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Comparison of carbon footprints and eutrophication impacts of rural on-site wastewater treatment plants in Finland

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A B S T R A C T

In many sparsely populated areas, such as the Finnish countryside, most houses are not connected to centralized sewers due to excessive distances. On-site wastewater treatment plants are therefore necessary to reduce local emissions to meet the legislatory limits. Dozens of on-site wastewater treatment applications are marketed to households, with varying operating costs and pollution reduction potentials. The installation and use of these systems will cause environmental impacts outside the site, through their supply chains. The aim of this study is to analyze the potential tradeoff between the reduction of local emissions and the increase in life cycle impacts. Six alternatives were chosen for comparison, including the energy-demanding small sewage treatment plants and the various types of soil systems (including source separation systems). The results show that the dry toilet in combination with gray-water treatment had the least impact and the package plants the greatest. However, which is the optimal on-site system solution for a certain property is strongly dependent on the local conditions and, therefore, appropriate guidance is definitely needed.

1. Introduction

Issues related to protection of freshwater resources are growing more and more topical worldwide. Wastewater treatment systems are designed to minimize the environmental impacts of wastewater. In modern industrialized countries, a central sewer system leads wastewater from urban areas to be treated at municipal wastewater treatment plants (WWTPs), but in rural areas, the wastewater should be treated on-site without pollution to nearby freshwater ecosystems and groundwater.

Finland is a sparsely populated country, and approximately one million people, around 20% of its inhabitants, live in houses that are not connected to central sewage systems. This means that about 350,000 permanent residences and a further 450,000 holiday homes must treat their own wastewater on-site. Wastewater from sparsely populated areas and secondary residences is the second most significant source of phosphorus loading to water systems today, after agriculture. Finland has almost 200,000 lakes, often with settlements nearby. Phosphorus in wastewater from rural homes contributes considerably to the eutrophication of inland water systems.

The Government attempts to control the emissions with new regulation, in the Government Decree on Treating Domestic Wastewater in Areas Outside Sewer Networks (209/2011) (referred to below as the "On-site Decree"). This decree sets minimum standards for wastewater treatment and the planning, construction, use, and maintenance of treatment systems. The main goal of the On-site Decree is the conservation of nearby water systems, such as wells and beaches. Also, hygiene and health issues are considered. Before the new decree, the fundamental requirements set forth in relation to on-site wastewater treatment dated from the 1960s. Therefore, a significant proportion of on-site systems will require improvements if they are to meet the requirements of the decree. It is hoped that the new regulations will lead to reduction in the total phosphorus load from the current level of almost 400 metric tons a year to less than 150 metric tons.

Several studies show that the performance of on-site systems varies greatly and is often strongly dependent on their maintenance (for example Hellström and Jonsson, 2003; Vilpas and Santala, 2007). The problem is to find reliable information for comparison of systems in order to identify the best solution available for each individual household. The aim of this study was to provide objective information to consumers, public authorities, and

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producers by increasing knowledge of different on-site systems on the Finnish market through comparison of their environmental impacts over their life cycle. Carbon footprint and freshwater eutrophication were chosen for more in-depth evaluation. There exist only a few studies that consider the life-cycle impacts of on-site systems. In general, these focus on few systems and address variation between similar types of systems (Benetto et al., 2009; Dixon et al., 2003; Tidåker et al., 2007; Emmerson et al., 1995). In this article, we compare six alternatives representing the full spectrum of treatment systems commonly used in Finland.

2. Material and methods

2.1. Description of the systems

The goal and scope of the study was to analyze the commonly available on-site wastewater treatment options for rural areas of Finland. Six alternatives were chosen for comparison: 1) sequencing batch reactor (SBR), 2) biofilter, 3) soil infiltration, 4) buried sand filter, 5) holding tank for black water and soil infiltration for gray water, and 6) dry toilet with gray-water treatment. Two sub-alternatives were used for dry-toilets: soil infiltration A) or pre-fabricated gray-water filter B). In the last two systems listed, gray and black water were sewered separately. The alternatives chosen represent average products on the market, not any particular commercial products. All products are capable of reaching the purification performance of the on-site decree (85% reduction in phosphorous, 40% in nitrogen and 90% of biological oxygen demand (BOD)).

The alternative on-site systems and the sludge treatment are described briefly below, and a summary of the assumptions is given in Table 1.

2.1.1. Sequencing batch reactor

A sequencing batch reactor is a prefabricated biological–chemical wastewater treatment plant in which the wastewater is purified in batches. Its operation is based on an activated sludge process. In addition, the phosphorus is chemically precipitated. The SBR studied includes a polyethylene tank with two chambers (storage and process), along with technical equipment, including, for example, a central processing unit, four pumps (feed, discharge, sludge, and chemical), an air compressor, and internal pipework. Wastewater is led into the SBR's storage chamber, from which a predefined batch of wastewater is pumped to a process chamber. In this process chamber, wastewater is purified by aeration and phosphorus is precipitated. In the final phase, wastewater is settled and clarified wastewater discharged. Some sludge from the process tank is recycled to the storage chamber to stabilize the process, but the excess sludge is pumped to a separate tank to be transported by truck for treatment at the municipal WWTP.

2.1.2. Biofilter

A biofilter is a prefabricated biological–chemical continuous-flow wastewater treatment plant. The process is based on carrier technology wherein the culture media for microbes are carrier units made of plastic. In addition, the phosphorus is chemically precipitated. The type of biofilter studied includes a tank made of polyethylene with 3–4 chambers as well as technical equipment, including, for example, a central processing unit, three pumps (transfer, recirculation, and chemical), and internal pipework. Wastewater is pre-treated in the biofilter's sedimentation chamber(s) (1–2), from which it flows to a process chamber. The recirculation pump circulates wastewater through the plastic filter media, after which the phosphorus is precipitated. Finally, the wastewater is clarified and discharged. Sludge from the final clarification/process tank can also be recycled and fed back to the sedimentation chambers. Excess sludge from the sedimentation chamber is transported for treatment at the municipal WWTP.

2.1.3. Buried sand filter

A buried sand filter is a sand and gravel filled excavation. Wastewater is trickled through the layers and purified biologically–mechanically in the process. The buried sand filter is constructed as a wide excavation filled with suitable sand and gravel (a filter bed). Wastewater is pre-treated in a three-chamber septic tank, from which it is distributed onto the filter bed. Wastewater infiltrates through the filter bed and is collected into the pipes in the bottom and led to a discharge. Sludge from the septic tank is transported for treatment at the municipal WWTP.

2.1.4. Soil infiltration

Soil infiltration is a wastewater treatment system in which the properties of natural soil are used to purify wastewater biologically–mechanically. The soil infiltration includes a shallow

Table 1
The basic assumptions of the on-site systems used in this study.

	SBR	Biofilter	Buried sand filter	Soil infiltration	Holding tank and soil infiltration	Dry toilet and soil infiltration	Dry toilet and gray-water filter
Life span (years)	30 (tank) 8 (equipment)	30 (tank) 8 (equipment)	30 (tank) 20 (filter bed)	30 (tank) 20 (infiltration)	30 (tank) 20 (infiltration)	30 (dry toilet) 20 (infiltration)	30 (dry toilet) 30 (gray-water filter)
Energy consumption (kWh/a)	365	700	0	0	0	0	22
Chemical consumption (l/m^3)	0.25 (PIX 115)	0.25 (PIX 115)	0	0	0	0	0
Excavation volume (m^3)	36 (plant) 5 (pipes)	36 (plant) 5 (pipes)	30 (tank + pipe) 102 (filter bed)	30 (tank + pipe) 41 (infiltration)	51 (tank) 5 (pipes) 30 (infiltration)	25 (tank + pipe) 30 (infiltration)	5 (pipes)
Sand and gravel for construction (m^3)	25	25	82	28	25	25	0
Maintenance service (times per year)	1	1	0.1	0.1	0.1	0.1	0
Removal of sludge (times per year)	2	2	2	2	1	1	0
Treatment efficiency (%)					(infiltration)	(infiltration)	(gray-water filter)
Organic matter	90	90	90	90	90	90	
Total phosphorus	80	80	70	80	80	80	20
Total nitrogen	40	40	30	40	40	40	20
Eutrophication emission factor[a]	0.7	0.5	0.5	0.15	0.15	0.15	0.5

[a] The eutrophication emission factor used in this study describes the amount of nutrients that ends up in the freshwater ecosystem. This factor is at its highest in the SBR case since the nutrients are more likely to reach the water system. This results from the fact that in the SBR the effluent is discharged less often but in larger quantities, whereas in other systems the effluent flow is lower and discharged continuously.