Life cycle management for assessing systems of urban water management: case studies and methodological gaps

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Abstract Triggered by climate change, local freshwater scarcity and rising public awareness towards ecological issues, environmental aspects are becoming key decision criteria for planning of urban water management infrastructure. Simultaneously, the implementation of measures according to the EU Water Framework Directive requires huge investments in the coming years for both upgrading of existing infrastructure and the construction of sewer networks or treatment plants. Among existing tools for environmental impact assessment, LCA offers the most accepted and comprehensive method to support decision makers with information on the environmental profile of new investments or upgrading of existing infrastructure. This paper describes on-going case studies using LCA for systems of urban water management and raises potential difficulties while applying LCA in the water sector.

1 Introduction

Triggered by climate change, local freshwater scarcity and rising public awareness towards ecological issues, environmental aspects are becoming key decision criteria for planning of urban water management infrastructure. Simultaneously, the implementation of measures according to the EU Water Framework Directive (2000/60/EG [1]) requires huge investments in the coming years (numbers for EU??) for both upgrading of existing infrastructure and the construction of sewer networks or treatment plants. The ultimate target of a "good ecological and chemical status" (EU-WFD) for the surface waters of Europe can only be reached by decreasing the impact of urban water management on these eco-systems. However, this often comes at the expense of higher energy and resource demand, thus leading to a shift of environmental impacts towards other categories of environmental concern. This effect will further hamper the reduction of primary energy demand and greenhouse gas emission, which is a strategic target of the European Commission (Fig.1, [2]).

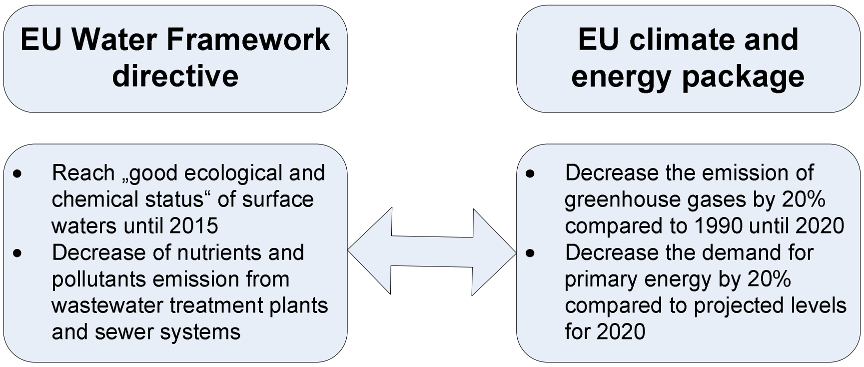

Fig.1: Conflicting priorities of future systems for urban water management

Due to the long amortisation of water infrastructure (>25a) and large capital needs within the water sector, it will be crucial to optimise future investments in terms of environmental benefits. The following issues are exemplary within discussion in the field of urban water management:

- The targets of the EU-WFD will require a further reduction of pollutant emissions from wastewater treatment plants (WWTP). The extensive removal of organics, nutrients or trace pollutants can only be reached with additional treatment steps using advanced technologies for tertiary filtration or removal of micropollutants. However, the upgrading of WWTP can lead to a considerable increase in energy and resource demand, and the choice of a suitable technology should take into account this shift of environmental impacts to comply with targets for decreasing energy demand and the emission of greenhouse gases.
- The excessive input of nutrients nitrogen (N) and phosphorus (P) into surface waters can lead to a degradation of these eco-systems, causing algal blooms and subsequent oxygen deficiency (eutrophication). The reduction of nutrient inputs can be achieved with a multitude of measures for both point sources (e.g. urban WWTP or sewer systems) or diffuse sources (e.g. agriculture). Both types of measures will have different efficiencies, costs and related environmental impacts, which should be quantified and taken into account while setting up goal-oriented

management plans for whole catchment areas, optimizing the investments for environmental protection measures.

- Wastewater can be a source of both physical and chemical energy (e.g. heat recovery, conversion of organic matter into biogas with anaerobic digestion) and valuable resources (plant nutrients, metals). Different existing and emerging technologies are available to recover these resources. However, wastewater treatment is a complex and multi-step process, and changes in process layout can have an impact on upstream or downstream treatment stages. Consequently, emerging technologies in the field of resource recovery from wastewater have to be assessed comprehensively ("life cycle perspective") with all related environmental impacts to identify the most sustainable solutions and systematic approaches for the overall system.
- Historically, wastewater infrastructure in urban areas consists of a gravity sewer system collecting both wastewater and rainwater run-off (combined sewer) and transporting it to a centralized WWTP. In case of heavy rain events, the hydraulic peak load of the sewer system is exceeded, and diluted raw wastewater is discharged directly into surface waters (combined sewer overflow, CSO). Hydraulic decoupling of surface run-off or a separate sewer system for rainwater can prevent CSO events, and rainwater management can also contribute to the relief of local water resources. Additionally, small decentralized treatment units increase the flexibility of the system to adapt to a change in boundary conditions (e.g. rain patterns due to climate change) in the future. The identification of optimized solutions should take into account the entire system and its related processes, including resource demand for both operation and infrastructure.

Thus, the need for consistent methods assessing all environmental impacts of urban water management is obvious. Among existing methods for environmental impact assessment, LCA offers the most accepted and comprehensive tool for systematic assessment of these impacts in a consistent and manageable framework. The results of an LCA can support decision makers with comparable information on the environmental profiles of all technological options on the table, enabling them to take a well-founded decision based on the results of both ecological as well as economic information.

This paper presents on-going case studies of LCA in the field of urban water management, exemplifying current applications of LCA for processes within the water sector. All activities relate to the city of Berlin (3.4 Mio inhabitants) and its surroundings, representing a dense urban area in a highly industrialized country.

The paper concludes with the identification of methodological difficulties related to the application of LCA for systems of urban water management.

2 Case studies of LCA application in urban water management

2.1 Advanced wastewater treatment for phosphorus removal

In Germany, legal discharge standards for large wastewater treatment plants can be adjusted by local authorities, if these plants discharge their effluent into sensitive surface waters or if surface waters are extensively used by the public. In Berlin, the WWTP Ruhleben discharges water into the Havel river, thus affecting the quality of lake Wannsee downstream. Hence, the Berlin senate plans to impose strict discharge standards for phosphorus ($P < 80$ µg/L) and microbiological quality for the Ruhleben effluent, requiring tertiary filtration of the effluent prior to discharge. Available technologies include chemical precipitation combined with various filtration technologies and disinfection (e.g. membranes, sand filters, disc filters, UV), which differ substantially in efficiency, demand for energy and cleaning chemicals, and the ability to cope with hydraulic peak loads (heavy rain events). Within the project OXERAM [2], the environmental profile of various filtration processes will be assessed with LCA, including both operation and required infrastructure and maintenance (Fig.2). Process data is collected from pilot plants currently operating at WWTP Ruhleben and previous pilot trials of the Berlin water utilities (Berliner Wasserbetriebe, BWB). Finally, the results of the LCA will help BWB and the municipality to choose a suitable technology for tertiary filtration while knowing the related environmental consequences of this WWTP upgrade.

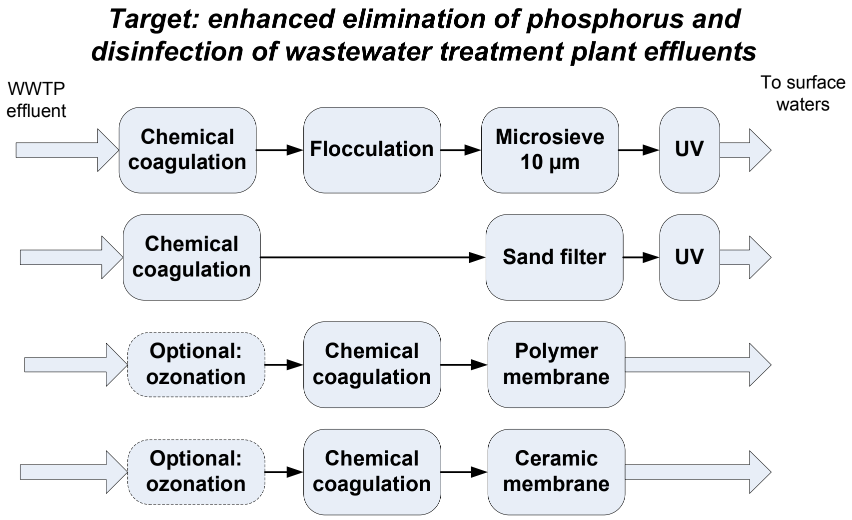

Fig.2: Advanced treatment of WWTP effluent via tertiary filtration

2.2 Limiting nitrogen emissions into surface waters

In the past, eutrophication of inland surface waters has usually been attributed to the excessive input of phosphorus as the limiting nutrient. Consequently, P input into surface waters has been dramatically reduced by implementing strict limits for P discharge from urban WWTP. Recently, nitrogen has come into focus as another possible trigger for eutrophication in certain surface waters, which would require a further reduction of N input. Nitrogen input into surface waters originates from both point sources (WWTP or combined sewer systems) and diffuse sources (agriculture), and for both types of sources several reduction measures are available (Tab.1). However, enhanced N reduction in WWTP below existing discharge limits comes at high expenses in energy and construction (tank volume) or with additional treatment steps such as biofiltration, and the resulting decrease in N input to surface waters may be marginal. In contrast, nitrogen input can also be efficiently reduced with a multitude of management measures in agriculture. Within the project NITROLIMIT [3], an LCA study will quantify the environmental impacts of enhanced N reduction for WWTP and compare them to those impacts from agricultural measures, using both a local case study from Berlin (Lower Havel) and a wider area of the catchment of upper Elbe.

Tab.1: Selection of measures for reduction of nitrogen input into surface waters

Point sources (WWTP + sewer)	Diffuse sources (agriculture)
Enhanced nitrification and denitrification (WWTP)	Reduction of erosion: changes in land use
Biofiltration of effluent (WWTP)	Riparian buffer zones, constructed wetlands
Storage tanks or post-treatment (CSO)	Fertilizer management
Decoupling of surface run-off (CSO)	

2.3 Optimising WWTP in terms of energy and nutrient recovery

This study is focussed on the operational aspects of wastewater treatment plants with the aim to optimise the recovery of energy and nutrients from wastewater [4]. Applying LCA for two case studies in Berlin and Braunschweig, the existing processes of wastewater treatment are analysed in terms of their environmental impacts, and promising optimisation measures are compared in their effect on the ecological profile. In Berlin, the focus is on the sludge treatment of a large WWTP, where the sludge is digested to recover biogas from the organic matter before it is incinerated in mono-incineration, power plants or cement plants. This case study quantifies the cumulative energy demand and global warming potential of the existing treatment line and proposes measures for its optimisation, including the addition of energy-rich co-substrates or sludge pretreatment by thermal hydrolysis prior to digestion. The Braunschweig study complements the energy analysis with the aspect of nutrient and water recycling to agriculture: in Braunschweig, parts of the WWTP effluent and sludge are applied directly to agriculture, thus enabling the reuse of nutrients and the substitution of groundwater required for irrigation. However, matching the seasonal demand of irrigation water and nutrients in agriculture with the relatively constant supply by the WWTP requires a careful management of the complex system and can still be improved, e.g. by the separate recovery of nitrogen from N-rich sludge waters. Here, LCA is used to show the inter-dependencies within this complex system of WWTP and agriculture, enabling the comparison between additional impacts with certain measures and related benefits for the enhanced recovery of energy and nutrients.

3 Identification of methodological gaps and difficulties

The setup of the LCA studies described above closely follows the framework of ISO 14040/44. In the course of setting up the LCA studies, issues for further discussion have been identified while applying LCA to systems of urban water management. In particular, the following difficulties were encountered:

- The definition of functional unit (FU): for wastewater treatment plants, the functional unit is related to the treatment of wastewater. Usually, the FU of a process describes the product of a system, which would be the release of purified wastewater treated to a certain standard. In practice, the effective quality of the effluent depends on the technology applied, the quality of the influent wastewater, and other process-specific boundary conditions. Different WWTPs or process technologies have different effluent qualities, complicating the comparison between them using a comparable FU. The definition of the FU related to the reference input flow (= raw wastewater) poses other difficulties, as the composition of the influent wastewater (i.e. the concentration of pollutants) can differ heavily between WWTPs. Hence, the definition of FU can easily affect the comparison between different WWTPs or technologies.
- WWTPs are traditionally built to prevent negative impacts of wastewater discharge on surface waters. Within this function, both chronic and acute effects have to be accounted for, e.g. both the reduction of annual nutrient loads and the prevention of toxic shock loads of NH3 in case of hydraulic or concentration peak loads. However, life cycle impact assessment is usually capable of accounting average emissions of a process, without quantifying possible impacts from short-term peak loads. In contrast, the process design of WWTP is adapted to the prevention of peak loads, affecting the overall process efficiency. This function cannot be reflected properly within toxicity indicators of LCA.
- For emerging contaminants such as organic micropollutants (e.g. pharmaceuticals) or pathogenic microorganims, characterization factors for impact assessment of damage to human health or ecosystem quality are not yet available for most LCIA methods. In addition, effects of urban water management on issues of biodiversity (e.g. invasive species) should be addressed in impact assessment methods.
- Dynamics of WWTP operation are relatively high due to a) variations in wastewater volume and pollutant loads and b) the involvement of temperature-dependent biological processes. Thus, both diurnal (day vs.

night) and seasonal variation in energy and chemicals demand and effluent quality are common features of dynamic WWTP process models. However, LCA is naturally based on static input-output models with process data representing an "average" point of operation. This inherent discrepancy requires a careful adaptation of WWTP operational data into the LCA model, especially while accounting the effect of changes in the existing process scheme.

4 Conclusions

The present paper describes the need for comprehensive methods for environmental impact assessment methods for systems of urban water management, triggered by the contrary political strategies of improving protection of surface waters and reducing energy demand and greenhouse gas emissions. Several case studies from the Berlin area describe specific research issues that are currently tackled using LCA as a framework, focussing on advanced wastewater treatment for nutrient removal and the decrease of energy and resource demand in urban WWTPs. Finally, certain difficulties and methodological gaps are identified which arise during the setup of these studies to address specific issues of urban water management with LCA: a) the definition of a comparable functional unit b) the transfer of dynamic processes such as WWTP into static input-output models of LCA and c) gaps in life cycle impact assessment regarding emerging pollutants or pathogenic microorganisms.

5 References

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