ecological and chemical quality of urban water systems is generally attributed to discharges from sewer systems (SSOs and CSOs) only. Subsequently, municipalities and water boards are trying to further reduce the emissions from sewer systems with the application of best available technology (BAT). It is questionable, however, whether these proposed investments will be effective with respect to receiving water quality, as the emissions from sewer systems and wastewater treatment plants (wwtps) are only a proportion of the total load of pollutants entering the receiving waters.

In order to be able to assess the relative impact of sewer systems on urban water system quality and the potential improvement achievable with best available technologies, the RIONED foundation and STOWA (foundation for applied research in water management) have launched the project 'Pollutant fluxes in urban water systems'. The main objective of this project was to assess whether today's knowledge on emission levels from sewer systems is sufficient to address the relative contribution of sewer discharges to receiving water quality problems.

The research project had to answer the following questions:

1.   What are the dominant receiving water quality problems in urban water systems?

2.   What is the relative contribution of sewer systems to the receiving water quality problems?

3.   To what extent can BAT measures prevent receiving water quality problems?

In order to be able to answer these questions, a methodology has been developed to calculate the receiving water quality problems based on the calculated total pollution loads discharged towards the urban water system and the characteristics of the receiving water body. This paper describes the methodology developed within this project, illustrated on a full scale case in Arnhem, the Netherlands.

2   METHODS

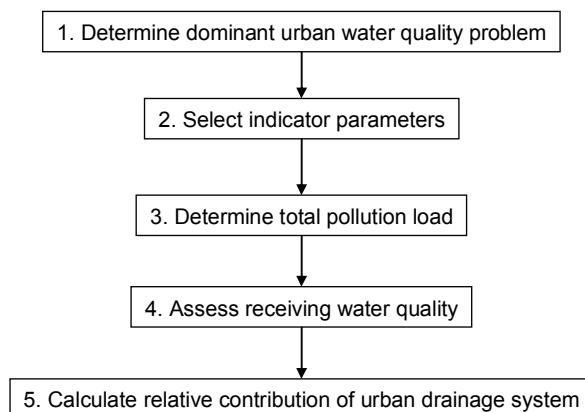A schematic of the developed assessment methodology is shown in figure 1.

Figure 1. Assessing relative contribution of urban drainage system to receiving water quality problems

2.1 Determine dominant urban water quality problems

The dominant urban water quality problems are typically related to the morphology of the receiving water body, such as hydraulic retention time, water depth and discharge. Given the morphology, figure 2 can be used to get a first idea of the potential water quality problems.
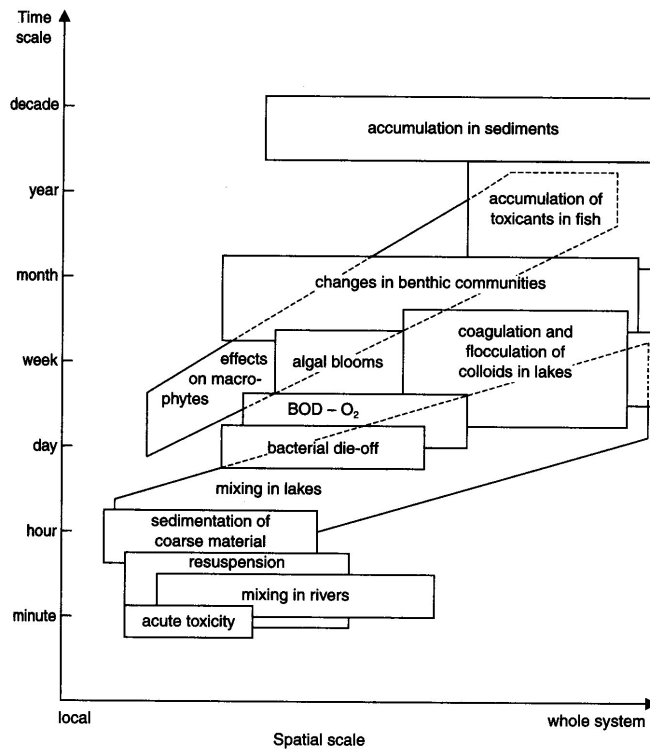

Figure 2. Time and space scales for receiving water impacts (after House et al. (1993))

At the scale of an urban pond or urban canal, the dominant receiving water problems are oxygen depletion, eutrophication (causing blue-green algae blooms, poor eco diversity and odour), acute and long term toxicity and hygienic pollution. The impact of endocrine disruptors in wastewater is normally absent in these small waters, as the proportion of dry weather flow discharged to these systems is insignificant.

Since the dominant urban water quality problems vary strongly for systems of different size, the methodology of figure 1 has been developed and tested for space scales ranging from a small urban pond to a regional water body. For clarity, this paper focuses on the urban pond. The main characteristics of a typical urban pond are assumed as follows:

- Dimensions: 30 x 100 $m^{2,}$ with a maximal water level variation of 0.3 m at a depth of 1.5 m (deep) and 0.5 m (shallow);

- Shore: sheeting 50%, reed 50%, trees: shadowing and falling leaves on 50% of the water body;

- Limited maintenance: dredging each 20 years, thick sediment layer;

- No inward or outward seepage;

- Lots of ducks (20 – 40), intensively fed by local residents.

The characteristics of the connected surface are:

- Residential area of 2 ha (20,000 m^2) of connected paved surface, with two variants of sewer systems:

  - Separated sewer system, discharge into the pond via storm sewer outfalls (SSOs);

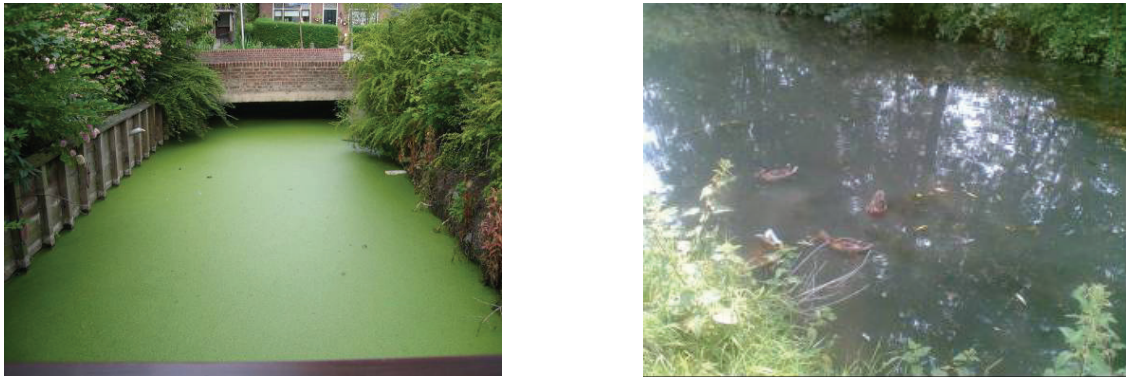 - Combined sewer system, discharge into the pond via CSO.

Figure 3. Examples of urban ponds. Note the duckweed in the left picture, being an indicator of eutrophication. The grayish color of the pond in the right picture is due to a CSO event.

2.2 Selection of indicator substances

Each receiving water quality problem can be attributed to one of more indicator substances. Table 1 gives an overview of the pollutants taken into account related to a specific water quality problem.

Water quality problem	Indicator substance
Oxygen depletion	BOD
Eutrophication	nitrogen, phosphorus
Acute and long term toxicity	PAH, glyphosate (N-(phosphonomethyl) glycine), cadmium, chrome, copper, lead, mercury, nickel and zinc
Hygienic pollution	Total coliform / E. Coli

Table 1. Water quality problems and associated pollutants

2.3 Determine total pollution load

An urban canal or pond is typically loaded with pollutants from various sources. The main sources identified are:

- Dog excrements (derived from average number of dogs per hectare catchment area times the annual production of dog excrements and its typical composition). For e.g. phosphorous the emission per dog ranges between 0.16-0.32 kg P.

- Excrements of waterfowls (derived from the number of ducks per hectare receiving water times the production of bird excrements and its typical composition). For e.g. nitrogen the annual emission amounts to 0.2-0.8 kg N per duck.

- Old bread fed to ducks (a tradition in the Netherlands), but not taken up. This amount is derived by counting the proportion of bread fed to the ducks and determining the portion not being eaten.

- Fallen leaves (49-62 mg zinc per kg foliage)

- Direct deposition of rain water (calculated from the annual precipitation times the mean concentration in rainwater)

- Direct run off from banks.

- Urban drainage system (comprising either CSOs or SSOs in the exemplified system)

The emission from the urban drainage system has been estimated by multiplying an event mean concentration (EMC) with the total runoff volumes, which is a common approach for estimating annual pollutant loads (Mourad et al., 2004). The runoff volumes are calculated with a rainfall runoff model coupled with a reservoir model. The EMCs per pollutant derived form the Dutch STOWA storm water database (Boogaard and Lemmen, 2007). This database shows an enormous variation in EMCs, equivalent with the variation in the comparable ATV database, (Fuchs et al., 2004); see also Salvia-Castellvi et al.(2005). Therefore, the mean and the 10 and 90 percentile values have been taken in order to assess the sensitivity of the results for the variation in EMCs found in literature. Figure 4 shows the relative contribution of the various sources of pollution to an urban pond receiving stormwater from a storm sewer for phosphate and zinc.
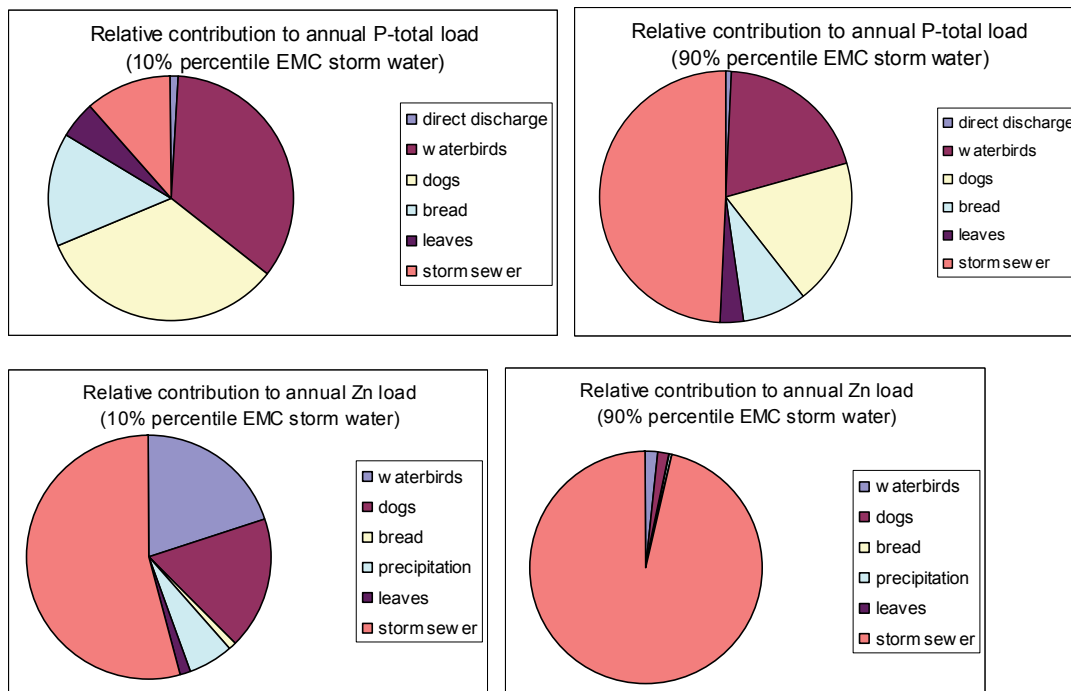
Figure 4. Relative contributions of the urban drainage system to the total load of phosphorus (upper charts) and Zinc (lower charts), depending of different concentrations in the STOWA storm water database

2.4 Assessing receiving water quality: integrated modeling

Since INTERURBA I (Lijklema et al., 1993) many researchers have developed integrated models for sewers systems, wwtps and receiving water bodies. Only a few (Bach et al., 2007) have incorporated diffuse pollution or pollution from other sources as well. In this project, the impact the total pollutant load to the receiving water quality has been assessed with relative simple and straightforward models.

2.4.1 Empirical phosphorus model

For the nutrients an empirical phosphorus model has been used (Hosper, 1997 and Meijer, 2000). It predicts the phosphorus concentration related to the load, retention time en depth. It makes it reasonably possible to predict if a water system is algae dominated and thus turbid or not. The predicted water quality is a mean stationary concentration; the model does not calculate peak concentrations. The model is based on data from many lakes and ponds in the Netherlands. In general, empirical models show a rather large dispersal in the results. Nonetheless, the model does give insight in the most important parameters that contribute to the mean phosphorus concentration, like residence time, depth and load.

2.4.2 First order removal model for nitrogen

For nitrogen, the loads are calculated into a mean concentration with the use of a simple stationary first order removal model. The overall removal rate is assumed to be 0,03 day^{-1}, representing the total removal of nitrogen by nitrification and denitrification. The sensitivity of the model for the chosen removal rate becomes larger with longer residence times. For systems with short residence times (like small urban water systems fed by large storm water sewers) the total load is more important than the

removal. Therefore, the results will be more reliable for such systems.

2.4.3   Complete mix model and TEWOR oxygen depletion model

With respect to BOD and coliforms it is estimated that the emissions are completely mixed in the urban pond. The subsequent oxygen depletion had been modeled with TEWOR, a model based on Streeter and Phelps (1925). The input of this model is the concentration of BOD after complete mixing of 50% the total load in the pond. The other 50% of the total load is assumed to sediment rapidly, not impacting short term oxygen demand.

2.4.4   Receiving water sediment quality model

An estimate of the sediment quality with respect to heavy metals is also based on a complete mixing approach. The concentration heavy metals and PAH in the sediment (expressed as µg/kg) is calculated by dividing the total load of pollutants by the total load of suspended solids. It is assumed that the suspended solids will equally disperse over the bottom surface. For small systems, like the urban pond, this is a valid assumption; for larger systems, like a polder, this approximation should not be applied.

2.5   Assessment methodology

The calculation results of the sensitivity analysis have been assessed graphically, see table 2. For each situation of water type and pollutant nine results were calculated: the combination of three concentrations for the pollutant from the waste water system and three loads for the same pollutant from the other sources. Each from the nine resulting water concentrations is referred to two values:

- the value for the maximum acceptable risk concentration (MAC)
- two times this value (2·MAC).

The result is colored green (below MAC), orange (between MAC and 2·MAC) or red (Above 2·MAC).

Urban pond: Concentration total N in surface water				
Norm (MAC): 2.2 mg/l		Annual load from other sources (kg/y)		
		17	48	78
Annual load from storm sewer (kg/y)	14	1.1	2.2	3.2
	20	1.3	2.4	3.4
	61	2.7	3.8	4.9

Table 2. Example of graphical water quality assessment

2.6 Calculate relative contribution of urban drainage system

The relative contribution of urban drainages systems is significant, if three conditions are met:

- There exists a water quality problem;
- The grade of the water quality problem is sensitive for variations in the EMCs;
- The water quality problem can be solved by measures in the urban drainage system.

After assessing the relative contribution of the urban drainage system, one is able to determine the possibility of solving water quality problems by measures in the urban drainage system. The effect of different measures is calculated, like treatment of runoff by lamella settlers or soil filters. (Langeveld *et al.*, 2008).

3   CASE ARNHEM MOLENBEKE

After developing the described method it was applied to a full scale pilot in Molenbeke, Arnhem, the Netherlands. In Molenbeke the urban drainage system and receiving water system has recently been retrofitted. Figure 3 shows the district Molenbeke in 2001 and 2009. The receiving waters in the district comprise two ponds and a creek, the Molenbeek.
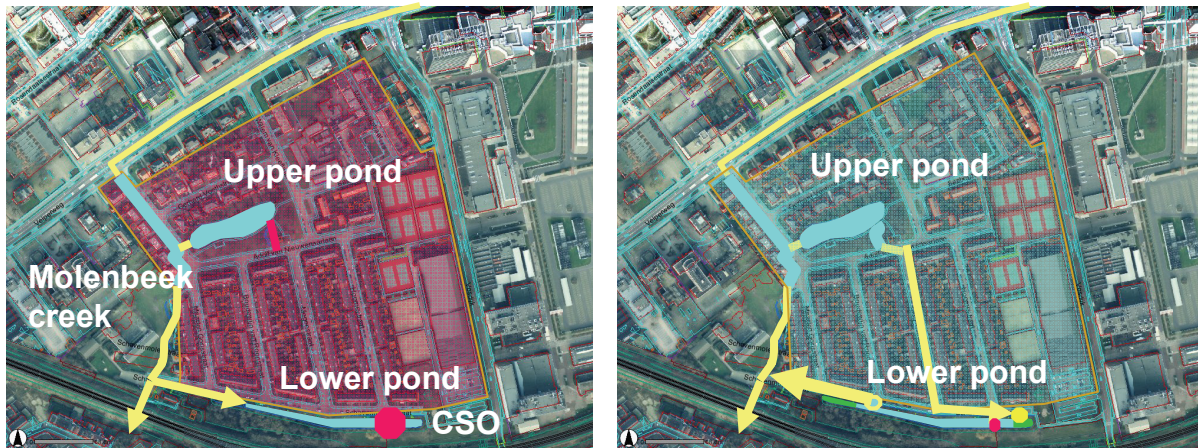
Figure 3. Molenbeke urban drainage and water system 2001 (left) and 2009 (right). Red area: combined sewer system; blue area: separated sewer system

In 2001, the urban drainage system was a combined system dating from 1930, with a CSO discharging to the lower pond, having a storage capacity of about 1600 m^3. The upper pond was flushed by the Molenbeek creek, discharging directly into the combined sewer. The main problems associated with the urban water system were:

- Old and defective combined sewer;

- Frequent CSO discharges to lower pond (right hand picture of figure 1), resulting in a very low receiving water quality with respect to eutrophication, oxygen depletion, hygienic parameters and sediment quality;

- Discharge of relatively clean water from the creek and pond into the combined sewer and subsequently to the wwtp.

In 2009, the district has been provided with storm sewers. The upper pond discharges into the storm sewer, which also connects the upstream and downstream pond. A pump in the lower pond manages the water level and discharges the surplus into the downstream Molenbeek creek. Two helophyte filters at both ends of the lower pond filter the discharge from the SSOs.

In addition, the following measures have been taken:

- The existing combined sewer was relined;

- The ponds were dredged (2002);

- Two helophyte filters were realized (2008);

- A dog walk location was constructed (2008);

- An anti-duck-feeding-campaign was held (2009).

Nonetheless, the chemical water quality of the downstream pond remained unsatisfactory with respect to nutrients. As the municipality had taken all realistic measures to improve receiving water quality, the assessment method described in this paper was used to determine the cause of the unsatisfactory situation with respect to the nutrient levels in the pond.

4 RESULTS AND DISCUSSION

4.1 Developed assessment methodology

4.1.1 Uncertainties in pollutant loads

For all pollutants, there appeared to be a high uncertainty in the calculated loads from the urban drainage system and from the other sources. For example, the average nitrogen concentration in storm water runoff in the STOWA storm water database is 1.7 mg/l, while the 10 and 90 percentile values are respectively 1.2 and 5.2 mg/l. Applied to the characterized urban pond, the nitrogen load

from the storm sewer varies depending of the concentration from 14 kg/year to 61 kg/year, as shown in table 2. The uncertainties in the loads from other sources are also quite large, for the urban pond mostly due to uncertainties in amounts of animals and feeding. The large uncertainties in yearly loads cause a broad range of resulting surface water quality, all equally realistic. As a consequence, without detailed additional information the nitrogen concentration in an average pond might vary between 0.5* MAC and 2.5 *MAC. This indicates that site specific knowledge of the EMC, also referred to as SMC (site mean concentration) is necessary to be able to assess receiving water quality and the impact of measures.

4.1.2   Assessment of total pollutant load versus receiving water impacts

In an emission based approach, measures are compared based on their impact on the total load discharged to the receiving waters. In an immission based approach, measures are judged by the impact on the receiving water quality. The difference between both approaches is illustrated in table 3. Table 3 shows that for the mean EMC derived from the STOWA database, the annual load of phosphorus to the pond from a 2 ha separated sewer system is with 3 kg P larger than the load from a 2 ha combined sewer system, with 1.9 kg P. Nonetheless, the resulting receiving water quality for the situation with a separated sewer system is much better, ranging from 0.12 to 0.62 mg P/l in the pond, depending on the loads from other sources. A comparable annual load of 2.9 kg from a combined sewer system results in a concentration of 0.63 to 3.40 mg P/l. The difference in impact on receiving water quality is easily explained by the retention time in the pond, which is significantly longer for the combined sewer situation. The retention time directly depends on the annual hydraulic load from the sewer system, being 600 mm/y via a SSO and 37 mm/y for a CSO. This causes the storm sewer to flush the pond much more than a combined system, which has a positive effect on the resulting Phosphorus concentration. Otherwise, the effect on the total N concentration is the opposite: longer residence times cause lower average concentrations as degradation of nitrogen simply takes time.

Urban pond: Concentration total P in surface water				
Standard (MAC): 0.15 mg/l		*Annual load from other sources (kg/y)*		
Annual load via SSO (kg/y)		*0.2*	*7.2*	*14*
	0.9 (10% percentile EMC)	0.04	0.3	0.5
	3.0 (average EMC)	0.1	0.4	0.6
	11.3 (90% percentile EMC)	0.4	0.7	0.9
Urban pond: Concentration total P in surface water				
Standard (MAC): 0.15 mg/l		*Annual load from other sources (kg/y)*		
Annual load via CSO (kg/y)		*0.2*	*7.2*	*14*
	1.3 (10% percentile EMC)	0.3	1.7	3.1
	1.9 (average EMC)	0.4	1.8	3.2
	2.9(90% percentile EMC)	0.6	2.0	3.4

Table 3. Total P: load and effect of separate system and combined system

4.1.3   Public health risks: hygienic reliability

Public health risks related to sewage and stormwater are mostly associated with exposure to bacteria and viruses. SSO discharges are assumed to be safe with respect to public health. The concentration levels of E.Coli in storm sewers are an order of magnitude lower than in combined sewers, but still range between 10^3 and 10^5/100 ml. This levels showed to be sufficient to increase E.coli levels in the urban pond above the 500 E.Coli/100ml of the EU bathing water standard for storm events with a return period of only 2 weeks. In other words, urban waters receiving SSO discharges are continuously hygienically unsafe. Avoiding direct contact with receiving waters is therefore advocated.

4.2   Results district Molenbeke Arnhem

Table 4 shows the nutrient levels measured in the Molenbeke pond before and after retrofitting. The MAC for phosphate was and is met, but the concentration of nitrogen after retrofitting is still 2·MAC.

In order to be able to identify the determining factor explaining the observed receiving water quality in

the Molenbeke pond, the receiving water quality was analyzed using the approach given in figure 1.

Measured concentrations	MAC	2001	2007
Total P (mg P/l)	0,15	0,1	0,1
Nitrate-N (mg N/l)		5	3,8
Total N (mg N/l)	2,2	6	4

Table 4. Receiving water quality Molenbeke pond (Vermonden and Velthorst, 2008)

For most pollutant sources, such as the SSO, local measured data was available, thus decreasing the confidence intervals. The number of ducks and dogs (in-)directly delivering excrements to the pond was counted in a field study. This site visit also revealed that the 'no duck feeding campaign' is not yet fully effective, see figure 4.
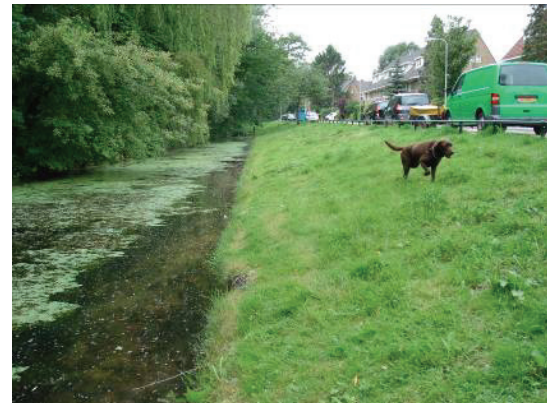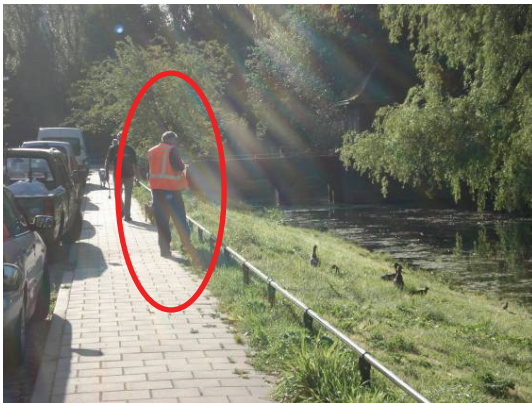

Figure 4. Molenbeke pond, May 2009. *Left*: The man in orange was feeding ducks a full plastic bag with bread
Right: the banks are still used as a dog toilet

The explanation for the too high nitrate and total N concentrations appeared to be the nitrate concentration in the Molenbeek creek. The creeks in the south Veluwe area, where the Molenbeek wells up, contain high nitrate concentrations due to decennia of enrichment from agriculture ammonia emissions. Figure 5 shows the nitrogen concentration in the pond to be quite sensitive to the concentration in the creek. With concentrations of 4 mg N/l and higher in the creek, the MAC-concentration in the pond is impossible to accomplish, which is in accordance to observed concentration levels.
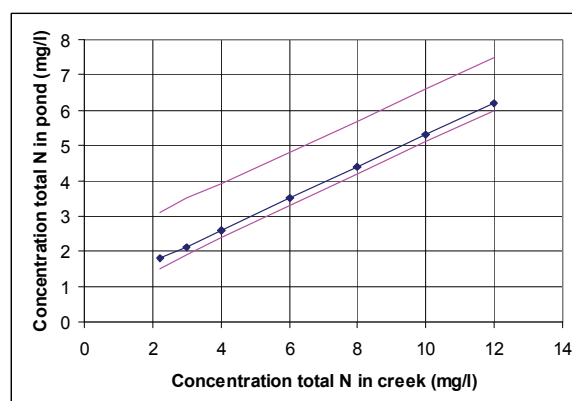

Figure 5. Calculated concentrations total N with respect to the concentration total N in the Molenbeek creek. Average values are shown with upper and lower boundaries.

5   CONCLUSION

5.1   Assessment of receiving water quality

The integral assessment of receiving waters revealed that the urban drainage system is only one of the determining factors with respect to receiving water quality problems. The morphology of the receiving waters and the non-sewer sources of pollution, such as waterbirds, dogs, or inflow of external surface water might be equally important. This conclusion underlines the necessity to changes today's emission based approach and adopt an integral and immission based approach.

In order to be able to fully benefit from the approach described in this paper, the lack of knowledge on the relation between EMCs and sewer system characteristics and the pollutant laoding of other sources needs to be addressed.

5.2   Case Molenbeke

The Molenbeke case showed that retrofitting sewer systems and receiving waters can significantly improve the receiving water quality. The case study also showed that external factors, in this case the background concentrations in the base flow of the creek, can still determine the resulting receiving water quality. This example illustrates the necessity of a fully integrated approach if all receiving water impacts are to be assessed.

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