Decision support tools for urban water and wastewater systems – focussing on hazardous flows assessment

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Abstract The Swedish research programme *Urban Water* has developed a concept of a multi-criteria basis intended to support decision-making for urban water and wastewater systems. Five criteria groups were established for sustainability assessment of urban water systems: Health and Hygiene, Environment, Economy, Socio-culture, and Technology. Each criterion requires a set of indicators corresponding to quantifiable facts and figures, or qualitative data to comparatively assess the different alternatives in the decision process. The decision support process starts as a baseline study where the existing conditions are addressed. Alternative strategies of the future urban water system are developed and analysed by different tools and methodologies in assessing the five criteria groups. Eventually, the results and conclusions are integrated and synthesised into a basis for decision-making.

As an example of a decision support basis for chemical safety, a barrier perspective was introduced to find out if and to what extent hazardous substances can be stopped, diverged, or transformed at various points in the wastewater system. A set of barriers was suggested, i.e. behaviour, systems design, process design, optional recipients, and organisational. The barrier approach was applied to two alternative municipal wastewater system designs – a combined wastewater system vs. a source separated system – analysing the fate of phosphorus, cadmium, and triclosan. The study showed that the combined system caused a higher substance flow to the receiving waterbody than the separated system. The combined system also brought more phosphorus and cadmium to the farmland than the separated system, but only half the amount of triclosan.

Keywords Barriers; decision support; hazardous substances; substances flow analysis; sustainability

Introduction

Strategic decisions support is critical in developing urban water and wastewater systems in a more sustainable direction. This paper presents a concept of how to comprehensively approach these complex issues. The Swedish research programme *Urban Water* has developed methodologies and tools for the integrated sustainability assessment of urban water and wastewater systems. Figure 1 shows a framework of an integrated urban water system that has been equally divided into three subsystems:

- the *organisation* owns, plans, finances, and manages the urban water system, and may be public or private, central or local
- The *users* use the water and need to get rid of the waste products
- The *technical system* (pipes, pumps, treatment plants, etc.) supplies the water and takes care of the wastewater.

The aim of this paper is to describe a multi-criteria basis concept, serving as decision making support for urban water and wastewater systems. As an example of a decision support basis for chemical safety, a barrier perspective will be introduced and exemplified by a barrier approach regarding the fate of hazardous substances in two different wastewater systems.

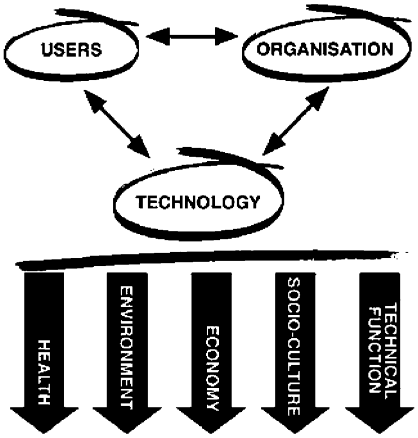

Figure 1 A framework for the integrated sustainability assessment of urban water and wastewater systems as suggested by the Swedish research programme *Urban Water*

Criteria and indicators of sustainability

Five criteria groups were established for sustainability assessment of urban water systems (indicated by the arrows in Figure 1).

Health and hygiene. Users of the urban water system should be protected from water-borne diseases and harmful effects of hazardous chemical substances.

Environment. The environment should be protected from the harmful effects in surface water bodies, soil, and ground water bodies. The misuse of natural resources should be minimised – in particular caution should be observed regarding the use of fresh water, energy, and nutrients.

Economy. The user must be able to afford the price of water and sanitation. The organisation must be able to finance the investments, operation, and maintenance. Societal costs must be reasonable and acceptable.

Socio-cultural. Households are vital parts of the urban water system. They must be able to manage their part, and have a reasonable level of comfort. Organisations involved must have the institutional capacity for implementation, as well as operation and maintenance.

Technology. Proper technology should be used and adapted to the local conditions. The chosen technology must be reliable and cost-effective.

To achieve comprehensive sustainability assessments of urban water systems, all five groups of criteria need to be included. A set of indicators should be established for each criterion, corresponding to quantifiable facts and figures or qualitative data that make the comparative assessment of different alternatives in the decision process possible. In a case study from the Swedish town of Surahammar, different alternatives for wastewater management were developed and assessed by a group of local stakeholders together with a research group from the *Urban Water* programme. For the five criteria groups, a total of 15 indicators were selected.

Health and hygiene

1. Microbial risks: Exposure to pathogens
2. Chemical risks: Exposure to pharmaceutical residues

Environment and use of natural resources

3. Flows of heavy metals to water (**Cd**, Hg, Cu, Pb)
4. Flows of heavy metals (**Cd**, Hg, Cu, Pb) to farmland
5. Reuse of nutrients (N, **P**, K, S) to farmland
6. Use of energy (kWh/a,p)
7. Discharge of nutrients to water (P, N)

Economy

8. Annual cost
9. Transition cost
10. Financial risks

Socio-culture

11. Institutional capacity, incl. split of responsibilities and risks between actors
12. Possibilities for learning and participation
13. Social robustness
14. Comfort

Technical function

15. Technical robustness

Assessment of hazardous substances in wastewater systems

One of the many problems in managing urban water and wastewater is how to cope with all the hazardous or potentially hazardous chemicals transported in water and wastewater systems. In urban areas, numerous sources generate wastewater, e.g. households, enterprises, public locations, industries, storm drainage, etc. Diffuse sources presently account for the major part of hazardous substances in municipal wastewater. A lack of knowledge on the impact of many chemicals on human health and the environment is cause for concern (Commission of the European Communities, 2001). The flow of hazardous substances from society to the surrounding nature is a consequence of industrialisation, urbanisation, and welfare that is built into society's physical infrastructure as well as our social behaviour. Since wastewater systems are sub-systems of urban infrastructure, hazardous substances are channelled via wastewater flows. However, existing wastewater management strategies are ineffective tools in changing society's metabolism of substances. Rather, existing water-borne sanitary systems signal to their users that it actually *removes* their often inconvenient waste just by opening the tap or flushing the toilet. Therefore, it seems relevant to search for wastewater management tools that support a shift in perspectives by combining a traditional end-of-pipe perspective with more systems-oriented perspectives that link the use of resources and spreading of hazardous substances to their underlying causes and driving forces (i.e. consumption and lifestyle) rather than only focusing on the emissions.

A prospective tool for decision support is a barrier approach, designed for the management of hazardous flows in wastewater systems. A barrier is defined by the *Oxford English Dictionary* as "a fence or material obstruction of any kind erected (or serving) to bar the advance of persons or things, or to prevent access to a place". In wastewater management the barriers perspective aims at understanding the hazardous flows throughout the wastewater system, and finding out if and to what extent hazardous substances can be stopped, diverged, or transformed at the source or during transport through the system. Five kinds of barriers are suggested (see Figure 2).

A barriers interpretation of a substance flow analysis (SFA)

In a fictitious example, the substance flows for a town of 10,000 persons were compared and the results interpreted in a barriers perspective for two types of wastewater systems

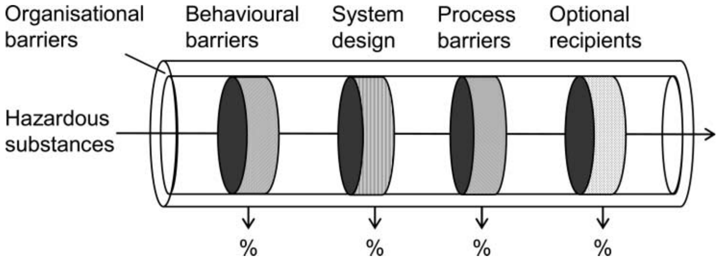

Figure 2 A schematic outline of the barriers concept illustrating four of the suggested barriers embraced by the fifth organisational barrier (the tube), which by legislation and administrative measures directly or indirectly can affect the other barriers

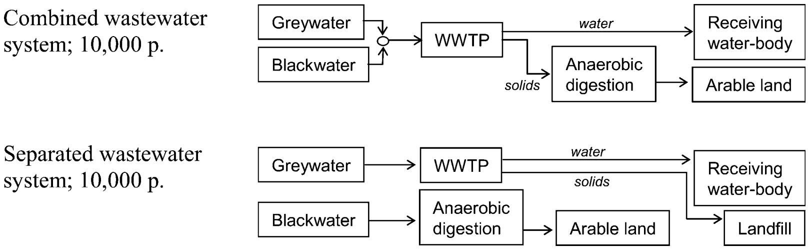

Figure 3 The combined wastewater system is a conventional municipal system while the separated system separates grey- and blackwater at the source (in the houses). The wastewater treatment plant (WWTP) comprises both mechanical and biological process units as well as chemical precipitation of phosphorus

– a combined wastewater system versus a source-separated system (Figure 3). The study was restricted to a selection of three representative chemical substances, i.e. phosphorus (P), cadmium (Cd), and triclosan, which typically occur in municipal wastewater systems and for which it has been possible to collect data. Input data are presented in Table 1. Neither stormwater nor industrial sewage was considered.

A comparative substance flow analysis (SFA) showed that the combined wastewater system caused a higher substance flow to the surrounding nature than the separating system. The water-body received 74% more P, 21% more Cd, and 18% more triclosan from the combined wastewater system, while the arable land received 23% more P, 65% more Cd, but only half the amount of the triclosan from the combined wastewater system than from the separating system. However, the residual substance flow from the separating wastewater system was instead directed to the landfill.

The combined effect of the System and Process barriers was considered from the viewpoint of the receiving environment – the waterbody and the arable land. Concerning the protection of the receiving waterbody, 95–99% of the phosphorus and the triclosan

Table 1 Input data for the substance flow analysis comprised specific amounts of P, Cd, and triclosan in domestic wastewater fractions (grams per person and year). Blackwater is defined as urine, faeces, flush water, and toilet paper from low-flushing water closets. Greywater is defined as domestic wastewater without any input from toilets, corresponding to wastewater from bathing, showering, hand washing, laundry, and the kitchen sink

		Greywater	Blackwater
P	kg p^{-1} $year^{-1}$	190[a]	548[a]
Cd	g p^{-1} $year^{-1}$	15[a]	4[a]
triclosan	g p^{-1} $year^{-1}$	60[b]	13[b]

[a] Vinnerås (2002). [b] Palmquist (2001); Andersson and Jensen (2002)

flows and 60–68% of the cadmium flow in both of the wastewater systems were obstructed by the barriers. By adding a nanofiltration membrane as an additional process barrier, the protection of the receiving waterbody increased noticeably to 98.8–100% for all of the substances.

The system barrier, i.e. the separated system design, worked particularly well for Cd, where almost half (47%) was directed to the landfill instead of to the surrounding nature. The combined barrier effect for P to arable land was low – 3% in the combined wastewater system and 26% in the separated, considered advantageous in a nutrient recycling perspective.

In total, the combined system supplied the arable land with more phosphorus (7.2 tonnes per year) than the separated system (5.5 tonnes per year), yet a lesser amount of triclosan (55 versus 104 grams per year). Since triclosan was decomposed to a high degree in the activated sludge process in the WWTP, a larger amount of triclosan was degraded in the combined system (87%) than in the separated wastewater system (4%). Regarding the potential effects in soil, the numerous species of micro-organisms in the soil and a larger oxygen uptake favour soil-based systems rather than waterbodies for the biodegradation of anthropogenic organic substances, such as triclosan (Linusson, 1992).

The mass flow of cadmium to arable land was considerably higher from the combined wastewater system (114 g per year) than from the separated system (40 g per year). Since heavy metals such as Cd are not needed by plants and most of them may be toxic to soil microbes, plants, and animals, including humans, accumulation of these elements in the soil might be harmful in a long term perspective (Palmquist and Jönsson, 2004). The very low natural concentration of some heavy metals, e.g. silver, in the soil means that even small additions rapidly increase the soil's concentration (Palmquist and Jönsson, 2004).

For the flow of the three selected substances, the combined wastewater system seems to potentially cause higher risk to both the waterbody and the arable land than the separated system due to the overall higher substance flows and particularly, the potential accumulation of Cd in soil.

System barriers

System barriers relate to the infrastructural and technical design of urban water and wastewater systems. The extremes vary with separation of urine, faeces, greywater, and stormwater occurring at the source, while combined flows that mix wastewater occur from numerous other sources. In the SFA, one quarter of domestic wastewater phosphorus emerged in the greywater and three quarters in the blackwater. For cadmium and triclosan the result was almost the opposite, i.e. 80% in the greywater and 20% in the blackwater. This relevant information about the system barrier is needed to decide on the design of the system.

Process barriers

Treatment plant process units provide various separation and degradation processes. In the performed SFA, the WWTP process units were aggregated into overall treatment efficiencies with 97% of phosphorus and 60% of cadmium (Swedish EPA, 2002), and 95% of triclosan (McAvoy *et al.*, 2002; Hartmann and Ahring, 2003) being separated from the water phase. The separated portions were assumed to be built into the solids. The organic substance triclosan, however, was 'removed' by 90% degradation in the aerobic activated sludge process, and by 20% degradation in the anaerobic digestion process (McAvoy *et al.*, 2002). As well, 87% triclosan left the combined system by degradation in both processes while 4% left the separating system by degradation in the anaerobic digestion process only. Anthropogenic compounds such as triclosan may undergo various transformation reactions in organisms and in the environment (including WWTP processes), leading to more hydrophilic derivatives with higher mobility in the aquatic environment and a lower potential for bioaccumulation (Lindström *et al.*, 2002). However, transformation reactions may sometimes render a compound more lipophilic than the parent compound itself. Therefore, the 'removal' of anthropogenic compounds in the WWTP does not necessarily represent true degradation, but rather a transformation into other derivatives.

Separation processes are sedimentation, chemical precipitation, sand filtration, and membrane processes. Membrane processes have been found to be widely applicable for water treatment. As a stand-alone process, a membrane will separate wastewater into two streams, a purified stream that can be discharged and a concentrated stream containing most of the pollution load. As in all separation processes the concentrated residues have to be taken care of. When modelling a nanofiltration membrane as an additional process barrier in the WWTP the substance flows to the receiving waterbody were considerably reduced.

Optional recipients

Optional recipients are highly dependent on the geographical context, which could be lakes, rivers, the sea, or soils. The SFA showed that the barrier effect for Cd was moderate in both systems. An additional membrane filtration would protect the receiving waterbody, though to protect the arable land additional measures were required. Here, *optional recipients* could be a matter of discussion. The wastewater sludge from the combined wastewater system might be applied in soil applications other than as fertiliser for food production, to safeguard clean food production. Palmquist and Jönsson (2004) claim that the fertilising potential of wastewater sludge must be questioned in the long-term perspective. In a study of metal/nitrogen ratios, 12 studied hazardous metals (including Cd) showed higher ratios than what the plant uptake can counter balance, implying metal accumulation in the soils. Optional recipients may be a reuse (recycling) of wastewater residues, such as irrigation of parklands, or production of construction-soil. In Sweden, sewage sludge has been recently used to cover mining slag deposits.

Behavioural barriers

An alternative form of source control would be to tackle the behavioural (or users') barriers, such as the information campaign about cadmium in artist paint, performed by the Stockholm Water Company. Artist paint may contain up to 45% Cd, which is the pigment in these paints. According to the Stockholm Water Company, their municipal WWTPs receive more than 30 kg of Cd per year originating from artist paints (www.stockholmvatten.se). They recommend the use of alternative paints, and instruct how to handle the cleaning of brushes and waste. The barrier effect of such measures is very difficult to assess and one should probably not be overconfident in the response. As a consequence, it becomes essential to phase out hazardous substances in consumer goods and products.

Organisational barriers

Organisational barriers include legislation and administrative measures at global, national, and local levels, and represent a wide spectrum. In Europe, large scale regulatory and organisational changes are governed by the EU, e.g. the Water Framework Directive (WFD), whose specific objectives are to achieve a "good status" for all European waters by 2015, with sustainable water use throughout Europe (Commission of the European Communities, 2002).

According to Azar *et al.* (2002), the current objective is to heavily regulate, or even phase out the use of cadmium. But cadmium is mined as a by-product of zinc, and if

OECD countries phase out cadmium, the price will drop, possibly resulting in dissipative uses in non-OECD countries. Bans on detergents containing phosphate is another example. This action was successful in reducing the phosphate flows to the receiving waterbodies, but as the tenside compounds that replaced the phosphate showed to be persistent (and thus relatively resistant to degradation in the WWTPs), this ban (barrier) replaced one environmental hazard with another. These examples highlight the importance of studying how material flows are nested, as well as the importance of analyzing links between energy and materials' systems. Other organisational barriers for hazardous flows in society are:

- chemicals policy, e.g. REACH based on the "White Paper – Strategy for a future chemicals policy" (Commission of the European Communities, 2001)
- emission regulation, e.g. IPPC directive (Integrated Pollution Prevention and Control) (Council Directive 96/91/EC)
- technical regulations, regarding the technical design and function of wastewater systems
- fertilising policies, e.g. the farmers' and the food industries' approach to the use of wastewater residues (e.g. biosolids) on arable land
- eco-labelling regulation (Regulations European Commission No. 1980/2000).

The proposed barrier structure (see Figure 2) aims at protecting humans and ecosystems from the harmful effects of hazardous chemical substances. However, the barriers also associate to the sustainability criteria (Figure 1). According to Table 2, all barriers are intersected by more than one criterion, elucidating their multi-disciplinary character. The overall purpose of the barriers approach relates mainly to the two criteria: *Health and Hygiene* and *Environment*. Furthermore, to achieve changes in a set of barriers, cost will arise, explaining why the *Economy* criterion was thought to be relevant for most of the barriers. The multi-disciplinary nature of the barriers approach may have practical implications for the disciplines and participants involved, as it comes to, for example, choice of methods and cooperation.

The decision support process

The process of developing urban water and wastewater management/systems in a more sustainable direction – in a city or a part of a city – may essentially be described by the following four steps:

1. The existing conditions should be addressed in a base-line study, including the establishment of indicators.
2. Alternative strategies (scenarios) are developed, preferably in co-operation with major stakeholders and representatives for the organisation, the users, and the supplier of the technical system.
3. Hereafter, the alternative strategies are analysed by using the proper tools and methods to assess the five criteria groups. The tools may be of various types – advanced mathematical models, graphical tools, as well as process support and multi-criteria decision aids (Söderberg and Kärrman, 2003) for communication and

Table 2 The primary associations of the barriers and the sustainability criteria

Barriers	Sustainability criteria
Organisational barriers →	Economy, Socio-culture
Behavioural barriers →	Socio-culture, Economy
System design →	Technical function, Economy, Socio-culture
Process barriers →	Technical function, Economy
Optional recipients →	Health and hygiene, Environment

integration of the different groups of criteria. Structured dialogues are important features in this process.

4. The results and conclusions are eventually synthesised to form a basis for decision-making. This process involves a great deal of complexity which is why a well defined structure and an experienced process leader are required to guide the process.

Tools and methods for sustainability assessment

Central elements in the decision support process are the development of methodologies and tools for sustainability assessment of urban water and wastewater systems. Various methodologies and tools have been developed and tested by the *Urban Water* programme.

- A substance flow analysis is needed as a basis for all other studies. The flows, sources, and the fate of water and its major constituents, such as nutrients, pathogens, and harmful chemicals, must be clear for all alternative strategies.
- Risk analyses reveal major characteristics of the systems. Analyses of microbial, chemical, and technical risks are essential. Financial risks must be considered as well.
- Economic assessments include estimating the costs for users and house owners, the municipality (or water company), and society at large. The financing of investments and operations is crucial, which becomes even more critical in areas or cities where the infrastructure is less developed and/or the organisation is unclear or weak.
- Socio-cultural aspects include institutional capacity as well as user aspects. Institutional capacity may be investigated through interviews and document studies for the case in focus. These investigations are often based on checklists and the results are communicated by the use of graphical tools. Focus groups and other interactive communication methods have shown to be efficient methods for investigating user aspects.
- Multi-criteria syntheses transform the gathered results to a basis that supports strategic decision-making. Different methods are needed for (a) process support for planning and decision-making and (b) multi-criteria decision aid. Both computer-based methods and simpler methods have been developed and tested in different applications within the *Urban Water* program. The degree of involvement from experts may vary, as the degree of sophistication of the method.

Conclusions

Five criteria groups were established for sustainability assessment of urban water systems: Health and Hygiene, Environment, Economy, Socio-culture, and Technology. Each criterion requires a set of indicators corresponding to quantifiable facts and figures and qualitative data that make comparative assessment of different alternatives in the decision process possible.

The decision support process starts as a base-line study where the existing conditions are addressed after alternative strategies of the future urban water system are developed. Those options are analysed by different tools and methodologies assessing the five criteria groups. The results and conclusions are integrated and synthesised into a basis for decision-making.

As an example of a decision support basis for chemical safety a set of barriers was suggested, i.e. behaviour, systems design, process design, optional recipients, and organisational. The intention of a barriers perspective in wastewater management is to find out if and to what extent hazardous substances can be stopped, diverged, or transformed at various points in the wastewater system, generating prerequisites for systems analysis, risk assessment, improvements of the system, and communication.

The barrier approach was applied for two alternative municipal wastewater system designs – a combined wastewater system vs. a source separated system – to analyse the fate of phosphorus, cadmium, and triclosan. The study showed that the combined system caused a higher substance flow to the receiving waterbody than the separated system. The combined system also brought more phosphorus and cadmium to the farmland than the separated system, but only half the amount of triclosan. Combining the effects of the System barrier and the Process barriers was insufficient in protecting farmland from Cd for either of the two studied systems. To improve the protection of the environment, Behavioural and Organisational barriers also have to be considered.

Hazardous substances may be obstructed differently by the different barriers. The most relevant barriers depend on, for example, the substance's character, the status of the receiving environment that should be protected, and what measures are affordable.

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