VA-teknik
CHALMERS

CHALMERS UNIVERSITY OF TECHNOLOGY
Department of Sanitary Engineering
S-412 96 GÖTEBORG
Sweden
Telephone Nat 031 - 772 10 00
Int +46 31 772 10 00

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LICENTIATE THESIS

Analysis of Waste Water Systems, with Respect to Environmental Impact and the Use of Resources

ERIK KÄRRMAN

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Abstract

The studies that comprise this licentiate thesis have two objectives: 1) to evaluate the environmental aspects and the resource management of various types of waste water systems, 2) to study various concepts (methodologies) for system choice when planning a new or change an existing waste water system. These objectives have been studied in a few projects, documented in four papers, presented as appendices to this report.

An introductory work was initiated as a study of existing waste water systems in Sweden, using a wide range of technologies to establish a methodology to evaluate the capacity of environmental protection, nutrient recycling and functional aspects. The case studies contain three conventional waste water systems with sewers and treatment plants and three alternative systems: a waste water irrigation system, a constructed wetland and a system with earth closets and separated treatment of grey water in a system with constructed wetland and a sand filter. The study showed that the systems were mainly constructed for reasons of environmental protection and sanitation. The criteria of nutrient recycling has been less considered. The existing system has great potential for phosphorus recycling, but the residuals are not often used as fertilizers. The use of energy for operation is greater in a waste water treatment plant than for treatment in sand filters or ponds. Earth closets including a heating system and a fan were the most electricity-consuming example. The treatment plants studied needed less land-area and had economic advantages compared with the small scale treatment examples. It should be noted that local conditions could impact on the results considerably, and the technical solutions are therefore not easily compared.

None of the six systems studied in the initial study was constructed for nitrogen recycling. One strategy for this is to handle urine separately and use it as a fertilizer for agricultural applications. Urine is the largest contributor of nutrients to waste water, estimated as 50% of phosphorus and 80% of nitrogen. From an investigation, average values of nutrient concentrations were 1.0 g P/person,day and 13 g N/person/day. Studies of daily variation showed that most of the nutrients appear in urine produced at home between 5:00 p.m. to 8:30 a.m. Urine separation is promising in terms of environmental protection aspects, and urine is also a high quality fertilizer. However a lot of research and development remain to be done before one could consider implementing urine separation systems.

Studies of methodologies for system choice mainly concern the concept of Environmental Impact Assessment (EIA). The demand of an EIA, according to Swedish environmental laws, is to permit an overall assessment of the impact of a planned installation, activity or measure on the environment, health and conservation of natural resources. EIA studies were carried out in Bergsjön and Hamburgsund, where the existing conventional waste water systems were compared to local treatment of mixed waste water and local treatment with urine separation. The urine separation system is favourable because of the comparatively low use of natural resources (lowest energy use, largest recycling of nutrients) and low degree of eutrophication. A deeper analysis of the energy aspects of the alternatives in Bergsjön,was carried out with an exergy analysis. The study shows that the hypothetical calculated exergy consumption during operation will be lower in a system with local treatment and urine separation toilets than in a conventional alternative.

Sammanfattning

De studier som har ingått i föreliggande licentiatuppsats har haft två övergripande syften 1) att utvärdera förmågan till miljö- och resurshänsyn i olika befintliga avloppssystem, 2) att studera olika utvärderingsmetoder som kan användas för att välja teknisk systemlösning när ett nytt avloppssystem skall anläggas eller ett befintligt skall förändras. Flera delprojekt har utförts, vilka finns redovisade i rapportens fyra appendix.

Ett inledande arbete initierades för att studera befintliga svenska avloppsanläggningar med ett brett spann av olika typer av teknik. Ett syfte med arbetet var att utveckla en metodik för utvärdering av miljöskydd, resurshushållning och driftsaspekter. De studerade anläggningarna bestod av tre konventionella system med ledningsnät och reningsverk och tre alternativa system: ett system med bevattning av lagrat avloppsvatten, en rotzons-anläggning och slutligen ett system med torr hantering av toalettavfall och behandling av bad- ,disk- och tvättvatten i ett system av rotzonsanläggning och markbädd. Studierna visade att anläggningarna i första hand är utformade med hänsyn till miljöskydd och hygien. Mindre hänsyn tas till återvinning av näringsämnen i avloppsvatten. De flesta befintliga system har trots allt en god förmåga att avskilja fosfor, men det är inte så ofta som de fosforrika restprodukterna används som gödselmedel i jordbruket. Energi-användningen är större i storsskaliga reningsverk än i småskaliga behandlingsanläggningar som filterbäddar eller biodammar. Torra toaletter med uppvärmning och fläkt för att avdunsta vatten är den mest elförbrukande lösningen av de studerade. Exemplen innehållande avloppsreningsverk kräver mindre ytor och är mer kostnadseffektiva än de småskaliga exemplen. Det bör dock noteras att de lokala förutsättningarna i hög grad påverkar resultatet av jämförelserna.

Ingen av de sex studerade anläggningarna är utformad för återvinning av kväve. Ett sätt att återvinna en stor del av näringsämnena i avloppsvatten är att källseparera urin. Urin är den största källan till näringsämnena i avloppsvattnet, uppskattad som 50% av fosfor- och 80% av kväveinnehållet. En undersökning av insamlade dygnsprover gav i medeltal 1.0 g P/person,dag och 13 g N/person,dag. Dygnsvariationer studerades också. Resultaten visade att de personer som ingick i studien utsöndrade merparten av kväve och fosfor i urinen under den tid de var hemma på dygnet. Urinsorterande system är en lovande teknik, men mycket forskning och utveckling återstår innan systemen kan implementeras på bred front.

Metodikstudierna gällande systemval var koncentrerade kring Miljökonsekvens-beskrivningar, (MKB). Enligt svenska krav ska en MKB möjliggöra en samlad bedömning av en planerad anläggnings, verksamhets eller åtgärds inverkan på miljön, hälsan och hushållningen med naturresurser. MKB-studier utfördes på avloppshanteringen i två orter; Bergsjön och Hamburgsund. Dagens system jämördes med alternativen lokal behandling av avloppsvattnet i filterbäddar och urinsorterande system. MKB-studierna visade att de urinsorterande sytemen var fördelaktigast p g a lägst resursanvändning och minst bidrag till eutrofiering. Även en exergianalys utfördes på fallstudien Bergsjön. Studien visade att exergianvändningen, med givna antaganden, är lägre i ett urinsorterande alternativ än i det befintliga systemet.

Preface

This licentiate project has been financed by the Swedish Council for Building Research (BFR). Extracts from an additional research project, *ECO-GUIDE,* is also included. The *ECO-GUIDE* project was financed by BFR, VA-FORSK at the Swedish Association of Water and Sewage Works (VAV) and the Council for Planning and Coordination of Research (FRN).

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Erik Kärrman, Göteborg, March 8, 1997.

Contents

1. Background

1.1 Short historical background

The handling of waste water has been a topic for discussion in Sweden and in other countries, throughout the 1990th. The discussion has been focused on environmental aspects and the consumption of resources. The existing waste water systems have also been developed during the last hundred years, as the water closet was first introduced in the early years of the 20th century. The reason for this was on the first hand to improve sanitary conditions. The water closet improved the sanitary conditions but caused environmental problems in the receiving waters. However, water driven systems have been developed and enlarged gradually since then. In 1990, Sweden had the most advanced treatment of waste water of the European countries (SCB 1995), see table 1.

Table 1. Waste water treatment of different European countries of the year 1990 (extract from SCB 1995).

	% of households connected to a waste water system	Part with primary treatment[1]	Part with secondary treatment[2]	Part with advanced treatment[3]
Sweden	95	1	10	84
Denmark	98	8	69	21
Finland	76	0	0	76
Norway	57	13	1	43
Netherlands	93	1	83	8
Spain	53	11	38	4
Great Britain	97	8	65	14
Germany	86	6	50	30
Latvia	69	20	48	..

1) Mechanical treatment
2) Biological treatment with 90% removal of organic matter *or* chemical treatment (phosphorus removal).
3) Biological-chemical treatment, supplemented with nitrogen removal, etc.

At the time when water driven systems were implemented, the efforts shifted from trying to improve the sanitary conditions in towns to dealing with the environmental problems in the receiving waters. Treatment plants were built to remove organic matter and nutrients before discharge to a lake or the sea. The requirements regarding purification has increased gradually and are still increasing. Today, there are several international conventions to protect specific seas or sea areas. Sweden has ratified the Paris and Helsinki Conventions. The aims of these conventions include protection of the North Sea and the Baltic Sea. The countries that have signed up these conventions, are subject to requirements concerning discharges of nitrogen, phosphorus and heavy metals. The large coastal waste water treatment plants in Sweden today have to halve the discharges of nitrogen, from the 1985 level. Table 1 shows that a very large number of the Swedish treatment plants, by 1990 had biological chemical treatment, supplemented with nitrogen removal, etc. One conclusion from these statistics is that large investments have been made lately to improve the existing sanitary systems. This should be borne in mind when the potential of alternative systems are further discussed.

The UN environmental conference held in Rio de Janeiro in 1992 also gave input to the discussions of sanitary systems. The Rio declaration and Agenda 21 were formed at this conference. Agenda 21, an action plan for the 21st century, aims to deal with the main environmental problems and to provide support for a sustainable development.

The existing waste water systems are discussed in a sustainability perspective. The systems have been critizised for insufficient economization with materials and energy. It is well known today that phosphorus is a limited resource and must be recycled in the future. Today the phosphorus from human urine and faeces is removed from waste water in the treatment plants and will consequently be found in the sewage sludge. It is not unusual that the sludge is disposed at a landfill either because it is contaminated with heavy metals or because farmers prefer other fertilizers. Phosphorus from apatite is instead used in the agriculture. Apatite is taken from mines and is a limited resource. With today´s technique of mining and today´s consumption, there will only be enough apatite resources to last 150-200 years (Fredrikson 1994). Phosphorus is therefore the substance from waste water that is the most urgent to start recirculating, but nitrogen, potassium, carbon, sulphur and micro-nutrients are also essential to agriculture.

The two most important topics in the waste water debate are the protection of receiving waters and the economization with nutrients. Below, a few examples from the debate in Sweden are presented. It should be noted that these are examples and not a comprehensive review of the debate.

Guterstam and Ridderstolpe (1991) wrote that the present sewerage system is built without taking account recycling of resources. Urine with very high concentrations of nutrients is mixed with large volumes of waste water from bathing, dish and laundry. A large number of the 90 000 chemical products, used in Swedish society can be found in the mixed waste water from domestic and industry use. Anders Schönbäck, ex-head of the Environmental and Health Department of the municipality of Tanum says: the water closet will never serve as an economically or ecologically good solution (Schönbäck 1994). Schönbäck took part in a decision where connections to the sewerage system were no longer allowed for new buildings in Tanum. Wolgast (1992) adds a hygienic aspect to the debate of the water driven waste water system. Approximately 99% of bacteria and viruses in waste water are removed in waste water treatment plants. Still 100 millions bacteria and viruses per person and year are discharged to the receiving waters. Lakes and rivers are therefore permanently virus infected, and may contribute to the increase of youth diabetes transmitted via bathing water.

Lind and Peters (1993), on the other hand, say that there are no realistic alternatives today *to waste water treatment plants. No other solution can give the same degree of purification before discharge. The water closet is not a system error according to Balmér (1993). It is, in Sweden where lack of water is not a problem, not a waste of resources to use tap water for transportation of urine and faeces. This would only be the case if the costs were lower to install a double pipe system. Balmér (1993) does not believe in a double pipe system. If the WC were eliminated, the consumption of water would only decrease from 200 to 150 liters per person and day, and there would still be a need for advanced treatment of the remaining waster water, i.e. waste water from bathing, dish and laundry. So there would be no advantages looking at treatment aspects. Larsson (1996) shows that water closets are, in fact, the most favourable alternative for small scale systems. The reasons are the major phosphorus recycling and the low costs.*

The examples show that the debate has become a matter of black and white, with very little understanding of the opponent´s arguments and therefore it is important to investigate the existing system and new systems from a sustainability perspective.

1.2 System analysis of waste water handling

One constructive way of continuing to work with the waste water problem complex is to formulate basic criteria a majority of involved people agree upon. A project of this kind has been carried out by the Swedish Environmental Protection Agency. An initial study, aimed at formulating criteria was carried out through discussions at seminars with a wide range of actors involved in the waste water handling process. The criteria were sorted into the following headings (SNV 1995a):
-Transmission of infections and sanitation
-Environmental impact and efficient use of resources
-Technical and socio-economic criteria

The first heading includes the risk of transmission of diseases and other health aspects. The key to future waste water systems is to achieve effective recycling of resources and at the same time to minimize the risks for survival of viruses and parasites. Under the heading of "Environmental impact and efficient use of resources", it is mentioned that a sanitary system with good environmental protection is very often at a same time a system with effective use of resources. Subcriteria under this heading cover 1) resources in waste water and 2) resources needed for treatment and utilization of residuals. The first category includes: phosphorus, nitrogen, potassium, micro-nutrients, humus, energy and water. The second category includes: receiving waters land and air, energy, resources to produce the system, components and resources for system operation. The subcriteria under the heading of "Technical and socio-economic criteria" are: technical reliability, economy, suitable design for the users, effects on municipal planning and responsibility issues.

Further work is ongoing at the Swedish Environmental Protection Agency to establish quantitative goals that should be fulfilled by the year 2021, for various aspects of the process found under the heading of Environmental impact and efficient use of resources. (SNV 1997, unpublished).

There is also a great need to develop methodologies where system alternatives can be evaluated according to criteria. A literature review from 1994 showed that most comparative studies between various waste water systems only consider one specific aspect (Kärrman 1995a). There were, however, a few studies where more than one parameter was quantified. Jenssen *et al.* (1992) compare various types of so called ecological treatment systems, with an evaluation of around 20 parameters in a three degree scale. There are also studies to be found where existing waste water systems have been compared concerning various aspects, for example treatment capacity, economy, operation and maintenance (Fasteneau *et al.* 1990); *environmental* protection, nutrients recycling, economy, use of land surface and energy (Kärrman 1995b; Kärrman 1996).

A couple of studies have been carried out, during the 1990th, aimed at comparing various system alternatives for waste water treatment for one or two well defined areas. Gujer (1996) compares four concepts of sanitation strategies for the city of Zürich. The comparison regards among others, use of resources (water consumption, chemicals etc.), energy use, possibilities for nutrient recycling and public acceptance. The ECO-GUIDE project (Malmqvist *et al.* 1995) contains studies in two urban areas in Sweden; the Bergsjön suburb of Göteborg and the Hamburgsund village in Tanum municipality. Two alternatives to the existing systems were formulated in each area. The alternatives (including the existing systems) were evaluated and compared with an Environmental Impact Assessment (EIA) (Stenberg *et al.* 1996) and Life Cycle Assessment (Tillman *et al.* 1996). The Bergsjön case has also been evaluated with an exergy analysis (Hellström and Kärrman 1997). Finally, a system analysis of organic waste for the town of Uppsala (Nybrant *et al.* 1996) in Sweden has been carried out with the simulation tool ORWARE (Nybrant *et al.* 1994; Nybrant *et al.* 1996). The system analysis includes 12 different system alternatives for handling of organic waste (including waste water).

In the ECO-GUIDE project (Malmqvist *et al.* 1995), the existing conventional waste water systems were compared to local treatment of mixed waste water and local treatment with urine separation. The present report has a special focus on the EIA study, because this was a subproject of the ECO-GUIDE project in which the author took part.

Environmental Impact Assessment (EIA)

This section describes the EIA study from the ECO-GUIDE project (Stenberg *et al.* 1996). The EIA study was carried out as an EIA study according to Swedish environmental legislation. The demand of such an EIA is to permit an overall assessment of the impact of a planned installation, activity or measure on the environment, health and conservation of natural resources. According to Canter (1993), an EIA study contains six activities after the issues are defined: impact identification, description of affected environment, impact prediction, impact assessment, decision making and communication of results.

The impact identification was done with the support of a checklist, developed from CEQA (1986). The descriptions of the affected environments of Bergsjön and Hamburgsund were made after ocular inspection and studies of maps and documents from the municipalities. The impact prediction was done mainly in a qualitative way. There are a number of possible environmental effects of the waste water system, for example eutrophication of the sea or soil erosion caused by increased flow in the local watercourses in Bergsjön and there are contributions from the system to these effects. Outlets of nitrogen from the system might cause eutrophication, or a large discharge of treated waste water might cause erosion, for example. Because of the difficulties of predicting the effects quantitatively, the simple assumption of "less discharges/emissions, the better" was often used.

The results of an EIA are often presented in a text, discussing assessed possible impacts, and also with comparative tables including quantitative results. In the present study the analysis was taken one step further. The impacts were sorted into three categories:

A. Nature's conditions
B. Human conditions
C. Realization aspects

Category A contains aspects that could have an impact on a sustainable development. Examples from category A were considered the most important, followed by B and C.

A few aspects from category A were assessed as more important than others. This was done according to regional environmental goals (Miljö i väst 1995), where priority was given to 9 environmental problems. The waste water systems could contribute to three of these problems:

Acidification
Use of natural resources
Eutrophication

Identified emissions with a possible impact on these effects were assessed as the most serious. (In a normal EIA process this kind of "valuation methodology" above is not used until the decision-making phase.)

The urine separation system is favourable because of the comparatively low use of natural resources (lowest energy use, largest recycling of nutrients) and low degree of eutrophication (smallest discharges of nutrients to the recipient). In spite of these two aspects, the urine separation system contributes more to the acidification than the other alternatives. The urine separation system includes more transports of residuals and therefore causes greater emissions of sulphur oxides and nitrogen oxides. Eutrophication is, however, valued as more important than acidification, because of the quantities the waste water systems generates in relation to the total anthropogenic impact in the region.

Exergy analysis
One reflection from the EIA study, discussed above, is that there will always be a wide range of different aspects that one have to value in one way or another. One way of studying the use of resources with a single parameter is to carry out an exergy analysis. Exergy is the part of energy that is convertible into all forms of energy (Wall 1977).

This section consists of a summary of the exergy analysis of the Bergsjön case study (Hellström and Kärrman 1997). The study includes the following calculations:
- Exergy analysis of heat transportation in sewage

- Analysis of the chemical exergy of organic matter, nutrients and exergy of chemicals and electricity needed for operation.

The energy value of the sewage, in terms of heat, is calculated as the temperature difference between the sewage and the ambient air times the heat capacity of water. The exergy is then calculated as the energy times the Carnot factor. It should be noted that no energy or exergy is available if the ambient temperature is higher then the sewage temperature (Hellström 1997). The result shows that the largest input of exergy to a sewerage system, during operation, is attributable to heating of tap-water.

Considering the flows related to handling of organic matter and nutrients, it is obvious that the flows of organic matter dominate. It is also shown that the possibilities of recovering some of the exergy as methane gas will have a strong influence on the total exergy consumption needed for operation. In comparison with the flow due to nutrients it is obvious that the flow due to phosphorus is almost insignificant, while the flow due to nitrogen has a significant impact on the results. This reflects the statement that one important reason to recycle nitrogen is the large amount of exergy needed to produce nitrogen fertilizer.

The study of the alternatives in Bergsjön (Malmqvist *et al.* 1995) shows that the hypothetical calculated exergy consumption during operation will be lower in a system with local treatment and urine separation than in a conventional alternative.

Comparisons of different system studies

A contextual and methodological comparison was carried out between Environmental Impact Assessment (EIA) and Life Cycle Assessment (LCA), based on the ECO-GUIDE case studies (Tillman *et al.* 1997). This report shows that the two concepts cover slightly different aspects, although there are overlaps. EIA considers local impacts such as noise, smell and effects on local creeks where treated waste water is discharged. The EIA also discusses effects of land use, an aspect that the LCA does not cover. The LCA on the other hand contains a more systematic evaluation of the use of natural resources and global environmental impacts than the EIA.

There were also some differences between the system boundaries used. In the EIA, the analysis was delimited to the following activities: collection and transport of waste water, transport to storage or treatment, production and transport of resources needed for the operation of the system, discharge to receiving waters and improvement and transport of residuals. The building of the systems has only been analysed for energy use.

The LCA was divided into a core system and an enlarged system. The system boundaries of the core system are similar to those chosen in the EIA. The enlarged system also considers the impact on other technical systems as an effect of the various waste water techniques. Affected systems include: tap water production, energy use (heating systems for buildings, electricity production, *etc.*) and the use of mineral fertilizers in agriculture.

The comparison between alternatives in the LCA and the EIA was done in different ways. The LCA was done with an argumentative, verbal, qualitative evaluation (made by the analyst). The evaluations were, however, supported by three formal quantitative weighting procedures: the EPS method, the environmental theme valuation method and the ecological scarcity method. In the EIA an initial sorting of the different aspects was done. A category with the most important aspects was first sorted out using the socio-ecological principles formulated in Holmberg (1995). The further evaluation was carried out taking into consideration regional environmental goals and, finally, the alternatives contribution to an environmental effect compared with the total contribution of anthropogenic activities to the effects in the region, *i.e.* the higher the contribution from the waste water system - the higher priority.

The EIA and the LCA did not come to the same ranking between the alternatives in Bergsjön and Hamburgsund, although the urine separation system was found to be preferable in both Bergsjön and Hamburgsund in both the EIA and the LCA.

When comparing all the system studies, described in the beginning of this chapter, some noteworthy similarities and differences were found.

The ORWARE project (Nybrant *et al.* 1994; Nybrant *et al.* 1996) has a lot in common with the LCA study of ECO-GUIDE. The system boundaries are very similar to the core system (see above). One difference between the studies is, however, that the ORWARE case study (Nybrant *et al.* 1996) pay attention to all organic waste produced in the society, and not only to waste water. ORWARE is a computer based simulation tool, and can more easily evaluate a larger number of alternatives compared with in an LCA.

The study of Gujer (1996) is the most delimited analysis of the studies mentioned in this chapter. It is an energy analysis of different waste water handling. The study contains a comparison of the energy use with different types of waste water handling.

In the ECO-GUIDE and ORWARE projects the urine separation alternative consists of source separated urine and a separate pipe system to storage tanks outside the buildings. In spite of Gujer´s example, this type of system is today running in several small scale applications.

In the criteria from SNV (1995a), it was expressed that three main criteria should be considered when a waste water system is analysed: 1) Transmission of infection and sanitation, 2) Environmental impact and efficient use of resources, and 3)Technical and socio-economical criteria. In all studies discussed in this chapter Environmental Impact and Efficient use of resources are carefully analysed, but none of the studies includes methods for assessment of risks for transmission of infection and sanitation. None of the studies takes into account Socio-economic criteria such as technical reliability, economy, suitable design for the users, effects on municipal planning and responsibility issues.

All the studies mentioned in this chapter have a urine separation system included as a technical alternative. The studies also all show that the urine separation technique have great potential. In The ECO-GUIDE project the urine separation system was found to be the most advantageous in both Bergsjön and Hamburgsund. The ORWARE study of Uppsala did not give a strict answer about "the best technique", but it could be noted that the urine separation alternatives had advantages in terms of nutrients recycling, but on the other hand they require more energy for transport and caused more air emissions than, for example, the conventional waste water system.

The study by Gujer (1996) also shows a great potential for a urine separation alternative, but there is an important system difference compared with ECO-GUIDE and ORWARE: the urine is released to the existing sewer so the urine may be collected at the treatment plant. The urine is preferably released at night when the sewer only contains a low flow with mostly unpolluted infiltration water. The system is favourable compared with traditional systems, compost toilets and a combined alternative. The reasons for this include that the urine separation alternative provides the best waste water composition for efficient treatment, the lowest total electricity consumption, the lowest consumptions of materials and chemicals for operation.

It is, however, noted that several other criteria must be considered before a urine separation system could be chosen for a large settlement in the reality (Gujer 1996; Stenberg *et al.* 1996; Jönsson *et al.* 1996 and Hellström and Kärrman 1997). As mentioned above the studies discussed here mainly consider environmental impact and use of resources. So it could be stated that the urine separation system has a great potential regarding nutrient recycling, minimization of discharges to receiving waters *etc.* Today a great deal remains unknown concerning urine separation systems. Research activities and further evaluations of existing urine separation systems are needed before more general implementation can be recommended. The next chapter discusses the present experience of urine separation systems in greater detail.

1.3 Urine separation systems - state of the art

Today´s system design of urine separation systems is based on source separation. The toilets are equipped with two bowls, one for urine and one for faeces. A small amount of water is used for flushing. Measurements in the community Understenshöjden in Stockholm where the urine separation toilet "Dubletten" has been generally installed, have shown 0.34 liters/person,day (Jönsson *et al.* 1997). For further transport, the urine is led by gravity to underground tanks near the houses. The urine is then transported by truck to agricultural areas for use as a fertilizer. Blackwater (faeces and flush water) can either be treated in local facilities or led to a conventional sewer system. There have been quite a bit of interest in implementing urine separation systems in Sweden. From a questionnaire to the municipalities in Sweden in 1995/96, 68 out of 235 positive answers stated that at least one urine separation system has been implemented in the municipality (Hanæus and Johansson 1996). Experience of these systems is, however, not very well documented. Hanæus and Johansson (1996) investigated the 11 largest of these systems. The experiences from this study showed that the systems were working well. However, a few problems have been identified. These problems can often be assigned to the design and the use of the toilets and the accuracy of the construction of the system. Most of the problems concern unpleasant odour indoors, tedious cleaning of the toilets, troublesome installation of the toilets, high volumes of flush water and seepage into the sewer system.

Urine is the largest contributor of nutrients to household waste water according to SNV (1995b), estimated as 50% of phosphorus and 80% of the nitrogen. A comparison between key values from the literature, a collection study (24-hour samples from 30 adults, one sample per person) and measurements in the urine separation system of Understenshöjden is presented in table 2.

Table 2 Nitrogen and phosphorus in urine and volume urine excreted per person and day.

	Key values (SNV 1995b)	Collection study (Hellström and Kärrman 1996)	Measurements (Jönsson *et al.* 1997)	Measurements (Jönsson *et al.* 1997), re-calculated**
Nitrogen (g/person/day)	11	13	4.9	8.5
Phosphorus (g/person/day)	1	1.0	0.42	0.73
Volume urine (l/person/day)	1.0	1.5	1.0 (1.34*)	1.73 (2.31*)

*Volume urine solution (urine+flush water).
**Recounted to 24-hours values. The inhabitants were at home on an average 13,9 hours per day.

The key values presented in SNV (1995b) are calculated from a combination of data from a mixture of various studies carried out in the years 1939-1963, often containing a very narrow limited test group. Hellström and Kärrman (1996) studied a wider group of people - 15 women and 15 men, ages 23 to 62 years, and conducted that the key values were quite reliable. The Swedish nutrient intake per person has increased during the period 1960-1992 (Becker and Robertsson 1994) and could possibly explain the higher value of nitrogen in the collection study. The higher nutrient intake today should, however, affect the phosphorus value too, but does not. The measurements in the existing system show lower contents of phosphorus and nitrogen than the key values and the collection study. Possible explanations are, according to Jönsson *et al.* (1997): occasionally incorrect separation, many of the inhabitants were children, and many of the inhabitants were vegetarians (vegetables contains less nutrients than animal products).

An important aspect of urine separation is the infection risk. This risk is closely connected to fecal contamination, owing to incorrect source separation of urine. Fecal contamination of urine from full scale tanks was studied by analysing coprostanol (Jönsson *et al.* 1997). The results indicated that there was very little fecal contamination. Olsson (1995) observed that fresh urine is a good substrate for survival of bacteria. Storage is therefore necessary for sanitation before urine is spread on farmlands.

An important aspect concerning nutrients is the conversion of nitrogen. In undiluted fresh urine, most nitrogen can be found as urea, but the conversion to ammonia begins quickly.

A combination of high ammonia concentration and high pH, leads to nitrogen losses owing to ammonia evaporation. Laboratory experiments with undiluted urine indicate small losses of nitrogen, and that the conversion to ammonia is slow (Hellström and Kärrman 1996; Hanæus *et al.* 1996), but measurements in full scale urine pipes and tanks show pH 8-9 and that 79-96% of the nitrogen is present as ammonia (Kirchmann and Pettersson 1995; Olsson 1995; Hellström and Kärrman 1996; Hanæus and Johansson 1996; Jönsson *et al.* 1997 and Hanæus *et al.* 1997). The conclusion is that there is a great risk of ammonia evaporation, when the stored urine is spread on farmlands.

The handling of urine in agriculture has not yet been thoroughly studied. Handling of manure is another research field, where much remains to be done. One could expect that urine should be less effective as a nitrogen fertilizer than mineral nitrogen, while spreading urine always lead to ammonia emissions. In a field study where urine from livestock and mineral fertilizers were spread, no significant differences in yield were found between spreading of urine from livestock or mineral fertilizers (Rodhe and Johansson 1996). Analysis of linear relationships between ammonia release and yield showed that the yield was largely independent of the size of the ammonia emission and no simple relationship could be demonstrated (Rodhe and Johansson 1996).

Fertilizer use efficiency has also been studied (Kirchmann and Pettersson 1995). Initial pot experiments shows that the fertilizing effect of urine is comparable to mineral fertilizers.

Another aspect that has not been discussed is the fact that urine is not as nutrient-concentrated as today´s mineral fertilizers. Energy use and emissions are therefore greater for spreading urine than mineral fertilizers.

2. Objectives and methodology

2.1 Objectives

The work presented in this thesis has two main objectives:
1) To evaluate the environmental aspects and the resource management of various types of waste water systems.
2) To study various concepts (methodologies) for system choice when planning a new or changing an existing waste water system.

2.2 Methodology

The work with the first issue included formulation of parameters, evaluating environmental and resource aspects quantitatively. The parameters were then applied to six existing Swedish waste water systems. A specific study of the potential of nutrients recycling in urine sorting systems was also carried out. The study included phosphorus and nitrogen analysis of human urine.

The work with the second issue was mainly conducted in the ECO-GUIDE project where two urban areas were studied: the Bergsjön suburb of Göteborg and the village Hamburgsund in the municipality of Tanum. Two alternatives to the existing systems were formulated in each area. The alternatives (including the existing systems) were evaluated and compared with several approaches. An Environmental Impact Assessment approach and an exergy analysis are presented in this thesis (the author of this thesis took part in these two subprojects).

2.3 Scope

The objectives have been studied in several projects, documented in four papers, presented as appendices to this report. Paper 1 describes an introductory study, initiated to examine existing waste water systems in Sweden with a wide range of technologies and to establish a couple of indicators, aimed to evaluate the capacity of environmental protection, nutrient recycling and functional aspects. Paper 2 describes a specific study made to evaluate the potential for nutrient recycling of urine separation systems. Paper 3 includes a description of the concept Environmental Impact Assessment (EIA). Paper 4 shows how the use of resources can be evaluated by means of an exergy analysis combined with studies of nutrient flows. Both papers 3 and 4 include case studies, originally formulated in the ECO-GUIDE project (Malmqvist *et al.* 1995).

3. Summary of papers and discussion

Paper 1 contains an introductory study, initiated as a study of existing waste water systems in Sweden using a wide range of technologies to establish a methodology to evaluate the capacity of environmental protection, nutrient recycling and functional aspects. Five parameters were established and used for evaluation of six existing Swedish waste water systems. The case studies contain three conventional waste water systems with sewers and treatment plants (Ryaverket, Ernemar and Ölmanäs) and three alternative systems: a waste water irrigation system (Roma), a constructed wetland (Höja) and a system with earth closets and separated treatment of grey water in a system with constructed wetland and a sand filter (Toarp).

The study showed that the systems were mainly constructed for reasons of environmental protection and sanitation. The criteria of nutrient recycling has been less considered. The existing system has great potential for phosphorus recycling, but the residuals are not often used as fertilizers. The use of energy for operation is greater in a waste water treatment plant than for treatment in sand filters or ponds. Earth closets including a heating system and a fan were the most electricity-consuming example. The treatment plants studied needed less land-area and had economic advantages compared with the small scale treatment examples.

The case studies also showed that the scale of the system does not affect the potential for recycling phosphorus. There is a potential for recycling 90-100% of the phosphorus in all case studies except for Höja. A comparison between the largest scale system, Ryaverket, and the smallest scale system, Toarp, shows that there seems to be no reason to change from a large-scale water-based system to a small-scale dry system. The Toarp system is more expensive, uses a greater land surface and more energy than Ryaverket. If there is a reason to abandon large-scale sytems, then it must be found outside the parameters presented in this method.

It should be noted that local conditions could impact on the results considerably, and the technical solutions are therefore not easily compared.

None of the six systems studied in **paper 1** was constructed for nitrogen recycling. One strategy for this is to handle urine separately and use it as a fertilizer for agricultural applications. An investigation was carried out to determine the contents of phosphorus and nitrogen in urine per person and day, and to study the daily variation of the same substances. Average values of nutrient concentrations were 1.0 g P/person,day and 13 g N/person/day. The study of daily variation showed that most of the nutrients appear in urine produced at home between 5:00 p.m. to 8:30 a.m. Concerning nutrient recycling, it would therefore be advantageous to give priority to the construction of urine separation systems in residential houses, while urine separation at work may be less beneficial. An opposite argument is, however, that more people use a toilet at a place of work. A greater volume of urine is therefore collected, which probably also means more nutrients. The investigation is presented in **paper 2** together with studies carried out by Daniel Hellström, Luleå University of Technology, of nutrient retention and transformation during storage.

Paper 3 consists of two parts; 1) A general a description of Environmental Impact Assessment (EIA) and 2) Case studies. Part 1 gives an overview of the concept and a discussion of contextual and methodological aspects of EIA. Part 2 contains EIA-studies of waste water systems (the existing system and alternatives) in two areas of Sweden: Bergsjön (Göteborg) and Hamburgsund (Tanum municipality). Part 1 is an extract from Tillman *et al.* (1997). Part 2 is an extract from Stenberg *et al.* (1996).

The demand of an EIA, according to Swedish environmental laws, is to permit an overall assessment of the impact of a planned installation, activity or measure on the environment, health and conservation of natural resources. An EIA contains six activities after the issues are defined: impact identification, description of affected environment, impact prediction, impact assessment, decision making and communication of results.

In The EIA studies Bergsjön and Hamburgsund, the existing conventional waste water systems were compared to local treatment of mixed waste water and local treatment with urine separation. The urine separation system is favourable because of the comparatively low use of natural resources (lowest energy use, largest recycling of nutrients) and low degree of eutrophication (smallest discharges of nutrients to the recipient). In spite of these two aspects, the urine separation system contributes more to the acidification than the other alternatives. The urine separation system includes more transports of residuals and therefore causes greater emissions of sulphur oxides and nitrogen oxides. Eutrophication is, however, valued as more important than acidification, because of the quantities the waste water systems generates in relation to the total anthropogenic impact in the region.

A deeper analysis of the energy aspects of the alternatives in Bergsjön, has been carried out in **paper 4**, with an exergy analysis. Exergy is the part of the energy that is convertible into all forms of energy (Wall 1977). The exergy analysis is combined with studies of nutrient recycling. The study shows that the hypothetical calculated exergy consumption during operation will be lower in a system with local treatment and urine separation toilets than in a conventional alternative. The amount of phosphorus that could be recycled is the same for alternatives studied, but the amount of nitrogen that could be recycled is considerably higher for systems with urine separation. The analysis was carried out in cooperation with Daniel Hellström, Luleå University of Technology. The methodology for the exergy analysis of waste water systems has been developed from Hellström (1997).

4. Further work

Methodologies to consider the use of resources in and emissions from waste water systems have been successfully developed in several studies discussed in this report. Further work for taking into account sanitation aspects and socio-economic evaluations will be very important, including studies of social acceptance, hygiene risks, economy and organization.

There is also a great potential for developing LCA, simulation tools and exergy analysis to be concepts available for planners and engineers. There is also a need to develop methodologies or indicators to evaluate existing systems.

The case studies discussed in this report show great potential for new technologies. Urine separation systems and vacuum systems with compost are two examples of promising technologies. These technologies have, however, to some extent only been theoretically formulated. There is a great need for further research and development before these systems can be implemented. For example, the environmental impact of using residuals from these systems in agriculture has not yet been thoroughly studied.

Today, there are plans to implement alternative waste water systems in several Swedish communities that need renovation. It will be of great interest to analyse these examples in terms of energy and exergy use, nutrient flows, *etc.* This information would be very useful for evaluation of the system studies discussed in this report, partly consisting hypothetically formulated system alternatives.

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Appendix 1

11 EVALUATION OF VARIOUS WASTEWATER SYSTEMS, METHODS AND APPLICATIONS

ERIK M. KÄRRMAN
Department of Sanitary Engineering, Chalmers University of Technology, Göteborg, Sweden

ABSTRACT

Five parameters were established to evaluate various wastewater systems. The evaluation concerns environmental protection, nutrient recycling and functional aspects. The five parameters are: losses of phosphorus and nitrogen to a receiving water, recycling of phosphorus, economy, land surface use and energy. The parameters were applied to six existing Swedish wastewater systems. These six examples included three systems with wastewater treatment plants and three systems without. Instead of treatment plants, these latter three systems treat wastewater with earth closets, constructed wetlands, sand filters and stabilization ponds. A comparison was made between large-scale and small-scale systems from a recycling perspective. There is a high potential to recycle phosphorus in both systems, but there are strong advantages in economy, land surface use and energy in the larger scale systems. The main disadvantage of the large-scale systems is the poorer quality of the recycled product (sewage sludge). It was discovered that the losses of phosphorus and nitrogen to a receiving water, recycling of phosphorus and land surface were easily evaluated. The parameters of economy and energy were more complicated to evaluate and the values contain a large degree of uncertainty.

INTRODUCTION

There are a number of requirements that existing wastewater systems have to fulfill. Up to the present, the two most important requirements have been sanitary aspects and environmental protection aspects. The sanitary aspects concern the risk for transmission of disease through the wastewater system and must be minimized. Environmental protection is primarily concerned with the quality of the receiving water. In the foreseeable future, the wastewater systems will be expected to fulfill a third requirement. Knowledge about phosphorus as an exhaustible nutrient leads to the conclusion that phosphorus from wastewater must be reused as a fertilizer in agriculture. In addition to these requirements, it is important that the wastewater systems are functional, easily managed and convenient for the users.

Today there is a need to develop criteria and evaluation methods for wastewater systems to find out if the above requirements are being fulfilled. Another reason for using an evaluation method is to choose the best available techniques when planning a new wastewater system.

This study was done to establish parameters that evaluate environmental protection, nutrient recycling and functional aspects of wastewater systems. Several studies have been done to compare environmental protection qualities of various wastewater systems. Two comparison studies of removal percentages of BOD, nitrogen, phosphorus and settleable solids in various small-scale on-site systems have been done by van der Graaf et al. (1989) and Jenssen et al. (1992). The removal percentage parameter can be improved to evaluate both the protection of a receiving water and the recycling of nutrients. In this study, two parameters concerning percentage losses of phosphorus and nitrogen to a receiving water and percentage recycling of phosphorus have been established.

The functional aspects that have been evaluated in this study are economy, land surface use and energy. Economic comparison studies often refer to operational costs. The operational costs for various sizes of wastewater plants have been studied by Balmér and Mattsson (1993) and the operational costs of sewage treatment for different methods and treatment stages by Vermes and Kutera (1984). In a study by Fasteneau et al. (1990), an economic comparison was taken one step farther. Investment, maintenance and operational costs were all taken into account. This economic parameter is also used in the present study.

The energy usage for various wastewater treatment methods has been compared by Berry (1993) and the electricity consumption in various wastewater treatment plants by Balmér and Mattsson (1993). In the present study the energy usage for both transport and treatment is evaluated. Finally, the land surface parameter is defined as the utilization of land surface for wastewater treatment construction. Both Jenssen et al. (1992) and Fasteneau et al. (1990) compared the land surface claim for various types of wastewater constructions. In the present study the term "claim" has not been used because land surface is not always a limiting factor. This article considers the development of evaluation parameters for wastewater systems. The parameters are tested through case studies.

DEVELOPMENT OF A METHOD

The five evaluation parameters selected were:

- losses of phosphorus and nitrogen to a receiving water (%)
- recycling of phosphorus (%)
- economy (SEK/person/year)
- land surface (m^2/person)
- energy (kWh/person/year)

LOSSES OF PHOSPHORUS AND NITROGEN TO A RECEIVING WATER

This parameter describes the percentage loss of phosphorus and nitrogen from wastewater to a receiving water. Usually total phosphorus and nitrogen are analyzed and the flow is measured in incoming wastewater to a treatment facility. The content of phosphorus and nitrogen multiplied by the flow gives the loading rates for phosphorus and nitrogen at the inlet. The loadings for phosphorus and nitrogen in the discharges can be calculated by means of the same operation. Finally, the percentage losses can be calculated by comparing loading at the inlet and in the discharge.

RECYCLING OF PHOSPHORUS

The purpose of this parameter is to calculate the percentage recycling of phosphorus for use in farming. The calculation is carried out in a similar way to the calculation of losses above. The loading of phosphorus in the inlet is calculated by means of the measured flow and the analyzed content of phosphorus. Examples of recycled products from wastewater are sludge, compost, treated wastewater for irrigation, sediments from stabilization ponds etc. Often, the amount of recycled products used in agriculture and the content of phosphorus are both known. The quantity of phosphorus used is calculated by multiplying the quantity of the recycled product by the content of phosphorus.

ECONOMY

Annual costs for investment, operation and maintenance are summed up and converted to the price levels of the year 1993 according to the Swedish building index. The investment costs are converted into an annuity cost. For this, a hypothetical four percent capital interest has been used. The estimated technical lifetimes for various wastewater plant constructions are: plant and parts at 30 years, except mechanical parts at 20 years and electronic equipment at 10 years. The technical lifetimes of pipes are estimated at 50 years, tunnels at 100 years, buildings at 50 years, stabilization ponds at 30 years, sand filters at 20 years, constructed wetlands for graywater at 20 years and constructed wetlands for both black- and graywater at 10 years. The formula used for calculating an annuity cost from investment costs is:

$$Annuity\ factor = \frac{\frac{p}{100}\left(1+\frac{p}{100}\right)}{\left(1+\frac{p}{100}\right)^{n}-1}$$

Where p is the capital interest and n the estimated technical lifetime.

After calculating the annuity costs of investments, the costs of operation and maintenance during the year 1993 are added. Information was found in annual reports or obtained through interviews with the managing director or operation engineer of the specific system.

LAND SURFACE

This parameter considers the utilization of land surface for wastewater treatment constructions. The use of land surface for other parts such as pump stations in a sewer system is not considered as a cost. The use of land surface was based on maps.

ENERGY

The energy parameter in this study is defined as the use of energy for the transport of wastewater from households into the treatment construction and the use of energy for treatment. Annual reports or interviews with the managing director or operation engineer of the specific system were used for obtaining energy data. In chemical wastewater treatment, coagulants are used. Ødegaard and Karlsson (1994) have calculated the total requirement of energy for raw material, production and transport of coagulants (under Scandinavian conditions). The values they found for the final products were approximately 200 kWh/t for iron chloride/sulfate, 320 kWh/t for aluminum sulfate and 310 kWh/t for aluminum chloride. Sometimes the use of energy for pumping is not documented. In these cases the use of energy has been calculated by knowing the flow and the lifting height. The formula used is:

$$E = \frac{g \times Q \times H}{t \times \eta}$$

where

E = use of energy
g = gravity
Q = lifted flow of wastewater
H = lifting height
t = pump time (time of operation)
η = pump efficiency

CASE STUDIES

The evaluation methodology was applied to six existing Swedish wastewater systems:

- Ryaverket in the Gothenburg region, with 550,000 persons connected (Figure 11-1).
- Ernemar in the community of Oskarshamn, with 20,000 persons connected (Figure 11-2).
- Ölmanäs in the community of Kungsbacka, with 5,800 persons connected (Figure 11-3).
- Roma in the community of Gotland, with 1,500 persons connected (Figure 11-4).

- Höja in the community of Ängelholm, with 150 persons connected (Figure 11-5).
- Toarps ecovillage in the community of Malmö, with 48 persons connected (Figure 11-6).

A description of transport, treatment system and recycled product of the six cases is presented in Table 11-1.

TABLE 11-1 TRANSPORT, TREATMENT SYSTEM AND RECYCLED PRODUCT OF THE SIX CASES.

Case	Transport	Treatment	Recycled product
Ryaverket	Sewer system	Treatment plant, biological and chemical treatment, no nitrogen reduction. Continues flow. Discharge to the sea.	Sewage sludge
Ernemar	Sewer system	Treatment plant, biological and chemical treatment, nitrogen reduction. Continues flow. Discharge to the sea.	Sewage sludge
Ölmanäs	Sewer system	Treatment plant, biological and chemical treatment, nitrogen reduction. Intermittent flow. Discharge to the sea.	Sewage sludge
Roma	Sewer system	Stabilization and storage ponds. No discharge to a receiving water.	Irrigation water, sediments
Höja	Sewer system	Constructed wetland. Discharge to a river.	Reused soil
Toarp	No transport	Earth closets, constructed wetland and sand filter for graywater treatment.	Compost, reused soil

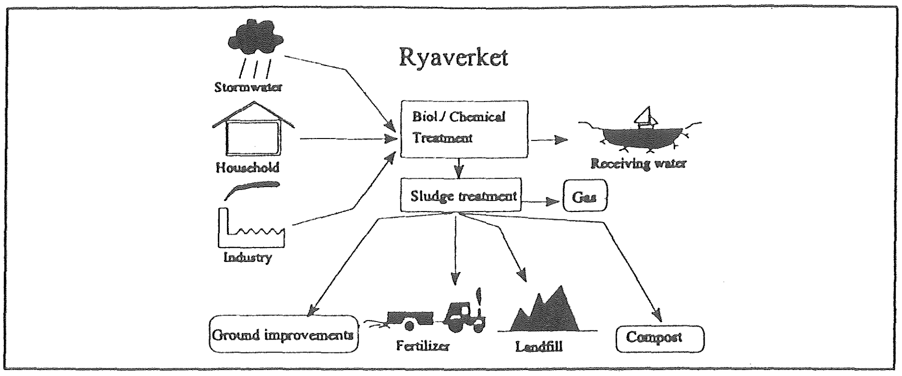

FIGURE 11-1 The wastewater system of Ryaverket.

DATA COLLECTION

RYAVERKET

Losses of phosphorus and nitrogen, recycling of phosphorus, land-surface use, and energy are calculated as described above (Development of a method). Values for use of energy have been provided from annual reports of Ryaverket and personal messages from the operation engineer at the Gothenburg sewer system. The economic parameter has been divided into two parts: annual costs for treatment and annual costs for transport. The annual costs for transport were calculated as the costs for maintenance, operation and investment during one specific year (in this case the year 1992 was used). Parts of the sewer system of Ryaverket are nearly one hundred years old and the investments are therefore too old to be converted to the price level of 1993.

ERNEMAR

Losses of phosphorus and nitrogen, recycling of phosphorus, land surface use and use of energy have been calculated as above. The use of energy includes one exception. No data of the energy use in the sewer system was provided. This part of the energy use is supposed to be low compared to the use in the treatment plant. An assumption for the use of energy in the sewer system of 10 kWh/person/year has been made. This value has been taken from

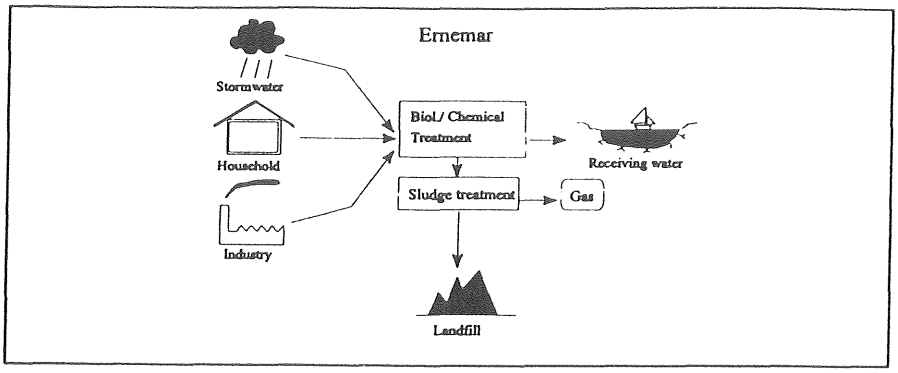

FIGURE 11-2 The wastewater system of Ernemar.

Ryaverket, which has a similar sewer system. The economic parameter is divided into annual costs for treatment and annual costs for transport. The transport costs were not converted to the price level of 1993, for the same reason as described for Ryaverket. The annual costs of the Ernemar sewer system are the sum of costs of operation, maintenance and investment for one specific year (in this case 1993).

ÖLMANÄS

Losses of phosphorus and nitrogen and use of land surface are calculated as above. The sewage sludge from Ölmanäs is mixed with sludge from another treatment plant in Kungsbacka. No separate analysis of the content of phosphorus has been done for the Ölmanäs sludge. The recycling of phosphorus has been calculated by comparing the incoming quantity and the discharge quantity of phosphorus. The annual costs for treatment were calculated as described in the section Development of a method. No information about the costs specifically for the Ölmanäs sewer system is available. There is information available only about the economics of the entire sewer system of the community of Kungsbacka. Neither annual costs for transport, nor use of energy has been evaluated. No specific information for use in the treatment plant or the sewer system is available.

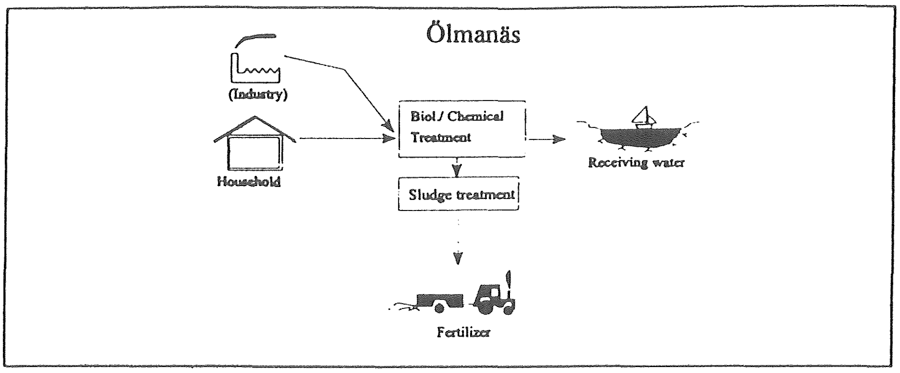

FIGURE 11-3 The wastewater system of Ölmanäs.

ROMA

There are no discharges to a receiving water from the Roma wastewater system, which means no losses of phosphorus and nitrogen and a complete recycling of phosphorus by means of irrigation water and sediments from the ponds. The parameters of economics, land surface and energy are calculated as described in the section Development of a method.

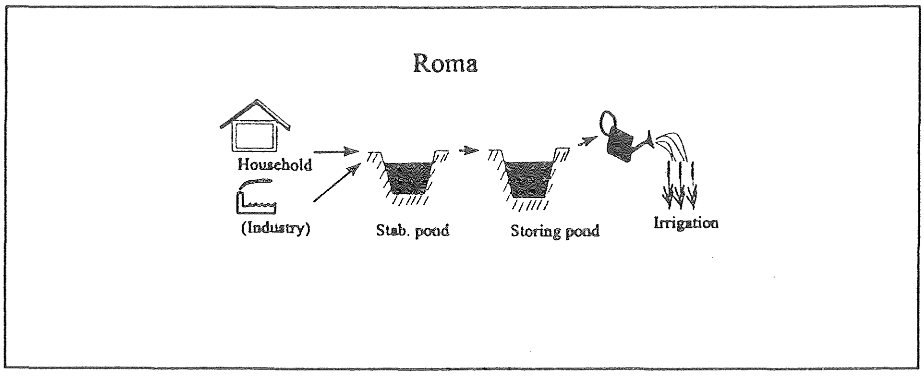

FIGURE 11-4 The wastewater system of Roma.

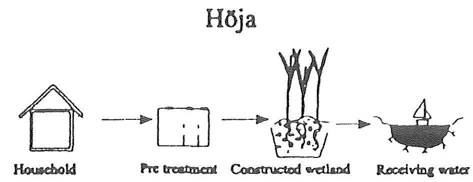

FIGURE 11-5 The wastewater system of Höja.

HÖJA

Losses of phosphorus and nitrogen, economics, land surface and energy are calculated as described initially. For calculating the energy use, the formula from Development of a method has been used. The recycling of phosphorus is calculated by comparing the incoming loading of phosphorus and the discharge loading of phosphorus.

TOARP

There is no discharge to a receiving water from Toarp, which means no losses of phosphorus and nitrogen. No discharge also means that the whole quantity of phosphorus stays in the system and is available for recycling. For the economic parameter only the annual costs of investment are evaluated. Operation and maintenance is expected to be done by the citizens of Toarps ecovillage. An economic value has not been assigned to their work. The land surface is calculated as described in Development of a method. The use of energy for pumping in the graywater treatment system is calculated by the formula from Development of a method. The use of energy in the earth closets has not been measured. Use of energy from earth closets has been measured in the Solbyn ecovillage, in the community of Lund by Bülow-Hübe and Blomsterberg (1992). These data have been used for estimating the use of energy in Toarp.

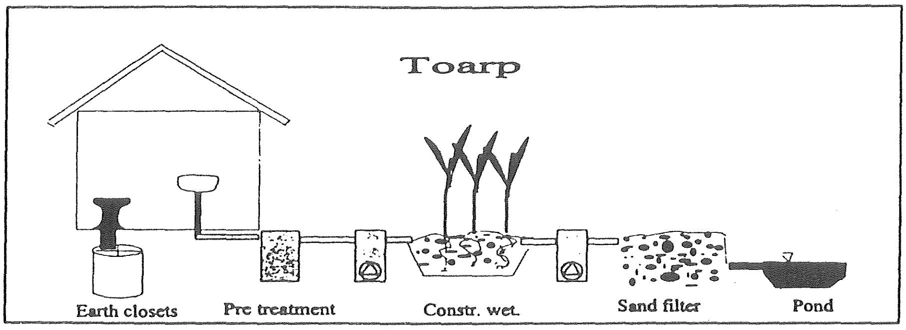

FIGURE 11-6 The wastewater system of Toarp.

RESULTS

Table 11-2 presents the results of the evaluation of the parameters losses of phosphorus and nitrogen to a receiving water and recycling of phosphorus. The recycling of phosphorus is divided into the actual recycling today and the phosphorus available for recycling from the system (for example if the whole quantity of sewage sludge from a treatment plant or all the compost from earth closets were recycled.)

TABLE 11-2 LOSSES OF PHOSPHORUS AND NITROGEN AND RECYCLING OF PHOSPHORUS.

Case	Losses total-P	Losses total-N	Recycled total-P today	Available total-P for recycling
	%	%	%	%
Ryaverket	9	89	9	91
Ernemar	3	51	0	97
Ölmanäs	10	31	90	90
Roma	0	0	100	100
Höja	55	64 *	0	45
Toarp	0	0	0	100

*) Kjeldahl nitrogen was analyzed, not total-N.

TABLE 11-3 FUNCTIONAL PARAMETERS.

Case	Annual costs for treatment	Annual costs for treatment and transport	Land surface	Use of energy
	(SEK/p, yr)	(SEK/p, yr)	(m^2/p)	(kWh/p, yr)
Ryaverket	320	530	0.11	62
Ernemar	350	460	0.35	130
Ölmanäs	420	Not evaluated	0.62	Not evaluated
Roma	Not evaluated	380	80	11
Höja	1,280	Not evaluated	8.0	8
Toarp	3,080	3,080	25	250

Table 11-3 shows the results from evaluating the functional parameters of economics, land surface and use of energy. The economic parameter is divided into annual costs for treatment and annual costs for treatment and transport.

DISCUSSION

Two interesting considerations concerning wastewater systems are brought forward in the case studies: the consideration of environmental protection and phosphorus recycling. The second consideration is discussed here. The parameter recycling of phosphorus is divided into the actual current recycling of phosphorus and the potential for recycling phosphorus (see Table 11-2). The reasons why the total quantity of phosphorus is not used as a fertilizer in farming vary. Because of an uncertainty among both farmers and the public about the risks of spreading pollution to foods through sewage sludge, only a very small part of the sewage sludge from Ryaverket is recycled. The problem is obvious in the Ernemar case where the sewage sludge is polluted with a high level of cadmium. The farmers there are not allowed to use it as a fertilizer. Concerning Höja, no decision has been made concerning use of soil when reconstructing the wetland. If the soil is used as a soil amendment in farming, then recycling of about 45% of the phosphorus is possible. For the example Toarp, there is currently no transport of compost from earth closets to farmland. The nutrients are used only for local cultivation by the citizens of the ecovillage. Used soil from the constructed wetland and the sand filter can also be recycled as described for Höja.

From Table 11-2 it is clear that the scale of the system does not affect the potential for recycling phosphorus. There is a potential for recycling 90-100% of the phosphorus in all case studies except for Höja. A comparison between the largest scale system, Ryaverket, and the smallest scale system, Toarp, shows that there seems to be no reason to change from a large-scale water-based system to a small-scale dry system. The Toarp system is more expensive, uses a greater land surface and more energy than Ryaverket (see Table 11-3). If there is a reason to abandon large-scale systems, then it must be found outside the parameters presented in this method. A positive aspect of small-scale systems from the recycling perspective is the quality of the recycled product. The sewage sludge in large-scale systems is usually polluted by coagulants, chemicals from households, heavy metals from stormwater, pollution from industry outlets etc. The advantage of an earth closet is that the compost includes only human urine and feces and contains less pollution than sewage sludge. One conclusion from this particular study is that there is a need for researchers to find the polluting sources for wastewater. It is also of great interest to specify the quality of sediments from stabilization ponds, soil from constructed wetlands, compost from earth closets etc.

Some advantages of the method of evaluation developed in this study are that some easily evaluated parameters have been defined to describe how a system fulfills the criteria for the protection of receiving water and the recycling of nutrients. The parameters also describe functional aspects of economics, land surface and use of energy. One disadvantage of the parameters is that they do not highlight the effect of local aspects (hydrology, geology, topography, types of buildings, etc.). There is also a parameter missing concerning the sanitary aspects. Sanitary aspects of wastewater systems can be evaluated by measuring coliform bacteria per 100 ml of effluent as described for example by Schurr (1970). Another sanitary aspect that should be evaluated is the health risk from operation and maintenance activities as described by Fasteneau et al. (1990).

The case studies show that some of the parameters are relatively simple to evaluate and some parameters are more complicated. For existing wastewater systems the parameters of losses of phosphorus and nitrogen to a receiving water and recycling of phosphorus are easily evaluated. The land surface parameter is also easily evaluated. The other functional parameters of economics and energy use are more complex, and the values therefore include a large element of uncertainty if they are possible to evaluate at all.

ACKNOWLEDGMENTS

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Appendix 2

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Nitrogen and Phosphorus in Fresh and Stored Urine

D. Hellström[1] and E. Kärrman[2]

[1] Division of Sanitary Engineering, Luleå University of Technology, S-971 87 Luleå, Sweden

[2] Department of Sanitary Engineering, Chalmers University of Technology, S-412 96 Göteborg, Sweden

Keywords: Nitrogen, Phosphorus, Urine, Storage, Separation, Wastewater, Sewage, Recycling

Abstract

One strategy for nutrients recycling from wastewater is to handle urine separately and use it as a fertilizer for agricultural applications. At present, there are only a few applications of urine separation in Sweden and, in most of the applications, the urine is separated in the toilet and stored in a tank. This study was divided into an investigation of the composition of fresh urine and a study of nutrient retention and transformation during storage of stored urine. The aim of the investigation of fresh urine was to determine the content of phosphorus and nitrogen in urine per person and day, and to study the daily variation of the same substances. Average values were 1.0 gP/day and 13 gN/day. The study of daily variation showed that the largest part of the quantities of phosphorus and nitrogen will appear in urine, produced at home, between 17.00-08.30. The aim of the storage studies was to estimate nitrogen losses and changes of pH and NH_3-N concentration during different storage conditions. Laboratory experiments with undiluted urine were carried out during a period of three months. The results indicate that the nitrogen concentration decreases in sampled urine through some separation process in the urine, but that losses through evaporation of ammonia were small. The increase of NH_3-N and pH is a slow process in undiluted urine and is inhibited by acidification or a low storage temperature.

Background

Today, there is an ongoing discussion concerning nutrient recycling from human urine and faeces. Phosphorus is a non-renewable substance and is therefore important to recycle. By using sewage sludge from wastewater treatment plants as a soil improver in agriculture, the greater proportion of phosphorus from wastewater can be recycled [1]. In spite of this, there is a concern over the quality of, and health risks related to, the use of sewage sludge. In the sewer system, urine and faeces are mixed with household wastewater, stormwater and industrial discharges, and will inevitably be polluted by heavy metals and toxic organic substances. These substances will be found in sewage sludge. As a result of this, sewage sludge is often disposed to a landfill. A strategy for recycling of nutrients is to handle urine separately and use it as a fertilizer [2]. A literature review concerning the content of several substances in the fractions; greywater, urine and faeces has been carried out by Sundberg [3]. One part of Sundbergs combination of data shows that urine is the source of around 70% of phosphorus and around 90% of nitrogen in blackwater (wastewater from water closets). The fact that urine contains almost all nitrogen from food increases the advantages of urine separation. Examples of advantages of recycled sewage sludge are nitrogen recycling to agriculture and minimisation of discharges of nitrogen to receiving waters. Sundbergs [3] study is based on data from studies of very specific groups of persons. The intake of food varies between groups of persons [4], which motivates the analysis of urine from a wide population of people.

There are only a few applications of urine separation in Sweden as yet. In most of the applications, the urine is separated in the toilet and stored in a tank. The tank is emptied by a farmer who collects the urine to use it as a fertilizer for agricultural applications. It is important that the system for collection, storage and handling of human urine is constructed for minimizing losses. The experience from storage and handling of animal urine is that nitrogen losses can be large. Thus, it is also desireable to study how different storage conditions influence the risk of losses of nitrogen, during storage and distribution of human urine. It is also known that urea in contact with wastewater relatively quickly decomposes into ammonia. Thus, it is interesting to study how fast the speciation of nitrogen in urine changes. The main losses are expected to occur through ammonia evaporation and thus the pH, concentration of total nitrogen and ammonia were investigated.

Objectives

The aims of the experiments in this study were:

- To estimate the content of phosphorus and nitrogen in whole day samples of urine, and to study the daily variation of the same substances.
- To study the losses of nitrogen as well as changes in pH and ammonia concentration under different storage conditions.
- To study the effect of urine handling on ammonia and nitrogen concentration.
- To compare the urine quality after storage of undiluted urine with the quality of stored urine from houses with systems for urine separation.

Experiments with fresh urine

Experimental

The aim of this study was to determine the content of phosphorus and nitrogen from one person during one day (24 hours), and to describe the daily variation of the same substances. One sample containing the total urine volume from one day was collected from each person, which means that the study can only describe urine in general, and not show any differences between various groups of people. The studied group of people is office working adults (not manual labour workers). The study includes analysis of daily samples of urine from 30 persons, with ages between 23 and 62 years. The sample of people included 15 females and 15 males. The daily variation was studied for 10 of the 30 persons. For these 10 persons each urination was collected separately, which means that 4-10 samples were collected per day for each person. Phosphorus analysis was made by a HACH method. The methods for analysing total phosphorus and phosphate were compared. No significant difference between the two methods in terms of concentration was found, so the less complicated phosphate method was chosen. The nitrogen analysis was carried out by means of Dr. Langes method for total nitrogen.

Results

The volume of urine and the content of phosphorus and nitrogen from the 30 persons in the sample are presented in table 1. The results of phosphorus and nitrogen for the whole group correspond with results from analysis of urine from persons with a normal diet [5]. There is a notable difference in quantity of phosphorus between females and males (see table 1). This is probably a result of the lower body weight of females. In a biological handbook, phosphorus in urine is related to body weight [6]. Urine from a person with a body weight of 70 kg is usually in the range of 130-300 mg N/day,kg and 10-15 mg P/day, kg. Recalculated to a value per person with a body weight of 70 kg gives 9-21 gN/pd and 0,7-1,1 gP/pd, which are values close to the results presented in table 1.

Table 1 Volume of urine and content of phosphorus and nitrogen.

	Volume (l/person,day)	P (g/person,day)	N (g/person,day)
The whole group	1.5 ± 0.5	1.0 ± 0.4	13 ± 3
Females	1.5 ± 0.5	0.8 ± 0.3	12 ± 3
Males	1.5 ± 0.5	1.1 ± 0.3	14 ± 3

The results from the studies of the daily variation of phosphorus and nitrogen in 10 persons urine are presented in figure 1.

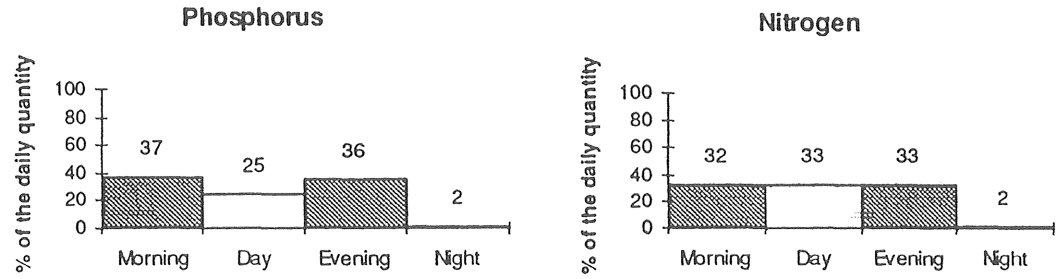

Figure 1 Daily variation of phosphorus and nitrogen in urine from 10 persons.

The day has been divided into four periods, in figure 1. The morning period is between 05.00 and 08.30 (15% of the day), the day period is between 08.30 and 17.00 (35% of the day), the evening period is between 17.00 and 24.00 (30% of the day), and the night is between 00.00 and 05.00 (20% of the day). It can be noticed from figure 1 that the morning urine includes around a third of the total quantity of phosphorus and nitrogen from one day. One reason for this is that the test persons had not urinated for several hours before the morning urination. All the ten test persons were urinate at least one time during the morning period. Only two of the ten test persons urinated during the night period. Test persons are usually at home during the time periods, represented with filled staples in figure 1, and at work during the time period, represented with an unfilled staple, and consequently 75% of the daily quantity of phosphorus and 67% of nitrogen can be found in the household urine. Concerning nutrient recycling, it would therefore be advantageous to give priority to the construction of urine separation systems in residential houses, while urine separation at work may be less beneficial.

Experiments with stored urine

Experimental

Two laboratory experiments were performed to investigate how the nitrogen and ammonia concentration changed during storage. A third experiment was performed to investigate the loss of nitrogen by poor handling after storage. In addition to these experiments, samples of stored urine were taken from an "ecological village". In water closet systems for separation of urine and faeces there will always be some amount of flushwater and probably some contamination of faeces into the urine storage tanks. Therefore, it was desireable to compare the results from the laboratory experiments with the composition of stored urine from an "ecological" village with a separated toilet system. The village, Björsbyn, is located about 5 km from Luleå. Urine was sampled from a urine tank with a volume of 10 m^3. The urine has been continously collected since september 1994 and the samples were taken in May 1995. The tank is placed underground which means that the temperature was below 5°C during the storage period.

In the laboratory experiments, bottles containing 80-85 ml of urine were used. In experiment 1, was the urine sampled by decanting 60 ml from each bottle, after storage. The aim of the decanting procedure was to investigate if there are any separation processes *in* the urine during storage. Instead of decanting, the whole samples were used for analysis in experiment 2. All samples in the three experiments have been frozen until analysis for NH_3-N, total nitrogen and phophorus. The pH was determined immediately after sampling (before freezing). The preparation of samples for measurement was done according to Swedish standard (SIS 02 81 02, SIS 02 81 31 and SIS 02 81 34). The concentrations of total nitrogen, NH_3-N and total phosphorus were then measured by using an automated procedure for analysis (an autoanalyser - TRAACS 800 - Bran+Lubbe). It should be noted that both dissolved ammonia and ammonium are measured in the NH_3-N analysis.

The laboratory experiments were performed with undiluted urine from five males and five females, ages between 25 and 50 (see table 2).

Table 2 Quality of the urine, used in experiments 1-3.

	pH	Tot-N, g/l	Tot-P, g/l	NH_3-N, g/l	N/P
Morning urine	5.88	8.5	0.94	0.50	9.09
Day urine	6.08	7.25	0.98	0.41	7.44

Experimental design

Experiment 1 was run as a two level factorial design experiment, where effects of several storage conditions were investigated. A 2^5 factorial design allows a preliminary screening of factors that might effect urine quality without unnecessarily detailed experiments. A 2^5 factorial design requires 32 samples. Two levels of exposure were tested for five parameters:

- *Storage time*. The urine was stored for 9 and 64 d, respectively.
- *Temperature*. The samples were either stored at room temperature (about 23 °C) or in a refrigerator (about 6 °C).
- *Acidified/unacidified*. A dosage of 0.60 ml 4 M H_2SO_4 /100 ml urine was used to achieve an initial storage pH 3 in 16 of the 32 storage bottles.
- *Type of urine*. The urine was separated into two categories, morning- and dayurine, see table 2. The time-periods are defined in figure 1.
- *Sealed/unsealed storage*. Sixteen (16) samples were stored sealed and the remaining were stored unsealed. The samples were further placed in a sealed plastic box with a volume of three litres.

Only two different storage times were investigated in experiment 1. Thus, to follow the changes in concentrations as a function of storage time, experiment 2 was performed. In experiment 2, sixteen samples of mixed urine (50 % of each urinetype) stored for 1, 2, 5, 9, 15, 30, 64 and 87 days. Eight of the samples were stored in 4-6°C and the remaining were stored at room temperature. The urine was mixed after storage, and thus the effect of precipitation/sedimentation was eliminated.

In experiment 3 urine samples, stored for 9 and 64 days respectively, were stirred in an open 400 ml beaker for 24 hours. Before mixing, the urine had been stored in sealed bottles at room temperature. The pH, ammonia and nitrogen concentration were measured at selected intervals during the stirring period.

Results

In experiment 1, it was found from the factorial design, that the changes in nitrogen concentration only depend on length of storage time. No other significant effects were observed. The average concentration of nitrogen stored for 64 d was about 7.4 g tot-N/l and urine stored for only 9 d had an average concentration of 10.1 g tot-N/l. The 95 % confidence interval for the difference in nitrogen concentration between urine stored for 9 and 64 days respectively, was (1.71, 3.57) g tot-N/l. The 95% confidence interval for the difference in nitrogen concentration between urine stored during 9 and 64 days respectively, was (1.71, 3.57) g tot-N/l.

Of the studied variables, time, addition of acid and storage temperature and interactions of these, had a significant effect on the NH_3-N concentration. It is noteworthy that the increase in NH_3-N concentration is detectable for short storage times only if the urine is stored in room temperature *and* stored without addition of acid. For long storage times it seems to be no increase in NH_3-N concentration, if the temperature is kept low and acidification has been done. If one of these variables is on the high level, the increase is marginally (from 0.45 to 0.52-0.56 g amm-N/l). It is only during long storage time, high temperature and no acidification that the increase is "dramatic" (from 0.45 to 1.25 g amm-N/l).

Considering pH it is noteworthy that a combination of high temperature, long time, no acidification and unsealed storage gives the highest increases. The final pH with this combination was about 8.1-8.6. As a comparison it could be mentioned that storage in unsealed bottles placed in a refrigerator gives neglible increase in pH even if the urine was stored for 64 days.

From experiment 2, no decrease in nitrogen concentration could be detected. The concentration of NH_3-N and the pH increase during storage in room temperature but not when the samples were stored in a refrigerator (see figure 2). It should be noted that the NH_3-N concentration increases during the whole period of analysis.

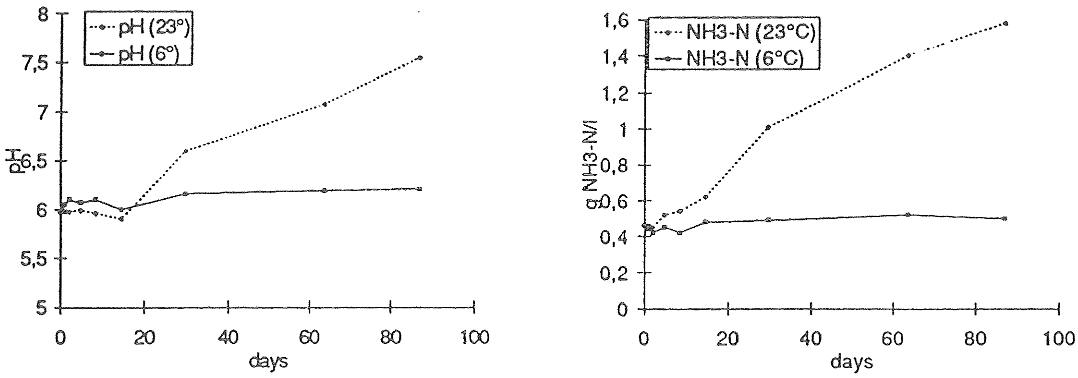

Figure 2 Changes in pH and NH_3-N during storage in 6°C and 23 °C, respectively.

In experiment 3 an increase in pH for both 9 days and 64 days storage time was found. A small increase of NH_3-N and nitrogen concentration due to evaporation could be noted during both runs. No losses of nitrogen were detected.

The samples for analysis in the storage tank at Björsbyn were taken at three different depths. There was no large difference in concentration between the samples. The urine contained 0.90 g tot-N/l, 0.77 g NH_3-N/l, 0.037 tot-P g/l and 0.036 PO_4-P g/l. The N/P ratio was 24.7. The pH in the tank was 8.86.

Discussions and conclusions

The study of stored urine indicates that losses of nitrogen are small during storage of human urine. The decrease of nitrogen concentration during storage in experiment 1 is probably explained by a separation process within the urine, because the differences between different storage conditions were insignificant. The statement about small nitrogen losses during storage is also confirmed by the fact that it was impossible to detect any losses of nitrogen in experiments 2 and 3, and that the N/P-ratio was high in the stored urine from the "ecological" village.

It has been shown that factors such as storage pH and temperature are important for changes in urine quality. The conversion of organic nitrogen into NH_3-N is a slow process, favoured by high temperature and inhibited by addition of acid. It is interesting that about 85 % of the nitrogen in the long stored urine from the "ecological" village occurs as NH_3-N. This is probably explained by the relative long storage time and the dilution due to flush water and probably some fecal contaminants. It is interesting to compare the results from Björsbyn with the ratio between NH_3-N and total nitrogen in domestic wastewater and urine, which normally is 0.8. The relatively high concentration of NH_3-N combined with a high pH indicates that there is a risk for nitrogen losses due to ammonia evaporation during handling of stored urine. Thus, the problem with nitrogen losses from stored human urine needs to be further investigated.

Wastewater systems with urine separation have advantages compared to systems where nutrients are recycled from sewage sludge. Urine contains less quantities of heavy metals and toxic organic substances, but includes almost the whole quantity of nitrogen from food intake. There is still one aspect of urine separation to consider; the whole quantity of phosphorus from food intake will not be found in the urine. From a study of food habits in Sweden [7], the daily intake of phosphorus was determined as 1,3 g/p,d for adult females and 1,5-1,8 g/p,d for adult males. A comparison to the present study of fresh urine in table 1, shows that 30-40% of phosphorus from intake will not be found in urine. There is also a content of phosphorus in faeces [8]. An example of a study of metabolic balance in adult males [8], shows that for two different diets the faeces include 40% and 50% of phosphorus from intake, respectively. Recycling of phosphorus from faeces and maybe even greywater should be taken into consideration, while constructing a wastewater system with urine separation. Phosphorus is a non-renewable resource and the phosphorus from wastewater should therefore be recycled.

The results of the studies of daily variations of phosphorus and nitrogen in urine show that the urine separation system should on the first hand be applied to houses where people live. The morning, evening, and night urine contained 75% of phosphorus and 68% of nitrogen from the test groups one-day sample of urine.

Acknowledgement

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Appendix 3

A general description of Environmental Impact Assessment (EIA), with two examples of EIA for waste water systems

Part 1, A general description of Environmental Impact Assessment (EIA).

Author:
Erik Kärrman

Department of Sanitary Engineering, Chalmers University of Technology, S-412 96 Göteborg, Sweden

Mainly an extract from Tillman, A.M, Kärrman, E. And Nilsson, J. (1997). Comparison of Environmental Impact Assessment, Life Cycle Assessment and Sustainable Development Records, at the general level and based on case studies of waste water systems, report from the ECO-GUIDE project. Report 1997:1. Technical Environmental Planning, Chalmers University of Technology, Göteborg, Sweden.

Part 2, Case studies

Authors:
Majlis Stenberg*, Ann-Carin Andersson** and Erik Kärrman

*)VBB Viak AB, Göteborg, Sweden, **) VBB Viak AB, Jönköping, Sweden.

(Mainly an extract from Stenberg, M., Andersson, A.-C. and Kärrman, E. (1996) Environmental Impact Assessment applied to alternative wastewater systems in Bergsjön and Hamburgsund, Report from the ECO-GUIDE project. Report 1996:1, Department of Sanitary Engineering, Chalmers University of Technology, Göteborg, Sweden. (in Swedish).

Notations

This essay consists of two parts; 1) A general description of Environmental Impact Assessment (EIA) and 2) Case studies. Part 1 gives an overview of the concept and a discussion of contextual and methodological aspects of EIA. Part 2 contains EIA-studies of waste water systems (the existing systems and alternatives) in two areas of Sweden; Bergsjön (Göteborg) and Hamburgsund (Tanum municipality). The framework of part 1, influenced by De Smet *et al.* (1996), is formulated to be used for comparative studies of various evaluation concepts.

Part 1: A general description of EIA

"EIA can be described as a process for identifying the likely consequences for the biogeophysical environment and for man's health and welfare of implementing particular activities and for conveying this information, at a stage when it can materially affect their decision, to these responsible for sanctioning the proposals" (Munn 1979).

As Munn points out, EIA aims to serve as decision support. EIA supports decisions on different levels. The two most common applications of EIA are proposed projects (construction of roads and bridges, localisation's of industries and landfills, changes in waste water systems *etc.*.) and municipal planning. In recent years, Strategic Environmental Assessment (SEA) has been introduced, meaning EIA applications for strategic decisions (policies, plans and programmes).

There is a close connection between EIA and legislation. The history of EIA begins in the USA, with the National Environmental Policy Act (NEPA) of 1969 (US Congress 1969). In Sweden, EIA was first included in the Road Act in 1987, followed by an inclusion in approximately twenty laws in 1991. In Sweden, the term EIA, or "Miljökonsekvensbeskrivning", has the double meaning of doing the assessment and the meaning of the final document. In the USA the process of doing an EIA is called EIA, whereas the final document is called Environmental Impact Statement (EIS). In some cases only a simpler investigation is carried out. This sort of document is called an Environmental Assessment (EA). The British, however, have adopted the term Environmental Assessment (EA) to describe the process and use Environmental Statement (ES) for the developer's EIA document. In this report, EIA will be used as the only term, meaning both the process and the document (Jörissen and Coenen 1990).

Nations which have introduced EIA in their law, have their own requirements regarding an EIA. There is, however, an international agreement about the EIA procedure. In figure 1 the EIA procedure is summarised as a flow diagram.

As shown in figure 1 the EIA procedure contains several activities. The proposed activity for the study is first defined. After that, an initial environmental evaluation is carried out. Usually the initial study is not enough to serve as decision support. In these cases the process continue with an EIA analysis. The EIA analysis starts with a scoping part. Scoping is an open process designed to determine the scope of issues to be addressed in the EIA document. When the issues for the study are defined, the analysis continues with identification, prediction and assessment of impacts. The need for monitoring and mitigation are also identified and described. The analysis will result in an EIA document, which will support the decision-makers in approving or rejecting the proposed project. If the decision makers approve, the project can be implemented. After implementation, the identified monitoring program, described in the EIA document, begins. Finally the results of measurement are compared with predicted impacts in the EIA (auditing).

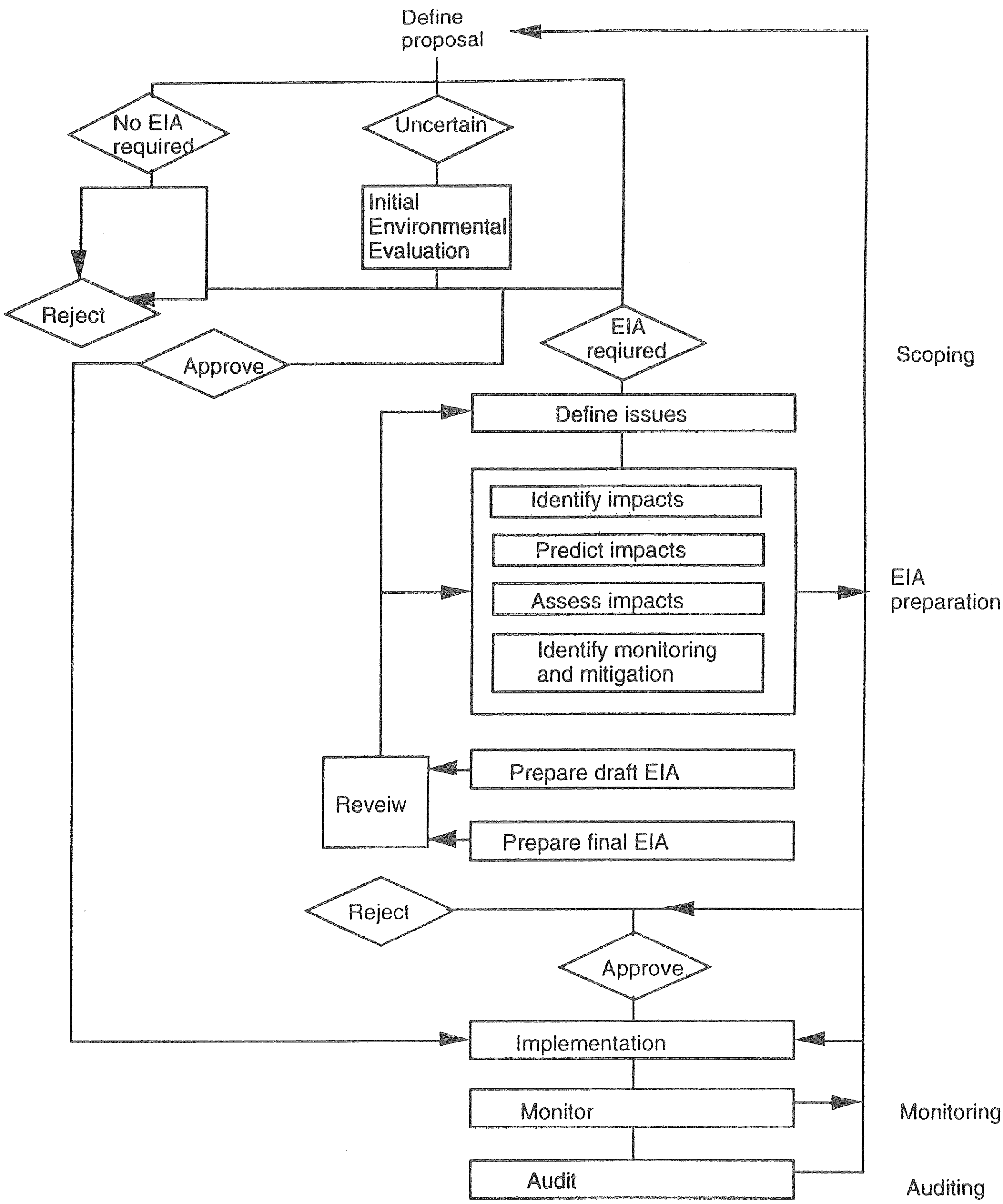

Figure 1. Flow diagram showing the main components of an EIA-system (after Wathern 1988).

As mentioned above, there is an agreement about what activities should be included in the EIA procedure. On the other hand, from one EIA to another, there is a free choice for the analyst and other persons involved in the process to choose methods and techniques, convenient for the specific application. Since EIA was founded in the early 1970s, methods and techniques for carrying out the various activities in EIA have been developed. These methods and techniques are reviewed in several papers and reports, *e.g.* Coleman (1977), Rosenberg *et al.* (1981), Bisset (1978, 1980, 1988), Skutsch and Flowerdew (1976) and Nichols and Hyman (1982).

When the term EIA is further used, the meaning is the EIA concept according to the Swedish Environmental Protection Act. The aim of such an EIA is to provide an environmental impact assessment of the impact of a planned installation, activity or measure on the environment, health and conservation of natural resources (Swedish Ministry of the Environment and Natural Resources 1993).

CONTEXTUAL ASPECTS

Aim of concepts
The aim of an EIA is to support a decision. The results of an EIA is not interesting per se, only in relation to a specific purpose.

Actors, decision makers and objects of decision
The Swedish Environmental Protection Agency (1995) defines the affected parties and their roles in the EIA process (formulation of EIA according to the Environmental Protection Act and Nature Conservation Act). The affected parties are: the Applicant, the County Administrative Board, the Municipality and the Authority. The *applicant* is responsible for carrying out the EIA, or for commissioning an analyst or investigator to do so, for being in consultation with affected authorities, for consulting with other affected parties and the public and for paying the costs of the EIA. The *County Administrative Board* supports the applicant with advice about EIA methodology, gives information about plans and policies and available background data, at least concerning the "no action" alternative. It is obvious that the applicant must be in consultation with the *municipality*, concerning the physical planning of the studied area. The *authority* is the examiner of the EIA. The County Administrative Board is often also in the role of the "authority", and therefore plays a double role in the EIA process, as adviser and examiner.

The EIA is a compulsory support in decision-making for permit applications according to several laws. But the EIA is one of several such supports. The decision-maker for a permit application is the regional or national authority, *i.e.* the Country Administrative Board or the National Franchise Board for Environmental Protection.

There are principally two types of decision-making in which EIA is used:
1) in permit applications for proposed projects,
2) to support town planning and comprehensive municipal planning.

Proposed projects with EIA applications have some characteristics in common: the projects are located to specific sites and the projects are expected to cause considerable environmental impact. Construction of roads and bridges, localisation of landfills and industries, changes in waste water systems and exploitation of natural resources are examples of projects where EIA is applied. The use of EIA in municipal planning also deals with proposed projects, but with more comprehensive description of projects and a more comprehensive analysis of environmental impacts.

Historical development of concepts and legal status

The history of EIA began in the USA, with the National Environmental Policy Act of 1969 (NEPA). In Sweden, EIA was first included in the Road Act in 1987, followed by approximately twenty other acts in 1991.

The Swedish Environmental Protection Act and other environmental acts declares that a permit application shall contain an EIA. The EIA is one of several supports for a decision. The law says only that an EIA shall enable an overall assessment of the environmental impact of a planned installation, activity or measure on the environment, health and conservation of natural resources (Swedish Ministry of the Environment and Natural Resources 1993).

Retrospective / prospective

An EIA is always carried out to support decisions looking forward in time (prospective). An EIA-document is however also used after implementation of the project, for monitoring and auditing (retrospective).

METHODOLOGICAL ASPECTS

In EIA, the word method has a highly specific meaning. A distinction is made between methods and techniques. EIA techniques are concerned with predicting future states of specific environmental parameters such as noise levels. EIA methods are concerned with collating, arranging, presenting and sometimes interpreting data. These data has often been provided by means of a technique (Bisset 1988). Various methods are needed to carry out all the activities included in an EIA. Some methods can be used for more than one activity, but no single method can deal with all activities.

Several EIA methods were used in the ECO-GUIDE case study (part 2 of this essay). Canter (1993) has formulated a table where methods are categorised in relationship to which activities in the EIA procedure they support. In table 1 the methods used in the case study of ECO-GUIDE have been categorised according to Canter (1993).

Table 1.

EIA methods	Define Issues (Scoping)	Impact Identification	Describe affected environment	Impact Prediction	Impact Assessment	Decision making	Communication of results
Analogs (look-alikes)	x			x			
Checklists		x					
Flow Charts	x						x
Maps			x				
Socio-Ecological principles					x		
Literature Reviews		x		x	x		
Tables							x
Regional environmental goals					x		

Issues studied

EIA as a concept does not point out the issues that should be studied. This should be decided in the scoping phase for every new case. However, an analysis of impacts on the outer environmental is always included. Examples of other issues sometimes covered by EIAs are effects on urban quality, effects on historical and cultural quality and socio-economic and market effects. Direct effects, indirect effects and cumulative effects are predicted in EIA. Direct effects are caused by the action and occur at same time and place. Indirect effects are caused by the action but are later in time or further removed in distance from the direct effects and yet are reasonably foreseeable. Cumulative effects result from the incremental impact of the proposed action when added to other past, present, and reasonably foreseeable future actions, regardless of which agency or person undertakes them (Bass and Herson 1993). Since EIAs are site specific, local environmental impact may be studied in detail, whereas global issues are less well dealt with.

In the case studies the considered aspects were delimited by the formulation of EIA from the Swedish Environmental Protection Act; influence of the environment, health and conservation of natural resources (Swedish Ministry of the Environment and Natural Resources 1993).

Basis for comparison

Prospective studies, aimed at giving support for choice of action, do so through comparing different alternative actions. When doing comparisons, something must be kept constant in all compared alternatives. This is what here is called "basis for comparison".

The basis for comparison in EIA can either be the proposed activity or the area of exploitation. For localisation applications, the comparison of alternatives is made on the basis of a constant activity and with the localisation as variable. The EIA of alternative waste water systems in Hamburgsund (one of the cases) is an example where the exploited area is constant and the technical solution of the activity (waste water treatment) varies among the alternatives.

System boundaries
The type of system boundaries required for an EIA, varies from one case to another. System boundaries must be defined early in the EIA process. Usually, the system boundaries concerns, what changes that should be studied, effected by a proposed activity, boundaries in time and space, choose of alternatives and choose of methods for the EIA-study (Swedish Environmental Protection Agency 1995).

The proposed activity must however be defined technically. It is impossible to define, in general terms, the system boundaries of the proposed activity in relation to the natural system. Normally, there is no point in delimiting the geographical area of the study. In a Swedish EIA, the conservation of natural resources must be taken into consideration. For this aspect the time boundaries are of great importance. For every case study, it must be established whether the whole life cycle of the studied system is studied or whether the conservation of natural resources only concerns the operation of the system.

Data - input and output
Different concepts require different types of data, and also produce different types of data. One sub-division is the one between data on the physical system and data on the social system. Examples of the first are data on flows of energy and matter in the technological system and data on processes in the natural system. Examples of the second are monetary data and data on values held by humans. Another subdivision is the one between quantitative and qualitative data.

To prepare an EIA, various data is required for the following activities:
-description of the proposed project and alternatives,
-description of the affected area,
-identification and prediction of possible impacts.

The impacts of the proposed activity and alternatives must be described quantitatively, *e.g.* emissions to land, water and air. The affected area is described both quantitatively and qualitatively. The localisation of the project is described in relations to dwellings, agriculture, receiving waters *etc.*. and the condition of affected land and water is described, *i.e.* ecological, geological, hydrological and climatological aspects are considered.

The data of the technical systems and the affected area are handled with methods for identification, prediction and assessment of impacts. In these activities, values of involved persons are added. The output from the process is therefore assessed environmental impacts. The impacts are usually presented in a disaggregated form. There are also examples of developed methods for aggregating impacts, for example the *Batelle system* (Dee *et al.* 1973) and *A comprehensive methodology for Assessing Environmental Impacts* (Sondheim 1978). In these methods a the total environmental impact is aggregated into a one-dimensional measure.

Evaluation of results

As mentioned before, the results from an EIA analysis is usually presented in a disaggregated manner. However, Swedish legislative documents clearly state that the EIA document shall contain the applicant's conclusions (Swedish Environmental Protection Agency 1995). The applicants must therefore find a means to aggregate all information of the various alternatives, to carry out a comparison. There are existing EIA-methods where aggregation of parameters is included, *e.g.* Dee *et al.*. (1973) and Sondheim (1978). The main evaluation of results will however be conducted by the decision makers.

An EIA can be useful as a support for decision-making only if the various aspects are valued. Valuation steps can be included any time in the EIA process. The applicant has a responsibility to involve the public in the EIA-process (Swedish Environmental Protection Agency (SEPA) 1995). Consultation is a keyword in SEPA's description of Swedish EIA. The applicant should be in consultation with the public, societies, organisations, other companies *etc.*. The public should be able to influence the EIA during the process. The public can, on the first hand, influence the phase of identification of possible impacts, where they can participate in choosing relevant impacts to study.

There are also EIA-tools, which include valuation. One of the most well-known tool is the Leopold matrix (Leopold *et al.* 1971). The Leopold matrix contains environmental parameters on one axis and characteristics on the other. The magnitude and the importance of the possible impacts are placed in the boxes of the matrix. The user of the matrix must be able to value the magnitude and importance on the basis of his/her knowledge. Another tool that include a weighting system (values) is overlay technique, described by Wathern (1988) among others. There are also methods based on value functions, for example the Environmental Evaluation System (EES), where environmental quality is expressed on single scale (Dee *et al.*. 1973). Another method, developed by Sondheim (1978) uses expert and weighting panels to reduce all information from an EIA into one single "score" for each evaluated alternative.

Part 2: Case studies

OBJECTS OF STUDY

One of the objects chosen for the study was Bergsjön, which is a suburb of Göteborg with 12 600 inhabitants, living mostly in rented apartment houses. There are no large industries Bergsjön, only an area with a number of small scale industries and offices. Stormwater runoff is not connected to the waste water system in the area.

The other area of the study is Hamburgsund, a coastal village with normally 900 inhabitants, which is increased to 1700 during the summer. Half of the population live in single family houses, the other half in apartment houses. There is no industry in Hamburgsund.

DESCRIPTION OF COMPARED ALTERNATIVES

Detailed technical descriptions of the scenarios studied have been published in elsewhere (Malmqvist *et al.* 1995), with some additional facts in Tillman *et al.* (1996a) and Stenberg *et al.* (1996). A summary is given in the following. An important delimitation in the study as a whole is that industrial waste water and storm water runoff is not considered, the study is limited to sewage from households and similar objects (schools *etc.*.).

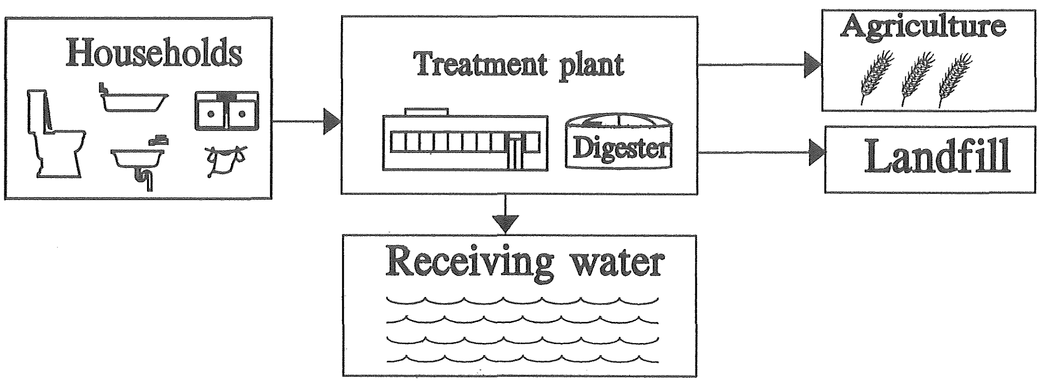

Figure 2. A schematic flow chart of alternative 0 of Bergsjön

In both Bergsjön and Hamburgsund, there are existing waste water systems with conventional handling of waste water, *i.e.* collection and transport of household waste water in sewers and treatment in a waste water treatment plant. Bergsjön is today connected to the regional plant; Ryaverket, which serves around 550 000 persons. A schematic picture of alternative 0 in Bergsjön is given in figure 3. Hamburgsund, on the other hand, has a local treatment plant which is situated in the fishing port, in the central parts of Hamburgsund. In both cases the waste water is treated mechanically, biologically and chemically. The sludge from Ryaverket is partly recycled to agriculture and partly deposited. The sludge in Hamburgsund is transported by truck to a larger waste water treatment plant (in Tanumshede) for dewatering, before being deposited on a landfill.

The objectives of the alternatives to the existing system were to formulate local systems, carrying out all the treatment in the area of Bergsjön (see Figures 3 and 4). The main difference between alternative 1 and 2, is that there is no need for changes of installations inside the buildings in alternative 1, and the sewer within the area can still be used. Alternative 2, on the other hand, means a totally new system, including new toilets with urine separation, three different pipe systems for urine, blackwater and greywater and a totally new transport system outside the buildings.

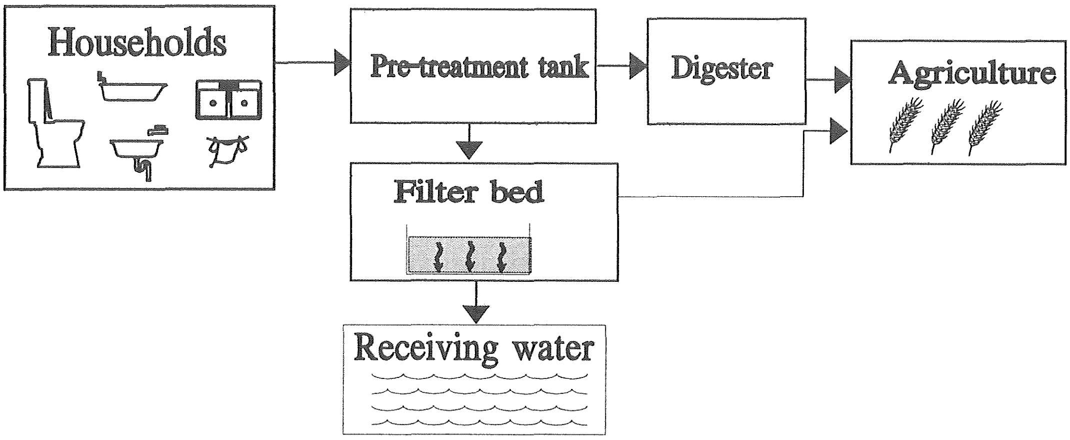

Figure 3. A schematic flow chart of the alternative 1 of Bergsjön

In alternative 1, the treatment of sewage contains a series of processes, starting with pre-treatment (removal of solids in septic tanks) followed by filter beds. The filter beds are expected to remove phosphorus, organic matter, and even parts of the nitrogen via nitrification/denitrification. In the Bergsjön case, the treated water will then be discharged to local creeks. Sludge from the pre-treatment tanks are transported by truck to a biogas production facility, also sited in Bergsjön. The residual product from the digester and the filter sand, saturated with phosphorus, are transported to farmland and used as a soil improver. In the Hamburgsund case, the treated water will be discharged to the sea, via a ditch and two dams. During the summer it is suggested that the water is used for a hay cultivation. Sludge from the pre-treatment tanks will be transported by truck to a sludge drying bed. After six months the sludge is considered to be of good hygienic quality, and is by then ready for use on farmlands.

In alternative 2, the household sewage is handled in three fractions; urine, blackwater (faeces, flush water and toilet paper) and greywater. Urine and blackwater are separated by means of source-separation toilets. Small amounts of flush water are used for both the toilet fractions, around 0,2 l per flush. For further transportation, the urine is led by gravity to underground tanks nearby the houses. The urine is then transported with trucks to agriculture for use as a fertiliser. In the Bergsjön case, the blackwater is led in a low-flush vacuum system to storage tanks nearby the buildings, this is also the suggested system for parts of Hamburgsund with apartment buildings. In the Bergsjön case the blackwater is transported to fermentation and in the Hamburgsund case to drying beds. In single family houses with basements, in Hamburgsund, the faeces is suggested to be composted in the basements. In single family houses without basements it is flushed to a pre-treatment tank, from which the liquid phase is led to the grey water system, whereas the solids are transported by trucks. Greywater is treated in the same kind of filter bed system, as the one chosen in alternative 1 both for Bergsjön and Hamburgsund.

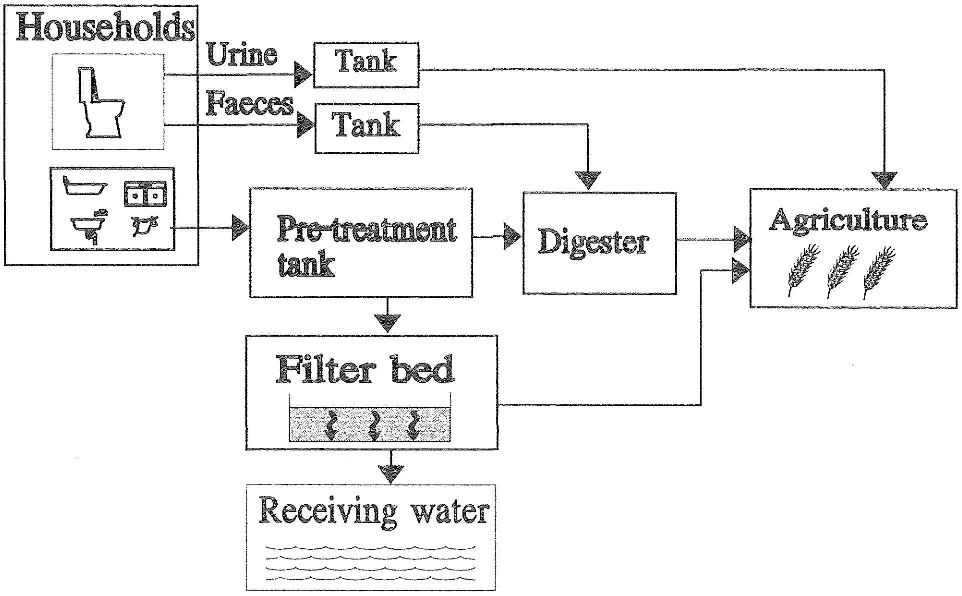

Figure 4. A schematic flow chart of alternative 2 of Bergsjön

MAIN FINDINGS OF CASE STUDIES

Methodology

The case studies of Bergsjön and Hamburgsund were focused on the question: Is it more advantageous to keep the existing waste water system with planned re-constructions, or to change the system into alternative 1 or 2?

The system boundaries of the waste water system has been defined as; collection and transport of waste water, transport to storage or treatment, storage and treatment, production and transportation of resources needed for the operation of the system, discharge to receiving waters and improvement and transport of residuals. The study considers mainly the operation of the system. From the building of systems and production of components, only the energy use has been analysed.

The study was carried out as an EIA study according to Swedish environmental laws. The demand of such an EIA is to permit an overall assessment of the impact of a planned installation, activity or measure on the environment, health and conservation of natural resources.

According to Canter (1993), an EIA study contains six activities after the issues are defined; impact identification, description of affected environment, impact prediction, impact assessment, decision making and communication of results.

The impact identification was done with support of a checklist, developed from CEQA (1986). The headlines from the checklist, chosen as relevant for the present study were:

Land use
Effects on flora
Effects on fauna
Effects on landscape
Discharges to land
Discharges to air
Discharges to water
Noise
Smell
Health and security
Recreation values
Cultural values
Use of natural resources
Use of energy

The description of the affected environments of Bergsjön and Hamburgsund has been done by ocular inspection and studies of maps and documents from the municipalities.

The impact prediction was done mainly in a qualitative way. There are a number of possible environmental effects of the waste water system, for example eutrophication of the sea and soil erosion caused by increased flow in the local watercourses in Bergsjön and there are contributions from the systems to these effects; outlets of nitrogen from the system might cause eutrophication and a large discharge of treated waste water might cause erosion. Because of the difficulties of predicting the effects quantitatively, the simple assumption "the less discharges/emissions, the better" was often used.

The results of the EIA is often presented in a text, discussing assessed possible impacts, and also with comparative tables including quantitative results. In the present study the analysis has been put one step further. The impacts have been sorted in three categories:

A. nature's condition,
B. human condition,
C. realisation aspects.

Category A contains aspects that possibly could have an impact on sustainable development. Examples from category A are eutrophication and use of energy and other natural resources. The aspects covered by category B are effects that could possibly have an impact of the human life, *e.g.* health aspects, noise, smell *etc.*. Category C contains realisation aspects. In the present study it is only the use of land that is sorted under this category.

The aspects covered by category A was considered the most important followed by B and finally C.

A few aspects from category A have been assessed as more important than others. This is done according to regional environmental goals (Miljöfaktaboken 1995) In this document, priority has been given to 9 environmental problems. The waste water systems possibly effects three of them:

- acidification
- use of natural resources
- eutrophication.

Identified emissions with a possible impact on these effects has been valued as the most serious. (in a normal EIA process "valuation-methodology", as the one described above, is used first in the decision making-phase)

Main findings

Bergsjön

The two alternatives would both have greater impact than the existing system, with a periodically considerable increase of flow in the local watercourses, caused by discharges from filter beds. More transports by trucks within the Bergsjön area would also be required, generating noise and emissions to air, caused by the collection of sludge, urine, filter sand *etc.*. Alternative 2 contains the largest number of transports. Both the alternatives will also use large areas for filter beds. In alternative 2, the urine tanks and filter beds would be situated near the housing. This would mean a reduction of areas for playgrounds. Because of the location of the waste water facilities near the housing, there would probably also be unpleasant odours periodically, if alternative 2 were implemented.

Regarding regional effects, the waste water systems will contribute to eutrophication of the sea, because of discharges of nitrogen and phosphorus. The main difference between ths alternatives would be in terms of the nitrogen discharges. Urine contains around 80% of nitrogen from household waste water. Alternative 2 is therefore the most advantageous alternative when looking at outlets of nutrients. Another more or less regional effect is acidification. Alternative 2 contributes most because of the largest number of truck transports and therefore the largest emissions of sulphur- and nitrogen oxides.

Regarding the use of natural resources, alternative 2 is advantageous, with the greatest recycling of nutrients and the lowest use of electricity. One exception is the use of fossil fuels, which is greater than in alternative 1. For this aspect, the no action alternative, is the most favourable.

Table 2 describes a number of aspects with major influences on the effects in category A.

Table 2

	No Action	Alternative 1	Alternative 2
Recycling and discharges of nutrients			
Nitrogen to recipient (tonnes/yr)	29	45	2
-recycled (tonnes/yr)	7	7	62
Phosphorus to recipient (tonnes/yr)	1,4	3,6	1,6
-recycled (tonnes/yr)	13	13	15
Emissions to air			
SO_2 (kg/yr)	13	60	110
NO_x (kg/yr)	190	550	1050
Use of resources			
Electricity (MWh/yr)*	800	400	130
Fossil energy (MWh/yr)*	200	300	450
Energy recycling			
Electricity from biogas (MWh/yr)	350		
Heat from biogas (MWh/yr)	590	490	1020

*) Estimations of energy use for building the systems, are included

According to the described valuation, alternative 2, urine separation, is the most favourable alternative in Bergsjön. The reasons for this are the comparatively good results of the use of natural resources and eutrophication. The reason eutrophication is valued as more important than acidification, is the quantities that the waste water systems generates in relation to the total anthropogenic impact in the region. Today the waste water system contributes with around 0,01‰ to the emissions of nitrogen dioxides from the municipality of Göteborg. The corresponding comparison for nitrogen discharges to water is 2%. Therefore the nitrogen discharges to water has been considered as the most important aspect. Alternative 2 is most favourable looking at the use of energy (1 kWh electricty is here valued as equal to 1 kWh fossil energy).

Hamburgsund

Hamburgsund has a local system today, and the alternatives are also situated in the area of Hamburgsund. The sea is the receiving water for all three systems. Alternative 2 will cause the largest number of transports within the residential area, and therefore cause most noise, but the existing system contains the greatest overall amount of transportation, because of the transports of sludge between Hamburgsund treatment plant and Tanumshede treatment plant, and between Tanumshede and the Tyft landfill disposal. The no action alternative does therefore cause the largest emissions of nitrogen and sulphur oxides of the three alternatives.

The existing system does not contain nitrogen reduction, so both alternative 1 and 2 are more advantageous concerning the eutrophication aspect. There is no recycling of sewage sludge in the existing system.

Alternative 1 uses less energy and includes less transportation with trucks than alternative 2.

Table 3 describes a number of aspects with major influences on the effects in category A.

Table 3.

	No Action	Alternative 1	Alternative 2
Recycling and discharges of nutrients			
Nitrogen to recipient (kg/yr)	4500	2600	840
-recycled (kg/yr)	0	1100	4300
Phosphorus to recipient (kg/yr)	200	140	60
-recycled (kg/yr)	0	880	930
Emissions to air			
SO_2 (kg/yr)	7	7	9
NO_x (kg/yr)	56	55	77
Use of resources			
Electricity (MWh/yr)*	160	64	60
Fossil energy (MWh/yr)*	96	35	64

*) Estimations of energy use for building the systems, are included

According to the described valuation, alternative 2, will be the most favourable alternative in Hamburgsund, closely followed by alternative 1. The reason for this is that the highest priority has been given to nitrogen discharge. Alternative 1 is, in fact, the most favourable alternative both in terms of energy use (1 kWh electricity is here valued equal as 1 kWh fossil energy) and emissions to air.

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Appendix 4

EXERGY ANALYSIS AND NUTRIENT FLOWS OF VARIOUS SEWERAGE SYSTEMS

Daniel Hellström* and Erik Kärrman**

*\) Division of Sanitary Engineering, Luleå University of Technology, S-971 87 Luleå, Sweden. Phone +46 920 914 52. E-mail Daniel.Hellstrom@sb.luth.se
**\) Department of Sanitary Engineering, Chalmers University of Technology, S-412 96 Göteborg, Sweden. Phone +46 31 772 21 21. E-mail erik@sani.chalmers.se.

ABSTRACT

There is an increasing demand for more sustainable sewerage systems. An important tool in the analysis of the sustainability of a sewerage system is exergy analysis. It is possible, by using an exergy analysis, to estimate the consumption of physical resources. In the present study, the demand of resources in the sewerage system of Bergsjön, a district of Göteborg, Sweden, was evaluated through exergy analysis. The case study included the existing system and two sewerage system alternatives. One important aspect of a sustainable sanitary system is nutrients recycling from sewage to agriculture. The exergy analysis has therefore been complemented with an analysis of the mass-flows of phosphorus and nitrogen. The study shows that the hypothetical calculated exergy consumption during operation will be lower in a system with local treatment and urine separation toilets compared with a conventional alternative. The amount of phosphorus that could be recycled is the same for the studied alternatives, but the amount of nitrogen that could be recycled is considerable higher for systems with urine separation techniques.

KEYWORDS

Sustainability, exergy, phosphorus, nitrogen, urine separation

INTRODUCTION

There is an increasing demand for more sustainable sewerage systems, but the criteria needed to characterize such a system are not fully developed. Firstly, there is a need to define the term sustainable systems. One definition of sustainable development is that it is a development that "meets the needs of the present generations without compromising the ability of future generations to meet their own needs" (WCED, 1987). However, such a definition is unquantifiable and unverifiable (Ayres, 1996). Thus, different quantifiable criteria have been suggested (Ayres, 1996; Azar *et al.*, 1996; Holmberg, 1995) as well as a sustainable process index (Narodoslawsky and Krotscheck, 1995; Moser 1996). The suggested criteria show that several aspects should be taken into consideration in order to achieve a sustainable development. However, central criteria for a sustainable development are efficient use of physical resources and limiting the use of non-renewable resources. Hence, the study of how efficiently physical resources are used in sewerage system is of importance when discussing the sustainability of such a system.

Earlier studies of physical resources used in sewerage systems have been focused on the energy demand for different processes (Hydén and Lundgren, 1981; Ødegaard, 1995). However, studies based on the concept of energy provide little information about how efficiently physical resources are utilized. This is due to the indestructibility of energy, which means that energy is conserved in every process. Energy can only be converted into different forms. The conversion of energy in a process occurs by the consumption of the quality of the energy. Thus, energy could be regarded as a carrier of quality, and it is this quality that is consumed during the conversion of energy (Wall, 1977). The quality of a flow of energy could be defined as the useful part of the energy, *i.e.* that part that can perform mechanical work. The term for this part of the energy is exergy, which is strictly defined as that part of the energy that is convertible into all other forms of energy (Wall, 1977).

The concept of exergy could be illustrated by using an example from Holmberg (1995) discussing the turnover of energy in a waterfall. In a waterfall the particles are moving in the same direction and a turbine could be used to extract mechanical work. If this is not done, when the water reaches the bottom of the waterfall, its kinetic energy is converted into heat. The particles are then no longer moving in the same direction but they move individually in different directions. The energy is conserved, but the energy in the heat is not available for work like the kinetic energy of the falling water; *i.e.* its exergy is lower.

In the present study, exergy analysis is combined with a study of the mass-flows of phosphorus and nitrogen. One of four socio-ecological principles for a sustainable society from Holmberg (1995) says: *Substance from the lithosphere must not systematically accumulate in the ecosphere.* This principle motivates studies of the mass-flows of phosphorus. Phosphorus is a non-renewable resource, which advantageously should be recycled to the agriculture. Concerning nitrogen, one could say that the nitrogen itself is not a limited resource. However, significant quantities of energy are needed to produce nitrogen fertilizer (Bøckman *et al.* 1980). In addition, it should also be remembered that to achieve removal of nitrogen from sewage by biological methods, an extra input of energy and other physical resources are needed. On the other hand, a discharge of nitrogen into the recipient could result in eutrophication.

OBJECTIVES

The aim of the study is to compare three different sewerage systems by using exergy analysis and an analysis of the potential to utilise the nutrients from those systems in agriculture. This is done in order to achieve a measurement that, together with other parameters, could be used to estimate the sustainability of the systems.

DESCRIPTION OF SYSTEM ALTERNATIVES AND NUTRIENT MASS-FLOWS

The settlement Bergsjön in Göteborg, Sweden, was selected for a case study. Bergsjön has been used in a previous study; the "Eco-Guide" project (Malmqvist *et al.*, 1995), where the existing sewerage system and two alternatives have been evaluated by means of Life Cycle Assessment (Tillman *et al.*, 1996) and an Environmental Impact Assessment approach (Stenberg *et al.*, 1996). In the present study, the system alternatives and data from the "Eco-Guide" project have been used.

Bergsjön has 14000 inhabitants, where the main part of the people live in high-rise buildings. The existing system (alternative 0) contains a sewer system, where the sewage is transported to the sewage treatment plant; Ryaverket. Ryaverket serves a large part of the Gothenburg region, including 550 000 connected persons, industries and stormwater from parts of Gothenburg with combined sewers. A schematic picture of the existing system is shown in Figure 1. Figure 1 also contains mass-flows of phosphorus and nitrogen. The mass-flows are based on data from Malmqvist *et al.* (1995).

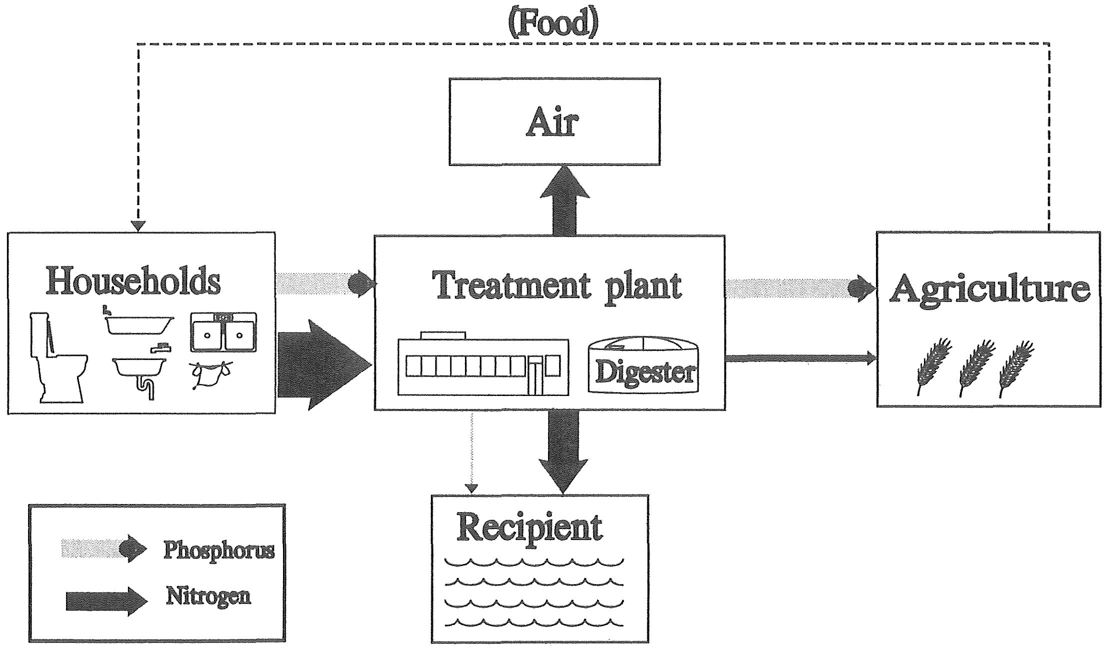

Figure 1. Schematic picture of alternative 0 with nutrient flows

The objectives of the alternatives to the existing system were to formulate local systems, carrying out all the treatment in the area of Bergsjön (see Figures 2 and 3). The main difference between alternative 1 and 2, is that there is no need for changes of installations inside the buildings in alternative 1, and the sewer within the Bergsjön area can still be used. Alternative 2, on the other hand, means a totally new system, including new toilets with urine separation, three different pipe systems for urine, blackwater and greywater and a totally new transport system outside the buildings.

In alternative 1, the treatment of sewage contains a series of processes, starting with pre-treatment (removal of solids in septic tanks) followed by filter beds. The filter beds are expected to remove phosphorus, organic matter, and even parts of the nitrogen via nitrification/denitrification. The treated water will then be discharged to local creeks in Bergsjön. Sludge from the pre-treatment tanks is transported by truck to a biogas production facility, also sited in Bergsjön. The residual product from the digester and the filter sand, saturated with phosphorus, are transported to farmland and used as a soil improver. In Figure 2, a schematic picture of alternative 1 is shown including mass-flows of phosphorus and nitrogen, based on data from Malmqvist *et al.* (1995).

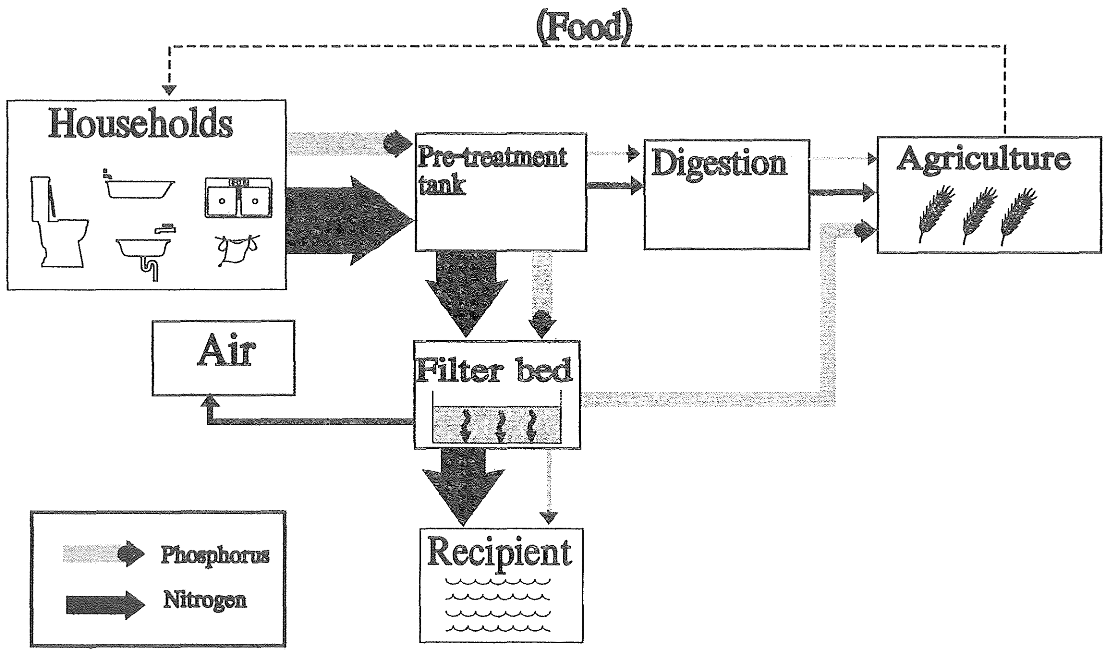

Figure 2. Schematic picture of alternative 1 with nutrient flows

In alternative 2, the household sewage is handled in three fractions; urine, blackwater (faeces, flush water and toilet paper) and greywater. Urine and blackwater are separated by means of source-separation toilets. Small amounts of flush water are used for both the toilet fractions, around 0,2 l per flush. For further transportation, the urine is led by gravity to underground tanks nearby the houses. The urine is then transported with trucks to agriculture for use as a fertilizer. Blackwater is led in a low-flush vacuum system to storage tanks nearby the buildings, for further transport by trucks to a biogas production facility. Greywater is treated in the same kind of filter bed system, as the one chosen in alternative 1. In Figure 3, a schematic picture of alternative 2 is shown including mass-flows of phosphorus and nitrogen, based on data from Malmqvist *et al.* (1995). The distribution of phosphorus and nitrogen in urine, blackwater and greywater is based on Swedish Environmental Protection Agency (1995). It is also assumed that there is no loss of nitrogen via ammonia gas from the urine handling.

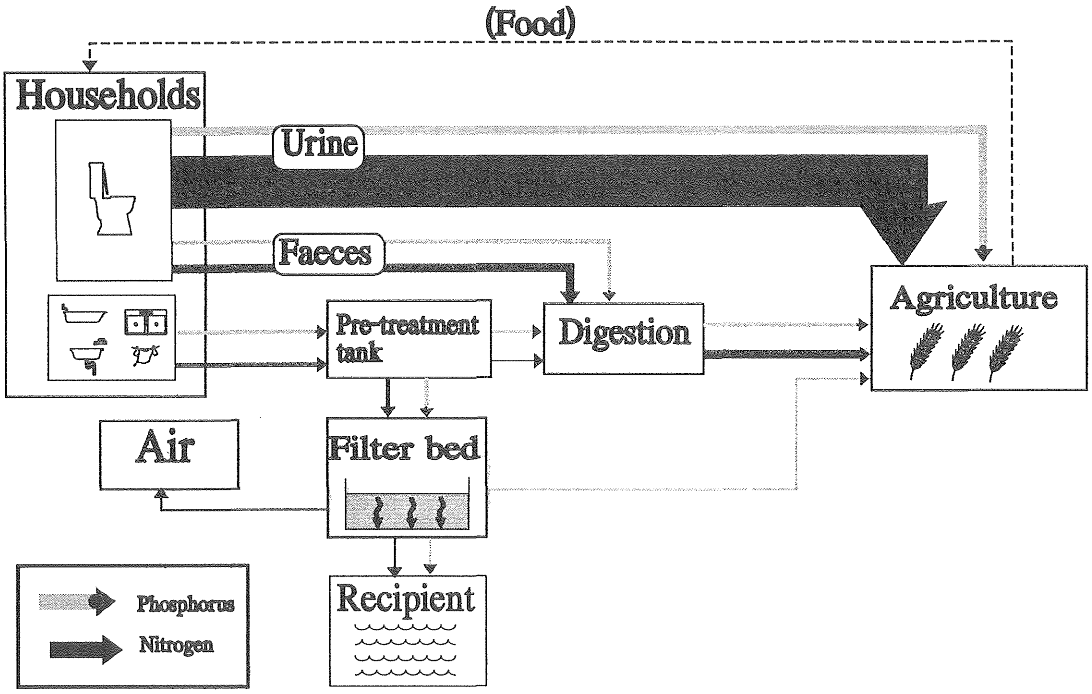

Figure 3. Schematic picture of alternative 2 with nutrient flows

METHODS USED FOR EXERGY ANALYSIS

The study includes the following calculations:

- Exergy analysis of heat transportation in sewage
- Analysis of the chemical exergy of organic matter, nutrients and exergy of chemicals and electricity, needed for operation

The activities, in the sewerage system, considered in this study is: heating of tap water, collection and transport of sewage, transport to storage or treatment, storage and treatment, addition of resources needed for the operation of the system, discharge to receiving waters and improvement and transport of residuals. The study considers only the operation of the sewerage system, and not the building and maintenance of the system or the production of resources needed (chemicals, electricity *etc.*.). Further, the exergy due to labour is assumed to be negligible compared with other exergy flows.

Exergy analysis of heat transport in sewage

The exergy flow due to heat is treated separately because it is not directly related to the transport and treatment of organic matter and nutrients. Further, it is assumed that the amount of warm water that is used is relatively independent of which system is used and hence calculations have been performed only for one system. However, the results for an exergy analysis of heat in water is very dependent on the temperature outside the system (Hellström, 1997). Thus, the calculations are made for two different months to illustrate the difference between summer and winter.

The energy value of the sewage, due to the heat, is calculated as the temperature difference between the sewage and the ambient air times the heat capacity of water. The exergy is then calculated as the energy times the Carnot factor, *i.e.* the difference between the water temperature and the ambient temperature divided by the water temperature. It should be noted that no energy or exergy is available if the ambient temperature is higher than the sewage temperature (Hellström, 1997).

The exergy content in water due to heat is consumed by cooling of water, *i.e.* heat is transported from the water to the surrounding ground or into the air. A significant amount of exergy is also consumed only by mixing warm and cool water. To emphasise this and to show that it is the quality of energy that is consumed, it is assumed that the loss of energy to the surroundings due to cooling of water will be zero. Further, the energy effect of the equipment for heating of tap water is assumed to be 100 % and it is also assumed that only electricity is used to heat tap water (including water used in laundries). Based on data from Bengtsson *et al.* (1981), it has been assumed that 30 % of the tap water had been heated to a temperature of 60 °C. It is also assumed that the temperature of the water leakage into the system will have a temperature equal to the air temperature of that month. By using the assumptions above and the data in Table 1, the temperature and the exergy of the sewage could be calculated.

Table 1: Data used to calculate the exergy content of sewage due to heat.

	January	July	Reference
water consumption, l/pe,d	195	195	Malmqvist *et al.* (1995)
leakage, l/pe,d	320	320	Malmqvist *et al.* (1995)
air temperature, °C	2.5	18.2	SMHI (1990-94)
tap water temperature, °C	2.4	17.9	Data provided by the Gothenburg Water Works

Analysis of the chemical exergy of organic matter and nutrients

A model for the calculations of the exergy of organic matter and nutrients is shown in Figure 4.

In the model, in Figure 4, the input to the sewerage system consists of the exergy of the substances in the sewage from the households and the exergy of additional inflows, necessary for the operation of the system and transport of sewage and residuals. The output consists of the discharge to the receiving water, named *losses* in Figure 4, and useful *residuals* like sludge, biogas *etc.*. It should be noted that it is only the exergy in the flows themselves that is considered.

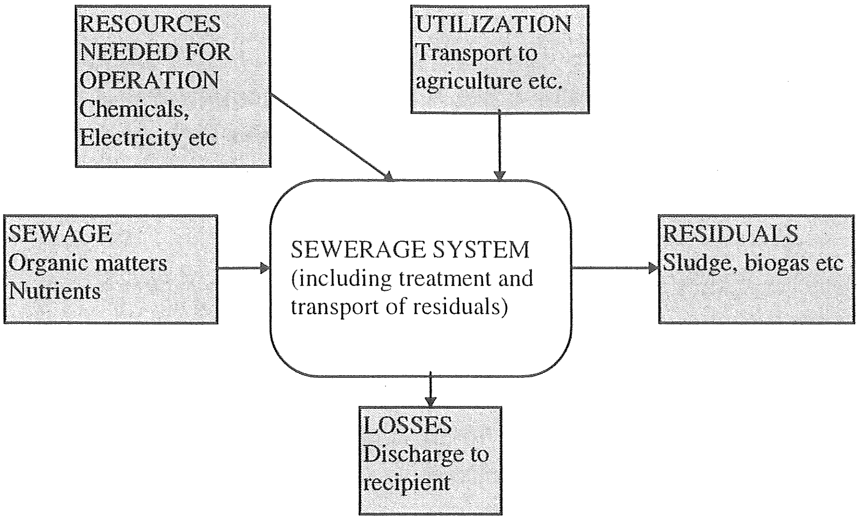

Figure 4. The model used for the exergy analysis of sewage treatment and handling of residuals

The flows considered in this analysis are those that are related to management and treatment of organic matter, nitrogen and phosphorus. Other nutrients, presence of hazardous compounds as well as other parameters influencing the water quality are not considered in this analysis. These parameters are important for sustainability but will be almost negligible in an exergy analysis. The effect of, for example presence of heavy metals in sludge, is probably not well estimated by using the exergy analysis (Hellström, 1997), *e.g.* the toxicity could not be measured using only exergy analysis.

Organic matter, nutrients as well as chemicals used in the treatment process are regarded as different chemical compounds. The exergy of a chemical compound is the amount of energy that will be released when the compounds react and the products go to equilibrium with the surroundings. This means that the exergy for a chemical compound is determined in the same way as Gibb's free energy, with the difference that the exergy is related to ambient conditions and Gibb's energy is related to standard conditions (Hellströn, 1997).

Tai *et al.* (1986) have shown that the standard chemical exergy for organic matter corresponds to the theoretical oxygen demand (13.6 kJ/g ThOD). Both COD and BOD are related to the Theoretical Oxygen Demand (ThOD) and could be used to estimate the total exergy flow due to organic matter. However not all organic matter is easily biodegradable and BOD will give an estimation of the amount of technically available exergy (Hellström, 1997). BOD_7 has hence been used in this study.

To simplify the calculation of the exergy of nutrients, it is assumed that all nitrogen exists as ammonium and all phosphorus as (HPO_4^{2-}). The standard chemical exergy for ammonium is 322.1 kJ/mole and for (HPO_4^{2-}) 134.1 kJ/mole (Szargut *et al.*, 1988). The standard chemical exergy for other compounds, such as precipitants, has also been collected from Szargut *et al.* (1988).

Concerning electricity, fossil fuel and methane gas, it should be mentioned that for those flows the input of exergy and energy will be equal because of the high quality of the used energy (Holmberg, 1995).

RESULTS

Exergy analysis of heat transport

Figure 5 shows that a large amount of exergy is consumed when heating water with electricity. However, the losses of exergy due to mixing of warm and cool water are significant compared with the exergy flows related to the handling and treatment of organic matter and nutrients (see Figure 6).

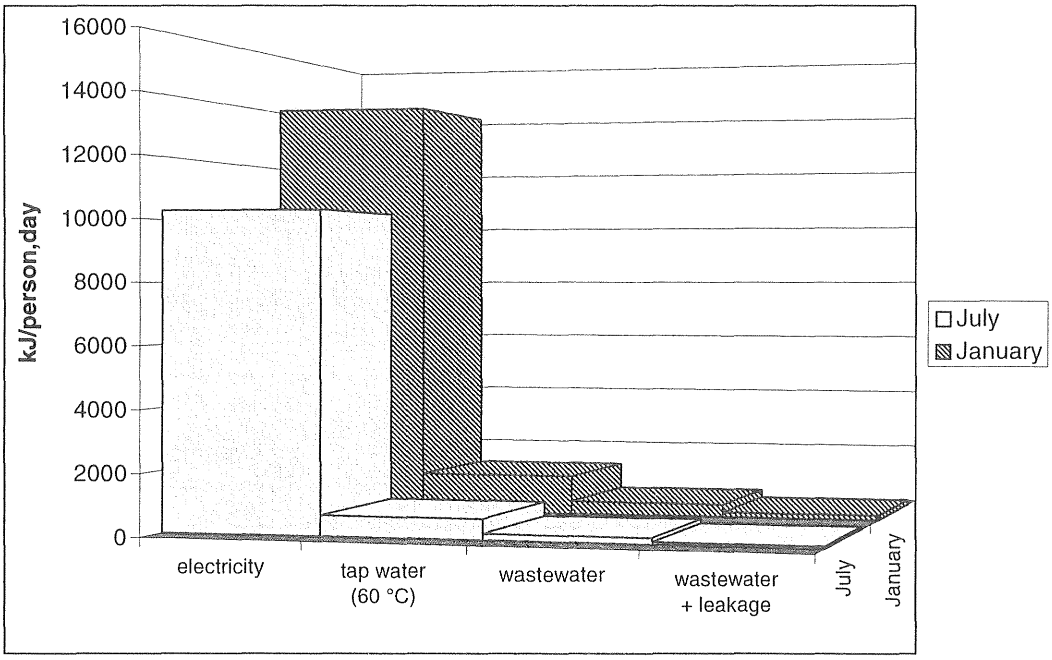

Figure 5. The calculated amount of exergy needed to heat tap-water with electricity and the exergy content in the heated water after different degrees of dilution with cold water. It should be noted that it has been assumed that energy losses are zero. Calculations based on data from Bergsjön.

Exergy analysis of organic matter and nutrients

The results of the exergy analysis of organic matter and nutrients are presented in Figure 6.

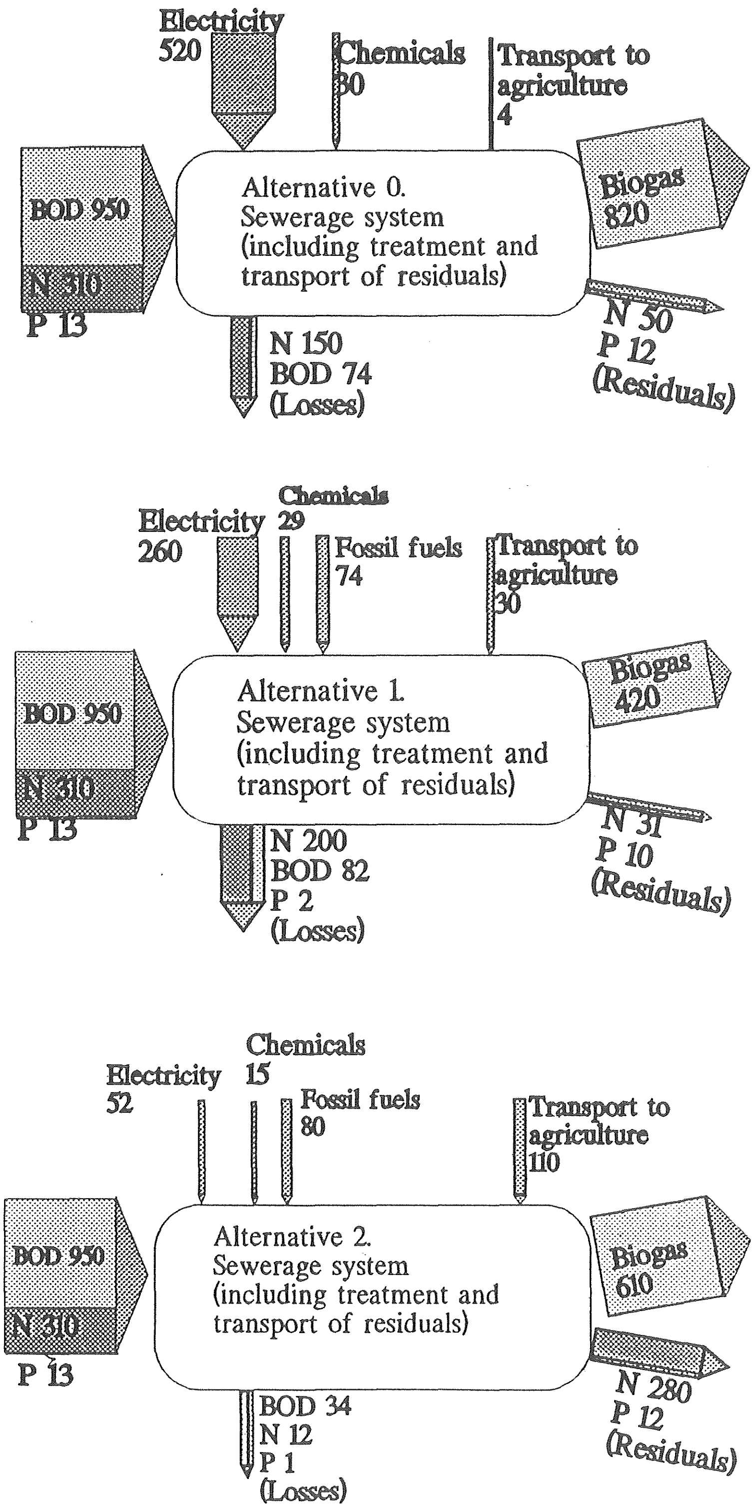

Figure 6. Exergy (kJ/person, day) of sewage treatment and handling of residuals

There are several ways to compare the system efficiency of the various alternatives, using the results from Figure 6. In Figure 7 the parameters *Operation* and *Total consumption* are presented.

Operation deals with the consumption of resources for operation and transport and is calculated as the sum of the exergy of operational resources and exergy needed for the transport of residuals to agriculture. In *Total consumption,* all exergy use has been seen as consumption, except for the useful residuals produced. *Total consumption* is calculated as the sum of exergy in: incoming sewage, operational resources and transport of residuals to agriculture minus the exergy in the residuals.

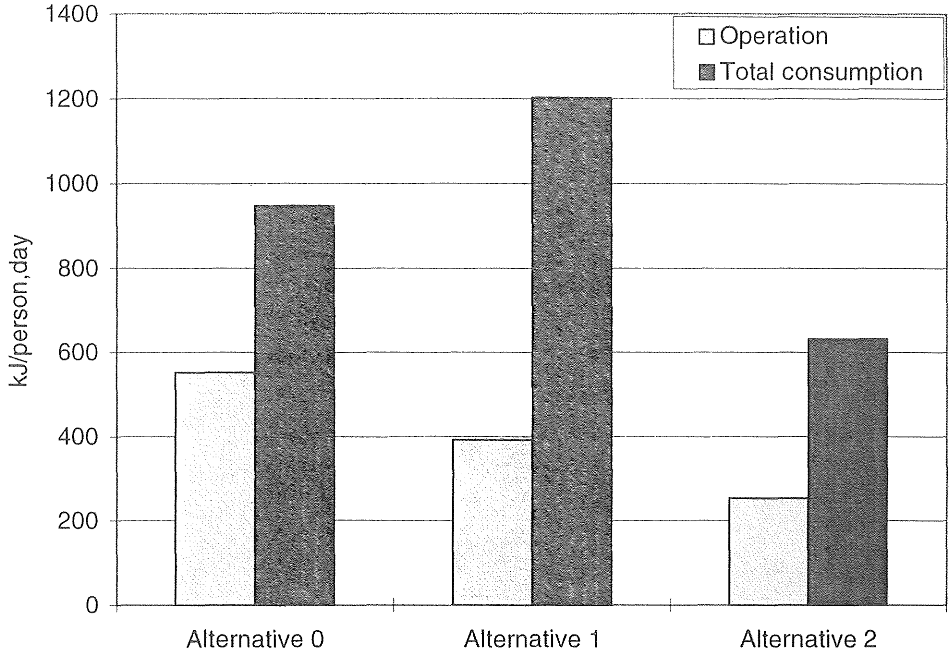

Figure 7. The total exergy consumption and the exergy of operational resources

Alternative 2 is the most advantageous system, looking at the exergy of operational resources. The main reason for this is the lower use of electricity. Alternative 2 has also the lowest total consumption of exergy. The main reasons for much higher total consumption in the two other systems, is the large electricity consumption in alternative 0 and the relatively ineffective utilization of organic matter in alternative 1.

As mentioned before, one of the most important aspects of the sewerage systems concerns nutrients recycling. The system efficiency of nutrients recycling can be further discussed, when the exergy parameters are compared with the degree of phosphorus and nitrogen recycling, (Figure 8).

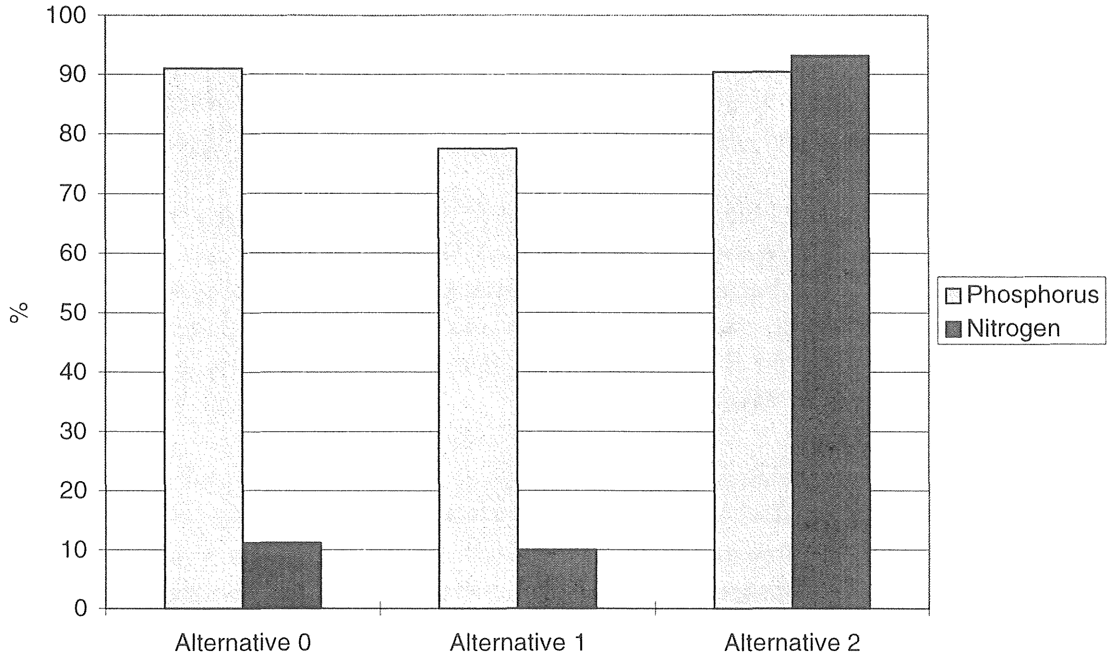

Figure 8. The potential for phosphorus and nitrogen recycling for the various systems

Figure 8 shows a great potential for phosphorus recycling for all the systems, but this is just the ideal image. The sewage sludge is not used to a large degree today, despite the high content of phosphorus. There is concern over the quality of, and health risks related to, the use of sewage sludge. In the sewer system, urine and faeces are mixed with greywater, stormwater and industrial discharges, and will inevitably be polluted by heavy metals and toxic organic substances. The quality of the residuals may probably be improved if either alternative 1 or 2 is implemented. But there are still a lot of unknown aspects about the systems in alternative 1 and 2. The knowledge about the health risks of, for example, the use of human urine as a fertilizer is today insufficient.

When comparing exergy parameters and nutrients recycling, one can see that alternative 2 is effective. Alternative 2 is the only alternative where nitrogen is seen as a resource. The effort in alternative 0 and 1 is to protect the receiving water from nitrogen discharge. The strategy has been to denitrify the nitrogen.

DISCUSSION

A combination of exergy analysis in order to estimate the use of physical resources and an analysis of the potential to utilise the nutrients from a sewerage system in agriculture could be helpful tools when discussing the sustainability for different systems. However, it should be emphasised that a low consumption of physical resources and a high degree of circulation of nutrients are not the only criteria that should be met in order to achieve a sustainable sanitary system.

The use of limited resources, such as phosphorus ores, needs special attention when discussing sustainability. However, an exergy analysis gives little information about the management of phosphorus within a system. Thus, a special study of phosphorus flows is necessary. By comparing the results from material balances and exergy analysis, a more detailed picture of the sustainability can be achieved.

The exergy analysis shows that the largest input of exergy to a sewerage system, during operation, is due to the heating of tap-water. It should be noted that the calculated exergy is underestimated because the energy losses to the surrounding air and ground are not included. However, the considerably amount of exergy consumed when heating tap water could be reduced if an energy source with a lower quality, such as district heating, is used instead of electricity.

Considering the flows related to the handling of organic matter and nutrients it is obvious that the flows due to organic matter dominate. It is also shown that the possibilities to recover some of the exergy as methane gas will have a strong influence on the total exergy consumption needed for operation. Comparing the flow due to nutrients it is obvious that the flow due to phosphorus is almost insignificant, but the flow due to nitrogen has a significant impact on the result. This reflects the statement that one important reason to recycle nitrogen is the amount of exergy needed to produce nitrogen fertilizer.

In this study only the direct inflow of exergy due to electricity and chemicals has been considered. If the total amount of exergy needed to operate a sewerage system should be estimated, the production of electricity and chemicals should also be analysed. However, the result of such analyses will be very dependent on how those products are produced.

The present study shows that local treatment of sewage, within a settlement of a town, could be an interesting alternative to large-scale sewerage systems. Especially a system with separate handling of three fractions of sewage; urine, blackwater and greywater is a comparatively good concept. The system is exergy effective and there is a great potential of phosphorus and nitrogen recycling. The separation systems are however not yet fully evaluated. The system has only yet been tested in small-scale systems, and the effects of the use of human urine as a fertilizer is not yet fully evaluated.

CONCLUSIONS

The study shows that the hypothetical calculated exergy consumption during operation will be lower in a system with local treatment and urine separation toilets compared with a conventional alternative. The amount of phosphorus that could be recycled is the same for the studied alternatives, but the amount of nitrogen that could be recycled is considerably higher for systems with urine separation techniques.

ACKNOWLEDGMENTS

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