Urban Water Journal, Vol. 3, No. 1, March 2006, 33 – 42

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Substance flow analysis of the wastewater collection and treatment system

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The holistic approach to water resources management introduced by the EU Water Framework Directive (WFD) implies the adoption of methodologies that are suitable to reveal the major pressures and impacts on the receiving waters at river basin level in an effective and efficient way. This study investigated the general adequacy of substance flow analysis (SFA) for the analysis of urban wastewater systems (urban catchment, sewer, WWTP, receiving water). The paper provides a description of the approach and a useful demonstration of the method through the illustration of a case study. The study considered the fluxes of six substances going to, through and from the wastewater management system. The results suggest that the proposed methodology can be used for the identification of stressors on the receiving water bodies and highlights that the scale dependency of results in such studies is of primary importance.

Keywords: Urban wastewater management; Spatial scale; Substance flow analysis; Systems analysis; Water Framework Directive

1. Introduction

The Water Framework Directive (CEC 2000) has introduced a crucial change in European policy on protection of water resources, shifting the focus from point source control of emissions to integrated pollution prevention and control at river basin level. Such an approach results in more freedom in basin management, which can lead on the one hand to a proper allocation of economic resources in pollution abatement, and introduces on the other hand complexity in the analysis.

In particular, in order to be able to prioritise interventions, the WFD explicitly requires the development of basin management plans, where the major pressures and impacts on the receiving water are revealed. An overview of the system behaviour can be produced by means of a systems analysis of the urban wastewater system (urban catchment, sewer, wastewater treatment plant and river).

The aim of this study is to illustrate a methodology to perform a thorough and wide-ranging systems analysis of the urban wastewater system. The authors recognise that urban environments may not always be regarded as the major sources of pollution (especially in developed countries, where agriculture plays a major role), nevertheless they still represent a powerful, flexible and responsive ‘control handle’ in river basin governance.

The outcome of the study will serve as a basis for the development of a decision support tool that gives assistance to the cost-effective development of urban wastewater systems for WFD compliance. The study is carried out within the scope of the EU project CD4WC (www.cd4wc.org) which is supported by the European Commission under the 5th Framework Programme.

A wide suite of tools are available to perform a systems analysis (Finnveden and Moberg 2001; Balkema *et al.* 2002). Substance flow analysis (SFA)—which consists of

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Urban Water Journal
ISSN 1573-062X print/ISSN 1744-9006 online
http://www.tandf.co.uk/journals
DOI: 10.1080/15730620600578694

accounting the flows of a substance to, through and from a system for a determined time period—combined with mass balances proved to be appropriate tools to highlight pressures on the environment, i.e., on the receiving water, and to pinpoint information gaps (Belevi 2002; Jeppsson and Hellström 2002).

The aim of SFA is to find out the most important emission and immission sources for the (group of) substance(s) under study. It enables policy makers to trace the origin of pollution problems and to assess management practices. While SFA has limited value for priority-setting and follow-up (Danius and Burström 2001), it is a useful tool for screening purposes, i.e., to identify critical areas that deserve further investigation (Lampert and Brunner 1999; Larsen 1999; Lindqvist-Östblom *et al.* 2001).

As a complement to SFA, the evaluation of a list of indicators helped to characterise the behaviour of sewers and WWTPs in environmental and economic terms. However, such results (Benedetti *et al.* 2006) are not shown in this paper; only SFA and mass balances are discussed here.

The Nete river basin in Flanders (Belgium) was chosen as a case study. This basin is named after its main river, a tributary of the Schelde, and it is composed of 29 sewer catchments.

2. Methodology

Within the wide set of components being part of the water cycle or interacting with it, only elements concerning the urban wastewater system are taken into account. Among this sub-set, the studied processes are the ones related to technical structures on which a water utility can act to improve the receiving water quality (sewer system and treatment plant), including actions on the receiving water itself. All possible interactions are to be considered between the elements included in such system analysis. The other compartments are assumed as flux sources or sinks, so only the interactions with processes in the system need to be taken into account. These compartments are described in table 1, and should be considered to define the boundary conditions.

The water supply system can be excluded from the study provided the concerning information (quantity of water used and entering the wastewater system) is contained in the information associated to water consumers, i.e., households and industry. Water reuse is in general of great importance in river basin studies, both for the positive environmental impact and for the reduction of water resources needs, but it is not included here because it is of no relevance for the under case study.

The methodology used implies as a first indispensable step a comprehensive collection of data and general information from wastewater operators, environmental agencies and authorities.

The major evaluation instruments adopted in this study are described below.

2.1 *Pollutants: BOD, COD, TN, TP, Zn*

They are considered as the most important pollutants for which data are commonly available, indicative of organic pollution with oxygen depletion and CO_2 emission (BOD and COD), of eutrophication potential in the receiving water (TN and TP), and of toxic contamination (Zn). Zinc was selected among other heavy metals since its loads in the case study basin are much higher than for the others, and it is the only one which has a concentration almost always above the detection limit, also in the effluent of WWTPs. Other substances like xenobiotics, endocrine disruptors, etc., are relevant to assess the state of an urban river catchment, and they can be analysed applying the tools presented in this paper.

2.2 *Sewer mass balances for water, BOD, COD, TN, TP, Zn*

They are calculated as the substance flow coming out of the sewer minus the flow entering the sewer, all divided by the inflow. Such mass balances are not likely to be closed due to the data-poor conditions, but they give indications on the quality of measurements and estimations, and can suggest the presence of unconsidered substance flows.

Table 1. Compartments outside the system defining the boundary conditions.

Compartment	Description
Atmosphere	It provides rain to the system, and receives gases and energy (heat losses).
Households	They introduce water, nutrients and pollutants.
Industry	It introduces water, nutrients and pollutants.
Agriculture	It is a source of nutrients and pollutants (e.g., pesticides).
Groundwater	It exchanges water and other substances with several system elements.
Surface water	It receives the output of the receiving water; it can be another river stretch, a lake or reservoir, coastal water, transitional water.
System administration	It exchanges energy and money with the requiring processes.
Residuals disposal	Sink for any other outflow from the system, e.g., sludge.

2.3 *Discharges in the receiving water by industries, households, sewers, WWTPs and agriculture*

It highlights which are the main stressors on receiving water bodies and their relative pressure on them. A ranking of intervention priorities can be made at basin scale to tackle problems more efficiently.

2.4 *Parasite water entering the sewer*

Mainly function of the sewer network age and materials, parasite water negatively affects treatment performance by dilution and hydraulic overloading. It can also reveal the presence of possible exfiltration, cause of sanitary risk of groundwater contamination.

2.5 *Stormwater discharged in the receiving water*

It is a direct pollutant discharged in the receiving water body from combined sewage and surface wash-out, entailing hydraulic stress as well.

3. Case study

The Nete river basin (1,673 km^2, 595,823 inhabitants), located in the eastern part of Flanders (Belgium) is the basin with the largest data set available in Flanders, due to specific studies regularly performed by VMM, the Flemish Environmental Agency (VMM 2001). The topography of the basin is distinctively flat. The basin is characterised by the presence of extensive agriculture and farming, and scattered urbanisation with some small towns.

The basin is constituted by 29 sewer catchments. The wastewater system (WWTPs and main connectors of sewer networks) is operated by Aquafin, which was founded by the Flemish Government in 1990 as the licence holder for the sewage treatment infrastructure in Flanders. The sewer networks from the households to the main connectors are managed by the municipalities. The design capacities of the WWTPs are summarised in figure 1.

Substance flows and mass balances were calculated on a yearly basis for the year 2002, which was a rather wet year in Flanders (1006 mm, while the average precipitation is around 750 mm/year) but did not lead to any flooding or malfunctioning of technical infrastructures.

Measured water flows in the system were available for the WWTPs influents (daily), at the closing section of the river basin (hourly) and for the effluents of monitored industries (periodically).

Water from households was estimated knowing the number of inhabitants and assigning a *per capita* water use (VMM 2001).

A fraction of the rainfall from atmosphere—the yearly rainfall in the basin was available, as an average of 11 measurement stations—was assumed to end directly in the receiving water body; another fraction, function of the impervious area in the basin, was routed through the sewer system (stormwater); the remaining rainfall was considered as draining to the water table or partly evaporating.

Parasite water was calculated by subtracting water flows from households and industries from the dry weather flow

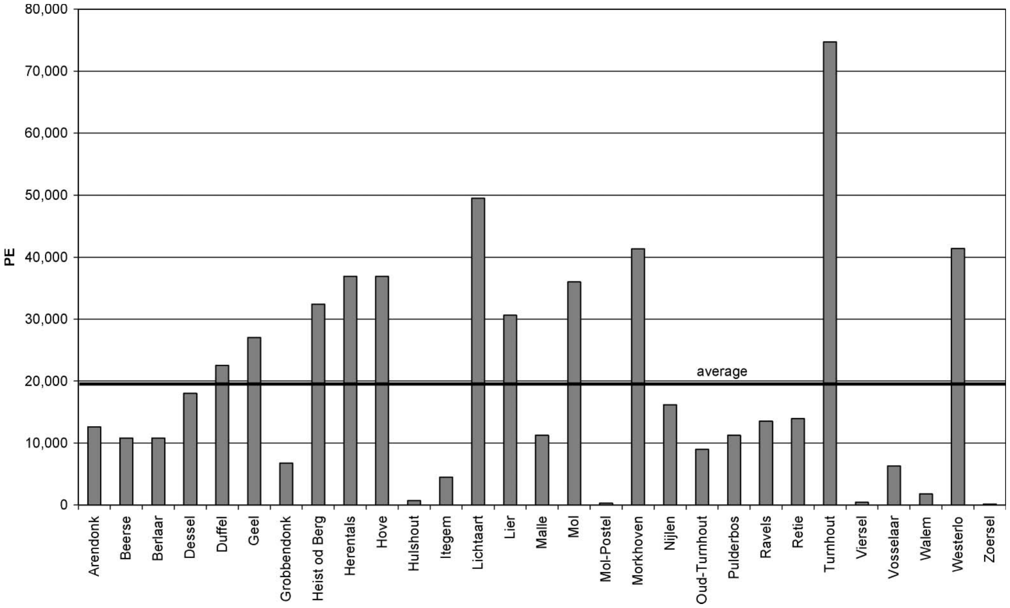

Figure 1. Design PE of WWTPs, on the basis of 54 gBODinh^{-1} d^{-1}.

entering the WWTP. The dry weather flow for each day of the year was calculated as the minimum of the daily inflows within a range of 10 days before and 10 days after that day (in total 21 days), and it expresses the flow without rainwater, with the assumption that at least one day of 21 is a dry day (Jardin 2003).

The water flow discharged directly into the receiving water body (CSO) was calculated as the total stormwater entering the sewer network minus the amount of stormwater treated in WWTPs. The flow of treated stormwater is the total water flow entering WWTPs minus the dry weather flow (Jardin 2003).

No pollutant loads have been estimated for stormwater since no data are available on this for the Nete basin, and any estimation would have entailed unacceptably large uncertainties. Only the zinc content of stormwater coming from roofs and gutters washing has been calculated according to Sörme and Langerkvist (2002).

Pollutant loads from households were estimated from the number of inhabitants and from the assigned daily substance release (table 2), which also includes grey water (VMM 2001).

The TN and TP loads from agriculture were obtained from data concerning manure application and the modelling of nutrients release (VMM 2001). No data exist on agricultural release of BOD and COD.

Pollutant loads from WWTPs and industries were calculated from water flow and pollutant concentration measurements available approximately every 10 days.

4. Results

Mass balances and flows of substances were calculated for each sewer catchment. The analysis at basin level is based on the figures obtained for the individual sewer catchments, except for the data of TN and TP release from agriculture, that were available at basin level only.

Referring to the evaluation instruments mentioned in the methodology section, the following results have been obtained.

4.1 *Water and pollutants (BOD, COD, TN, TP, Zn)*

Sankey diagrams (figures 2 to 7) show the substance flows of the substances entering, leaving and circulating in the system, by means of arrows whose thickness are proportional to the flows.

The substance flowing downstream was calculated for water only (figure 2), due to the absence of water quality measurements in the closing section of the river.

From figures 2–7, it can be seen that some BOD is removed in the sewer and that in the WWTP almost all the entering BOD is treated, while for COD the removal reaches a lesser extent. Concerning nutrients, most TN entering the system ends in the receiving water (~78%), while more than half of the TP entering the system is eliminated by the WWTP (~60%). The nutrient removal performance of the WWTPs is high because all of the plants >10.000PE are equipped with N and P removal and most of the plants with <10.000PE also have P removal.

4.2 *Sewer mass balances for water, BOD, COD, TN, TP, Zn*

Gaps in mass balances ((out-in)/in) were only calculated for the sewer network, with households and industry as inputs (rainfall and parasite water were also considered for the water balance) and WWTP and receiving water as outputs. Figure 8 shows the gaps in the sewer mass balance for the whole Nete basin for the substances taken into account. The chart shows that, e.g., for water, the flow measured at the outflow of the sewer system is 6% larger than the water flow estimated to enter the sewer system.

4.3 *Discharges in receiving water by industries, households, sewers, WWTPs and agriculture*

Concerning pressures directly impacting on the receiving water, figure 9 shows the relative contributions of the different substance loads discharged in the Nete.

4.4 *Parasite water entering the sewer*

Parasite water (figure 10) was calculated by subtracting water flows from households (assuming values in table 2) and industries from the dry weather flow entering the WWTP. Except in a few cases, most urban catchments show values relatively close to the average (~44%), which is in the expected range of values for the sewer network condition and topography. Note that for the smaller catchments (like Mol-Postel, Hulshout, etc.) small errors in the data can lead to great errors in the calculations.

Table 2. Production of substances per inhabitant per day, including grey water (VMM 2001).

Water	COD	BOD	TN	TP	Zn
112 $L \cdot inh^{-1} \cdot d^{-1}$	94 $g \cdot inh^{-1} \cdot d^{-1}$	44 $g \cdot inh^{-1} \cdot d^{-1}$	10 $g \cdot inh^{-1} \cdot d^{-1}$	1.7 $g \cdot inh^{-1} \cdot d^{-1}$	30.7 $mg \cdot inh^{-1} \cdot d^{-1}$

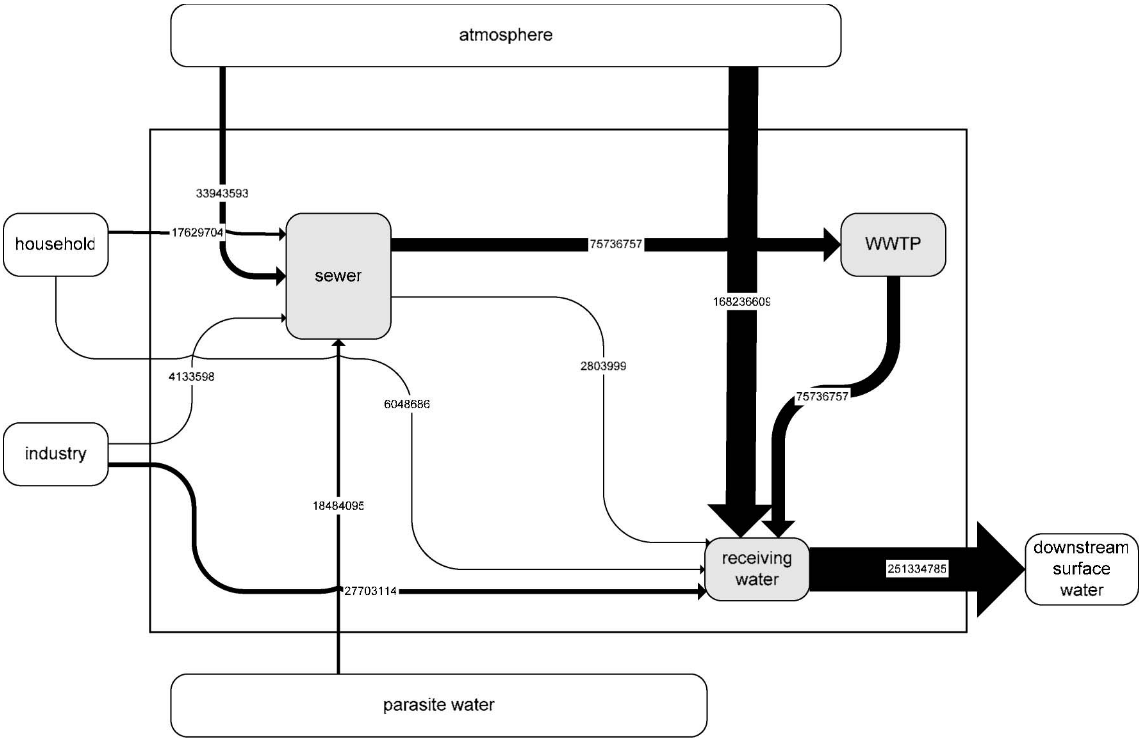

Figure 2. Sankey diagram—Nete basin—water [m^3/y].

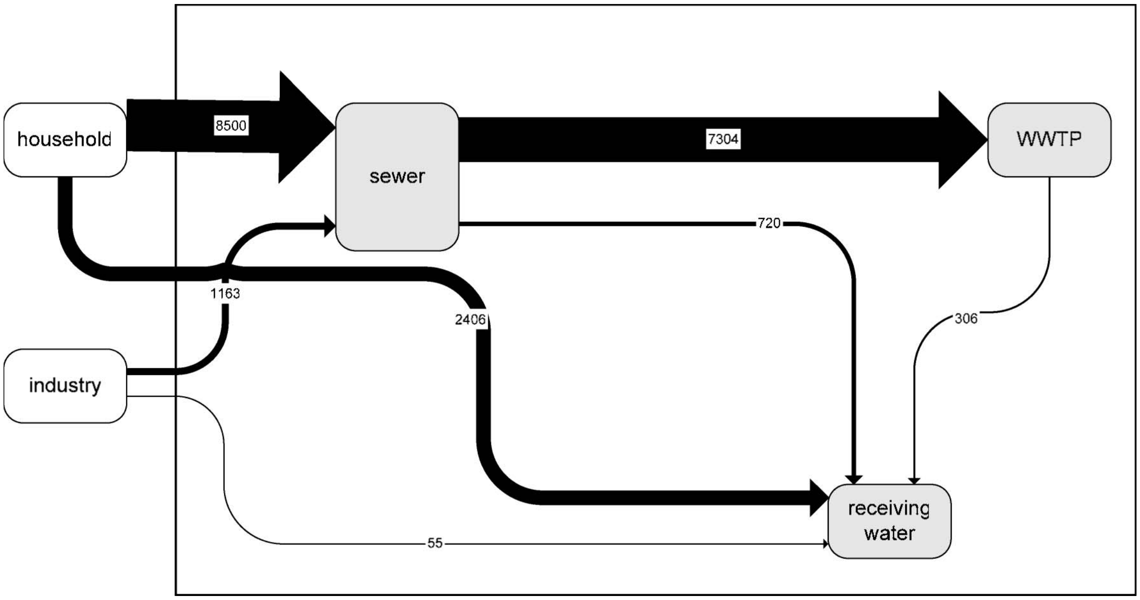

Figure 3. Sankey diagram—Nete basin—BOD [ton/y].

4.5 *Stormwater discharged in the receiving water*

The calculated water flows directly discharged into the receiving water body via CSOs (figure 11) show a large variance.

5. Discussion

Combining the information obtained from substance flow calculations and from mass balances with information provided by Aquafin, the following conclusions can be drawn:

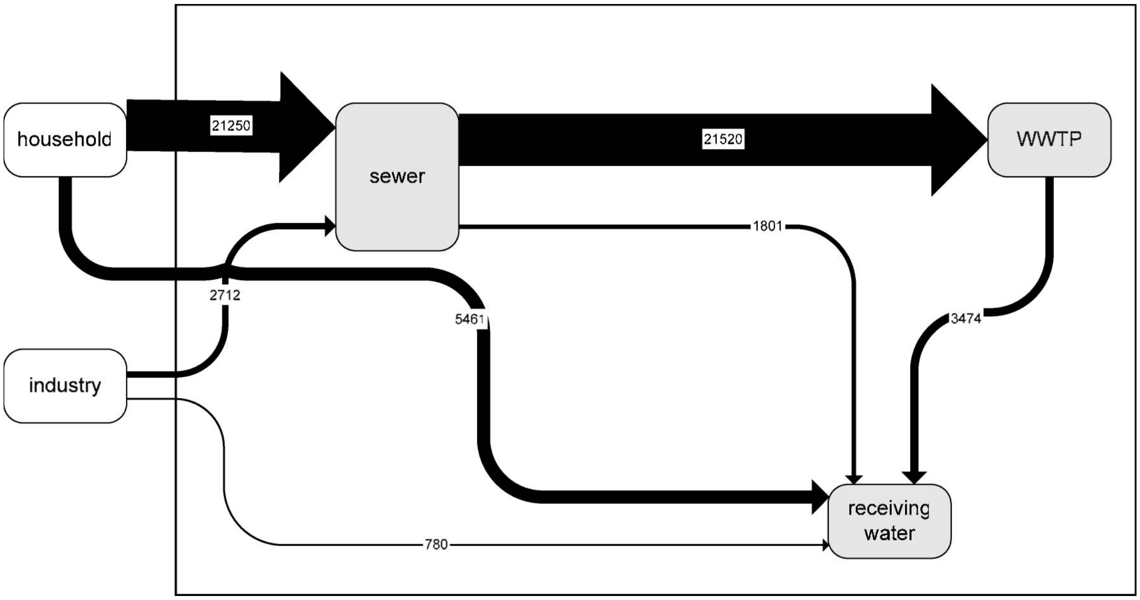

Figure 4. Sankey diagram—Nete basin—COD [ton/y].

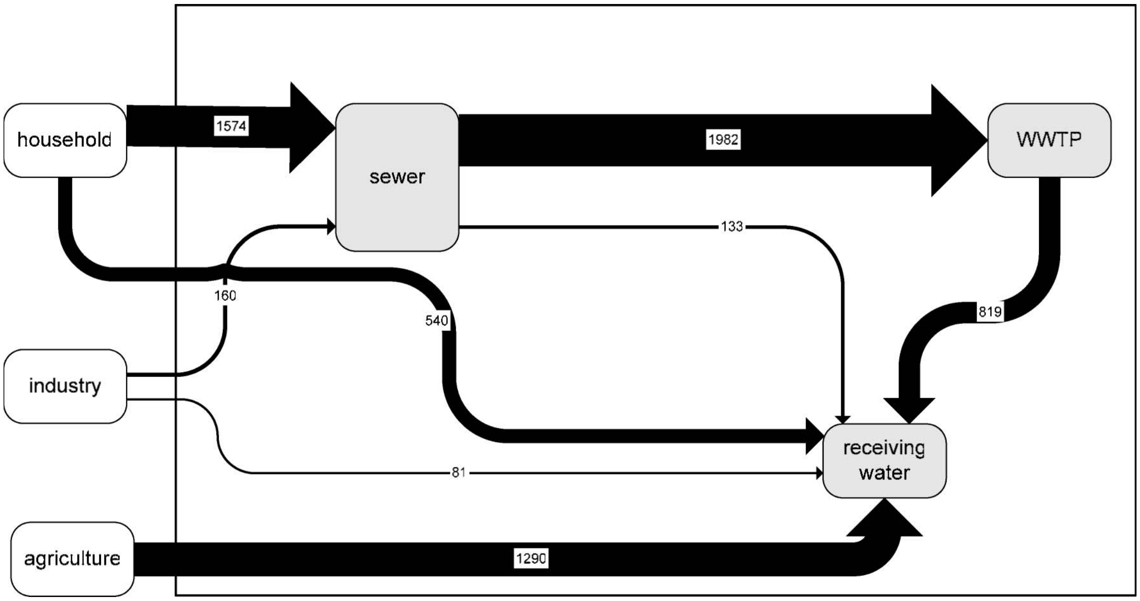

Figure 5. Sankey diagram—Nete basin—TN [ton/y].

Water (figures 2 and 8)—In the Nete basin the groundwater table is rather high (causing infiltration) and several ditches are connected to the sewer system, contributing to loads of parasite water (figure 10) and of pollutants, especially in rural areas. Furthermore, some CSO outlets are sometimes letting river water in the sewer system, for lack of flap valves and high water levels in river and ditches.

Pollutants—The mass balances of TN (+22%) and TP (+25%), as shown in figures 5, 6 and 8, suggest that the unaccounted ditches connected to the sewer network introduce significant loads from agriculture, to which BOD and COD loads should also be associated. This, together with the mass balances for BOD (−17%) and COD (−3%) shown in figures 3, 4 and 8, leads to the conclusion that organic pollution is degraded in the sewer. As expected, BOD is removed to a larger extent than COD. Concerning zinc (see figures 7 and 8) the main zinc sewer inflow that are not taken into account are probably the zinc content of stormwater (only the contribution

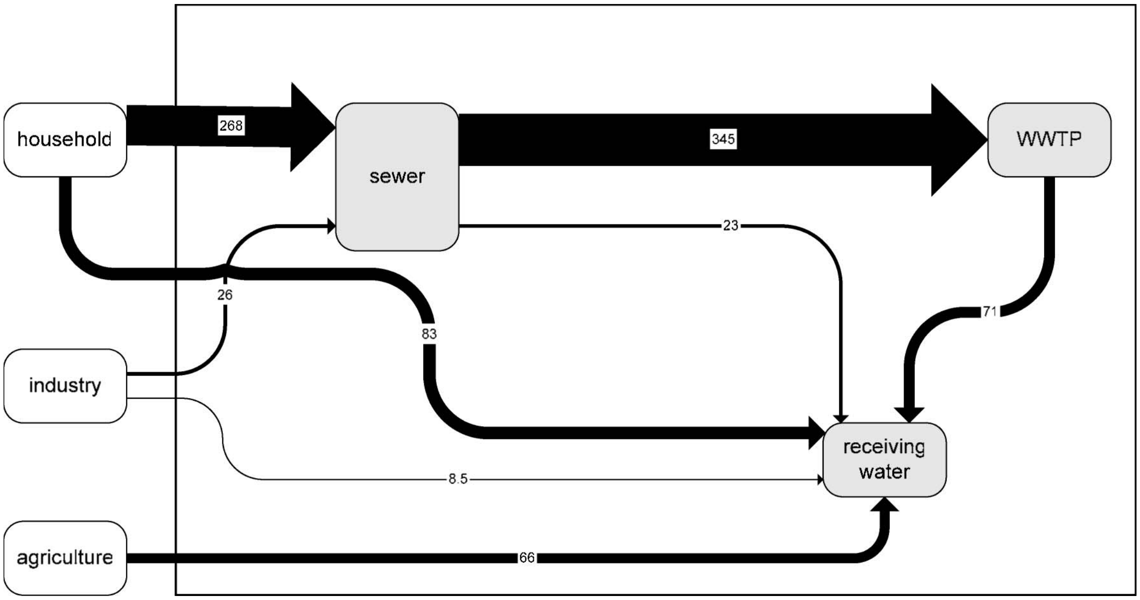

Figure 6. Sankey diagram—Nete basin—TP [ton/y].

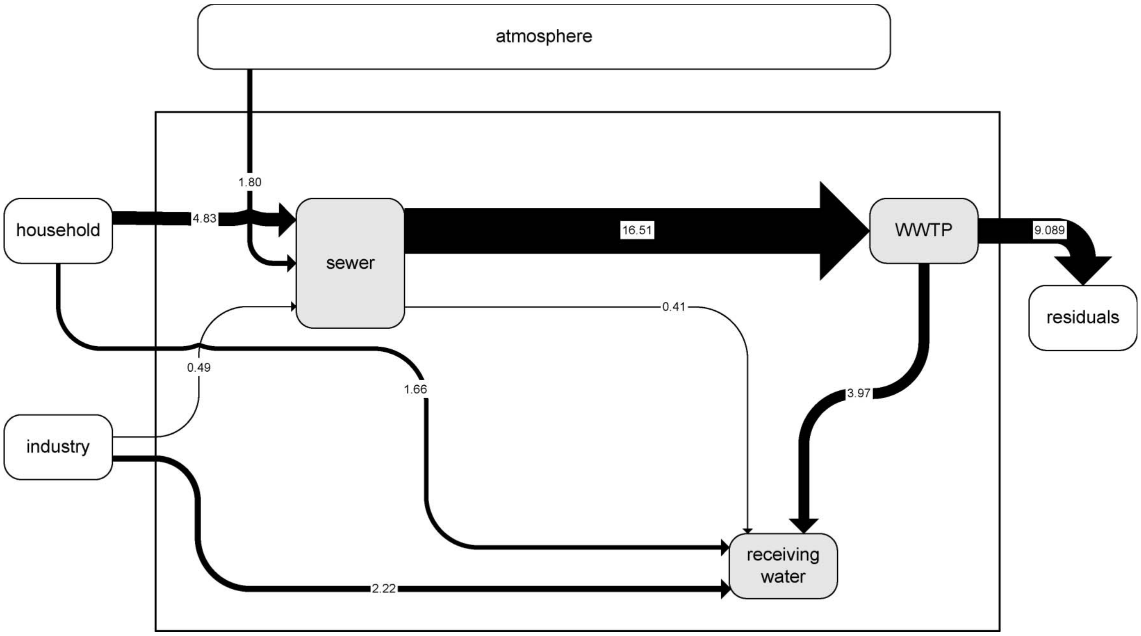

Figure 7. Sankey diagram—Nete basin—Zn [ton/y].

coming from roof wash-off was considered in the balance) and of tap water (Davis *et al.* 2001; Sörme and Langerkvist 2002); this leads to a 138% gap in the zinc mass balance.

From figure 9, it appears that untreated wastewater from households is the main stressor for acute oxygen depletion (BOD, 89% of load) for delayed oxygen demand (COD, 63%) and for eutrophication (TP, 43% and TN, 24%). Agriculture also has a relevant impact on eutrophication (TN, 44% and TP, 26%); no data were available on BOD and COD loads. WWTPs contribute substantially to all loads but are in no case the main stressor; they are for zinc, but only apparently because zinc contained in stormwater is significantly underestimated.

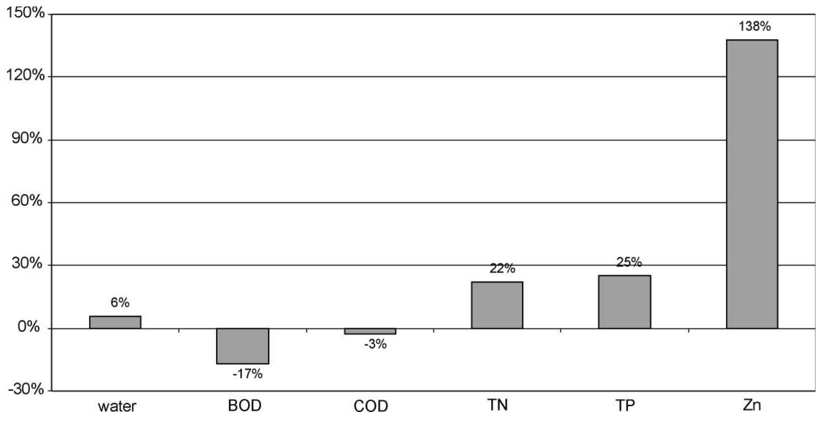

Figure 8. Gaps in the sewer mass balances—Nete basin.

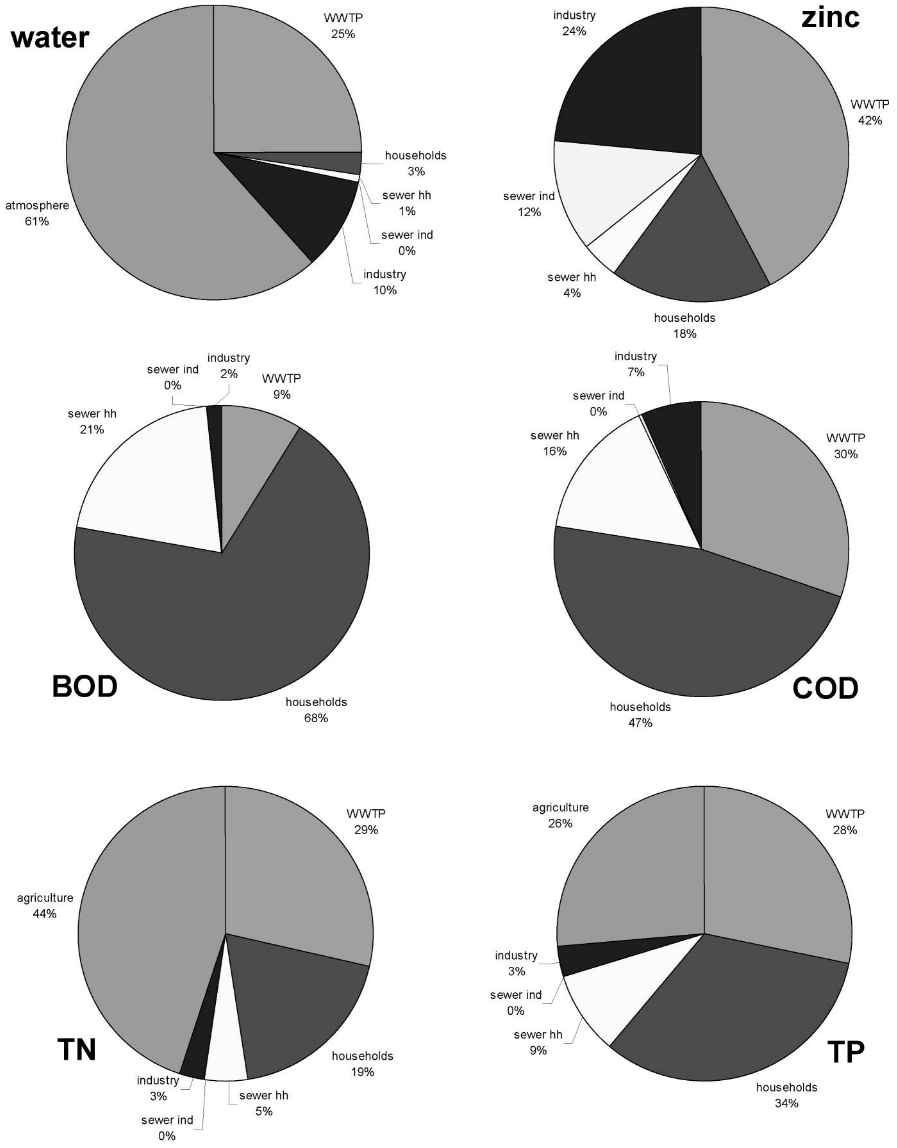

Figure 9. Relative loads into the Nete river—‘sewer ind’ and ‘sewer hh’ indicate the loads discharged in the receiving water via the sewer network by industry and household respectively; the other loads are directly discharged in the receiving water.

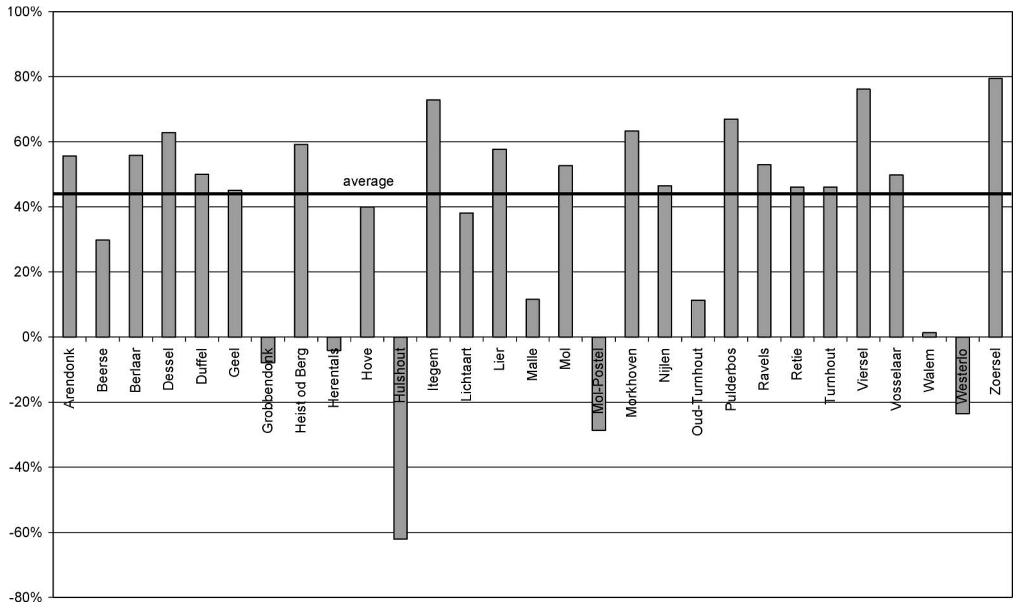

Figure 10. Percentage of parasite water.

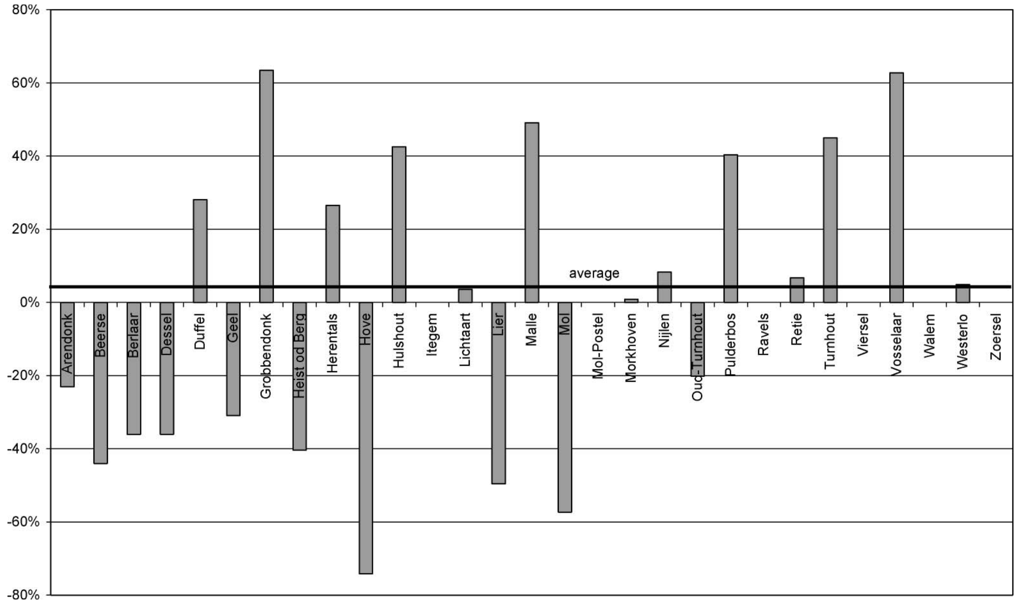

Figure 11. Percentage of estimated CSOs (relative to the total stormwater entering the sewer) for the 29 Nete catchments.

Concerning the calculated water flows directly discharged into the receiving water body via CSOs (figure 11), negative figures possibly indicate stormwater entering the sewer system via CSO due to a combination of a high water level in the river (higher than the sewer water level) and a lack of flap valve. However, the average value of 4% (relative to the total stormwater entering the sewer) for the whole Nete basin is well in the range of percentages found in literature (Schlütter and Mark 2003). The same behaviour—i.e., large variance for individual basins, but average in agreement with literature—was found for sewer mass balances.

This underlines an important aspect in this type of study: the spatial scale chosen. For large areas like a river basin, results are likely to fall in the narrow range of results found in similar studies, since several different contributions compensate each other, producing an average typical for a certain kind of large area. However, for small catchment areas with sewer catchments of small WWTPs, local boundary conditions and uncertainties play a major role and results vary to a large extent in seemingly similar areas.

It is expected that also the temporal scale of such studies has a similar influence on the results, with short periods showing high variability and long periods producing results closer to typical values.

6. Conclusions

A river basin system including fluxes running through such a system is described and illustrated; boundaries and interfaces are outlined. Through SFA, critical points in the system could be identified and can serve as indication for further, more detailed analysis.

In the investigated river basin, the main critical point for BOD and COD is the untreated wastewater from households, total nitrogen is mainly affected by agriculture and all the stressors (i.e. households, industries, WWTPs, agriculture) have a comparable importance concerning total phosphorus.

With regard to heavy metals (in this case zinc), the study indicates that it is difficult to obtain reliable substance flows, since the measurement of heavy metals in the influent and effluent of WWTPs is limited to 12 (randomly chosen) 24-hour composite samples a year and no water quality measurements are taken from combined sewer overflows.

The study highlighted the importance of the spatial scale selection. Values of some indicators at individual urban catchment scale show a large variance (e.g., mass balances, CSOs) but the average value for the whole river basin is well in the range of values found in literature. For large regions like a river basin, results are likely to fall in the range of results found in similar studies, but with small areas local factors and uncertainties play a major role. It cannot be overemphasized that the availability and accuracy of data play a crucial role in the analysis; therefore it is necessary to carry out an uncertainty analysis to provide a better picture to the decision-makers, and possibly give indications on the required adaptation of the existing monitoring programme.

Acknowledgements

The results presented in this publication have been elaborated in the frame of the EU project CD4WC, contract no EVK1-CT-2002-00118. The programme is organised within the Energy, Environment and Sustainable Development Programme in the 5th Framework Programme for Science Research and Technological Development of the European Commission. Peter A. Vanrolleghem is Canada Research Chair in Water Quality Modelling.

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