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SUBSTANCE FLOW ANALYSIS OF HAZARDOUS SUBSTANCES IN A SWEDISH MUNICIPAL WASTEWATER SYSTEM

Substansflödesanalys av farliga ämnen i ett svenskt kommunalt avloppssystem

by HELENA PALMQUIST, Div. of Sanitary Engineering, Luleå University of Technology
SE-971 87 Luleå, Sweden

Abstract

In a comparative substance flow analysis two wastewater management scenarios in the Swedish town of Surahammar were assessed – a Conventional Scenario vs. a Separating Scenario. The study was restricted to a selection of 16 representative hazardous substances, including metals and organic compounds. Quantitative data of the selected hazardous substances – their presence in grey- and blackwater, and their reduction rates in the wastewater treatment plant – were gathered from the literature and our own studies. The Conventional Scenario caused an overall higher flow of the selected hazardous substances to the surrounding nature. However, the difference between both scenarios regarding emissions of hazardous substances to the receiving water was small. In general, the Separating Scenario resulted in a significantly smaller flow of hazardous substances to arable land than the Conventional Scenario. A possible management approach was suggested to be used to interpret and compare different wastewater systems, and serve to find out if and how much the flow of hazardous substances can be stopped, diverged, or transformed at the source or during transport throughout the system. System design, process barriers, and organisational and behavioural barriers were suggested, but only the first two were assessed in this study.

Key words – Wastewater management, SFA, hazardous substances, metals, barrier, chemical risk assessment.

Sammanfattning

Med hjälp av substansflödesanalys (SFA) jämfördes flöden av farliga ämnen (miljögifter) i två olika scenarier i Surahammars kommunala avloppssystem. Ett konventionellt system jämfördes med ett källsorterande svartvattensystem. Studien innefattade 16 utvalda metaller och organiska substanser. Datainsamlingen till studien d.v.s. innehållet av de 16 ämnena i grå- resp. svartvatten, samt deras avskiljningsgrader i avloppsreningsverket gjordes från litteratur och från egna mätningar. Det konventionella systemet orsakade totalt sett ett större flöde av miljögifter till omgivande miljö än svartvattensystemet. När man betraktade utsläppen till vattenrecipienten så var skillnaden mellan systemen dock mycket liten. Däremot åstadkom det konventionella systemet ett betydligt större flöde av miljögifter till odlingsbar mark via slamspridning än via gödsling med svartvatten från det separerande systemet. Som förslag på hur man systematiskt kan hantera flöden av farliga ämnen i avloppssystem introducerades begreppet barriärer. Barriärer är en tankemetafor som syftar till olika metoder och strategier för att förhindra farliga flöden. De fyra typer av barriärer som föreslogs var systemdesign, processbarriärer, organisatoriska barriärer och brukarbarriärer. Av dessa utvärderades endast de två förstnämnda för de 16 utvalda ämnena.

Introduction

The main tasks of urban water and wastewater systems are to provide clean water for a variety of uses, handle and treat wastewater to prevent unhygienic conditions, and drain off stormwater to avoid damage from flooding. Preferably, this should be done without any negative environmental impact. However, the surrounding environment is affected in several ways by urban water and wastewater systems. Important features are (Hellström *et al.* 2004):

- Withdrawal of raw water for drinking water production
- Use of natural resources for the production of functional energy species, chemicals, and other goods and products
- Emissions to air and water from various activities that are directly or indirectly related to water supply, wastewater treatment, and stormwater handling
- Disposal of solid residues, such as wastewater sludge, by landfilling, agriculture, or other ways

To varying degrees, these features depend on and are being affected by societal activities that are often beyond the control of the urban water and wastewater sector, e.g. the numerous substances present in our society –

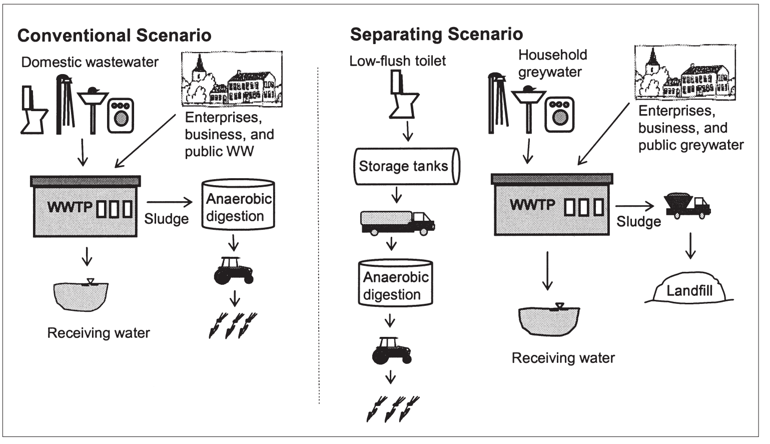

Figure 1. *The system boundaries for and the design of both wastewater management scenarios studied in a comparative SFA in the town of Surahammar (8,830 inhabitants).*

102,000 according to 'the White Paper' (Commission of the European Community, 2001). From the various uses of consumer goods and products, traffic, the corrosion of building materials and the urban physical infrastructure, etc., these substances are being channelled to municipal wastewater systems (Palmquist & Hanaeus, 2004).

This paper focuses on a comparative substance flow analysis (SFA) of 16 selected hazardous substances from two wastewater management scenarios in the Swedish town of Surahammar, see Figure 1. From a perspective of municipal environmental management, Burström (1999) claims that SFA can provide important quantitative and qualitative knowledge on the regional metabolism of different substances that support environmental planning and management in municipalities. SFA in municipal environmental management may also assist policy-makers in learning about structural inter-relationships between different socio-economic activities and the surrounding nature. Such an approach may support a shift in perspectives from a traditional end-of-pipe perspective to more systems oriented perspectives linking the using of resources and the spreading of hazardous substances to their underlying causes and driving forces (i.e. consumption), instead of focusing on the actual emissions (Lindqvist & von Malmborg, 2004). For instance, the wastewater treatment plants themselves do not cause eutrophicating emissions of nitrogen and phosphorus to lakes and coastal waters, but it is rather the anthropogenic consumption of animal food and other products in households (Lindqvist & von Malmborg, 2004). Within a wastewater system, SFA describes the substance flows from their various sources, via transport through sewers and treatment at the treatment plant, and eventually from emissions to air, water, and the disposal of solid residues. In a comparative study different wastewater management strategies (scenarios) may be assessed. The results provide a base for chemical risk assessment, give implications for system improvements, and may be used in communication with different stakeholders.

Objectives

The objective of this study was to present and compare the substance flows of 16 selected hazardous substances from two wastewater management scenarios in the Swedish town of Surahammar.

Moreover, the aim was to suggest a possible management approach to interpret and compare the flow of hazardous substances in different wastewater systems.

The two scenarios were: (1) a conventional wastewater system and (2) a source separating grey- and blackwater system (Figure 1). The hazardous substances selected were: Pb, Cd, Hg, Cu, Cr, Ni, Zn, Ag, Pt, Sb, Sn, triclosan, penta brome diphenyl ether (pentaBDE), 4-nonylphenol (NP), bis(2-ethylhexyl) phthalate (DEHP), and the two PAHs anthracene, and benzo(a)pyrene.

Method

In general, the basis of the SFA methodology is to obtain knowledge and understanding of the regional metabolism of a certain (group of) substance(s) within a given system. SFA often focuses on the stocks and flows of, for instance, heavy metals in the system and its surroundings (Lindqvist & von Malmborg, 2004). Basically, an SFA is performed in three phases: Initially, the system and system components to be studied are defined (Figure 1), the stocks and flows of the substance(s) studied are then identified and quantified (Tables 1 and 2), and finally, the quantitative results are interpreted in

Table 1. *Input data used in the SFA.* When multiple data sources were found, a data range was given from which a characteristic value (char. value) was selected for the calculations. References: 1 = Andersson and Jensen (2002); 2 = Baky et al. (2004); 16 = Palmquist (2001); 23 = Vinnerås (2002).

(mg p^{-1}, yr^{-1})	Blackwater			Greywater		
	Range	Char. value	*Ref.*	Range	Char. value	*Ref.*
Pb	8	8	*23*	350–475	413	*2, 23*
Cd	4	4	*23*	15–18	16.5	*2, 23*
Hg	3.6	3.6	*23*	1.5–4	2.8	*2, 23*
Cu	437	437	*23*	2900–3750	3325	*2, 23*
Cr	11	11	*23*	365–475	420	*2, 23*
Ni	30	30	*23*	450–584	517	*2, 23*
Zn	3916	3916	*23*	3650–4745	4198	*2, 23*
Ag	12.1–59.6	36	*1, 16*	2.9–10.6	7	*1, 16*
Pt	0.07–0.21	0.14	*1, 16*	0.6–0.8	0.7	*1, 16*
Sn	221–298	260	*1, 16*	58–66	62	*1, 16*
Sb	1.2–2.7	2.0	*1, 16*	7.7–10.6	9.2	*1, 16*
Triclosan	1.3–25.8	14	*1, 16*	7.7–83	45	*1, 16*
PentaBDE	1.1	1.1	*16*	0.4–8.0	4.2	*1, 16*
4-NP	41	41	*16*	29–92	61	*1, 16*
DEHP	46	46	*16*	620–1400	1010	*1, 16*
Anthracene	<	<	*16*	1.2	1.2	*1, 16*
Benzo(a)pyrene	<	<	*16*	0.7	0.7	*1, 16*

Table 2. *The assumed reduction rates of the processes in the WWTP.* The notation "*In effluent" (%)* shows the percentages of the inflowing substances that were not removed from the water phase during treatment, and thus left the WWTP in the treated wastewater. Degradation rates for the organic substances are presented for the activated sludge (AS) and anaerobic digestion (AD) processes. References: 7 = Federle, Kajser and Nuck (2002); 10 = Johansson (2003); 13 = MacAvoy et al. (2002); 14 = Marttinen et al. (2003); 18 = Paxéus (1999), 19 = Swedish EPA (2002); 22 = Wahlberg (2003).

	Degradation rates %				In effluent %	
	AS*	*Ref.*	AD**	*Ref.*		*Ref.*
Pb	–		–		20	*19*
Cd	–		–		40	*19*
Hg	–		–		40	*19*
Cu	–		–		15	*19*
Cr	–		–		30	*19*
Ni	–		–		75	*19*
Zn	–		–		15	*19*
Ag	–		–		10	*10*
Pt	–		–		75	*#*
Sn	–		–		2	*10*
Sb	–		–		65	*10*
Triclosan	90	*13*	20	*13*	5	*7, 13, 22*
PentaBDE	30	*#*	0	*#*	50	*22*
4-NP	25	*20*	0	*3*	15	*18, 22*
DEHP	29	*14*	20	*6, 8, 14*	6	*18, 14*
Anthracene	50	*#*	55	*21*	28	*18*
Benzo(a)pyrene	30	*#*	45	*21*	14	*18*

* Activated Sludge process ** Anaerobic Digestion process # Assumption

Table 3. *Results from the comparative SFA* – the total substance flows (kg/year) for the two WW management scenarios at the town of Surahammar (8,830 inhabitants) – the *conventional system* (conv) and the *separating system* (sep). The landfill was only part of the separating system (see Figure 1).

kg year^{-1}	Flows into the system			To receiving water		To arable land		To landfill
	Combined ww (conv.)	Greywater (sep.)	Blackwater (sep.)	Conv.	Sep.	Conv.	Sep.	Sep.
Pb	3.71	3.64	0.07	0.74	0.73	3.0	0.07	3.0
Cd	0.18	0,15	0.03	0.07	0.06	0.1	0.04	0.09
Hg	0.06	0.03	0.03	0.02	0.01	0.03	0.03	0.02
Cu	33	29	4	5	4.4	28	4	25
Cr	3.8	3.7	0.1	1.14	1.11	2.7	0.1	2.6
Ni	4.9	4.6	0.3	3.6	3.4	1.2	0.3	1.1
Zn	72	37	35	10.8	5.6	61.0	34.6	31.5
Ag	0.38	0.06	0.32	0.04	0.006	0.34	0.32	0.05
Pt	0.011	0.01	0.001	0.006	0.005	0.002	0.001	0.002
Sn	2.85	0.55	2.3	0.06	0.011	2.8	2.3	0.5
Sb	0.10	0.08	0.02	0.06	0.05	0.034	0.02	0.03
Triclosan	0.52	0.40	0.12	0.03	0.02	0.04	0.1	0.04
PentaBDE	0.05	0.04	0.01	0.02	0.02	0.02	0.01	0.01
4-NP	0.89	0.53	0.36	0.13	0.08	0.6	0.4	0.3
DEHP	9.32	8.92	0.40	0.56	0.54	5.0	0.3	6.0
Anthracene	0.01	0.01	<	0.003	0.003	0.002	<	0.004
Benzo(a)pyrene	0.01	0.01	<	0.001	0.001	0.002	<	0.004

accordance with the purpose of the study, e.g. regarding the potential to decrease the magnitude of a certain flow, or regarding the environmental impact of the flows studied (Table 3). In this study the SFA methodology was applied to structure and analyse the data principally gathered from the literature. From this procedure the substance flows of the 16 selected hazardous substances were calculated and the results interpreted.

Defining the system

The Swedish town of Surahammar was selected for the study. Surahammar is considered an ordinary small Swedish town (8,830 inhabitants), representative of a common Swedish municipality. Of Sweden's 9 million people, approximately 3 million live in small towns with between 200 – 10,000 inhabitants. A typical phenomenon of small Swedish towns, as exemplified by Surahammar, is the gradually decreasing population, meaning that the capacity of urban water and wastewater systems is not fully utilised. A typical condition is the proximity to agricultural areas. In Surahammar, the stakeholders have expressed an interest in the idea of recycling the nutrients from wastewater to arable land.

To achieve a comparative SFA study two different wastewater management scenarios were defined, see Figure 1. The **Conventional Scenario** is a Swedish wastewater system where the combined wastewater is generated from households, businesses, and public facilities. Wastewater from industries and stormwater was not included in the study. The wastewater is transported through a sewer system to the wastewater treatment plant (WWTP), where it is treated mechanically, biologically, and chemically before being discharged into a small river, while the sewage sludge is transported to arable land for use as fertiliser. Apart from minor simplifications, this scenario corresponds to the existing wastewater system in Surahammar.

In the **Separating Scenario** the wastewater system separates the blackwater from the greywater at the source (in the houses), followed by both flows being collected, transported, and treated separately. Blackwater is defined as urine, faeces, flush water, and toilet paper from low-flush toilets (ca. 1 l/flush) and is locally collected in municipal storage tanks and then transported by trucks to a separate anaerobic digestion line at the WWTP. The residue of the anaerobically digested blackwater is transported to agricultural land for use as fertiliser. Greywater is defined as domestic wastewater without any input from toilets, corresponding to wastewater from bathing, showering, hand washing, laundry, and the kitchen sink. The greywater is transported through the sewer system to the WWTP and treated mechanically, biologically, and chemically before its discharge into a small river. The sewage sludge (from greywater treatment) is deposed of at a landfill.

Stocks and flows of the substances

In view of the very large number of chemicals circulating in society today, one study can neither possibly cover them all nor can their known and unknown metabolites be credibly assessed. The SFA was restricted to 16 representative hazardous substances, including metals and organic compounds considered typical for a domestic wastewater system (i.e. they are used in households and appear in wastewater) and for which there was enough data to collect from. According to Palmquist and Hanæus (2004), the selection of hazardous substances in wastewater investigations is complex and the creation of a short comprehensive list of selected substances implies that many simplifications have to be accepted.

The presence of hazardous substances in wastewater

In the second step of the SFA, quantitative data of the selected hazardous substances – their presence in grey- and blackwater, and their reduction rates in the WWTP – was gathered from the literature and our own studies. The SFA input data, expressed as specific mass flows (mg per person and year), are presented in Table 1. The production of greywater was assumed to be 70 % from households and 30 % from businesses and public facilities. Moreover to simplify the substance flow analysis, neither industrial wastewater nor stormwater was assumed to enter the system in either of the cases.

Reduction rates in the wastewater treatment plant

For many substances, data from the separation and degradation processes in the WWTP were difficult to find. The obtained data often represented the concentrations of the substances in (a) raw wastewater from the influent flow to the WWTP and (b) in the effluent treated wastewater – providing the WWTP's overall reduction rates. Thus, the processes in the WWTP were regarded as an entity (a black-box model), whose reduction rates are presented in Table 2. The notation *in effluent (%)* in Table 2 shows the portions of the incoming substances not removed from the water phase during treatment, and thus leaving the WWTP in the treated wastewater. For instance, it was assumed that 20 % of the influent lead (Pb) would be emitted from the WWTP to the receiving water, while 80 % would end up in the sludge (Swedish EPA, 2002). However, some degradation of organic substances was expected in the activated sludge (AS) and anaerobic digestion processes (AD) (Table 2), e.g. for 4-nonylphenol (4-NP), 15 % of the influent amount was estimated to be emitted to the receiving water (Paxéus, 1999; Wahlberg, personal comm.). Of the 85 % surplus amount 4-NP, 25 % will be degraded in the activated sludge process (Tanghe et al., 1998) and 0 % in the anaerobic digestion step (Bruno et al., 2002). Thus, 64 % of the incoming 4-NP will eventually end up in the sludge to be later transported to arable land for use as fertiliser (in the Conventional Scenario).

Results and discussion

In the third phase of the SFA the quantitative results were interpreted as follows: the substance flows (kg per year) of the two scenarios were compared regarding (a) the substance flow entering the system, (b) the emissions of hazardous substances to the receiving water, (c) the emissions of hazardous substances to arable land, as well as (d) the substance flows disposed of at the landfill, see Table 3.

A Barriers Approach

As mentioned, wastewater is a complex and variable matrix of numerous substances, reflecting the chemicals society uses. The wastewater quality could, therefore, be considered somewhat as a 'given' parameter that varies over time and is uncontrollable. A *barrier approach* is here proposed as a tool for the management of hazardous flows in wastewater systems. As per the Oxford English Dictionary (2004), a barrier is defined 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 comprehending the hazardous flows throughout the wastewater system to find out if and to what extent hazardous substances can be stopped, diverged, or transformed at the source or during transport throughout the system. Four levels of barriers were suggested:

- *Organisational barriers* include legislation and administrative measures
- *System barriers* relate to the design of the wastewater system. An example of alternative system design is source separation of wastewater (urine, faeces, greywater, and stormwater) compared to systems with combined flows from numerous sources. The system design determines in which wastewater flows the substances end up.
- *Process barriers* include the treatment processes in the WWTP. These are physical barriers such as mechanical, biological, and chemical treatment processes.
- *Behavioural barriers* include the users' perspective. Do barriers for hazardous flows already exist in households and at other users, e.g. businesses and public facilities? Which consumer goods and products are consumed in the households? Does the level of knowledge, information campaigns etc. have any effect on people's water related behaviour?

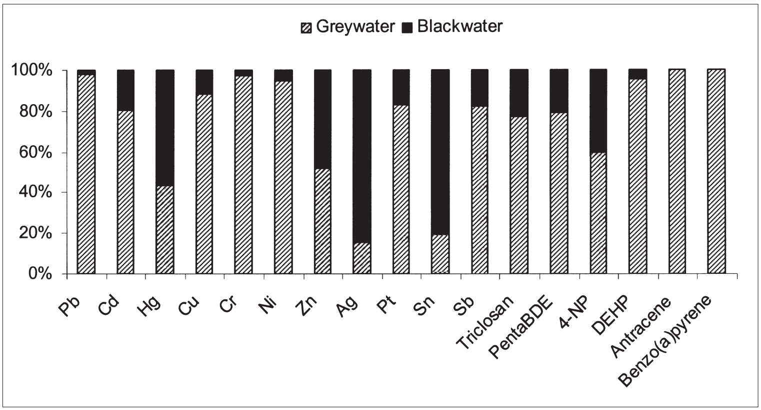

Figure 2. *Distribution of the selected hazardous substances between greywater and blackwater.*

Assessing two types of barriers or critical points where the investigated hazardous substances were stopped, diverged, or transformed was feasible from the two scenarios in Surahammar. Different *system designs* in the two scenarios, and the *process barriers* as represented by the mechanical, biological, and chemical treatment processes in the WWTP, were identified and quantified. The additional two types of barriers suggested – *organisational and behavioural barriers* – were found fundamentally different from the other two, as they required totally different investigation methods and have therefore not been further investigated in this study.

System barriers

Different system designs direct substances into either combined or separate wastewater flows. Figure 2 shows the wastewater content of the selected hazardous substances and their distributions in the grey- and blackwater fractions. The studied substances predominantly emerged in the greywater, with the exception of Ag and Sn subsisting to about 80 % in blackwater, and Hg, Zn, and 4-NP occurring between 40–60 % in the blackwater. The remaining 12 substances subsisted between 0–20 % in the blackwater.

By combining the grey- and blackwater, the Conventional Scenario caused higher flows of hazardous substances to end up on arable land (by the sludge) than the source separated blackwater from the Separating Scenario, see the results in Table 3. However, in the Separating Scenario, parts of the hazardous flow were instead directed to the landfill, which indeed relieves the pressure on the water and arable soil recipients, but instead transports the hazardous substances to another place.

For the emissions of hazardous substances to the receiving water, no considerable distinction could be made between the two scenarios. However, Kärrman *et al.* (2004) claim that changing from a conventional wastewater system to a separating system in Surahammar would imply decreased emissions of eutrophicating nutrients to the receiving water. A separating system would consequently allow significant amounts of nitrogen, potassium, and sulphur to be recycled to arable land, see Table 4.

Process barriers

Process barriers were represented in this application by the mechanical, biological, and chemical treatment processes in the WWTP. Figure 3 shows the distribution of the studied substances in the sludge and treated effluent wastewater after passing through the WWTP. Ni, Pt, Sb, and pentaBDE were the only substances with 50 % or more staying in the water phase. For the remaining 13 substances, 60–98 % ended up in the sludge.

Within the WWTP, the biological treatment processes – activated sludge and anaerobic digestion – provided degradation of the organic hazardous substances to various extents. According to Figure 4, triclosan, PentaBDE, and 4-NP were noticeably biodegraded more efficiently under aerobic conditions than anaerobic conditions, where triclosan showed the highest biodegradability of 90 % (McAvoy *et al.*, 2002). DEHP and the PAHs were almost equally efficiently degraded under aerobic and anaerobic conditions, see Figure 4.

Table 4. *Potential recycling of nutrients to arable land expressed as percentage of the nutrients flow entering the wastewater system.* From Kärrman et al. (2004).

	P	N	K	S
Conventional Scenario	86 %	5.3 %	14 %	5.4 %
Separating Scenario	66 %	74 %	70 %	30 %

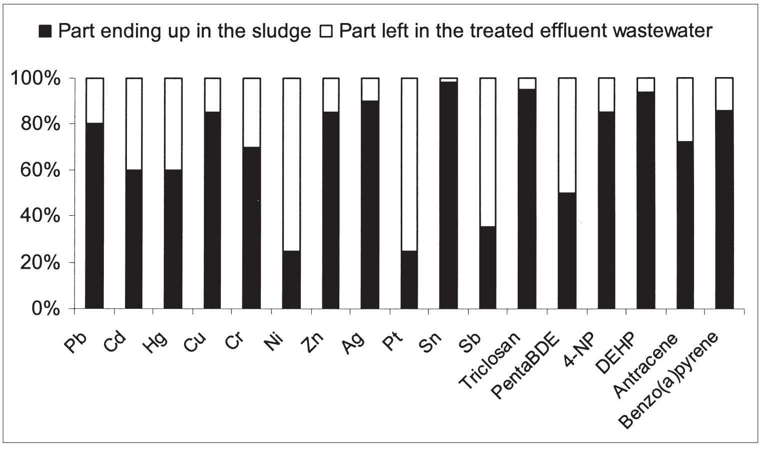

Figure 3. *Distribution of the studied substances in the sludge and in the treated effluent wastewater after the passage of the WWTP.*

The functions of the treatment processes as well as their potential performances are an important knowledge base for assessing and comparing different wastewater scenarios. For instance, triclosan was the only substance with a lower emission to arable land from the conventional scenario, possibly explained by the high degradation rate for triclosan in the activated sludge process (in the WWTP). The blackwater, however, did not pass the activated sludge process at all and was only treated in the anaerobic digestion step, with a degradation rate of 20 % for triclosan (McAvoy et al., 2002).

A relevant shortcoming of the SFA methodology applied in wastewater systems concerns the fate of the organic substances under investigation. When organic substances decompose (e.g. during treatment), metabolites are formed, though which metabolites are formed and their potential effects are not fully predictable neither inside the defined system nor in the recipients outside the system. Thus, formed metabolites cannot be evaluated with the SFA method unless a huge number of substances are incorporated in the study – covering both the parent substances and all their potential metabolites. If this is done, much more often difficult to find quantitative data is needed.

Combined barrier effect

It is not only important to identify each barrier within a defined system, but also assess the combined effects from all existing barriers. Evaluating the combined barrier effect implies considering the whole chain of barriers backwards from the actual receivers of the hazardous substances (the end-points), e.g. the receiving water, arable land, and landfill. To obtain the combined barrier effect, the reduced amounts of each barrier is multiplied at the end-points of the system. Figure 5 shows the combined barrier effects for the case of Surahammar, issued from the end-points (A) emission to water and (B) emission to arable land.

Emissions to water

The combined barriers effect regarding the emissions of the selected hazardous substances to water averaged 72 ± 24 % for the conventional scenario and 77 ± 22 % for the separating scenario, see Figure 5 (A). Thus, the difference between both scenarios was negligible, though the tendency was a slightly higher barrier protection in the separating scenario. Ni, Pt, Sb, and pentaBDE were the exceptions with effects not exceeding 60 %. According to Figure 3, those substances mostly re-

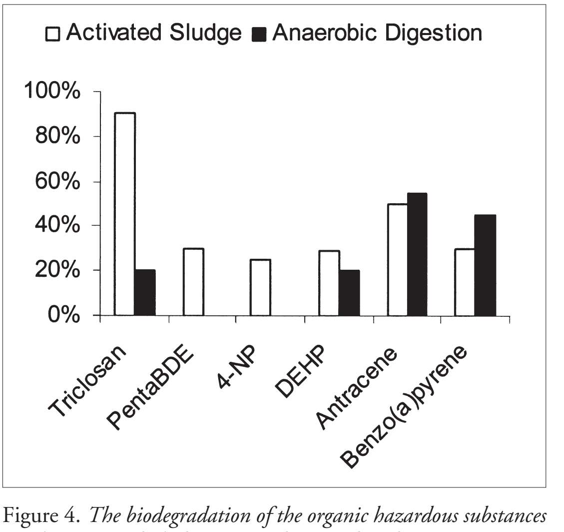

Figure 4. *The biodegradation of the organic hazardous substances in the activated sludge step and anaerobic digestion step.* For PentaBDE and 4-NP no biodegradation was expected under anaerobic conditions (see Table 2).

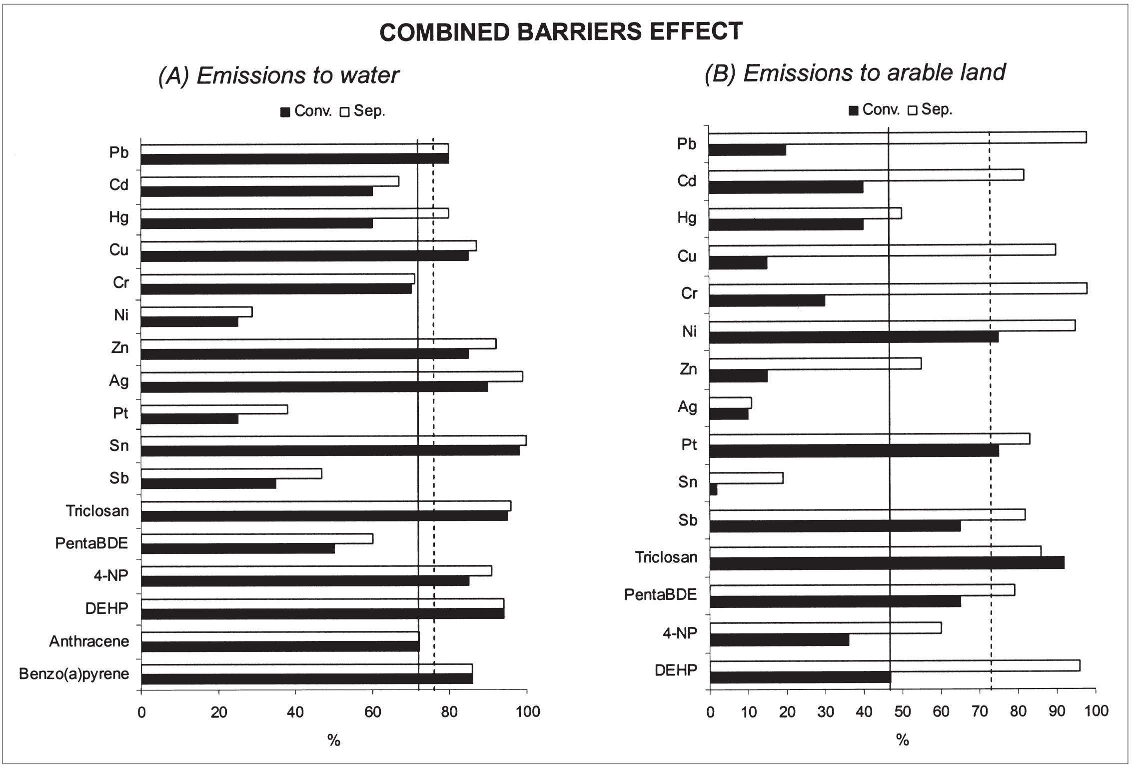

Figure 5. *For the system barrier and process barriers, the combined barriers effects were presented for the end-points (A) the receiving water and (B) the arable land.* The average combined barrier effects are marked in the diagrams by a vertical black line for the Conventional Scenario (–––) and by a vertical dotted line for the Separating Scenario (- - - -). The combined barrier effects for emissions to arable land could not be evaluated for the two PAHs because of lack of data.

mained in the water phase after treatment in the WWTP. In Surahammar, 18 kg year^{-1} Cd, 0.94 kg year^{-1} Hg, and 200 kg year^{-1} each of both Cu and Pb were in total from the local emissions to the receiving water (a small river) (Kärrman *et al.*, 2004), meaning that the wastewater system contributed 0.4 % Cd, 2 % Hg, 2.5 % Cu, and 0.4 % Pb (Conventional Scenario) of the total anthropogenic metal flux to the receiving water and 0.3 % Cd, 1 % Hg, 2.2 % Cu, and 0.4 % Pb in the Separating Scenario.

Emissions to arable land

The combined barriers effect regarding the emissions of hazardous substances to arable land averaged 47 ± 27 % for the conventional scenario and 73 ± 27 % for the separating scenario. Here, the differences between both scenarios were notably larger. The separating scenario provided higher barrier protection to the arable land for all substances except triclosan, which was effectively suppressed by aerobic biodegradation in the activated sludge process in the conventional scenario (Figure 5B). The barrier protection against Ag and Sn was weak in both scenarios (see Figure 5), possibly due to these substances occurring predominantly (80 %) in the blackwater (Figure 2) and the high degree of capture into the sludge in the WWTP (Figure 3) – two paths for transportation to arable land.

When the degree of barrier protection of certain cases is found to be weak, extended assessments may be necessary to fulfil an adequate base for decision making, i.e. to find out if poor barrier protection also implies high chemical risks. In the case of Surahammar, the mass flows of Ag to arable land were about 0.3 kg per year in both scenarios, and 2.8 kg per year in the conventional and 2.3 kg per year in the separating scenario for Sn, see Table 3. However, to evaluate any plausible chemical risks posed by quantified mass flows of hazardous substances, much complementary data is still needed, e.g. the toxicity of the substances in soil based systems, the area of the agricultural fields, the specific provision of fertiliser, etc. Such a risk assessment was beyond the scope of this article.

However, high levels of barrier protection do not guarantee chemical safety. Substances passing through the barriers even in very small amounts, but which are very toxic to the receiving environment, may pose a more severe risk than high volume substances with lower toxicity.

The evaluation of the comparative SFA of hazardous substances by applying a barriers perspective implied that a change from a conventional wastewater system to a source separating grey- and blackwater system in Surahammar would have a greater impact for the management of solid residues (i.e. the emissions to arable land) than for the effects in the receiving waters. The flow of hazardous substances to the receiving water would not be significantly affected by such a systems change.

Conclusions

In a comparative substance flow analysis, two wastewater management scenarios in the Swedish town of Surahammar were assessed – a Conventional Scenario vs. a Separating Scenario. The Conventional Scenario caused an overall higher flow of the selected hazardous substances to the receiving environment, i.e. the receiving water and the arable land. In the Separating Scenario parts of the hazardous flow were directed to the landfill.

In the Separating Scenario the studied substances predominantly emerged in the greywater with the exception of Ag and Sn that subsisted to about 80 % in blackwater, and Hg, Zn, and 4-NP that occurred between 40–60 % in the blackwater. The remaining 12 substances subsisted between 0–20 % in the blackwater.

It was suggested to use a management approach to interpret and compare different wastewater systems – serving to find out if and to what extent the flow of hazardous substances can be stopped, diverged, or transformed at the source or during transport throughout the system. In the barriers approach, system barriers (sb), process barriers (pb), organisational barriers (ob), and behavioural barriers (bb) were suggested, but only the systems and process barriers were assessed in this study.

The combined barrier effect (sb and pb) encompassed the whole chain of barriers backwards from the actual receivers of the hazardous substances (the end-points), such as the receiving water, the arable land, and the landfill.

Regarding emissions of hazardous substances to the receiving water, the difference between both scenarios was small, though with a slightly higher barrier protection in the Separating Scenario. The substances remaining to a high degree in the water phase after treatment in the WWTP and thus carried to the receiving water to a higher degree were Ni, Pt, Sb, and pentaBDE.

In general, the Separating Scenario provided a significantly larger barrier protection to arable land than the Conventional Scenario. Substances occurring predominantly in the blackwater (in the Separating Scenario) and substances that to a high degree were captured in the sludge in the WWTP (in the Conventional Scenario) were passed on to arable land. Hence, the overall barrier protection of the arable land was low for substances with those characteristics.

The evaluation of the SFA and the combined barriers effects in Surahammar implied that a change from a conventional wastewater system to a source separating grey- and blackwater system would have a greater impact for the management of solid wastewater residues than for the effects in the receiving waters.

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References

Andersson, A. and Jensen, A., 2002. Flows and composition of greywater, urine, faeces and solid biodegradable waste in Gebers. Uppsala: Department of Agricultural Engineering, Swedish University of Agricultural Sciences. Master thesis 2002: 05. ISSN 1101-0843 (In Swedish)

Baky A., Jönsson H., Hellström D., Jeppsson U. and Kärrman E., 2004. Composition of urine, faeces, greywater and biowaste for utilisation in the URWARE model. Urban Water Report 2004: x, Chalmers University of Technology, Göteborg, Sweden (to appear).

Bruno, F., Curini, R., Di Corcia, A., Fochi, I., Nazzari, M., and Samperi, R., 2002. Determination of surfactants and some of their metabolites in untreated and anaerobically digested sewage sludge by subcritical water extraction followed by liquid chromatographymas spectrometer. *Environmental Science & Technology*, **36**(19), 4156–4161.

Burström, F., 1999. Materials accounting and environmental management in municipalities. Journal *of Environmental Assessment Policy and Management*, **1**(3): 297–327.

Commission of the European Communities of 27 February 2001. The WHITE PAPER – Strategy for a future Chemicals Policy, Brussels, Belgium.

Ejlertsson, J., Nilsson, M-L., Kylin, H., Bergman, A., Karlsson, L., Öquist, M. and Svensson, B.H., 1999. Anaerobic degradation of nonylphenol mono- and diethoxylates in digestor sludge, landfilled municipal solid waste, and landfilled sludge. *Environmental Science & Technology*, **33**(2), 301–306.

Federle, T.W., Kajser, S.K. and Nuck, B.A., 2002. Fate and effects of triclosan in activated sludge. *Environmental Toxicology and Chemistry*, **21**(7), 1330–1337.

Hartmann, H. and Ahring, B.K., 2003. Phthalic acid esters found in municipal organic waste: enhanced anaerobic degradation under hyper-thermophilic conditions. *Water Science & Technology*, **48**(4), 175–183.

Hellström, D., Hjerpe, M., Jönsson, H., Malmqvist, P-A. and Palmquist, H., 2004. Implications of ecological sustainability for urban water management. *VATTEN*, **60**(1): 33–41.

Johansson, P. (2003). *Personal communication*. Contact: Stockholm Water Company, SE-106 36 Stockholm, Sweden.

Kärrman, E., Baky, A., Jeppsson, U., van Moeffaert, D., Jönsson, H. and Hellström, D., 2004. Environmental systems analysis for sustainable wastewater and organic waste management in a country town in Sweden. *Manuscript*.

Lindqvist, A. and von Malmborg, F., 2004. What can we learn from local substance flow analyses? The review of cadmium flows in Swedish municipalities. *Journal of Cleaner Production*, **12**: 909–918.

McAvoy, D.C., Schatowitz, B., Jacob, M., Hauk, A., and Eckhoff, W.S., 2002.Measurement of triclosan in wastewater treatment systems. *Environmental Toxicology and Chemistry*, **21**(7), 1323–1329.

Marttinen, S.K., Kettunen, R.H., Sormunen, K.M. and Rintala, J.A., 2003. Removal of bis(2-ethylhexyl) phtalate at a sewage treatment plant. *Water Research*, **37**(6), 1385–1393.

"Barrier, n.". Oxford English Dictionary Online. 6 Sep. 2004. <http://dictionary.oed.com/>

Palmquist, H., 2001. Hazardous Substances in Wastewater Systems – a delicate issue for wastewater management. Luleå: Div. of Sanitary Engineering, Luleå University of Technology. Licentiate Thesis 2001:65

Palmquist, H. and Hanæus, J., 2004. A Swedish overview of selecting hazardous substances as pollution indicators in wastewater. *Management of Environmental Quality: An international Journal*, **15**(2): 186–203.

Paxéus, N., 1999. Organic pollutants in wastewater from municipal wastewater treatment plants (Organiska för(or)eningar i avloppsvatten från kommunala reningsverk), The Swedish Water and Wastewater Association, Stockholm, Sweden, VA-FORSK report 1999•12. (In Swedish)

Swedish EPA, 2002. Aktionsplan för återföring av fosfor ur avlopp (Action plan for recycling of sewage phosphorus). Stockholm: Swedish Environment Protection Agency, Report 5214. (In Swedish – English summary and conclusions)

Tanghe, T., Devriese, G. and Verstraete, W., 1998. Nonylphenol degradation in lab scale activated sludge units is temperature dependent. *Water Research*, **32**(10), 2889–2896.

Trably, E., Patureau, D., and Delgenes, J.P., 2003. Enhancement of polycyclic aromatic hydrocarbons removal during anaerobic treatment of urban sludge. *Water Science & Technology*, **48**(4), 53–60.

Wahlberg, C., 2003. *Personal communication*. Contact: Stockholm Water Company, SE-106 36 Stockholm, Sweden.

Vinnerås, B., 2002. Possibilities for sustainable nutrient recycling by faecal separation combined with urine diversion. Uppsala: Dept. of Agricultural Engineering, Swedish University of Agricultural Sciences. Doctoral Thesis Agraria 353. ISSN: 1404–6249