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ENVIRONMENTAL SYSTEMS ANALYSIS OF WASTEWATER SYSTEMS IN A RIVER BASIN – CASE STUDY SÄVJAÅN

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Abstract

The EU framework directive states that all water bodies within the union should achieve good ecological status 2015. Reducing discharges from on-site wastewater systems is identified as an important means to ameliorate the quality of Swedish waters. This article presents a tool, VeVa River Basin, developed to assess the environmental impact from sewage systems in a river basin. Three scenarios for the year 2030 were compared with the existing systems in a case study of Sävjaån in the municipality of Uppsala, Sweden. Modelling results indicated that the phosphorus discharge to Sävjaån River from existing on-site wastewater systems could be reduced by 70 %. Consequently, existing systems in the area should be attended to, regardless of a presumptive future expansion in the area or types of wastewater systems chosen. The minimum phosphorus discharge was achieved in the scenario with connection to central systems, however the sensitivity analysis illustrates that the differences are marginal owing to variation in system performances. The modelling also included nutrient recycling, energy analysis and discharge of nitrogen, BOD_7 and cadmium. The future version of VeVa River Basin, where a cost module is included, will be a very useful tool for selecting measures in river basin management plans.

Key words – Environmental systems analysis; on-site systems; wastewater management; wastewater treatment; VeVa

Introduction

The share of the total phosphorus discharge to seawater from private on-site wastewater systems in Sweden is approximately 20 %, but there are variations from one part of the country to another and variations dependent on what type of reference base that is chosen for the calculations. The Water Authority for the North Baltic River Basin District assessed the share from private on-site systems to be 7 % of the total discharges and 10 % of the discharges from anthropogenic activities. The total amount of phosphorus discharges in Sweden from private on-site wastewater systems is 650 tonnes per year, while the phosphorus discharges from municipal wastewater treatment plants is 500 tonnes (Brandt et al 2005). This is remarkable since the number of households with private systems is much smaller than the number of households connected to municipal wastewater treatment plants. If all private on-site wastewater systems were upgraded to the standards recommended by the Swedish Environmental Protection Agency, the total phosphorus discharges from this category would be reduced with 40 % (Palm 2005). The EU framework directive states that all waterbodies within the union should achieve good ecological status by 2015. Reducing the discharge from private sewage systems is identified as an important means in the work of ameliorating the quality of Swedish surface waters. Attending to the large amount of private sewage systems that do not fulfil legal requirements of nutrient reduction will presumably make part of the forthcoming river basin management plans.

In the planning process for water and sanitation in a specific area, there is a choice not just between different technologies, but also between on-site systems for single households, local collective systems and connection to central systems.

The Swedish research program Sustainable Urban Water Management developed tools for planning of sustainable urban water and sanitation (Malmqvist et al 2006). One of the tools, URWARE, is used for environmental system analysis for a given urban area (Jeppsson et al 2005). A follow-up project was initiated to develop a new tool, the VeVa model, based on knowledge from URWARE for selection of appropriate solutions in former summerhouse areas (Erlandsson, 2007). The model has been further developed in order to enable the analysis of an entire river basin divided into several sub-areas with a mixture of sewage systems. This article presents the new tool, VeVa River Basin, applied in a case study of the river basin of Sävjaån, in the municipality of Uppsala, Sweden.

The VeVa model

The aim of the VeVa project was to develop a simple and user-friendly Excel-based model to support decision-makers when estimating the most appropriate wastewater solution for housing areas where no central sewer system exists. The model has one function where the environmental impact is compared between the systems when used for a specific transition area (Erlandsson 2007, Kärrman et al. 2008). The other function permits the user to make the comparison between complex scenarios where e.g. the number of inhabitants, percentage of summerhouses and the mixture of used systems can be varied in a river basin.

The VeVa model deals with two types of environmental issues: substance flow analysis and energy analysis. The substance flow analysis includes the fluxes of phosphorus, nitrogen, BOD_7 and cadmium to water and arable land. The discharge to water is divided into different types of recipients (groundwater, surface water within the studied area and surface water outside the studied area) according to the characteristics of each system. The fluxes to arable land are seen as the recycling potential of nitrogen and phosphorus and the thereby linked fluxes of cadmium. The recycling of nutrients is differentiated into fractions of easily available or unavailable to plants.

For the energy analysis both construction and operation phases are included, along with eventual energy recovery, using the principles of life cycle assessment. The model focuses on wastewater systems, but since the construction of pipes for drinking water often is performed at the same time as the construction of pipes for waste water when connecting households to common wastewater treatment plants, the supply of drinking water is included in all calculations. Schematic flow-chart of

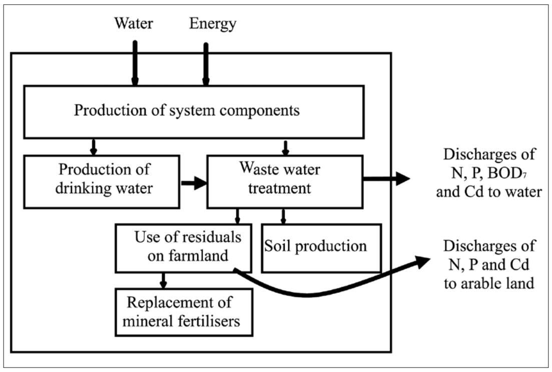

Figure 1. *Flow-chart for analysis with the VeVa model.*

the substance flow and the energy analysis is given in Figure 1.

The VeVa model consists of substance flow models of components in wastewater systems, such as pre-treatment tanks, filter beds, small wastewater treatment plants etc. These sub-models are linked together to form complete system structures for management of wastewater. Some of the models already existed in the first version of VeVa (Kärrman et al. 2008) while other models are designed for the first time in VeVa River Basin. Modelling results are principally given in annual average values.

System structures

Seven system structures for wastewater and three systems for drinking water were studied for the river basin of Sävjaån. The wastewater systems were sorted in three categories, each goes with its specific system for drinking water: 1) On-site systems for single households (private wells), 2) Local systems (local water works) 3) Connection to a central system (central water works). The seven wastewater systems are given in Table 1. More details about them are given by Erlandsson (2007) and Holm (2008).

The central systems are designed for over 100 000 p.e. (person equivalents), whereas the local system can be chosen for different dimensions; 75 p.e., 150 p.e., 400 p.e. and 1 000 p.e.

Connection to central large scale wastewater treatment plants

"Central wastewater treatment plant" should be interpreted as a treatment plant located outside the river basin in point, hence charging another recipient with nutrients and pollutions. The connection demands pipes

Table 1. *Studied systems.*

System	Category (wastewater treatment and drinking water)
Connection to large scale wastewater treatment plant 1	Central system
Connection to large scale wastewater treatment plant 2	Central system
Local collective wastewater treatment plant	Local system
On-site treatment plant	Single system
Closed collection tank	Single system
Filter bed system (expanded clay)	Single system
Infiltration	Single system

to be built long distances. The treatment process has been chosen to correspond to a modern, Swedish, large-scaled treatment plant, with chemical reduction of phosphorus and an activated sludge reactor designed to reduce nitrogen. In this study properties might be connected to two different treatment plants outside the river basin. The reductions in those two plants are the same for nitrogen (71 %), phosphorus (99 %) and BOD_7 (98 %), but differs for cadmium 80 % (Uppsala municipality 2003, 2004, 2005 and 2006) and 91 % (Lundh, P., pers. com.). The sewage sludge produced is assumed to be used as a fertiliser in agriculture.

Local collective wastewater treatment plant

The local treatment plant is a Sequencing Batch Reactor (SBR) including mechanical, biological and chemical treatment. The reduction is independent of the scaling. Figures for reduction may differ (Bengtsson et al. 1997). In this study typical reduction figures for a Biovac plant is used, which give 93 % for phosphorus, 40 % for nitrogen and 95 % for BOD_7 (Bengtsson et al. 1997). The reduction of cadmium is assumed to be the same as in the central wastewater treatment plant; 80 %. The sludge is transported to a central wastewater treatment plant where the sludge is mixed with municipal sludge and used as a fertiliser in agriculture.

On-site wastewater treatment plant

The system dimensioned for single households is a Sequencing Batch Reactor (SBR) including mechanical, biological and chemical treatment. Used figures for the reduction (Hellström & Jonsson, 2003) are 90 % for phosphorus and BOD_7, and 40 % for nitrogen. The reduction of cadmium is assumed to be the same as in the central wastewater treatment plant; 80 %. The sludge is transported to a central wastewater treatment plant where it is mixed with municipal sludge and used as a fertiliser in agriculture.

Pre-treatment tank

In the pre-treatment tanks particulate matter is separated from the water. This process involves a minor reduction of pollutants. In this study reduction figures are chosen in between the most extreme values found in the literature, which gives 7 % of phosphorus, 15 % of nitrogen and BOD_7 (Swedish Environmental Protection Agency, 1985 and 1990) and 25 % of cadmium (Wittgren et al. 2003).

Closed collection tank

Blackwater is conducted to a closed collection tank, which is emptied once a year. Blackwater is then transported to a central treatment plant where it is treated in the same way as incoming wastewater. The tanks are assumed to be completely tight, thus the local recipient is not charged with any pollution.

Greywater is lead to a pre-treatment tank and further to a filter bed after which the water reaches the local recipient. The reduction is accomplished by biological, chemical and physical processes when water is in contact with the filter material. The system is considered to be moderate in reducing nitrogen, phosphorus and cadmium but excellent in reducing organic matter. The performance of a filter bed is affected by age and the composing material, therefore figures for reduction found in literature varies considerably (Palm et al. 2002, Nilsson et al. 1998, Wittgren et al. 2003). Typical reduction figures are chosen, which give 50 % removal of nitrogen and phosphorus (Palm et al. 2002; Nilsson et. al 1998), 90 % for BOD_7 (Palm et al. 2002) and 30 % for cadmium (Wittgren et al. 2003) for the combined system pre-treatment tank and filter bed. Sludge from pre-treatment tanks is transported to a central wastewater treatment plant to be mixed with the municipal sludge and utilised as soil improver on farmlands, which is true for all systems with pre-treatment tanks. When the sand filter is saturated, the filter sand is assumed to be used as a technical soil in ground constructions.

Filter bed system with expanded clay

This system is similar to the filter bed system except for the use of expanded clay as filter media in order to remove phosphorus to a higher degree. This filter media is also expected, when it is saturated, to be used as a fertiliser in agriculture. Figures for the reductions of phosphorus and nitrogen in a filter with expanded clay are taken from Hellström & Jonsson, 2003 and the reductions of BOD_7 and cadmium are assumed from Krogstad et al. 2000. The total system with a pre-treatment tank and an expanded clay filter is excellent in phosphorus and BOD_7 removal (95 % and 91 % respectively) but on the other hand moderate in terms of treatment of nitrogen (50 %) and cadmium (30 %).

Infiltration

The wastewater is conducted to the infiltration through a pre-treatment tank. Water pipes spread the water into the ground where it percolates. Reduction processes as well as the variation in performance are the same as in a filter bed. A difference is that the construction is manufactured with natural material on site. The model handles both infiltration with groundwater and local surface water as the principal recipient. Assumed removal for the system is 30 % of nitrogen (Palm et al. 2002) and cadmium (Wittgren et al. 2003), 70 % of phosphorus (Palm et al. 2002) and 90 % of BOD_7 (Palm et al. 2002). When saturated, the material from the infiltration construction has no further use.

Case study Area Sävjaån

The new tool, VeVa River Basin, has been used in a case study of the river basin of Sävjaån, east of Uppsala, Sweden. The area of the river basin is 730 km^2 and embraces four municipalities, se Figure 2. The central parts are popular for living due to a beautiful varying landscape and the commuting vicinity to both Arlanda airport and Uppsala. However the supply of drinking water is poor in some areas, with a high contamination risk of relic salty groundwater, and the charge of phosphorus from private sewage systems on the river system is already excessive. In some areas wastewater contributes with as much as 40 % of the total phosphorus load (Orback 2007). The river basin of Sävjaån is the only part of the river basin of Fyrisån that has no migration obstacles to fish, thus being important for reproduction to many species. The lower part of the river system is designated a Natura 2000 site and several endangered species are found. Despite this, the ecological status concerning fish is classified as bad, in accordance to the EU-Water Framework Directive. It is probable that high phosphorus concentrations may be one of the parameters affecting the fish population in the area. According to municipal registers, the estimated number of households in the area is 8 600 of which 25 % are summer houses. A quarter of the households are connected to the central wastewater treatment plant "Kungsängsverket" in Uppsala, two thirds have private sewage systems and the rest (~7 %) are connected to minor local treatment plants. The private systems were distributed on 40 % of conventional systems with pre-treatment tanks followed by infiltration, 14 % of pre-treatment tanks followed by a filter bed, 17 % of closed collection tanks, 2 % of either reed beds, on-site wastewater treatment plants or dry toilets and 27 % of inferior systems (i.e. pre-treatment tanks solely). The focus of the study was to analyse whether a sage wastewater management of private on-site systems could half today's phosphorus load on river Sävjaån until year 2030 and moreover enable an expansion in the area. Three future scenarios were created and compared with regard to environmental impact and energy use: 1) Connection of houses along road 282 to central systems 2) On-site systems 3) Establishment of *local collective* treatment plants where possible. The inhabitants of the area differed between the scenarios. According to different expansion scenarios, identified by the municipality of Uppsala, 10 800 persons would live in the area in scenario 1 and 10 900 in the two others.

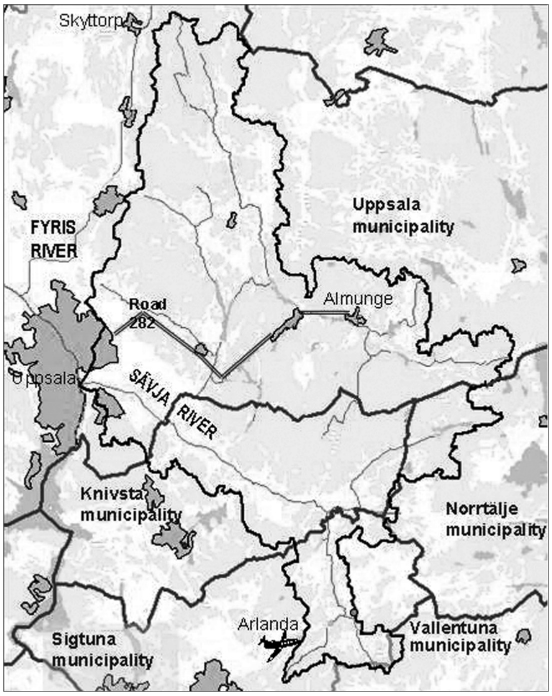

Figure 2. *The river basin of Sävjaån.*

Table 2. *Discharges to water from wastewater systems.*

	Nitrogen (tonne/year)				BOD_7 (tonne/year)				Cadmium (kg/year)			
	Existing systems	Sc.1	Sc.2	Sc.3	Existing systems	Sc.1	Sc.2	Sc.3	Existing systems	Sc.1	Sc. 2	Sc. 3
Surface recipient outside river basin	8	15	8	7	3	6	3	3	29	63	30	29
Groundwater (inside river basin)	9	10	16	7	8	9	14	6	43	57	86	38
Surface recipient inside river basin	19	15	25	31	76	15	25	23	118	41	68	80

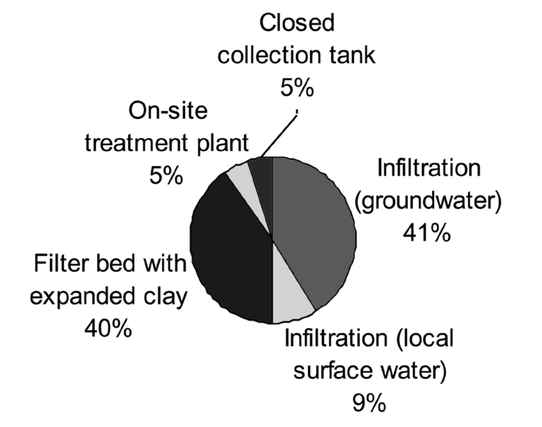

Figure 3. *The assumed partition of on-site systems.*

However, the partition of the different on-site systems was set to the same in all scenarios, see Figure 3. This particular partition is estimated and based upon present practices in the municipalities when choosing on-site systems. More details of each scenario are described by Holm (2008).

Results and discussion

Discharges to water

Discharges to water from calculations in VeVa are given in table 2 and Figure 4. In terms of eutrophication, Sävjaån River is assessed to be phosphorus-limited, Therefore emphasis is given to the phosphorus results. The results show that improving the existing sewage systems in the area diminishes the total load of phosphorus and BOD_7 significantly, whereas the loads of nitrogen and cadmium are not significantly affected. Scenario 2 (predominantly on-site systems) gives the largest total discharges for all substances. Discharges of phosphorus into groundwater and river Sävjaån shows that the existing average on-site system (including the local collective systems) does not achieve the basic Swedish legislated requirements upon private sewage systems, not even when excluding infiltrations with groundwater as recipient. Today's annual load of phosphorus on Sävjaån from wastewater is 3 tonnes, which could be diminished to less than 1 tonne (890 kg) just by attending to the private sewage systems so that they fulfil the specific requirements for sensitive areas. The total load from the area upon river Sävjaån and surface waters outside the

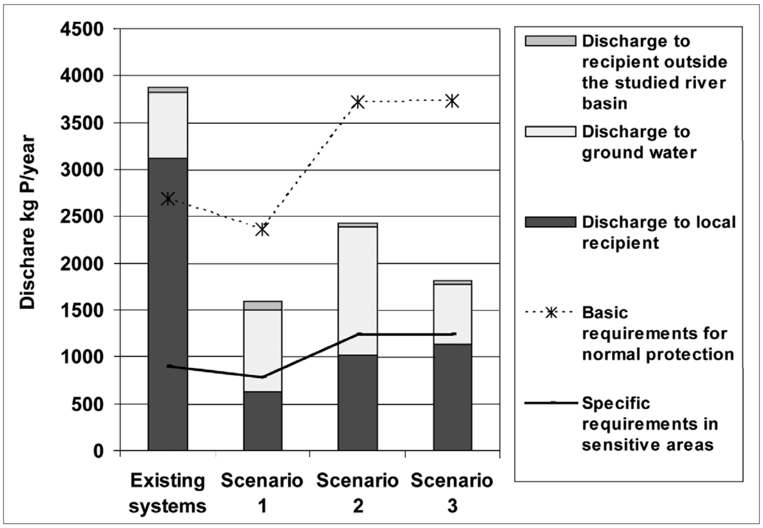

Figure 4. *Results in VeVa: discharge of phosphorus to different recipients. The lines indicate the discharge to the local recipient if all private systems in the scenarios fulfilled the requirements for either basic or specific protection.*

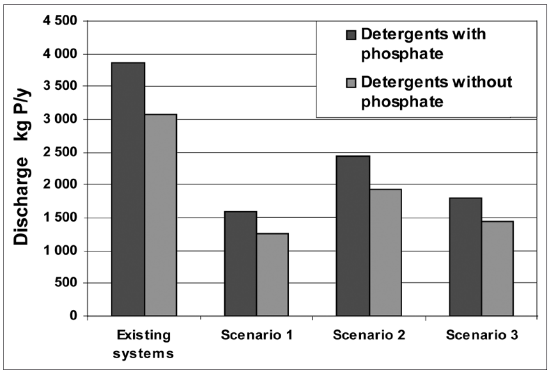

Figure 5. *Total discharge of phosphorus when using detergents, with and without phosphate.*

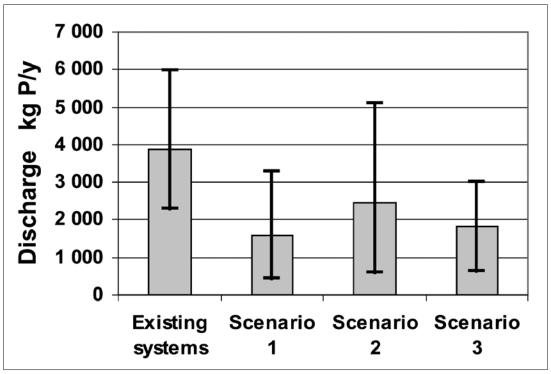

Figure 6. *Insecurity of results due to observed variations of system performance.*

river basin is reduced to ca 25 % of today's load for scenario 1 (certain areas to central systems) and 30 % for scenario 2 and 3. The low discharge in scenario 1 is partly explained by a smaller total population in the area compared to scenario 2 and 3, however, the main reason is the larger number of households connected to the central wastewater treatment plant with the utterly reduction efficiency of phosphorus. The total discharge from on-site systems in scenario 2 is higher than for scenario 3. Nevertheless scenario 2 gives a lower load upon river Sävjaån than the local collective systems, due to the discharge to groundwater from infiltration systems. The phosphorus load on river Sävjaån is halved in all three scenarios. A sensitivity analysis was performed in order to estimate the potential deload on river Sävjaån that a prohibition of detergents with phosphate would do. Figure 5 shows that the quantative difference is biggest for existing systems (reduction of ca 700–800 kg) and for on-site systems which have the greatest loads.

As previously described, the performance of the investigated wastewater systems varies, particularly for filter beds and infiltration. This insecurity has a significant influence on the results, which can be seen in Figure 6 where calculations in VeVa have been performed using the lowest and the highest figures of reduction for all included system. For example, the real total annual discharge of phosphorus from existing systems is hard to estimate, ranging from 2 200 kg to 6 000 kg, and the ranking between the future scenarios varies.

Since scenario 2 implicates the greatest part of on-site systems it is affected most by variations in performance and its span even surpasses its estimated discharge of phosphorus. The lowest reduction makes scenario 3 to the best choice, since there are fewer on-site systems than in the other scenarios. A low reduction accentuates the differences between the future scenarios, while a good performance reduces the divergence and merely no difference can be distinguished between them.

Energy use

The energy consumption is divided into fossil fuels and electricity. Holm (2008) and Erlandsson (2007) show that on-site systems consume predominantly fossil fuels while central and in particular local collective treatment plants use electricity. This characteristic consumption pattern can be distinguished for each scenario, but less accentuated since the scenarios have a mixture of different systems, see Figure 7. No scenario is definitely more favourable than the others seeing that the total energy consumption is about 900 MJ per person and year in all scenarios, differentiated only in regard to the division into fossil fuels and electricity.

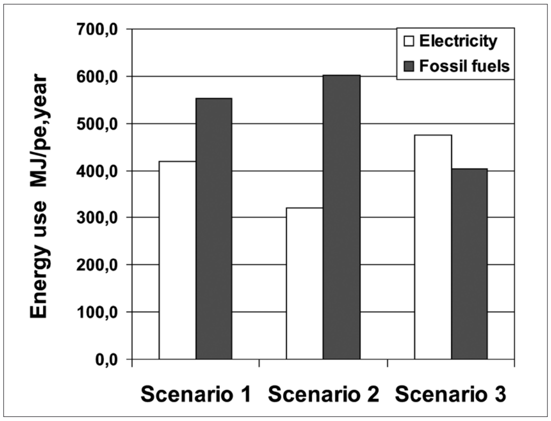

Figure 7. *Total annual use of energy including construction and operation phases for the different scenarios.*

Table 3. *Recirculation of nutrients and thereby linked fluxes of cadmium.*

Recirculated to arable land	Nitrogen (kg/person,year)			Phosphorus (kg/person,year)			Cadmium (mg/person,year)		
	Sc. 1	Sc.2	Sc.3	Sc.1	Sc.2	Sc.3	Sc.1	Sc.2	Sc.3
Available	0.08	0.09	0.13	0.19	0.15	0.19	12.8	11.13	12.49
Not Available	0.21	0.25	0.37	0.19	0.15	0.20	–	–	–
Soil Improvement	–	–	–	0.01	0.01	0.01	0.19	0.28	0.12

Recycling of nutrients

Recycling potentials are presented in Table 3. Scenario 3 is the most advantageous concerning recycling of nitrogen available to plants, due to the closed batch reactors in the local collective treatment plants which prevent nitrogen to escape into the air. The substantial part of the recycled nitrogen is not available to plants. Recycled phosphorus is in equal parts divided into available and not available to plants. Scenario 2 has the lowest potential of recycling, mainly due to the large number of infiltrations which are not recycled at all. The fluxes of cadmium follow those of phosphorus.

Conclusions

- The VeVa tool has been further developed to enable the analysis of the environmental impact from wastewater scenarios in River Basins, which is useful for the Water Authorities when establishing river basin management plans.
- By attending to existing private sewage systems the phosphorus load on river Sävjaån could be reduced by 70 %. Consequently, existing systems in the area should be dealt with in some way, regardless of the wastewater systems chosen and a presumptive future expansion in the area.
- The minimum phosphorus load on Sävjaån River is achieved in the scenario with connection to central systems, however the sensitivity analysis illustrate that the differences are merely marginal owing to variation in system performances.
- The differences of energy consumption between the systems are counterbalanced and the differences are barely distinguishable in the mixed scenarios in this study.

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References

Bengtsson, M., Lundin, M. & Molander, S. (1997). *Life Cycle Assessment of Wastewater Systems. Case studies of Conventional Treatment, Urine sorting and Liquid Composting in three Swedish Municipalities.* Technical Environmental Planning, Rapport 1997:9, Chalmers tekniska högskola, Göteborg. 99 p.

Brandt, M., Svensson, P. & Winqvist, E-M. (2005). *Källfördelning av näringsämnen på vattendistrikt. Tilläggsrapport till SMED&SLU rapport. Klassificering av påverkan av näringsämnen på rapporterings- och havsområden.* SMHI. 5p.

Erlandsson, Å. (2007). Environmental Assessment of Wastewater Handling in Transition Areas. (Miljöbedömning av VA-lösningar i omvandlingsområden), Master thesis, Swedish University of Agricultural Sciences (manuscript in Swedish)

Hellström, D. & Jonsson, L. (2003) *Bra små avlopp – sammanfattning. Utvärdering av 15 enskilda avloppsanläggningar.* Rapport nr 15, Stockholm Vatten. 5 p.

Jeppsson, U., Baky, A., Hellström, D., Jönsson, H. & Kärrman, E. (2005). *The URWARE Wastewater Tratment Plant Models.* Rapport 2005:5. Urban Water. 286 p.

Holm, C. (2008). Environmental assessment of wastewater management in the river basin of Sävjaån in 2030. (Miljösystemanalys för avloppshantering i Sävjaåns avrinningsområde år 2030), Master thesis, Lund University (manuscript in Swedish)

Krogstad, T., Jenssen, P., Stensen, G. (2000). Heavy metal accumulation in subsurface flow constructed wetlands treating domestic wastewater. P. 1078 in 7th Int Conf on Wetand Systems for Water Pollution Control, University of Florida, Vol. II.

Kärrman, E., Erlandsson, Å., Elfström, M., Olsson, S., Hellström, D., Björlenius, B., (2008). Tool for Environmental Assessment of Wastewater Handling in Transition Areas (Verktyg för miljösystemanalys av VA-lösningar i omvandlingsområden), Stockholm County Councils Office for Regional Planning

Naturvårdsverket. (1985). *Avloppsvatten – infiltration. Förutsättningar, funktion, miljökonsekvenser.* Nordisk samproduktion, Naturvårdsverket/Nordiska ministerrådet.

Naturvårdsverket. (1990). Allmänna råd 87:6. *Små avloppsanläggningar*

Nilsson P., Nyberg F. & Karlsson M. (1998) *Markbäddars funktion – kontroll och utvärdering av markbäddar* Rapport 4895, Naturvårdsverket. 57 p.

Orback, C. (2007, manuskript). *Utvärdering av enskilda avlopps betydelse för vattenkvalitén i sjön Trehörningen.* SLU, Institutionen för miljöanalys. 44 p.

Palm, O. Malmén, L. & Jönsson, H. (2002). *Robusta uthålliga små avloppssystem. En kunskapssammanställning*. Rapport 5224. Naturvårdsverket. 117 p.

Uppsala municipality. (2003*). Miljörapport 2003, Kungsängsverket, Uppsala.* Sanitation office Uppsala municipality. 22 p.

Uppsala municipality. (2004*). Miljörapport 2004, Kungsängsverket, Uppsala.* Sanitation office, Uppsala municipality. 22 p.

Uppsala municipality. (2005*). Miljörapport 2003, Kungsängsverket, Uppsala.* Sanitation office, Uppsala municipality. 22 p.

Uppsala municipality. (2006*). Miljörapport 2003, Kungsängsverket, Uppsala.* Sanitation office, Uppsala municipality. 22 p.

Wittgren, H., Baky, A. & Palm, O. (2003). Environmental systems analysis of small scale sanitation solutions. *Ecosan – closing the loop. Proceedings of the 2nd in. symp. on ecological sanitation, incorporating the 1st IWA specialist group conference on sustainable sanitation, April 7–11, 2003, Lübeck, Germany.*

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