Cost-effective development of urban wastewater systems for Water Framework Directive compliance – the CD4WC EU project

Lorenzo Benedetti*, Peter Krebs** and Peter A. Vanrolleghem*

**BIOMATH, Ghent University, Coupure Links 653, B-9000 Gent (Belgium)*

***Institute for Urban Water Management, Dresden University of Technology, D-01062 Dresden, Germany*

Abstract

This paper will introduce the CD4WC project and its first results after approximately 1.5 years from its beginning.

The project CD4WC deals with optimising the efficiency of the urban wastewater system. Various optimisation measures are investigated with regard to ecological consequences in natural water bodies and in regard with investment and operational costs.

The variety of possible systems approaches, operating strategies and management options will increase due to the implementation of the European Water Framework Directive. CD4WC aims to systematically identify ecological and economic synergy potential by making use of the degrees of freedom offered by the WFD philosophy. The various options investigated to induce potential benefits are:

- extensions and development of the sewer system;
- systems choice and possible extensions of the WWTP;
- measures in the receiving water to enhance morphology and self purification;
- source control measures;
- optimisation of the operation of present and of developed systems e.g. by RTC;
- systems integration considering and optimising the interactions between the subsystems;
- application of management tools including the evaluation of economic driving forces.

CD4WC further aims to evaluate the resulting cost savings and to put them into relation with additional costs originating from management and monitoring requirements required by the WFD, in order to achieve realistic cost estimation.

The main expected results of the project are:

- a list of options to extend the wastewater system and improve its performance;
- an evaluation of these options with regard to ecological consequences and investment/operation costs;
- quantification of cost savings due to increased degrees of freedom induced by the WFD approach; e.g. application of effective control measures as opposed to structural system extensions.

The project group is put together of four university research teams (TU Dresden, Ghent University, Innsbruck University, Panteion University of Athens) and of four companies operating wastewater systems (Ruhrverband, Aquafin, TIWAG, PVK Prague), supporting the project with their experience, their data and serve as “on-line users and testers” of the findings.

CD4WC is part of the CityNet project cluster.

Introduction

The project CD4WC deals with optimising the efficiency of the urban wastewater system with regard to ecological consequences in natural water bodies and with regard to investment and operation costs. The need to solve this problem is a direct consequence of the European Water Framework Directive (WFD) which requests to achieve good quality for ground and surface waters on a river-basin scale. With this new water-quality based approach, the design of the systems is by far less predetermined and the options to meet the goals become much more widespread. CD4WC will give guidance and support for this optimisation to operators, inasmuch the potential to improve the systems performance is identified while the cost-benefit ratio ought to be increased.

In CD4WC the benefits for the development of the urban wastewater system resulting from the WFD approach will be identified and quantified with regard to its ecological and economic consequences. Criteria to assess the ecological consequences are – besides the water quality – also secondary resources inputs such as energy, materials and chemicals.

Various options and strategies to develop the wastewater system are evaluated. Main emphasis is put on the dynamic interactions between the subsystems sewer system, WWTP and receiving water as well as on the possibilities of taking measures in the receiving water and at the sources.

The methods applied are analysis of river basin managers data to gain insight in experience, the performance of measurement campaigns to close information gaps, numerical modelling to assess systems changes and extensions, and economic balancing to evaluate alternative pollution control instruments, such as permits, fees and pollution trading.

Overview of the project

The problem

The European Water Framework Directive (WFD) requests to achieve good quality for ground and surface waters by organising water management on a river-basin scale and – with regard to impacts on natural water bodies originating from wastewater release – applying a combined emission and water-quality based approach. Managers and operators of wastewater systems on a regional scale *claim* that the approach requested by WFD will require additional authorities, management structures to be reorganised, and an improved performance of the wastewater system such that enormous investments will be necessary to meet the goals.

So far, it was not yet evaluated and quantified what potential benefits could result from the WFD approach, which is setting water-quality goals in the natural water bodies instead of prescribing the design of urban wastewater systems. With this new water-quality based approach, the design of the systems is by far less predetermined and the options to meet the goals become much more widespread. Also, interactions between the subsystems *sewer system*, *wastewater treatment plant* (WWTP) and *receiving water* as well as between different measures, such as source control or increase of the WWTP loading during wet-weather conditions, may result in synergy effects. The economic benefit from these synergy effects must be balanced against the additional costs resulting from the implementation of the WFD (as claimed by river-basin managers) in order to be able to quantify the consequences reliably.

Expected results

In the project, knowledge will be gained that serves both the scientific community as well as the water managers in Europe. The following results can be expected:

- a list of options to extend the wastewater system and improve its performance, among others namely the options resulting from integrated system operation;
- an evaluation of these options with regard to ecological consequences in order to found a basis for comparing various options;
- evaluation and comparison of the options with regard to investment and operation costs;
- quantification of cost savings due to increased degrees of freedom induced by the WFD approach of setting the goals in the receiving waters as opposed to the system extension that would conventionally be implemented by strictly following design guidelines.

Scientific knowledge is gained with regard to:

- the coupling of models of the subsystems sewer system, WWTP and receiving water as well as the description of the interfaces and the interactions across these interfaces;
- the quantification of loads to the receiving water caused by the various options of systems development; these loads are interpreted as indicators for ecological impacts.

The practice of European water management will profit from the results of the project CD4WC in the sense that:

- a basis for decision making is provided to improve the wastewater management;
- the efficiency of urban-water quality management can be improved and the associated cost/benefit ratio can be enhanced;
- not only technical aspects are evaluated but also the potential of economic tools to influence the system and the water management;
- a guidance on how to efficiently develop the wastewater system will be provided on a CD.

The innovation potential of the CD4WC project is to be seen against the background of the Water Framework Directive (WFD) and the problem of operators on how to develop and extend wastewater systems with an average lifetime expectancy of roughly 30 years (WWTP) to 80 years (sewer system). The innovative approach of the project is:

- to link the WFD approach with the needs of operators;
- to give guidance to develop the wastewater system from an integrated viewpoint;
- to assess the benefits of a wide range of extension strategies with regard to ecological and economic criteria;
- to link economic driving instruments with development scenarios.

Present estimations of the costs caused by the implementation of the WFD suffer from the assumptions that the new aspects and increased requirements introduced by WFD are added on top of the present activities of the operators and do hardly induce a positive feed back. While the additional costs have been already relatively well estimated it was hardly discussed so far whether the new approach to set the goals – that is to aim at maintaining good water quality in the natural compartments instead of installing the wastewater systems according to the characteristics of the urban catchment – may also result in cost savings. Following the new approach, the possible options of measures to reach a certain goal or to improve the water quality, respectively, are numerous indeed, whereas they are much more restricted when the system is extended according to conventional guidelines.

CD4WC aims to systematically identify ecological and economic synergy potential by making use of the degrees of freedom offered by the WFD philosophy, and evaluate the resulting cost savings and to put them into relation with additional costs originating from management and monitoring requirements required by the WFD, in order to achieve a realistic cost estimation.

For the evaluation of the development strategies, it is crucial to recognise that measures required by today’s guidelines are replaced by the investigated options and are therefore not causing costs any more, e.g. by increasing the combined water flow to the WWTP the increase of combined water retention volume is not necessary any more. Identifying cost savings in the CD4WC project means to counterbalance the capitalised investment and operation costs of the new options, which become possible due to the openness of the WFD, against the costs of the “classical approach”.

This outcome will support decision making of wastewater system operators and river basin managers. They are provided with various options to reach good water quality, evaluated with regard to ecological and economic consequences in view of an optimal development.

The project group is put together of four university research teams from middle and southern Europe and of four companies operating wastewater systems on a city or on a regional scale situated in middle and central (eastern) Europe. The latter are end users on the one hand, but are actively contributing to the project with their experience, their data and as “on-line users and testers” of the findings on the other hand. It is of vital importance to analyse existing data available from operating companies and to continuously include their feedback into the project development.

Numerical modelling

By means of numerical modelling the performance of systems changes and extensions can be assessed, which is an absolute need in the project. Models will be calibrated carefully in order to estimate the uncertainty associated with specific processes and to evaluate its sensitivity and reliability. Special attention has to be paid to the model selection, since it is crucial that the models are able to reflect all the processes considered decisive for certain options. In the project, models are to be applied which are able to represent the integrated wastewater system including the sewer system, the WWTP and the receiving water.

Appropriate model selection will include simplification of certain model parts in order to improve simulation efficiency. Since so-called integrated models described in publications are often not really able to deal with both-way interactions across interfaces between the subsystems, some model development may be necessary within the project.

Balancing the economic consequences

Using policy instruments in an economically effective way is a pre-requisite for the implementation of the water framework directive. Different instruments are more appropriate in different contexts. Performing a multi-dimensional evaluation of alternative pollution control instruments (permits, fees and direct regulation) in a case-study context and producing a standard methodology for the selection of the most effective combination of instruments in any context, is a very important task.

Overview on workpackages

The options where measures can be taken relate to the workpackages 2 to 8. Systems analysis carried out in workpackage 1 is necessary to prepare for most of the other workpackages. Synthesis of the deliverables from workpackages 2 to 8 is performed in workpackage 9 and concludes on potential synergy effects in the wastewater system.

WP1 Systems Analysis – Systems analysis of the integrated wastewater system primarily focuses on the relative potential and significance of impacts to the receiving water, originating from the various “outlets” of the wastewater system.

WP2 Sewer – Measures in the sewer system such as combined water retention tanks, combined or separate systems, and indicators for assessment on whether a sewer system may be an economic solution at all (e.g. meters of sewer per capita) are evaluated.

WP3 WWTP – Measures concerning the WWTP system and extension are investigated with regard to compounds removal efficiency and costs.

WP4 Receiving Water – The consequences of measures in the receiving water are analysed. Options are for example to improve the morphology and shading, to enhance aeration or to increase the base flow.

WP5 Source Control – Source control measures are investigated: to prevent pollutants and nutrients from entering the wastewater system, use and infiltration of stormwater, wastewater design based on the storage of urine, industrial wastewater and the sewage from separate systems.

WP6 Operation – Optimisation of the operation of individual subsystems is evaluated. Options are the application of real-time control (RTC) in the sewer system and in the WWTP, and “managing” the sewer sediments, i.e. prevent their build-up or remove them by flushing or mechanically.

WP7 Integration – Measures and subsystems are integrated across the interfaces of the subsystems. Examples are: increasing the loading of the WWTP during wet-weather conditions based on the dynamics in the sewer system, optimisation of the storage management for minimum receiving-water impact, or integrated RTC, i.e. sensoring in the WWTP or in the receiving water and take control actions “upstream” in the sewer system.

WP8 Economics – Comparison of alternative policy instruments, namely permits, charges and direct regulation, for the control of pollution at a river basin scale. Multi-dimensional evaluation of the different dimensions of the various instruments (administrative cost, adaptability to local user conditions, monitoring cost, etc).

WP9 Synthesis – A synthesis on the interactions and synergy potential between the above mentioned options and – most important – a cost-benefit analysis must follow the analysis of the single options. The outcome of the above listed workpackages must be synthesised with the aim of giving guidance towards the most effective system development. Of course, there cannot be a general best solution, it will depend on the initial conditions, i.e. the present system, and the boundary conditions, i.e. conditions such as the size of the catchment, the presence of industrial wastewater or the self purification capacity of the receiving water.

First results

Systems analysis

The aim of this work was to perform a thorough and wide-focused systems analysis of the integrated urban wastewater system (catchment area, sewer, WWTP, river). The outcome of the study will ultimately serve as a basis for the development of a decision support aid that gives assistance for the cost-effective development of urban wastewater systems for Water Framework Directive (WFD) compliance.

Among the wide suite of tools available to perform a systems analysis substance flow analysis (SFA) 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. The main

limitation of SFA lies in the uncertainty usually associated to the data used, which are also of different nature and origin. Using SFA as a tool for priority setting and follow-up is associated with considerable difficulties. However, it is still a useful tool for screening in order to identify areas for further and more detailed investigation.
The evaluation of a list of indicators helped to characterise the behaviour of sewers and WWTPs in environmental and economic terms. A further objective was to recognize the information gaps in the system owed to the typical methods of data collection and monitoring of the urban catchment. However, such results are not shown in this paper; only SFA and mass balances are discussed.
Two different approaches were adopted in the study to analyse urban wastewater systems. Both imply a comprehensive collection of data and general information from wastewater operators, environmental agencies and authorities. In the first approach a wide ranged analysis of a system at river basin scale is applied. The Nete river basin in Belgium, a tributary of the Schelde, was analysed through the 29 sewer catchments constituting the basin. In the second approach a more detailed methodology was applied. Two urban wastewater systems with different characteristics (one system is characterised through urban and one through rural influence) situated within the Ruhr basin (Germany) were separately investigated on a river stretch scale.
Substances to be analysed for the study were water, BOD, COD, TN, TP and Zn: water was selected since the analysis of its flows can reveal problems such as in- and exfiltration, WWTP overload, hydraulic stress to receiving water body; BOD and COD are indicators of organic pollution with oxygen depletion and CO_2 emission; TN and TP reveal eutrophication potential in the receiving water; Zn is the most detectable heavy metal (therefore measurements are fairly reliable) and is representative of toxic contamination. However, it is very difficult to obtain reliable flows for heavy metals due to the low detection limit and to the fact that a large fraction comes from stormwater, for which there are usually no quality measurements.
Within the wide set of components being part of the water cycle or interacting with it, only elements concerning the urban wastewater system were taken into account. Among this sub-set, the studied processes were the ones related to technical structures on which a water utility can act to improve the receiving water quality (sewer network, WWTP and receiving water body). For the processes included in this systems analysis all possible interactions were considered. The other compartments (households, industry, agriculture, atmosphere, groundwater, etc.) were assumed in this study as flux sources or sinks, so only the interactions with processes in the system were taken into account.

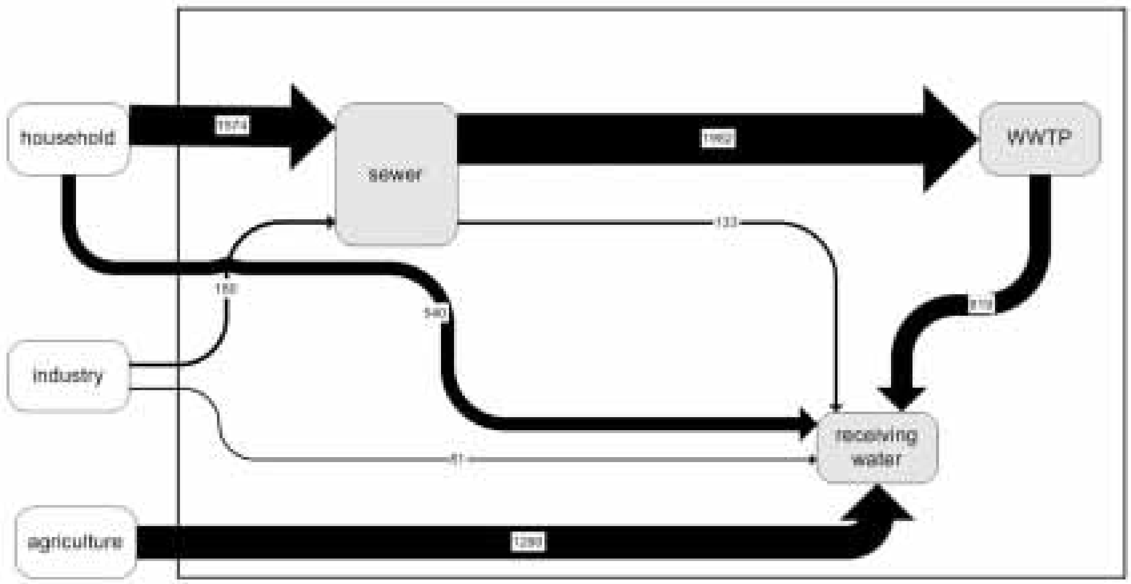

Figure 1 Sankey diagram for TN [ton/y] in the Nete.

Figure 1 gives an example of substance flows by means of Sankey diagrams. Loads from households are estimated from the number of inhabitants and daily substance release (TN: $10g \cdot inh^{-1} \cdot d^{-1}$).
Concerning pressures directly impacting on the receiving water, figure 2 shows substance loads discharged in the Nete relative to the total load. It appears that untreated households are the main stressor for acute oxygen depletion (BOD, 89% of load) for delayed oxygen demand (COD, 60%) and for eutrophication (TP, 45% and TN, 24%). Agriculture also has a relevant impact on eutrophication (TN, 44% and TP, 25%); it is to be noticed that no data were available on BOD and COD loads from agriculture. WWTPs contribute substantially to all loads but are in no case the main stressor; they are for zinc, but only apparently because of the fact that zinc originating from roofs and gutters is not measured in stormwater.

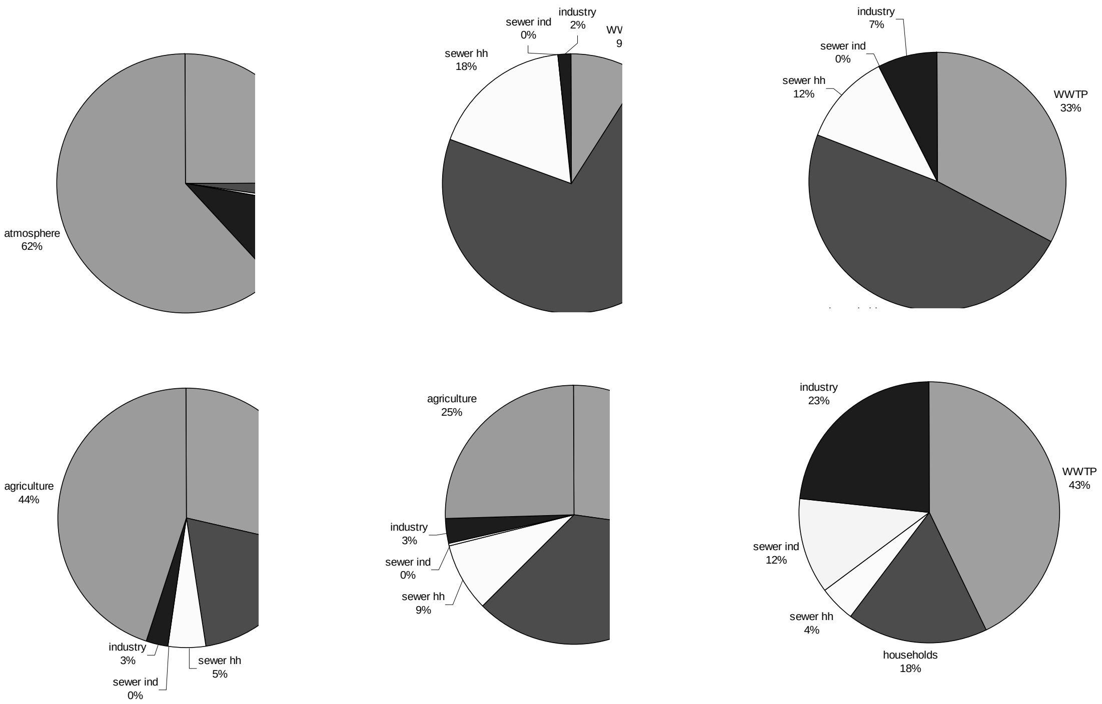

Figure 2 Relative loads into the Nete river – from left to right and from up to down: water, BOD, COD, TN, TP and Zn; “sewer ind” and “sewer hh” indicate the loads discharged in the receiving water via the sewer network by industry and household respectively

The calculated water flows directly discharged into the receiving water body via CSOs (figure 3) show a large variance. 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. The same behaviour – i.e. large variance for individual basins, but average in agreement with literature – was found for sewer mass balances (not shown).
This underlines an important aspect in this type of studies: the spatial scale chosen. For large regions 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.
More details on such study can be found in (Benedetti *et al.* 2004).

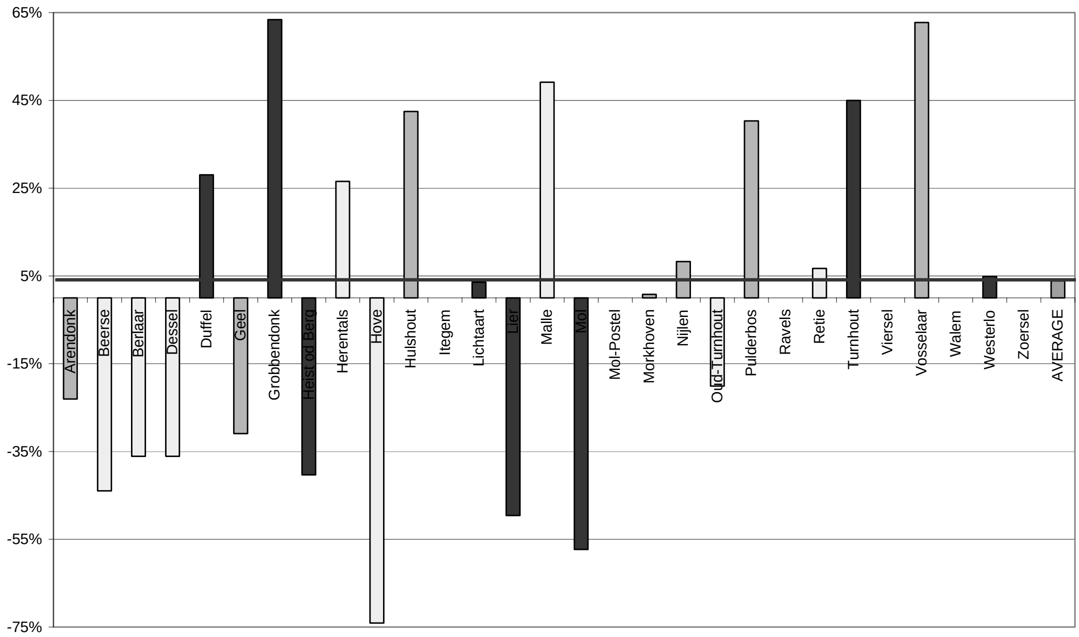

Figure 3 Percentages of estimated CSOs (relative to the total stormwater entering the sewer) for the 29 Nete catchments; in medium grey are reliable data, in light grey less reliable data, in dark grey scarcely reliable data

Integrated modelling

An integrated model of the urban wastewater system has been set up on a single software platform, WEST® (Vanhooren *et al.* 2003). It includes ASMs for the treatment plant, RWQM1 for the river and KOSIM for the sewer system.
Efforts have been spent in coupling such models. The Peterson and composition matrices that modellers are now familiar with are used as a basis to construct interfacing models between subsystems considered in wastewater treatment. Starting from continuity considerations and a set of transformation reactions between components used in the two models of the subsystems a set of linear algebraic equations needs to be solved. Such continuity-guaranteed interfacing of subsystems will facilitate optimization studies of the within-fence process units of a wastewater treatment plant or of the integrated urban wastewater system (Vanrolleghem *et al.* 2004).

References

Benedetti, L., Blumensaat, F., Bönisch, G., Dirckx, G., Jardin, N., Krebs, P. and Vanrolleghem, P. A. (2004). Systems Analysis of urban wastewater systems - two systematic approaches to analyse a complex system. In: *Proceedings of IWA 2004*, Marrakesh, Morocco, 19-24 September 2004.

Vanhooren, H., Meirlaen, J., Amerlink, Y., Claeys, F., Vangheluwe, H. and Vanrolleghem, P. A. (2003). WEST: Modelling biological wastewater treatment. *J. Hydroinformatics* **5** (1), 27-50.

Vanrolleghem, P. A., Rosen, C., Zaher, U., Copp, J., Benedetti, L., Ayesa, E. and Jeppsson, U. (2004). Continuity-based interfacing of models for wastewater systems described by Peterson matrices. In: *Proceedings of 10th World Congress on Anaerobic Digestion (AD10)*, Montreal, Canada, 29 August - 2 September 2004.